UN Climate Technology Centre and Network (CTCN), an operational arm of UNFCCC

Ministry of Forests and Environment, Government of Nepal

Customized weather and climate information system for climate-resilient agriculture in Nepal

Contract No.: UNEP/2022/339 (Umoja # 4700023937)

Output-2: Report on Diagnose the Existing System and Define the Needs

Accepted and approved for payment.
Bangkok, 27 January 2024

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THE SMALL EARTH NEPAL-2001

10 October 2023

RMSI

Acknowledgements

This Technical Assistance (TA) awarded by the UN-CTCN to RMSI a firm based in New Delhi (India) is duly acknowledged.

The study team would like to acknowledge and express heartfelt gratitude to Ms. Clara Landeiro (Regional Manager, Asia-Pacific, UN-CTCN) for providing her valuable support and directions in this project. We are also grateful to Mr. Sharad Babu Pageni (Under Secretary, CCMD, Ministry of Forests and Environment, Govt. of Nepal) and Dr. Buddi Poudel (Joint-Secretary and Chief, Ministry of Forests and Environment, Govt. of Nepal) for their guidance and support.

We would like to extend our sincere gratitude to Mr. Dhiraj Pradhananga (Project Proponent) from The Small Earth Nepal (SEN) for his support from the very onset of the TA.

Finally, we would like to extend our special thanks to all other stakeholders for providing necessary data and information required for the project and extending their full cooperation in this TA.

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List of Acronyms

AAS	Agro-met Advisory Bulletins
AICC	Agriculture Information and Communication Center
AITC	Agriculture Information and Training Center
AKC	Agricultural Knowledge Centres
AMIS	Agriculture Management and Information System
ARW	Advanced Research Weather
AWS	Automatic Weather Stations
AWS	Automatic Weather Stations
BRCH	Building Resilience to Climate Related Hazards
CAP	Common Alerting Protocol
CARIAA	The Collaborative Adaptation Research Initiative in Africa and Asia
CBS	Central Bureau of Statistics
CPDD	The Communication Publication and Documentation Division
CU	Cumulus
DANIDA	Danish International Development Agency
DHM	Department of Hydrology and Meteorology
D-Index	Index of Agreement
DTC	Data Testbed Center
ECMWF	European Centre for Medium-Range Weather Forecasts
EMS	Environmental Modeling System
ERA5	Fifth generation ECMWF atmospheric reanalysis
FAO	Food and Agriculture Organization
FMI	Finnish Meteorological Institute
GDP	Gross Domestic Product
GFS	Global Forecast System
GIDC	Government Integrated Data Center
GLOF	Glacial Lake Outburst Flood
GTS	Global Telecommunications System
HDI	Human Development Index
HPC	High-Performance Computer
IDS	Integrated Development Society
IDS	Integrated Development Society
IMPACT	The International Model for Policy Analysis of Agricultural Commodities and Trade
IMV	Internal Model Variability
INDC	Intended Nationally Determined Contributions
ME	Model Error
METAR	Meteorological Aerodrome Report

MFD	Meteorological Forecasting Division
MOALD	Ministry of Agriculture and Livestock Development
MoALD	Ministry of Agriculture and Livestock Development
MOFE	Ministry of Forests and Environment
MOS	Model Output Statistics
MoSTE	Ministry of Science, Technology and Environment
MP	Microphysical
MPI	Message Passing Interface
MYJ Scheme	Mellor-Yamada-Janjic Scheme
NAMIS	Nepal Agricultural Marketing Information System
NARC	Nepal Agricultural Research Council
NCAR	National Center for Atmospheric Research
NFS	Network File System
NFS	Network File System
NPT	Nepal Time
nRMSE	Normalized Root Mean Square Error
NTV	Nepal Television
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
POD	Probability of detection
PPCR	Pilot Program for Climate Resilience
R	Correlation Coefficient
RADAR	RAdio Detecting And Ranging
RIMES	Regional Integrated Multi-Hazard Early Warning System
RMSE	Root Mean Square Error
RRTMG	Rapid Radiative Transfer Model for General Circulation Models
SMS	Short Message Service
SYNOP	surface synoptic observations
TAF	Terminal Aerodrome Forecast
TS	Threat Score
UHI	Urban Heat Island
UK	United Kingdom
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	United Nations Framework Convention on Climate Change
UPP	Unified Post Processor
USAID	United States Agency for International Development
UTC	Universal Time Coordinated
VHLEC	Veterinary Hospital and Livestock Service Expert Center

WMO	World Meteorological Organization
WRF	Weather Research and Forecasting
WRF EMS	Weather Research and Forecasting Environmental Modelling System
WRFDA	Weather Research and Forecasting Data Assimilation

1 Background and Rational

Nepal has been ranked as the 9th most affected country towards climate change (Eckstein et al., 2018[1]) but is one of the least contributors to the emissions of greenhouse gases (0.11% of global share). Nepal was identified as one of the four global hotspots for climate change risk and impact of climate change is seen in various sectors like biodiversity, agriculture, livestock, water sources, soil, tourism, health, etc. (MoSTE, 2014[2]). According to DHM (2015), during the last four to five decades, the rate of increase in annual maximum temperature (0.04 ^{o}C yr-1) over the country was significantly higher than the rate of increase in minimum temperature (0.01 ^{o}C yr-1). The occurrence of cold days and nights has decreased significantly during the last few decades (World Bank 2020[3]).

Temperature is projected to increase in the future climates under both low and high emissions scenarios and in the medium (0.92–1.07°C) and long-term (1.72–1.82°C) (MoFE, 2019[4]). This increase in temperature is likely to be more visible during the dry months (December–May) (World Bank 2020). An increase in the number of 'hot' days will be 19–27 days by 2045 and 26–43 days by 2065 (MoFE, 2019). The High Mountains are likely to experience the greatest warming of all the regions, and the west is likely to warm more than the eastern regions (MoFE, 2019).

The annual rainfall has significantly decreased at the rate of 3.7 mm (-3.2%) per month per decade and under various climate change scenarios n is projected to reduce in a range of 10 to 20% across the country by the end of this century (INDC of Nepal, 2016[5]). This rate of decrease in rainfall was more significant during monsoon (Jun-Sep) period (World Bank, 2020). Rainfall is increasingly falling as rain instead of snow in the high mountains, resulting in a loss of water (174 gigatons) in the Himalayan glaciers (USAID 2017[6]). During the last few decades, there was an increasing trend in the occurrence of extreme rainfall events, especially over western mid-hills and central high mountain regions. Central lowland regions have been receiving more daily extreme rainfall leading to increased incidences of flash floods (Karki et. al. 2017[7]). The increasing high intensity rainfall over the western mountainous region is indicative of a higher risk of

[1] Eckstein, D., Hutfils, M.-L., and Winges, M. (2018). Global Climate Risk Index 2019: Who Suffers Most from Extreme Weather Events? Weather-related Loss Events in 2017 and 1998 to 2017. Berlin: German watch Nord-Süd Initiative eV.

[2] MoSTE. (2014). Second national communication report to UNFCCC. http://unfccc. int/ resource / docs/ natc/ nplnc2.pdf

[3] World Bank (2020) Climate Change Knowledge Portal. https://climateknowledgeportal.worldbank.org.

[4] MoFE (2019) Climate change scenarios for Nepal for National Adaptation Plan (NAP). Kathmandu: Ministry of Forests and Environment (MoFE).

[5] INDC of Nepal (2016). https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/Nepal/1/Nepal_INDC_08 Feb_2016.pdf

[6] USAID (2017) Climate Risk Profile: Nepal. Available at: https://www.climatelinks.org/ resources/climate-risk-profile-Nepal

[7] Karki, R. *et al.* (2017) 'Rising Precipitation Extremes across Nepal', *Climate*, 5(1), p. 4. http://doi.org/10.3390/cli5010004

soil erosion and landslides (Karki et. al., 2017). The severity and frequency of drought is increasing, which are more significant for droughts of longer timescales (Dahal et. al., 2016[8]).

In the future climates, rainfall is likely to be more erratic, though it is likely that it will increase in the future climate throughout the country especially in the central and western regions. Winters are projected to be drier, whilst summers along with the monsoon are likely to be wetter in the future climate scenarios (MoFE, 2019). Overall, Nepal is one of the most vulnerable countries to climate change, water-induced disasters and hydro-meteorological extreme events such as droughts, storms, floods, inundation, landslides, debris flow, soil erosion and avalanches. Summer monsoon rains may increase threefold, resulting in more frequent summer flooding (World Bank 2020). The number of wet and extremely wet days will not only increase the likelihood of flash flooding, but also other water-induced hazards like landslides and soil erosion (MoFE 2019).

In the light of this, one of the tasks of this study to diagnose the existing system of DHM and NARC to prepare the agro-met bulletins and how the information is being disseminated to the public. Besides, there is need to assess the users' requirement for the weather forecast and advisories.

[8] Dahal, P. *et al.* (2016) 'Drought risk assessment in central Nepal: temporal and spatial analysis', *Natural Hazards*, 80(3), pp. 1913–1932.

2 Existing climatological & meteorological information system of Nepal

The Department of Hydrology and Meteorology (DHM) of Nepal is a vital government agency responsible for monitoring and managing the country's climatological & meteorological information system of Nepal. The main objective of DHM is to collect hydrological and meteorological data throughout Nepal, process the data, publish it and disseminate the data to the users such as water resource planners, developers, researchers and data seekers for the verification of extreme hydrological and meteorological events required for different purposes. Its main activities include (a) collect and disseminate hydrological and meteorological data and information for water resources, agriculture, energy, and other development activities, (b) Issue hydrological and meteorological forecasts for public, mountaineering expedition, civil aviation, and for the mitigation of natural disasters, (c) mitigate weather, flood and drought induced disaster by providing early warning services to the concerned communities, (d) conduct special studies required for the policy makers and for the development of hydrological and meteorological sciences in the region and (e) promote relationship with national and international organizations in the field of hydrology and meteorology.

The DHM has a mandate from Government of Nepal to monitor all the hydrological and meteorological activities in Nepal. DHM collects hydrological and meteorological data throughout Nepal, process the data, publish it and disseminate the data to users such as water resource planners, developers, researchers and data seekers for the verification of extreme hydrological and meteorological events required for different purposes. The scope of work includes the monitoring of river hydrology, water quality, sediment, limnology, snow hydrology, glaciology, weather, climate, agro-meteorology, air quality and solar energy. The Department has also extended its services in the sector of General and Aviation Weather Forecast regularly. The department delivers periodical Climate Bulletin to the public through its website and generate Agrometeorological Notice for Agriculture Management and Information System (AMIS) too. Besides, the department is providing its 24/7-day service of Flood Forecasting and Early Warning to public and related agencies during the period of Monsoon Season. DHM also issues hydrological and meteorological forecasts for public, mountaineering expedition, civil aviation, and for the mitigation of natural disasters on regular basis.

In the present study, the existing climatological & meteorological information system of Nepal has been thoroughly analyzed. All the weather forecasts and meteorological information are disseminated through the web site of Meteorological Forecasting Division (MFD) of Department of Hydrology and Meteorology (DHM) as well as through the official website of DHM. The MFD is situated at Tribhuvan International Airport, Kathmandu and offering weather forecasts, warnings, and climate information.

2.1 Foresting services of MFD

2.1.1 Weather forecast services

The present condition and weather forecast (tonight and tomorrow) is being provided for 16 locations in Nepal. The spatial distribution of these locations is depicted in Figure 1. The past 24 hours' observations on Maximum Temperature, Minimum Temperature and Rainfall over these locations are regularly being updated on each day at 08.45 NPT. The interactive map of historical values of daily Tmax, Tmin, and rainfall is available for these locations and it makes the visualization of occurrence of weather extremes. The sunrise and sunset timings are also provided in the real-time data. The predicted ranges of Tmin and Tmax and rainfall probability (%) are provided for tonight and tomorrow, respectively. The present weather observations, weather conditions for tomorrow, and major synoptic features is being provided for across the country.

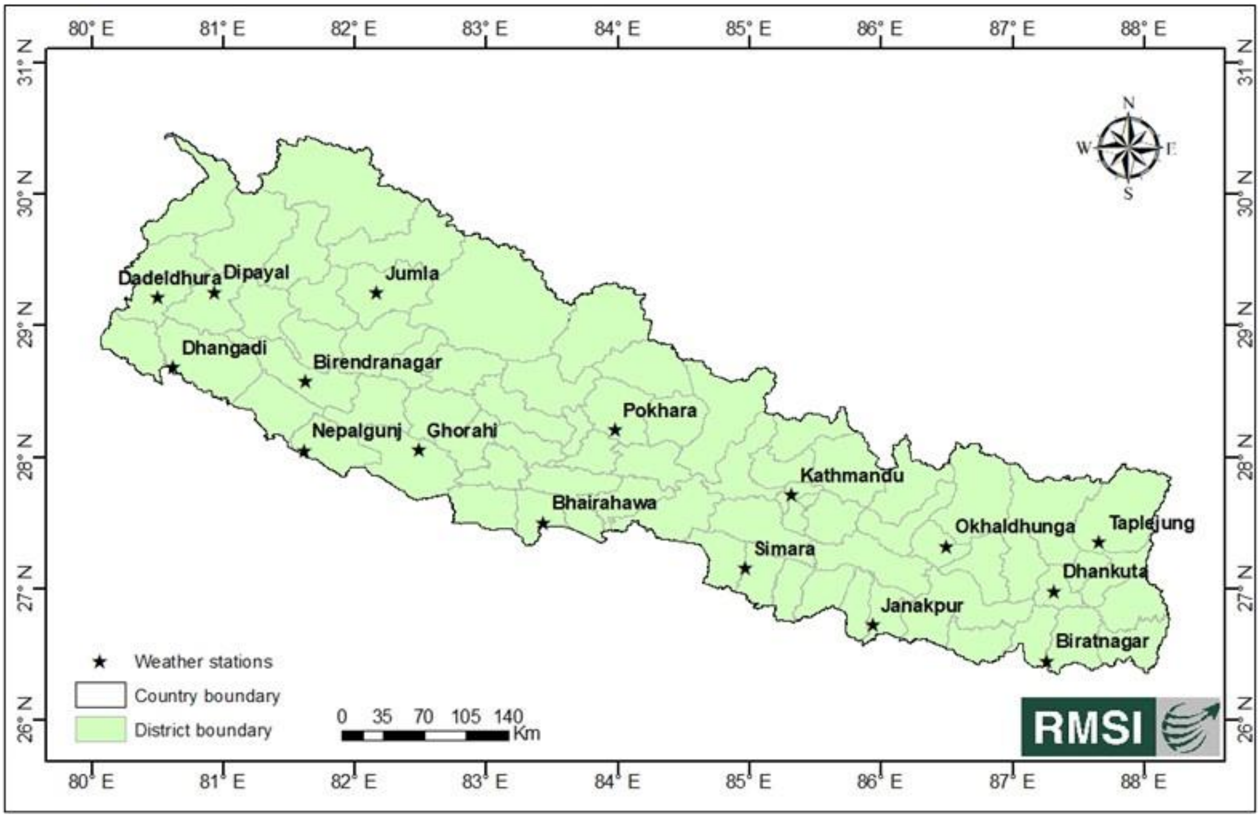

Figure 1: Spatial distribution of locations where weather forecast is being issued by MFD

2.1.2 High altitude forecast services

The high-altitude forecasts at the levels such as 3,000-5,500 m, 5,500-7,000 m, and >7000 m is being issued on daily basis for western, central and eastern regions in the country. The critical weather parameters such as temperature, wind speed and wind direction is being issued under this category. A qualitative probability for the occurrence for rain/cloud has been also issued in regional scale. The dissemination of this services has been depicted in Figure 2. As on 20th September 2023, it is last updated on the previous day afternoon (19th September 2023), hence it is observed that this service is timely updated.

24 hour forecast issued on 2023-09-19 18:00 NPT

Altitude (m)	Western			Central			Eastern		
	Wind Direction (deg N)	Wind Speed (knots)	Temperature (°C)	Wind Direction (deg N)	Wind Speed (knots)	Temperature (°C)	Wind Direction (deg N)	Wind Speed (knots)	Temperature (°C)
3000	240	5	11	240	5	11	220	5	11
5500	290	10	-1	230	5	-1	210	5	-2
7000	280	15	-11	280	10	-11	310	5	-11
9000	290	20	-26	280	15	-26	330	10	-26
Weather	Partly to Generally cloudy with chances of rain/snow at a few places.			Generally cloudy with chances of rain/snow at a few places.			Generally cloudy with chances of rain/snow at a few places.		

Figure 2:Dissemination of high altitude forecast by MFD

2.1.3 Numerical Weather Prediction (NWP) products

The DHM has made rapid progress in operationalizing different NWP model products for short-term weather forecasting. To improve the accuracy of weather forecasts over the conventional approach, the WRF version 3.2 was set up by Regional Integrated Multi-Hazard Early Warning System (RIMES) in the year 2010 A.D., under the project funded by Danish International Development Agency (DANIDA). The model, initially was deployed to run operationally once a day using GFS data of 1° X 1° resolution, had a single domain of 9 km horizontal resolution and the lead time of the forecast was 3 days.

During the year 2015, a newer version of the WRF EMS (V3.4.1.15.16) was set up at DHM, Nepal by Finnish Meteorological Institute (FMI) under the project FNEP-2. This version of the model was deployed to run operationally 4 times a day using GFS data of 0.5° X 0.5° resolution. This model had a parent domain of 12 km resolution and nested domain of 4 km resolution. The lead time of the forecast was 3 days. In the year 2020, under the PPCR BRCH project, an updated version of the WRF namely V4.1.2 was set up at DHM, Nepal and since then, the model is running operationally 4 times a day using GFS data of 0.25° X 0.25° resolution (higher resolution was possible with the installation of a High-Performance Computer (HPC) system with 768 cores installed at the Government Integrated Data Center (GIDC) under the PPCR-BRCH project. The model now has a parent domain of 9 km and nested domain of 3 km horizontal resolution (Figure 3).

The model configuration for the inner domain uses an ample buffer zone of five grid points and an exponential transition at the border. The numerical model domain includes the capital city of Kathmandu and other regions in Nepal. The lead time of the forecast is 3 days. Besides, a data assimilation system (WRFDA) has been set up using 3D VAR data assimilation system (data assimilation is undertaken to merge satellite derived data as well as those collected by AWS in remote data sparse regions). GTS data, AWS data and RADAR data are also being assimilated into the model. The WRFDA system runs operationally 4 times a day (00, 06, 12, and 18 UTC). High Performance Computers have been installed at DHM for running, computing and processing of the model and its outputs. The model performance is evaluated via statistical analysis using the correlation coefficient, deviation, and root mean squared error by comparing with observational data including, but not limited to, those from ground-based instruments.

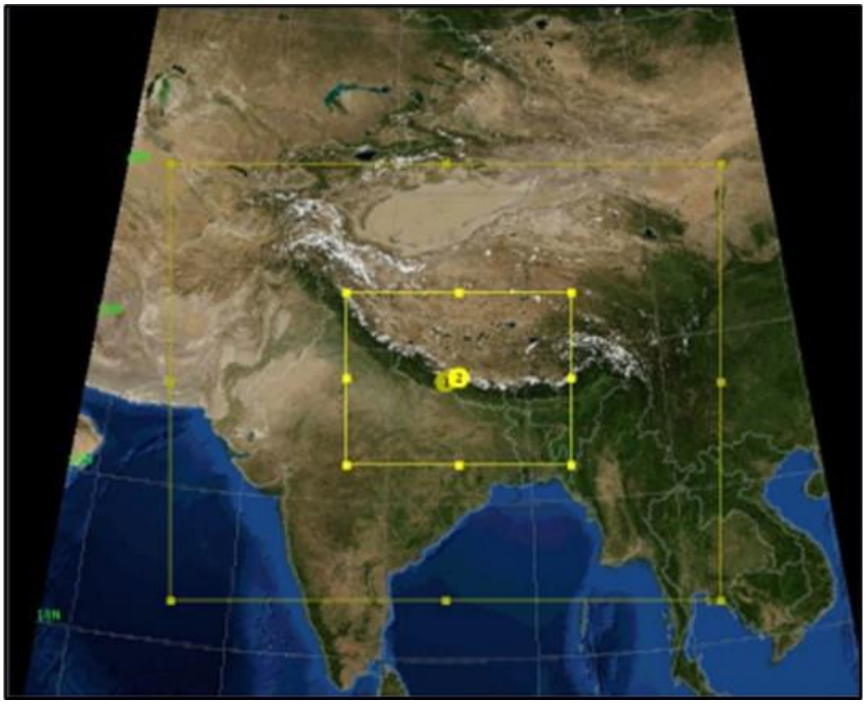

Figure 3: The WRF Model at DHM has two nested domains for the 9/3 km resolutions. The out yellow box is the 9 km domain, and inner yellow box shows the 2 ways nested high resolution 3 km domain

2.1.4 WRF Configuration at DHM

The configuration of the WRF being deployed for the short-term (3 days) weather forecast at DHM is given in Table 1.

Table 1: WRF Model configuration Details

Sr #	Parameters	Parent Domain (D01)	Nested Domain (D02)
1	Model Domain	South Asia	Nepal
2	Grid Resolution	9 km	3 km
3	Grid size	445 X 356	544 X 421
4	Map Projection	Lambert	Lambert
6	Time Steps	60 Sec	60 Sec
7	No. of vertical levels	38	38
8	History Interval	180 (min)	60 (min)
9	Radiation- Longwave	RRTMG (4)	RRTMG (4)
10	Radiation- Shortwave	RRTMG (4)	RRTMG (4)
11	Surface Layer option	Monin-Obukhov (2)	Monin-Obukhov (2)
12	PBL Schemes	MYJ (2)	MYJ (2)
13	Cloud Microphysics	Thompson (8)	Thompson (8)
14	Cumulus Parameterization	Tiedtke (6)	Tiedtke (6)
15	Land Surface Model	Noah Land Surface Model (2)	Noah Land Surface Model (2)

Sr #	Parameters	Parent Domain (D01)	Nested Domain (D02)
16	Forecast Length	78 Hours (3 Days + 6 hour)	78 Hours (3 Days + 6 hour)
17	Output format	grib2	grib2
18	Post-Processing	grads	grads

The operational modelling system at DHM comprises a number of components. The Systems uses a 16-core head node (hnode) and 23 compute nodes each with dual 16 core processors, for a total of 736 compute cores (hereafter referred to as the cluster). The hnode and the cluster are interconnected by an InfiniBand switch which allows 56 GB of communication for the parallel Message Passing Interface (MPI) communications which occur during the model run. They are also interconnected via a 1G bit Ethernet switch which is used to support NFS for data Input and Output during the model run.

The model output is currently being post-processed using the Data Testbed Center (DTC) Unified Post Processor (UPP) to generate grib2 output files. These are then used by grads to generate the desired output that is fed onto an internal DHM web server (the same server as the GFS data) and is made available to the DHM forecasters.

The model products are updated four times a day (00, 06, 12, 18 UTC), all having a time step of hourly data up to 72 hours (i.e., 3 days). Some of the products are also available on the DHM website (https://dhm.gov.np). The model forecast products are available under Meteorological Forecast > Model Forecast; which has the options of three different versions of the model products: e.g., WRF, WRF-DA and WRF-EMS. For the verification purposes, DHM currently uses WRF and WRFDA data from 012 UTC run for inferring a number of statistical metrics to validate precipitation and temperature forecasts.

2.1.5 Numerical weather output

In this category, the MFD is issuing 3-day forecast for the parameters such as precipitation, temperature, wind speed, and wind gust (Figure 4). In the case of precipitation, temperature, and wind speed, the animation is provided for next 3 days with images in 2-hour interval. It is being updated regularly on daily basis. However, in the case of wind gust, it is observed that, the forecast is not updated regularly and the animation is also not available. As on 20th September 2023, the latest update was available for 6th August 2023 (Figure 4).

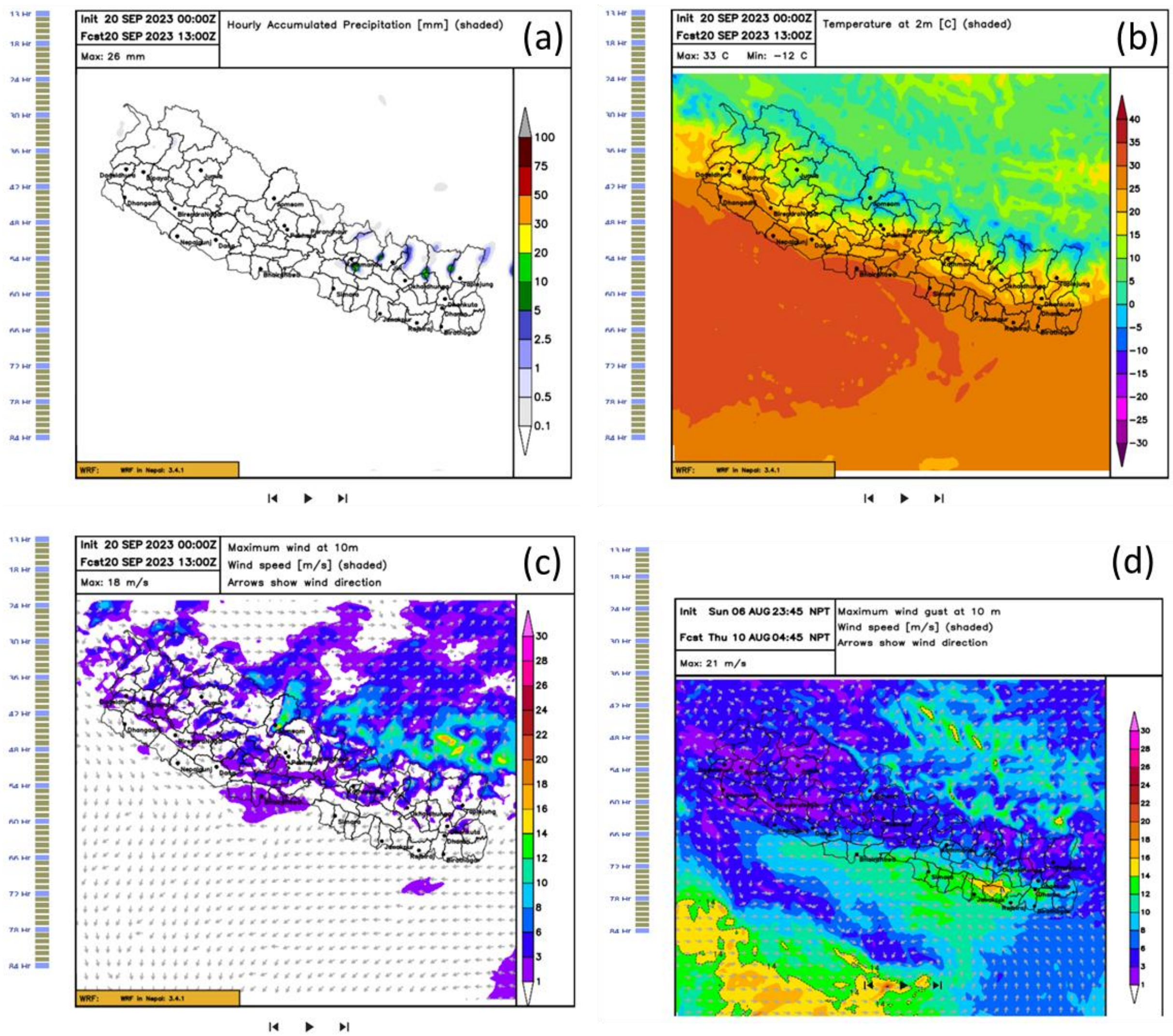

Figure 4: Three days weather forecast for (a) precipitation, (b) temperature, (c) wind speed and (d) wind gust

2.2 Meteorological services dissemination system of DHM

The website of the DHM offers a wide array of meteorological and hydrological services, and their details and current status are discussed below.

2.2.1 Country level forecast

It comprises country level weather forecasts, encompassing today's and tonight's outlook coupled with meteorological analysis. This service is being updated every day at 6 AM in the local language. The archives also available in the repository.

2.2.2 Three-day forecasts

It contains the weather forecast for the next three days. It is being issued at 06:00 AM (NPT) every day and contains meteorological analysis, weather status, and any warnings/advisories for the next three days. The archives also available in the repository.

2.2.3 Mountaineering forecasts

The high-altitude forecasts for levels such as 3,000-5,500 m, 5,500-7,000 m and >7,000 m is issued on daily basis for 5 high altitude provinces in the country (Province 1, Bagmati, Gandhaki, Karnali, and Sudurpaschim provinces). The critical weather parameters such as temperature, wind speed, and wind direction are issued in this category. A qualitative probability for the occurrence for rain/cloud is issued for these provinces. The dissemination of this services has been depicted in Figure 2. It is observed that this service is timely updated and the archives also available in the repository.

24 hour forecast issued on 2023-09-22 18:00 ***NPT***

	Province 1			Bagmati Province			Gandhaki Province		
Altitude (m)	Wind Direction	Wind Speed	Temperature	Wind Direction	Wind Speed	Temperature	Wind Direction	Wind Speed	Tempe
3000	170	5	10	140	5	11	210	5	13
5500	180	15	-4	110	15	-3	220	10	-3
7000	220	20	-13	260	20	-13	270	15	-12
9000	220	20	-26	210	25	-26	250	25	-28
Weather	Generally to Mostly cloudy with chances of rain/snow at some places			Generally to Mostly cloudy with chances of rain/snow at some places			Generally to Mostly cloudy with chances of rain/snow at a few pl		

Figure 5: Dissemination of mountaineering forecast through DHM website

2.2.4 Fog monitoring and forecast

It is a bulletin for mist and fog condition. The bulletin contains province level information on yesterday's maximum and minimum temperatures, today's minimum temperature, and transparency (visibility) forecasts for the next 24 and 48 hours. It was observed that, the latest update of this service was released on 2023-02-19 at 09:30:00 which means this service is being updated on regular basis.

2.2.5 Aviation meteorology

In this aspect, TAF and METAR services are available on an hourly basis and observed that this service is updated on regular basis.

2.2.6 Weekly weather outlook

It provides the weekly weather outlook for high mountain, mid mountain and Terai plains. This service is issued on every Friday for the next one week. This service has been updated on regular basis and the archives also available in the repository.

2.2.7 Urban meteorology

It provides the predicted temperatures and probability of rain for the tonight and tomorrow for the selected locations in the country. In addition to this daily information, comprehensive charts are available for a broader perspective. These charts encompass average maximum and minimum temperatures on a daily, weekly, and monthly basis, allowing for a better understanding of temperature trends over time. Furthermore, the charts also display average monthly rainfall data, aiding in tracking precipitation patterns and extreme maximum and minimum temperatures, as well as extreme rainfall within a 24-hour window throughout the year. The current status for city weather forecast was updated on 2023-09-22 at 06:00.

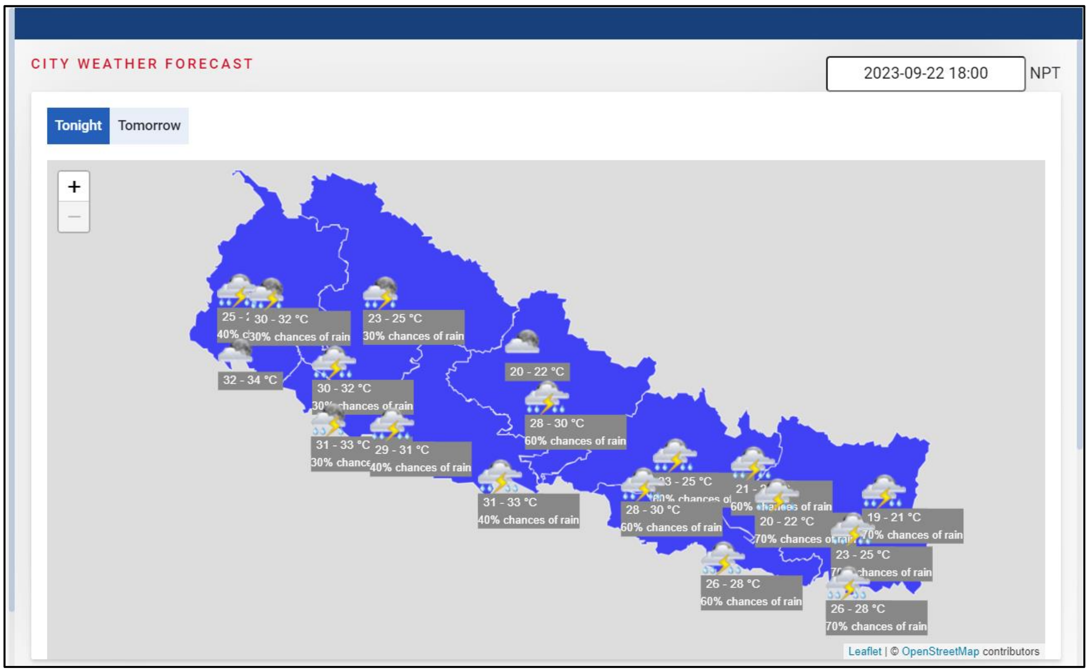

Figure 6:Dissemination of city weather forecast through DHM website

2.2.8 Impact-based forecast

Access to the impact-based forecast requires authentication through login credentials.

2.2.9 Tourism forecast service

It has been tailored to address heat and cold wave conditions, providing crucial information regarding precipitation, temperature, and wind gusts. This data is made available at both station and district levels and at present, there is no available information in this service.

2.2.10 NWP-based city forecast

It has been tailored to address crucial weather information regarding district and station level. However, presently there is no available information on this service.

2.2.11 Model forecast

This service provides the maps and map animation of the forecast by the Numerical Weather Prediction (NWP) models. It provides forecast in three categories namely Weather Research and Forecasting (WRF), WRF-DA (Data Assimilation) and WRF-EMS (Environmental Modelling System). The forecast is available for the parameters such as precipitation, temperature, wind gusts, relative humidity, as well as maximum and minimum temperatures. This forecast is disseminated through DHM website regularly on daily basis.

2.2.12 CAP alerts

This service provides the alerts based on Common Alerting Protocol (CAP) based on the data collected through climatological stations, automatic weather stations (AWS) and radiosondes. At present, no information is available on this service on the DHM website.

2.2.13 Weather warning

It is the service to alert the public about severe weather conditions expected over the next three days: today, tomorrow, and the day after tomorrow. This service contains a set of warnings indicated through different legends to convey the level of urgency and action required. This service is updated regularly by the DHM.

2.2.14 Highway weather

It has been tailored to address station-wise crucial weather information regarding precipitation, temperature, wind, sun, and visibility. It has been observed that, this service is not updated regularly on the DHM website.

2.3 Agro-met services

Agro-met services include a weekly weather bulletin which is regularly updated. However, no content is available about the other services in this category such as agro met products, service reports, climate indices for agriculture, and research categories.

2.4 Bulletin services

The bulletins from the divisions of DHM such as climate division, flood forecasting division, hydrological division, and meteorological forecast division are placed in this category and provided by the DHM.

2.5 Climate services

2.5.1 Daily weather summary

The Daily Weather Summary provides daily updates on weather conditions, offering the most recent precipitation data and records of maximum and minimum temperatures. This service is continuously updated on daily basis.

2.5.2 Daily climate monitoring

The daily climate monitoring service focuses on the Monsoon season from June to September 2023. Through precipitation graphs, illustrate daily accumulated precipitation levels alongside daily accumulated normal precipitation. Moreover, it provides insights on the temperature deviations from the normal and temperature variations during this period. This service is continuously updated on daily basis.

2.5.3 Seasonal climate monitoring

This service provides the daily variability of temperature and precipitation during a season for the country. It also provides the daily anomaly from normal. This report is updated at the end of the season.

2.5.4 Heat and cold wave monitoring

It provides the heat and cold wave bulletins at the time of occurrence of the events.

2.5.5 Long-range forecast

It provides the long-range forecast and seasonal outlook of southwest monsoon season.

2.5.6 Monsoon onset and withdrawal

It provides the information on onset and withdrawal of south west monsoon across the country and being updated regularly at the beginning and end of the season.

2.5.7 Normal climate

It provides the normal values of precipitation, maximum and minimum temperature, and relative humidity in daily, monthly and annual scales during the period 1981 to 2020.

2.5.8 Climate reports

It is the report of Precipitation and Temperature distribution over the country and regularly updated at end of the month.

The current status of various services disseminated through DHM website has been summarized in Table 2.

Table 2: Current status of various services disseminated through DHM website

Sr. #	Services	Service type	Status
1	Meteorological Forecast	Country forecast	Regularly Updated
		Three-day forecast	Regularly Updated
		Mountaineering	Regularly Updated
		Fog Monitoring and outlook	Regularly Updated
		Aviation Meteorology	Regularly Updated
		Weather outlook	Regularly Updated
		Urban meteorology	Regularly Updated
		Fog forecast	Last updated on 19-Feb-2023
		Impact based forecast	Requires login credentials
		Tourism Forecast	No Content Available
2	Climate Services	Daily weather summary	Regularly Updated
		Daily climate monitoring	Regularly Updated
		Seasonal climate monitoring	Regularly Updated
		Heat and Cold wave monitoring	Regularly Updated
		Long range forecast	Regularly Updated
		Monsoon onset &withdrawal	Regularly Updated
		Normal climate	Regularly Updated
		Climate report	Regularly Updated
3	Agromet Services	Weekly weather bulletin	Regularly Updated
		Agromet product	No Content Available
		Agromet service report	No Content Available
		Climate Indices for Agriculture	No Content Available
		Research	No Content Available
4	Bulletin Services	Climate division	No Content Available
		Flood forecasting division	No Content Available
		Hydrological division	No Content Available
		Meteorological forecast division	Regularly Updated

2.6 Meteorological observation network

The DHM in Nepal operates a comprehensive observation network that plays a crucial role in monitoring and understanding the country's weather patterns and hydrological conditions. A weather observation network is of paramount importance for a variety of reasons, as it serves numerous critical functions that benefit society, the economy, and the environment. The accurate weather observation is critical for weather forecasting, disaster preparedness and response, agricultural activities, transportation, aviation, energy production, water resource management, environmental protection and scientific research. The DHM is maintaining a vast network of meteorological observations and the details are explained below.

The spatial distribution of the meteorological stations and their current status has been depicted in Figure 7 and Figure 8.

2.6.1 Aero synoptic weather stations

An Aero Synoptic Weather Station, also known as an aviation synoptic weather station, is a specialized weather station designed to provide critical meteorological information for aviation operations. These stations are strategically located at airports and other aviation facilities to support safe and efficient air travel. It records a comprehensive set of meteorological parameters and atmospheric conditions that are crucial for aviation safety and operations. These parameters include temperature, precipitation, dew point, relative humidity, wind speed and direction, atmospheric pressure, visibility, cloud cover, lightning detection and so on. These parameters are continuously monitored and reported to pilots, air traffic controllers, and meteorologists to ensure the safe and efficient operation of aircraft in various weather conditions and at different stages of flight. There are 14 aero-synoptic stations are actively functioning under DHM across the country.

2.6.2 Agro-meteorological stations

Agrometeorological weather stations serve the specific purpose of providing meteorological and environmental data tailored to the needs of agriculture and farming. These specialized weather stations are strategically placed in or near agricultural areas and are designed to support agricultural planning, decision-making, and sustainable farming practices. The primary purposes of agrometeorological weather stations include crop management, irrigation management, disease and pest control, fertilizer and nutrient application, livestock management, scientific research and agricultural insurance. he parameters recorded in agrometeorological stations typically include precipitation, temperature, solar radiation, wind speed and direction, relative humidity, evapotranspiration, soil moisture and so on. Agrometeorological stations provide farmers with real-time data and forecasts tailored to their specific agricultural needs, enabling them to optimize resource management, reduce risks, and improve crop yields and quality. There are 21 agrometeorological stations have been installed by DHM, out of that 21 are presently functioning and 4 are temporarily closed.

2.6.3 Climatological stations

Climatological weather stations serve the primary purpose of collecting long-term meteorological data and climate information for a specific location or region. Unlike standard weather stations that focus on short-term weather conditions, climatological weather stations are designed to monitor and record climate-related parameters over extended periods, often spanning decades or even centuries. The climatological weather stations play a critical role in providing the historical climate data needed for climate research, long-term planning, and informed decision-making in various sectors, including science, agriculture, engineering, energy, and environmental conservation. These stations collect a range of meteorological parameters and climate-related data to monitor climate trends and variations which include temperature, precipitation, relative humidity, wind speed and direction, solar radiation, evapotranspiration, soil temperature etc. The climatological stations play a pivotal role in gathering and maintaining long-term climate data that are instrumental for climate scientists, researchers, policymakers, and other stakeholders in understanding and addressing climate-related challenges. There are 143 climatological stations have been installed by DHM, out of that 113 are presently functioning and 30 are temporarily closed.

2.6.4 Synoptic stations

A synoptic weather station serves the primary purpose of collecting and reporting meteorological data and atmospheric conditions on a regional or large-scale basis. These stations are strategically located to provide a comprehensive view of weather patterns and conditions over a specific area. The synoptic weather stations are a critical component of the meteorological infrastructure, providing the data needed to understand and predict weather and climate conditions on a regional and large-scale level. Their observations and reports have a wide range of applications, including weather forecasting, climate monitoring, disaster management, and scientific research. The parameters recorded in a synoptic weather station include temperature, precipitation, relative humidity, wind speed and direction, solar radiation, atmospheric pressure, visibility, cloud cover, radiosonde observations, upper air observations etc. These parameters are continuously monitored and reported by synoptic weather stations to meteorological agencies and organizations, enabling the generation of weather forecasts, severe weather warnings, and climate assessments. There are 7 synoptic stations are actively functioning under DHM across the country.

2.6.5 Automatic weather stations

Automatic weather stations (AWS) serve several important purposes in meteorology, research, and various applications across different industries. These stations are designed to collect meteorological data automatically and continuously, often without the need for human intervention. The parameters recorded in an AWS include temperature, precipitation, relative humidity, wind speed and direction, solar radiation, atmospheric pressure etc. There are 28 AWSs have been installed by DHM, out of that 27 are presently functioning and one is temporarily closed.

2.6.6 Precipitation stations

Precipitation monitoring stations, also known as rain gauges, are established with the primary purpose of measuring and recording only precipitation, specifically rainfall. They serve a wide range of purposes related to water resource management, disaster preparedness, agriculture, environmental conservation, and scientific research. There are 327 precipitation stations have been installed by DHM, out of that 296 are presently functioning and 31 are temporarily closed.

Table 3: List of weather observation network of DHM

Weather Station Type	Active	Temporary Closed
Aero-Synoptic	14	-
Agro-meteorology	17	4
AWS	27	1
Climatology	113	30
Precipitation	296	31
Synoptic	7	-
Total	**474**	**66**

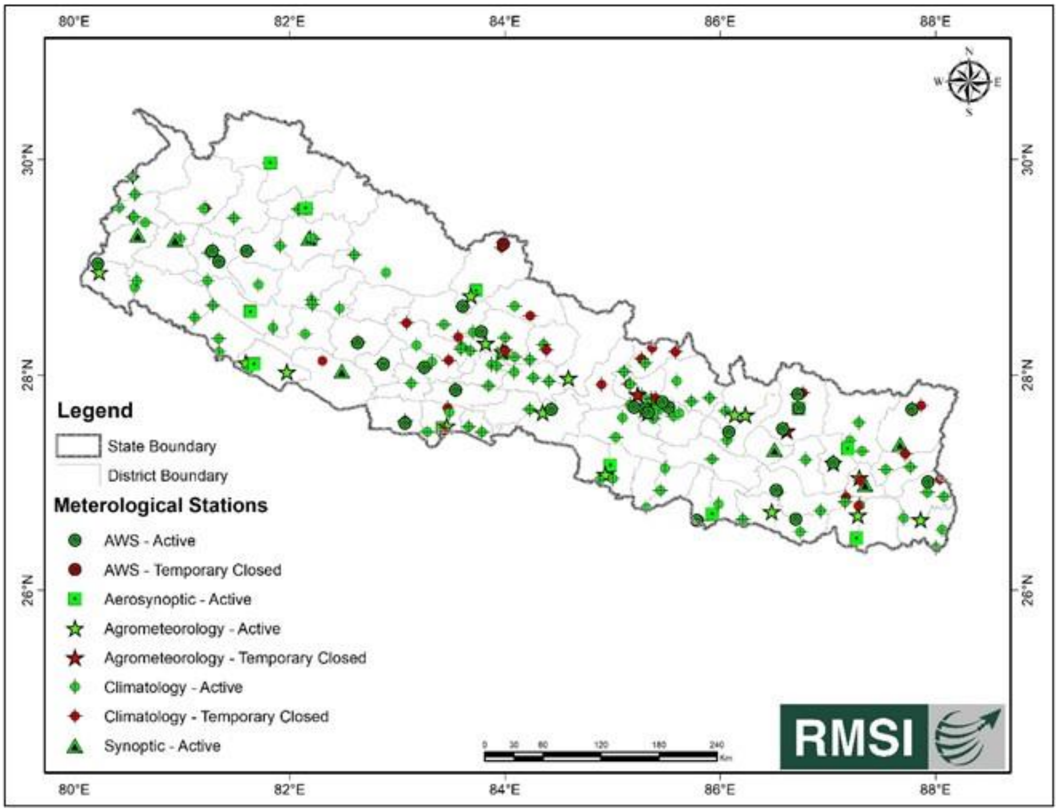

Figure 7: Spatial distribution of meteorological stations across Nepal and their current status

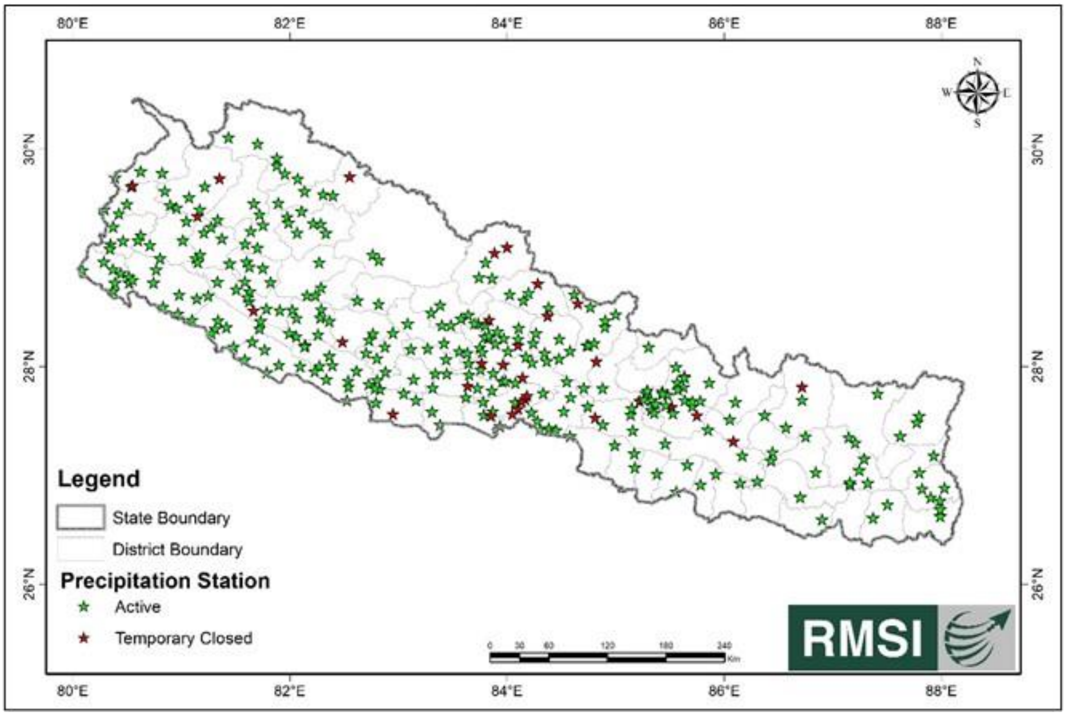

Figure 8: Spatial distribution of precipitation stations across Nepal and their current status

2.7 Recommendations to use weather forecast for the generation of Customized Weather and Climate Information System (CWCIS) to develop climate-resilient agricultural system in Nepal

2.7.1 Data collection

A comprehensive location and crop specific Agro-met Advisory Bulletin (AAB) can be prepared on the basis of CWCIS. The most important factor in the preparation of CWCIS is the collection of relevant datasets. The major data required for the same are as follows:

- The information on seasonal cropping pattern for area, production and productivity data needs to be collected in province and district level.
- The details of crop cultivars with special information on short duration, medium duration or long duration varieties for different seasons at province or district level.
- The information on area under rainfed and irrigated is essential for generating specific advisory for rainfed and irrigated regions.
- The information on normal sowing dates of different crops and its deviation in the current season for different provinces and districts. It will help in determining sowing operations or go for contingency plans in the case of insufficient soil moisture.
- Stage and condition of major crops over provinces and districts to suggest the farmers regarding management of insect, pest, irrigation to the crop, intercultural operations, etc.

- Real time soil moisture data to determine crop sowing and scheduling protective irrigation in irrigated farming system if soil moisture deficiency occurs at critical growth stages of the crop.
- Crop weather and crop pest relationship specific to the provinces and districts.

2.7.2 Proposed format of AAB based on CWCIS

A complete AAB should contain the comprehensive details of the following.

- Past Weather: Observed daily weather during the past one week in tabular format
- Weather Forecast: Quantitative weather forecast for next three days. On the basis of weather forecast, weather summary for the coming week can also be included.
- Category weather forecast: The category of weather forecast for the coming week. It means the rainfall is normal/above normal/below normal in percentage (%) and the temperature (maximum/minimum) is normal/above normal/below normal in ℃.
- Abiotic Stress Information: On the basis of weather forecast, abiotic weather-related stress on crops and livestock needs to be articulated. The crop specific advisory should consider the impact of weather on crops during the current and upcoming phenological stages and their ultimate impact on crop productivity.
- Biotic Stress Information: On the basis of real-time weather and weather forecast, the probability of the occurrence of pest and diseases need to be formulated. A sample format of AAB has been furnished in Table 4.

Table 4: Sample format of AAB

Agro-met Advisory Bulletin for the (Province/District)						No: ….		Date:		
Observed Weather During the Last Week							**Date**	**Weather Forecast**		
Day-1	**Day-2**	**Day-3**	**Day-4**	**Day-5**	**Day-6**	**Day-7**		**Day-1**	**Day-2**	**Day-3**
							Precipitation (mm)			
							Tmax (°C)			
							Tmin (°C)			
							Cloud Cover			
							RH-1 (%)			
							RH-2 (%)			
							Wind Speed (km/hr)			
							Wind Direction			

	Total (mm)	**Normal (mm)**	**Deviation (%)**
Precipitation During Last Week			
Cumulative Seasonal Precipitation			

During the coming days weather will be clear/cloudy/rainy condition. The rainfall will be normal/above/below normal by …%. The Tmax is expected to be normal/above/below normal by …°C and the Tmin is expected to be normal/above/below normal by …°C.

Name of Crop	Crop Stage	Agro-met Advisory
Crop-1		
Crop-2		
Crop-3		
.		
.		
Crop-n		

3 Verification of NWP 3-day weather forecasts products of DHM for the use of farming communities

An evaluation of WRF forecast issued by DHM has been conducted across the country as well as at selected locations and detailed methodology and results are presented in the following sub-sections.

3.1 WRF Prediction of short-term weather in Nepal

3.1.1 Numerical Weather Prediction: What is it?

The basic idea of numerical weather prediction is to sample the state of the fluid at a given time and use the equations of fluid dynamics and thermodynamics to estimate the state of the fluid at some time in the future. The main inputs from country-based weather services are surface observations from automated weather stations at ground level over land and from weather buoys at sea. The World Meteorological Organization (WMO) acts to standardize the instrumentation, observing practices and timing of these observations worldwide. Stations either report hourly in METAR reports, or every six hours in SYNOP reports. Sites launch radiosondes, which rise through the depth of the troposphere and well into the stratosphere. Data from weather satellites are used in areas where traditional data sources are not available. Compared with similar data from radiosondes, the satellite data has the advantage of global coverage, but at a lower accuracy and resolution. Meteorological radar provides information on precipitation location and intensity, which can be used to estimate precipitation accumulations over time. Additionally, if a pulse Doppler weather radar is used then wind speed and direction can be determined.

Models are *initialized* using this observed data. The irregularly spaced observations are processed by data assimilation[9] and objective analysis methods, which perform quality control and obtain values at locations usable by the model's mathematical algorithms (usually an evenly spaced grid). The data are then used in the model as the starting point for a forecast. Commonly, the set of equations used to predict the physics and dynamics of the atmosphere are called primitive equations[10]. These are initialized from the analysis data and rates of change are determined. The rates of change predict the state of the atmosphere a short time into the future. The equations are then applied to this new atmospheric state to find new rates of change, which predict the atmosphere at a yet further time into the future. This *time stepping* procedure is continually repeated until the solution reaches the desired forecast time.

The length of the time step chosen within the model is related to the distance between the points on the computational grid, and is chosen to maintain numerical stability. Time steps for global models are on the order of tens of minutes, while time steps for regional models are between one and four minutes. The global models are run at varying times into the future depending upon the computing resources at high speed available. For example, the UK Met Office's Unified Model is run six days into the future, the European Centre for Medium-Range Weather Forecasts model is run out to 10 days into the

[9] University Corporation for Atmospheric Research (August 14, 2007): "The WRF Variational Data Assimilation System (WRF-Var)". Retrieved May 25, 2022.

[10] Lynch, Peter (2006): The Emergence of Numerical Weather Prediction. Cambridge University Press.

future, while the Global Forecast System model run by the Environmental Modelling Center is run 16 days into the future. The visual output produced by a model solution is known as a prognostic chart. The raw output is often modified before being presented as the forecast. This can be in the form of statistical techniques to remove known biases in the model, or of adjustment to take into account consensus among other numerical weather forecasts. MOS or model output statistics is a technique used to interpret numerical model output and produce site-specific guidance.

Weather forecasting is the prediction of atmospheric conditions based on location and time. Every location will have its weather projections, making it relatively simple for farmers to know how and when to move (Short range forecast will be valid for 1-3 days while medium range forecast is valid for 5 to 7 days in the future. As a result of the interaction between weather and agriculture, precise weather forecasting is required for farmers to make informed decisions that will not result in losses. Temperature, sunlight, and rainfall all have a significant impact on crops. Temperatures, as well as proper water and food, are critical for livestock. Weather forecasting can thus be understood as a prediction or a statement indicating how and what will be the weather likely be the next day or the next few days.

3.2 Forecasting the Weather in Nepal: Focus on Hydrometeorological Disasters

Nepal's climate, influenced by elevation as well as by its location in a subtropical latitude, ranges from subtropical monsoon conditions in the Tarai, through a warm temperate climate between 4,000 and 7,000 feet in the mid-mountain region, to cool temperate conditions in the higher parts of mountains above 7,000 feet in Trans-Himalaya region. Nepal's weather forecasts suffer trained manpower and infrastructure crisis as there are only five weather stations around Nepal above 10,000 feet that can measure rainfall/snowfall thus stressing the need for installation of more automated weather stations in remote high lands to facilitate robust weather forecasts**.**

The frequency of natural disasters that occur due to extreme rainfalls is increasing these days across the globe and more often in countries/localities with mountainous terrain such as Nepal as a consequence of rising temperatures. Nepal is one of the most vulnerable countries to climate change, water-induced disasters and hydro-meteorological extreme rainfall events here cause widespread devastation, such as floods and landslides, resulting in loss of life and personal property damage. In particular, in Nepal, localized torrential rainfall has caused flash floods and mountain landslides, sometimes resulting in heavy casualties and property loss in recent years. To prevent such substantial damage, it is important to predict heavy rainfall over densely populated areas within a short time range. Therefore, accurate rainfall prediction is of great importance to take preventive measures.

The mesoscale Weather Research and Forecasting (WRF) model has been widely employed to forecast day-ahead temperatures and rainfalls (through dynamic downscaling over limited areas, it allows small-scale features to be resolved at high resolutions without the large computational overheads of global climate models). In fact, Short-term rainfall prediction in Nepal relies on mesoscale numerical weather prediction (NWP) model simulations in Department of Hydrology and Meteorology, Nepal. However, the deterministic predictions from the WRF model incorporate relatively large errors due to numerical discretization, inaccuracies in initial/boundary conditions and parameterizations, etc. Among them, the uncertainties in parameterization schemes have a huge impact on the forecasting skill of rainfalls, especially over Nepal which is located south of the Tibetan Plateau in a combination of fragile mountainous topography and ecosystems, and has highly variable monsoon-driven hydrological cycle.

Global Forecast System (GFS) data and/or ECMWF Reanalysis v5 (ERA5), most trusted large-scale datasets in terms of wind, rainfall, solar radiance, etc. are always used as the initial/boundary conditions for the regional high-resolution WRF model. Rainfall observations from all ground-based and encrypted stations over the country are interpolated to the WRF model grid points to evaluate the WRF model's performance of short-term weather variables. Besides, ERA5 hourly reanalysis data can be adopted to compare the simulated and observed the weather systems in regions of complex geographical features across Nepal.

Precipitation and cloud microphysical processes in numerical weather prediction systems pose one of the major forecasting challenges. Predicting the sub-grid scale phenomena such as clouds and precipitation, with some degree of accuracy, is still an ongoing ambitious project. Advances in computational resources boosted the use of more sophisticated physics schemes incorporated into models with higher resolutions grids. The choice of the proper combination of such schemes is a challenging task especially in case of high impact weather in which the forecast errors are expected to be large. To overcome the use of a single deterministic run, that represents the future state of atmosphere, one can use several runs from the same numerical weather prediction model but with different physical formulations. The uncertainty associated to the physical parameterizations of the forecast can then be assessed by the range of the different forecasts produced.

The Weather Research and Forecasting (WRF) Model, initially developed at NCAR in the United States, is a state-of-the-art mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. The model is a fully compressible, Eulerian and non-hydrostatic model that uses terrain-following, hydrostatic-pressure vertical coordinate with the top of the model being a constant pressure surface. The horizontal grid is the Arakawa-C grid. The time integration scheme in the model uses the third-order Runge-Kutta scheme, and the spatial discretization employs 2nd to 6th order schemes.

3.3 NWP at DHM, Nepal: Weather Research and Forecasting (WRF) Model

The DHM has a mandate from Government of Nepal to monitor all the hydrological and meteorological activities in Nepal. DHM collects hydrological and meteorological data throughout Nepal, process the data, publish it and disseminate the data to users such as water resource planners, developers, researchers and data seekers for the verification of extreme hydrological and meteorological events required for different purposes. The scope of work includes the monitoring of river hydrology, water quality, sediment, limnology, snow hydrology, glaciology, weather, climate, agro-meteorology, air quality and solar energy.

The Department has also extended its services in the sector of General and Aviation Weather Forecast regularly. The department delivers periodical Climate Bulletin to the public through its website and generate Agrometeorological Notice for Agriculture Management and Information System (AMIS) too. Besides, the department is providing its 24/7-day service of Flood Forecasting and Early Warning to public and related agencies during the period of Monsoon Season. DHM also issues hydrological and meteorological forecasts for public, mountaineering expedition, civil aviation, and for the mitigation of natural disasters on regular basis.

DHM has made rapid progress in operationalizing different NWP model products for forecasting future weather. To improve the accuracy of weather forecasts over the conventional approach, the WRF version 3.2 was set up by Regional Integrated Multi-Hazard Early Warning System (RIMES) in the year 2010 A.D., under the project funded by Danish International Development Agency (DANIDA). The model, initially was deployed to run operationally once a day using GFS data of 1^o X 1^o resolution, had a single domain of 9 km horizontal resolution and the lead time of the forecast was 3 days. During the year 2015, a newer version of the WRF EMS (V3.4.1.15.16) was set up at DHM, Nepal by Finnish Meteorological Institute (FMI) under the project FNEP-2. This version of the model was deployed to run operationally 4 times a day using GFS data of 0.5^o X 0.5^o resolution. This model had a parent domain of 12 km resolution and nested domain of 4 km resolution.

The lead time of the forecast was 3 days. In the year 2020, under the PPCR BRCH project, an updated version of the WRF namely V4.1.2 was set up at DHM, Nepal and since then, the model is running operationally 4 times a day using GFS data of 0.25^o X 0.25^o resolution (higher resolution was possible with the installation of a High-Performance Computer (HPC) system with 768 cores installed at the Government Integrated Data Center (GIDC) under the PPCR-BRCH project. The model now has a parent domain of 9 km and nested domain of 3 km horizontal resolution (Figure 3). The model configuration for the inner domain uses an ample buffer zone of five grid points and an exponential transition at the border. The numerical model domain includes the capital city of Kathmandu and other regions in Nepal. The lead time of the forecast is 3 days.

Besides, a data assimilation system (WRFDA) has been set up using 3D VAR data assimilation system (data assimilation is undertaken to merge satellite derived data as well as those collected by AWS in remote data sparse regions). GTS data, AWS data and RADAR data are also being assimilated into the model. The WRFDA system runs operationally 4 times a day (00, 06, 12 and 18 UTC). High Performance Computers have been installed at DHM for running, computing and processing of the model and its outputs. The model performance is evaluated via statistical analysis using the correlation coefficient, deviation, and root mean squared error by comparing with observational data including, but not limited to, those from ground-based instruments.

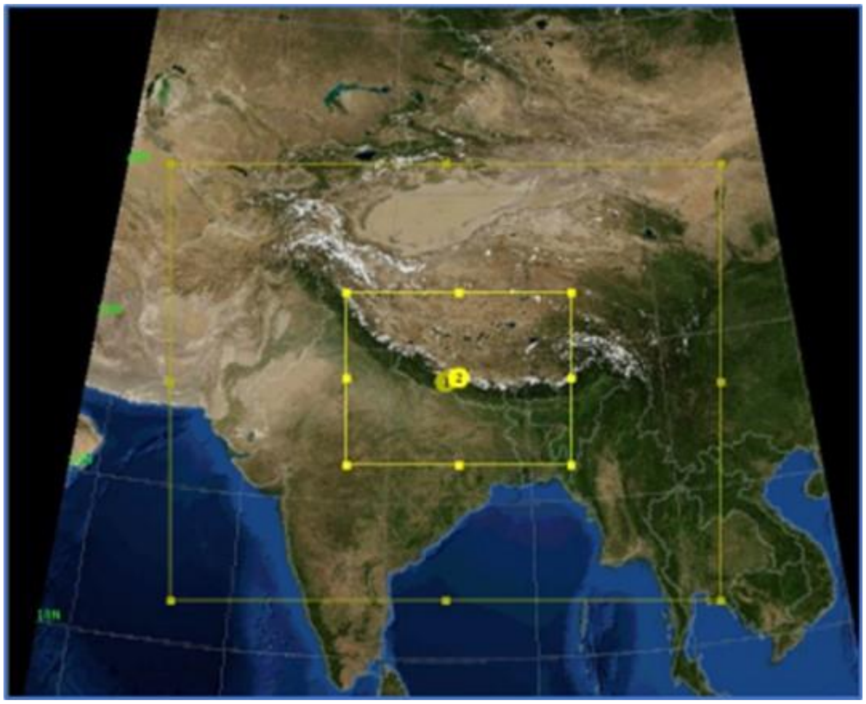

Figure 9: The WRF Model at DHM has two nested domains for the 9/3 km resolutions. The out yellow box is the 9 km domain, and the inner yellow box shows the 2 ways nested high resolution 3 km domain

3.3.1 WRF configuration at DHM, Nepal

The configuration of the WRF being deployed for weather forecast at DHM is as given in Table 1 below:

Table 5: WRF Model configuration Details

Sr. No.	Parameters	Parent Domain (D01)	Nested Domain (D02)
1	Model Domain	South Asia	Nepal
2	Grid Resolution	9 km	3 km
3	Grid size	445 X 356	544 X 421
4	Map Projection	Lambert	Lambert
6	Time Steps	60 Sec	60 Sec
7	No. of vertical levels	38	38
8	History Interval	180 (min)	60 (min)
9	Radiation- Longwave	RRTMG (4)	RRTMG (4)
10	Radiation- Shortwave	RRTMG (4)	RRTMG (4)
11	Surface Layer option	Monin-Obukhov (2)	Monin-Obukhov (2)
12	PBL Schemes	MYJ (2)	MYJ (2)
13	Cloud Microphysics	Thompson (8)	Thompson (8)
14	Cumulus Parameterization	Tiedtke (6)	Tiedtke (6)
15	Land Surface Model	Noah Land Surface Model (2)	Noah Land Surface Model (2)
16	Forecast Length	78 Hours (3 Days + 6 hour)	78 Hours (3 Days + 6 hour)

Sr. No.	Parameters	Parent Domain (D01)	Nested Domain (D02)
17	Output format	grib2	grib2
18	Post-Processing	grads	grads

The operational modelling system at DHM comprises a number of components. The Systems uses a 16-core head node (hnode) and 23 compute nodes each with dual 16 core processors, for a total of 736 compute cores (hereafter referred to as the cluster). The hnode and the cluster are interconnected by an Infiniband switch which allows 56 GB of communication for the parallel Message Passing Interface (MPI) communications which occur during the model run. They are also interconnected via a 1G bit Ethernet switch which is used to support NFS for data Input and Output during the model run.

The model output is currently being post-processed using the Data Testbed Center (DTC) Unified Post Processor (UPP) to generate grib2 output files. These are then used by grads to generate the desired output that is fed onto an internal DHM web server (the same server as the GFS data) and is made available to the DHM forecasters.

The model products are updated four times a day (00, 06, 12, 18 UTC), all having a time step of hourly data up to 72 hours (i.e., 3 days). Some of the products are also available on the DHM website - https://dhm.gov.np. The model forecast products are available under Meteorological Forecast > Model Forecast; which has the options of three different versions of the model products: e.g., WRF, WRF-DA and WRF-EMS. For the verification purposes, DHM currently uses WRF and WRFDA data from 012 UTC run for inferring a number of statistical metrics to validate precipitation and temperature forecasts.

3.4 Model validation and verification with observed data

A variety of data assimilation techniques are available for their application in DHM's WRF modelling system to use radiance (satellite) data assimilation, precipitation data assimilation, radar data assimilation, ETKF Ensemble Kalman filter assimilation, as well as 3D and 4D hybrid assimilation. The primary objective, at this moment, is to incorporate observed surface, upper air and radar-based data into the WRF-DA forecasting model to improve the initial conditions input to the model which should eventually improve the short-range forecast. There are complex systems which rely on both static error covariance estimates as well as ensemble estimated error covariance. For the verification, data simulated by WRF and WRF-DA simulations from 012 UTC run for the period from January 24 to December 31, 2021, which was archived at DHM for reviewing the model's performance on daily, monthly, seasonal and annual basis, has been used for key climate variables namely, maximum and minimum surface air temperatures and precipitation. The performance of the WRF forecast against observed data has also been done at selected three locations in the country. The spatial distribution of these locations is depicted in Figure 10.

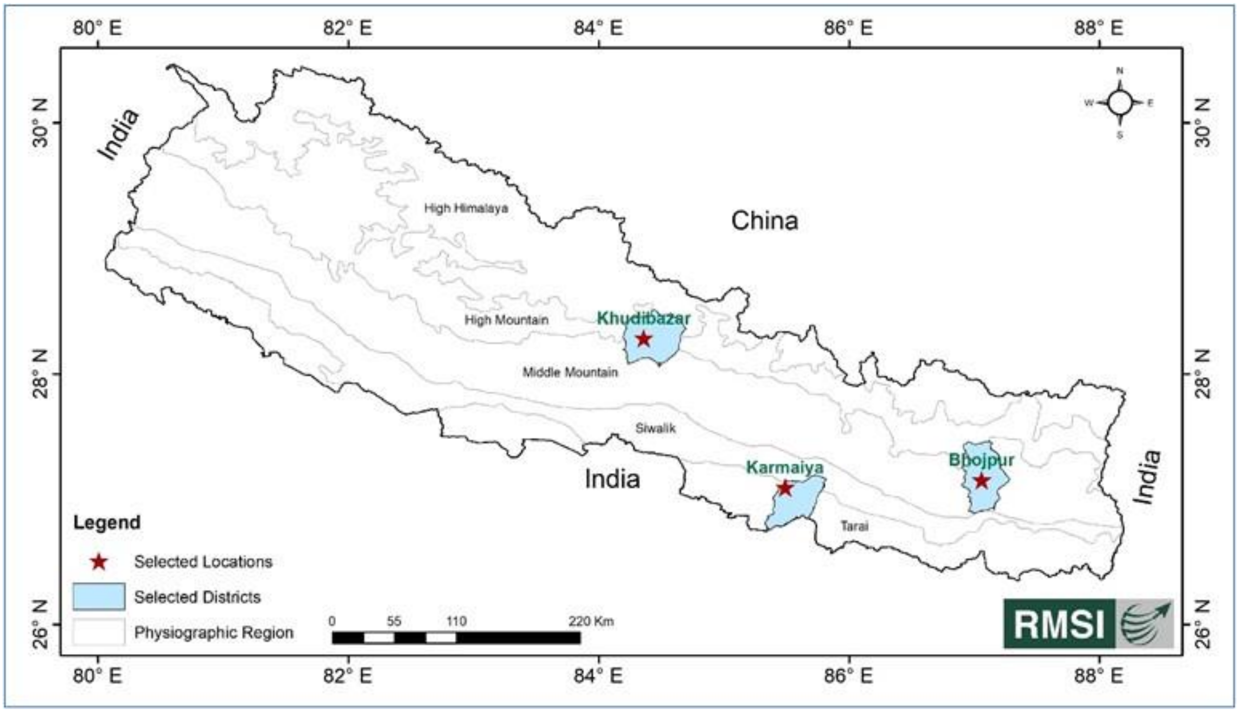

Figure 10: The spatial distribution of selected locations for the forecast evaluation analysis

A brief review of the performance of the WRF model in realistically simulating these variables over Nepal is presented below.

3.4.1 Surface air temperatures validation across the country

The observed daily temperature (Tmax, Tmin, and Tmean) averaged over Nepal as well as that simulated by WRF, and WRF-DA model versions are presented in Figure 11. It is evident that that both WRF and WRF-DA datasets tend to over-estimate the observed Tmax during February - April (Figure 11a), while under-estimate it for rest of the months although the difference is very nominal. Both WRF and WRF-DA data sets exhibit broadly similar pattern in between and with observations during the entire length of simulated period. Further, Tmin also follows the similar pattern as Tmax (Figure 11b).

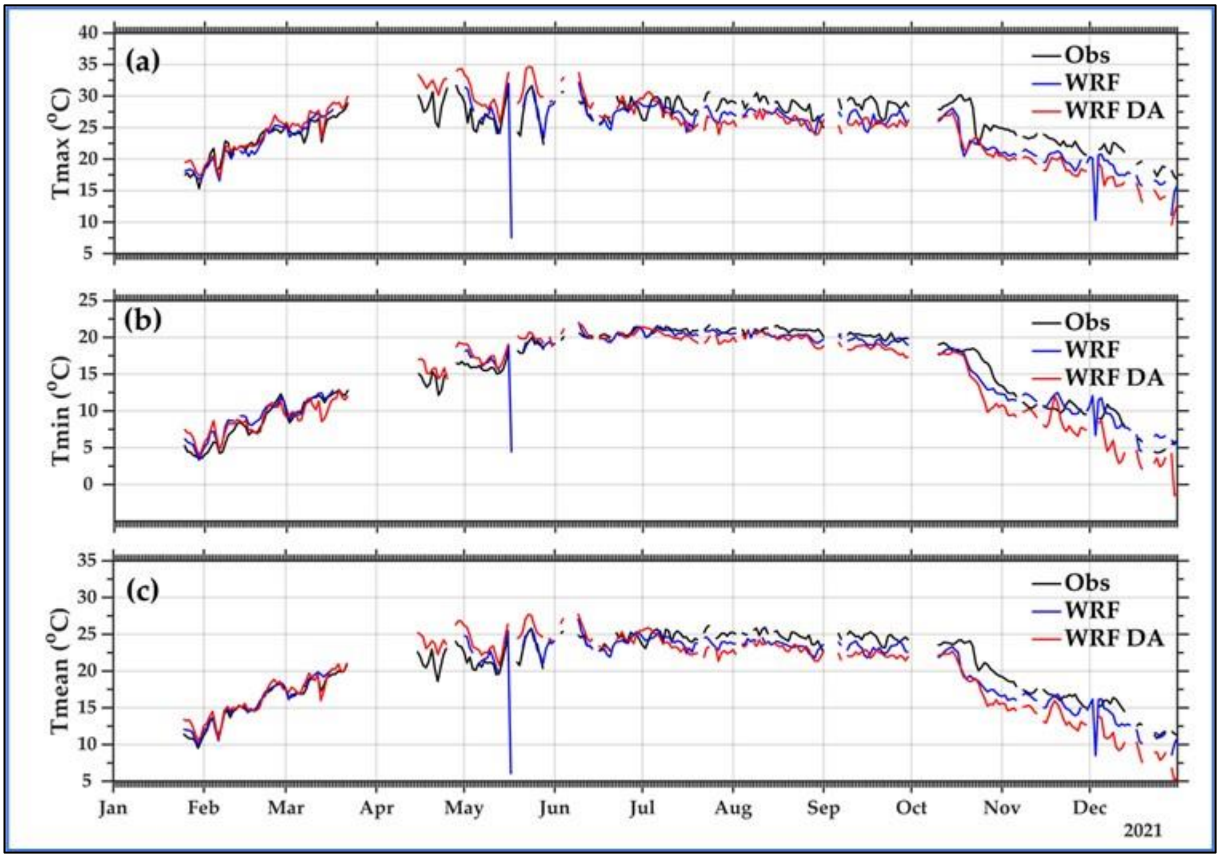

Figure 11: Temporal distribution of daily (a) Tmax, (b) Tmin, (c) Tmean in observed (Obs), WRF and WRF-DA datasets over Nepal

Figure 12 depicts the observed, WRF, and WRFDA monthly distribution of temperatures (Tmax, Tmin, and Tmean) averaged over Nepal during the year 2021. The monthly variation in Tmean simulated in WRF and WRF-DA model versions is very identical, although they both over-estimate the Tmean during April and May and under-estimate for rest of the months (Figure 12a). The largest under-estimation of observed Tmean is found for October month. Further the performance of WRF and WRF-DA model versions to estimate the observed Tmax and Tmin is very similar i.e., over-estimate during April and May and under-estimate for remaining months.

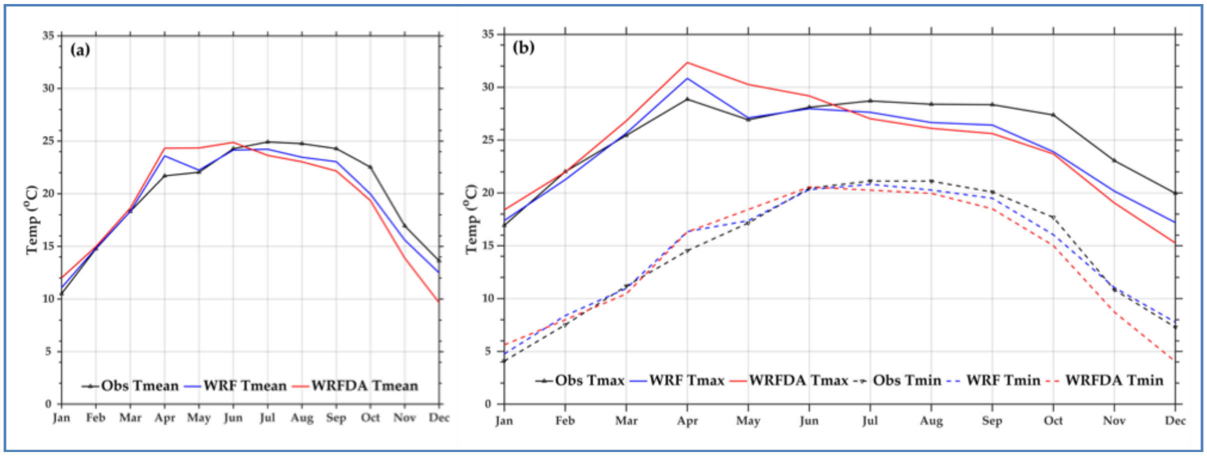

Figure 12: Annual cycle of monthly mean distribution of (a) Tmean and (b) Tmax / Tmin in observation, WRF and WRF-DA datasets over Nepal

The spatial distribution of annual mean observed, and WRF, and WRF-DA simulated temperatures at each station locations are presented in Figure 13. The temperature over Nepal decreases with increasing elevation, the higher Tmax temperature are observed in the low- and mid-elevations areas of the country, which is also similar in both WRF and WRF-DA Tmax data. The Tmax ranges between 5 to >30^{o}C in all three datasets. The average observed Tmax over the country is 25.3^{o}C, which is marginally under-estimated in both WRF and WRF-DA datasets. Average Tmax (24.62^{o}C) in WRF-DA dataset is closer to observation than WRF dataset. Further, Tmin over Nepal ranges between -5^{o}C to >25^{o}C in each of the two simulated datasets while in observed data set it ranges from 0 ^{o}C to >20 ^{o}C. In WRF dataset, only one station attains the Tmin value below 0^{o}C, while, in WRF-DA dataset three stations attain below freezing temperatures. The average observed Tmin value over the country is 14.41^{o}C, which is 14.44^{o}C in WRF and 13.80^{o}C in WRF-DA datasets. Thus, simulated Tmin in WRF dataset is closer to observations than in WRF-DA datasets. Tmean ranges from 5 ^{o}C to >20 ^{o}C in all datasets, while the WRFDA datasets shows the lowest Tmean of <5^{o}C. The average Tmean for observed data is 19.86^{o}C, which is 19.36^{o}C and 19.20^{o}C in WRF and WRF-DA datasets.

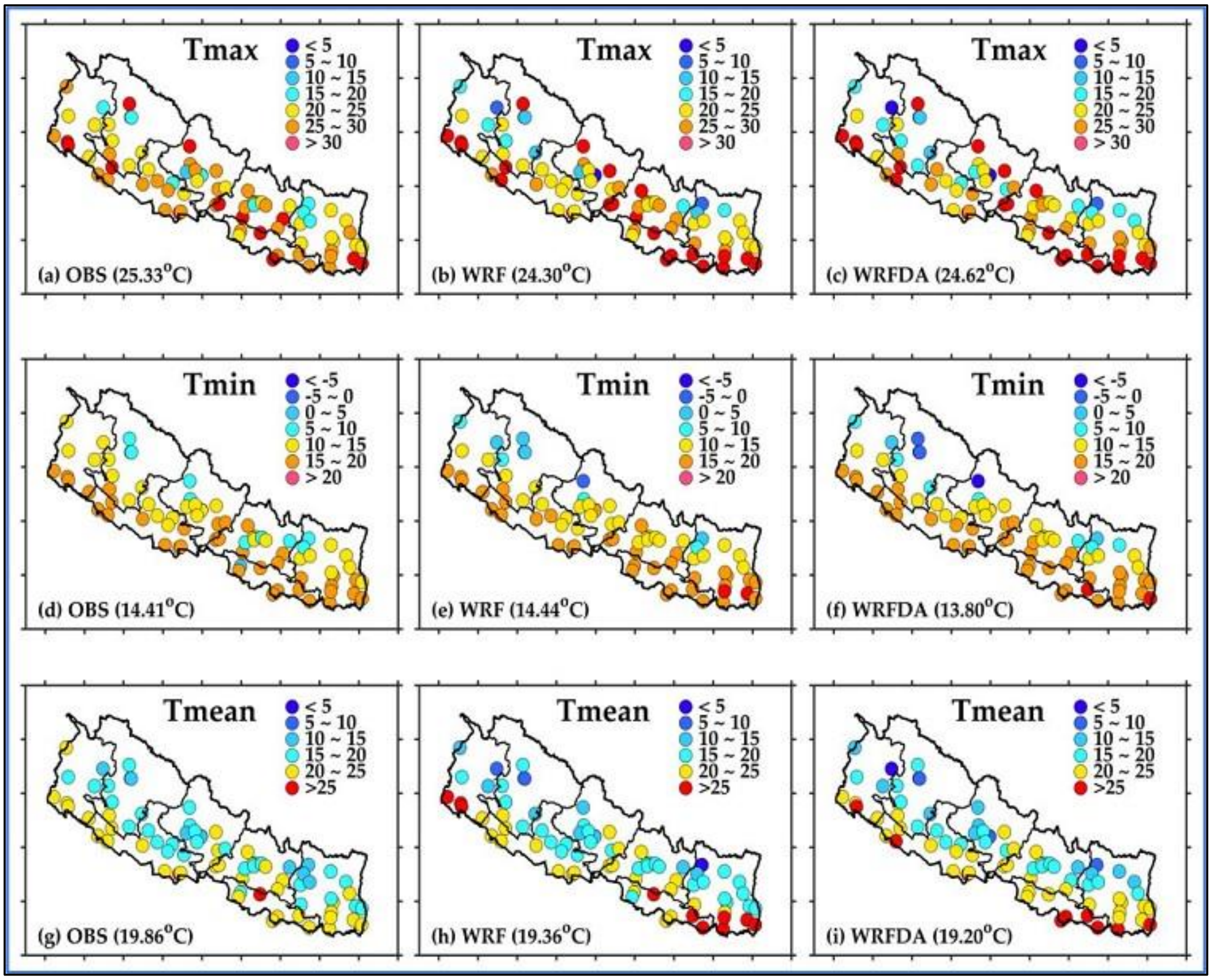

Figure 13: Spatial distribution of annual mean Tmax, Tmin and Tmean as Observed (a, d, g), and as simulated by WRF (b, e, h), and WRF-DA (c, f, i) over Nepal

A few statistical metrices of WRF and WRF-DA simulated for Tmax, Tmin, and Tmean over Nepal is presented in Table 6: Statistical metrics of Tmax, Tmin, and Tmean for WRF and WRF-DA datasets as compared with observed data. The WRF simulation under-estimated the Tmax (by -1.03 °C) and Tmean (-0.5 °C), whereas slightly over-estimated the observed Tmin (by 0.03°C) datasets. WRF-DA simulation under-estimated observed Tmax, Tmin, Tmean datasets. The higher correlation and lower RMSE value in WRF data than WRF-DA, indicate that WRF model simulates the observed temperature more realistically over Nepal. Overall, WRF model version also performs better in simulating the Tmin and Tmean than WRF-DA model version. For Tmax, WRF-DA simulation has slightly higher skill scores suggesting thereby that WRF-DA simulation can better represent the Tmax over Nepal.

Table 6: Statistical metrics of Tmax, Tmin, and Tmean for WRF and WRF-DA datasets as compared with observed data

Variable	Datasets	BIAS	CORR (R)	RMSE	ME	Skill	MEAN
Tmax	WRF	-1.03	0.86	3.56	1.03	0.7	24.31
	WRFDA	-0.71	0.79	4.20	0.71	0.73	24.62
Tmin	WRF	0.03	0.80	2.84	-0.03	0.87	14.44
	WRFDA	-0.61	0.78	3.49	0.61	0.76	13.80
Tmean	WRF	-0.50	0.88	2.42	0.50	0.67	19.37
	WRFDA	-0.66	0.84	3.08	0.66	0.61	19.20

3.4.2 Surface air temperature validation at selected three locations

The three days' weather forecast by WRF during the period Jan-2021 to Dec-2022 for maximum and minimum temperature were evaluated with observed datasets for the three selected locations. The inter-comparison of three days weather forecast with observed dataset for maximum and minimum temperatures at Bhojpur have been depicted in Figure 14 and Figure 15, respectively. These figures indicate that, the weather forecast over estimates for majority of the events for Maximum temperature (Figure 14). However, in the case of minimum temperature forecast at Bhojpur, the number of weathers forecast with over estimation and under estimation in comparison with observed values are uniformly distributed. [Figure 15]. The mean value of weather forecast is falling below the observed value for both maximum and minimum temperatures. The prediction of minimum temperature was observed more accurate than maximum temperature at this location. The performance evaluation for weather forecast in terms of statistical indices says that, the mean value of weather forecast falling close to observed values (Table 7). The excellent D-Index (Index of Agreement) and Correlation (R) values indicate that, the weather forecast captures the variability and pattern in of the observed values. The standard deviation of both observed and forecasted values are falling very close. However, in terms of quantitative bias measurement (normalized root mean square error [nRMSE]), it has been observed that the weather forecast holds an error of 13% and 9% for maximum and minimum temperatures, respectively.

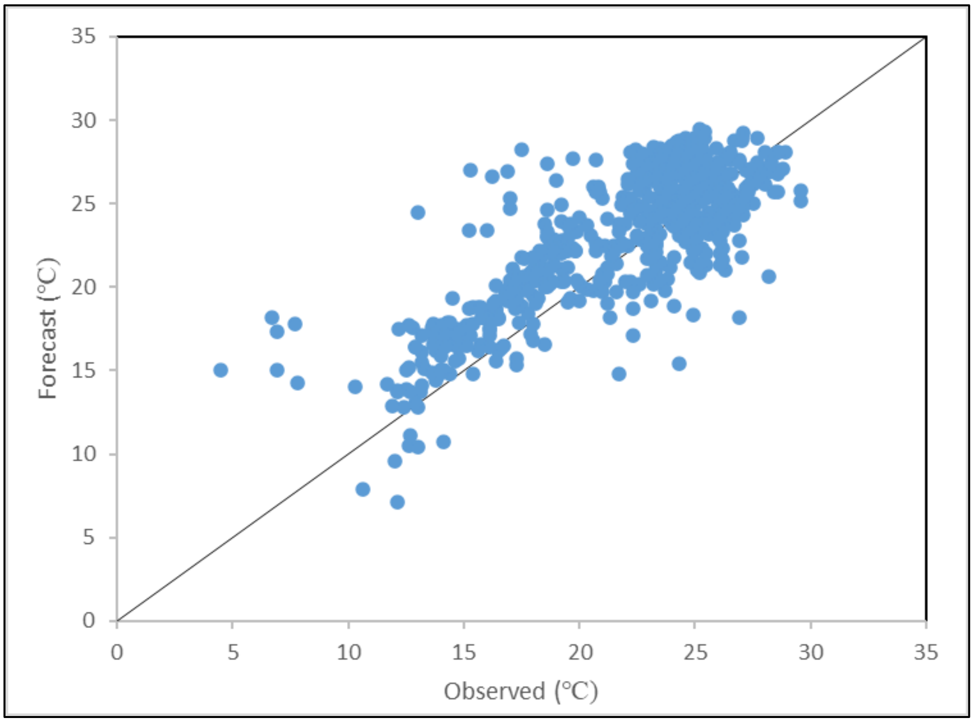

Figure 14: Inter comparison of three days weather forecast for maximum temperature with Observed data during Jan-2021 to Dec-2022 at Bhojpur

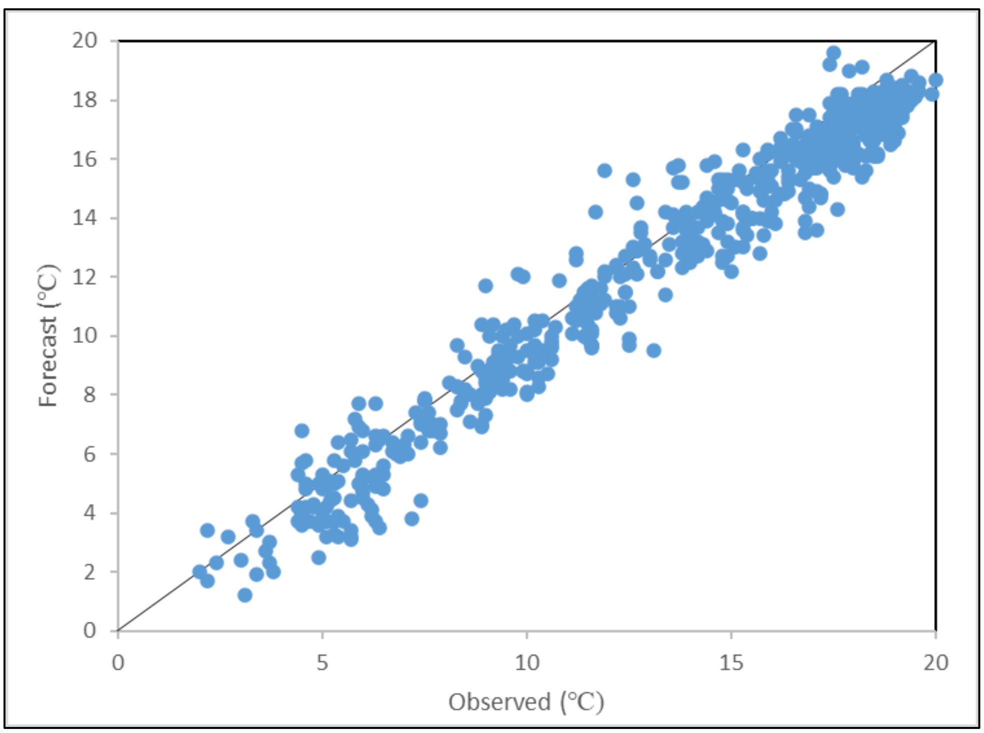

Figure 15: Inter comparison of three days weather forecast for minimum temperature with Observed data during Jan-2021 to Dec-2022 at Bhojpur

Table 7: Accuracy of 3-day weather forecast in terms of statistical indices for maximum and minimum temperatures at Bhojpur

Index	Maximum Temperature	Minimum Temperature
Mean (Observed)	22.98	13.56
Mean (Predicted)	21.65	12.83
Root Mean Square Error (RMSE)	3.09	1.24
D-Index	0.87	0.98
Normalized RMSE	13%	9%
Mean absolute Percentage Error	11%	9%
R	0.80	0.98
Standard Deviation-Measured (SDm)	4.16	4.88
Standard Deviation-Estimated (SDe)	4.52	4.79

The inter-comparison of three days weather forecast with observed dataset for maximum and minimum temperatures at Karmaiya have been depicted in Figure 16 and Figure 17, respectively. These figures indicate that, the weather forecast consistently under estimates in the case of maximum temperature and over estimates in the case of minimum temperature. The mean value of weather forecast falling below to observed values for maximum temperature and above for minimum temperature (Table 8). The standard deviation of both observed and forecasted values are falling very close. The excellent D-Index, nRMSE and R values indicate that, the weather forecast captures the variability and pattern in of the observed values and the quantitative value of error in weather forecast is less than 12% for maximum temperature and 9% for minimum temperatures at this location.

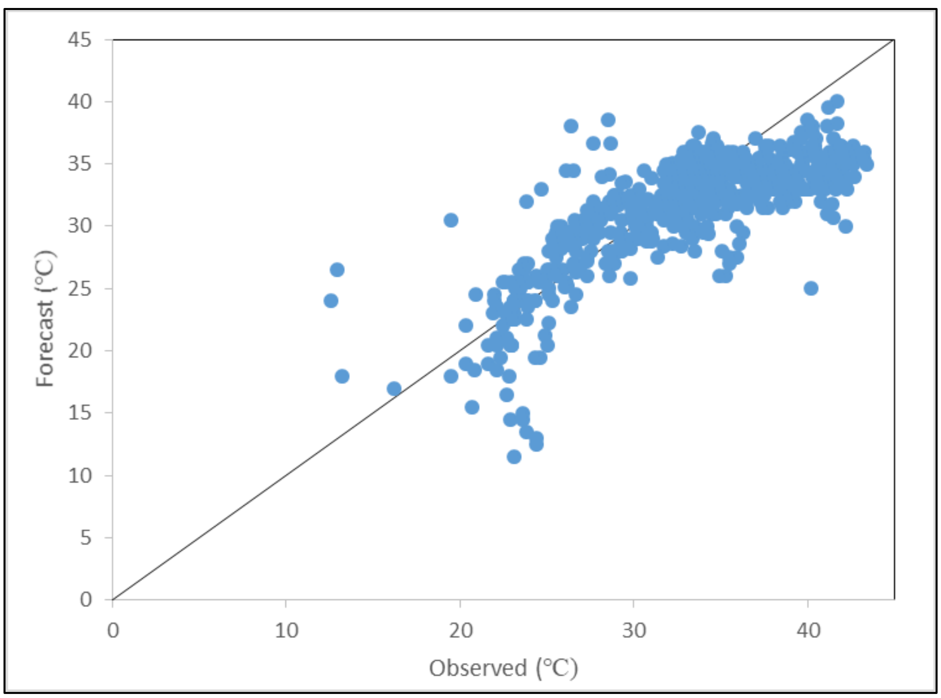

Figure 16: Inter comparison of three days weather forecast for maximum temperature with Observed data during Jan-2021 to Dec-2022 at Karmaiya

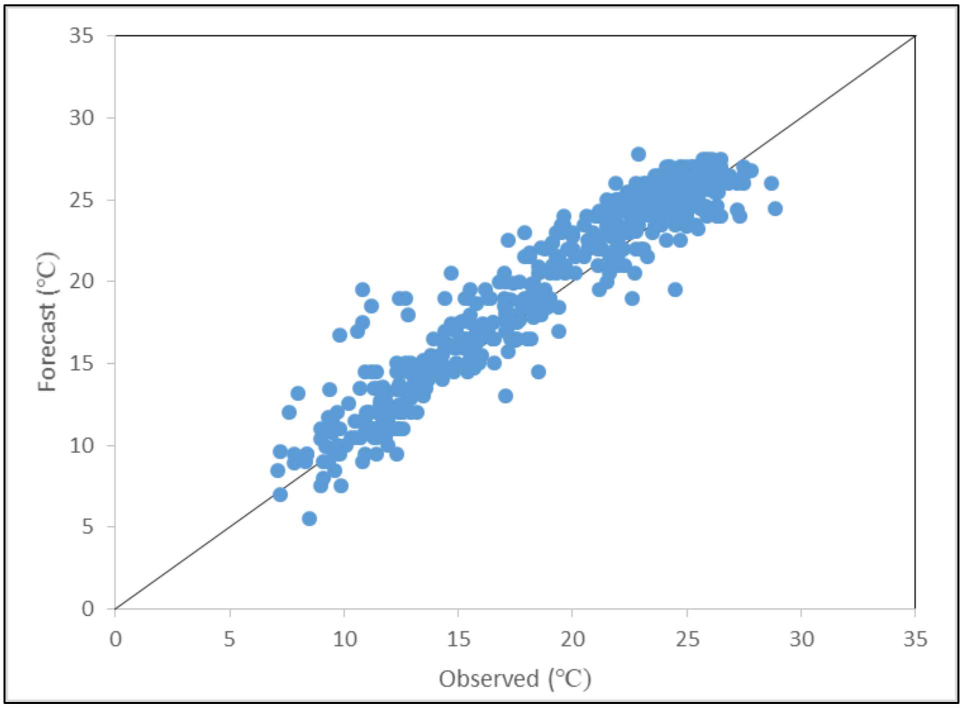

Figure 17: Inter comparison of three days weather forecast for minimum temperature with Observed (ERA5) data during Jan-2021 to Dec-2022 at Karmaiya

Table 8: Accuracy of 3-day weather forecast in terms of statistical indices for maximum and minimum temperatures at Karmaiya

Index	Maximum Temperature	Minimum Temperature
Mean (Observed)	32.03	19.75
Mean (Predicted)	31.07	20.73
Root Mean Square Error (RMSE)	3.83	1.88
D-Index	0.86	0.97
Normalized RMSE	12%	9%
Mean absolute Percentage Error	10%	8%
R	0.77	0.96
Standard Deviation-Measured (SDm)	4.68	5.58
Standard Deviation-Estimated (SDe)	5.82	5.48

The inter-comparison of three days' weather forecast with observed dataset for maximum and minimum temperatures at Khudibazar have been depicted in Figure 18 and Figure 19, respectively. These figures indicate that, the weather forecast consistently underestimate for both maximum and minimum temperature at this location. The performance evaluation for weather forecast in terms of statistical indices says that, the mean value of weather forecast falling very much below to observed values (Table 9). The better D-Index, nRMSE and R values indicate that, the weather forecast captures the variability and pattern in of the observed values and the quantitative value of error in weather forecast lies between 20% for maximum temperature and 15% for minimum temperatures at this location.

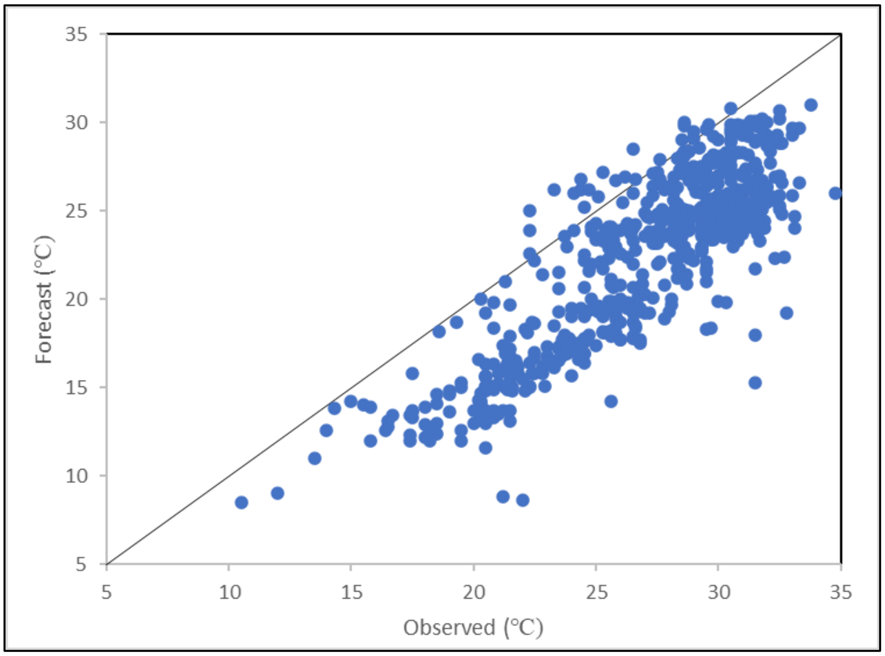

Figure 18: Inter comparison of three days weather forecast for maximum temperature with Observed data during Jan-2021 to Dec-2022 at Khudibazar

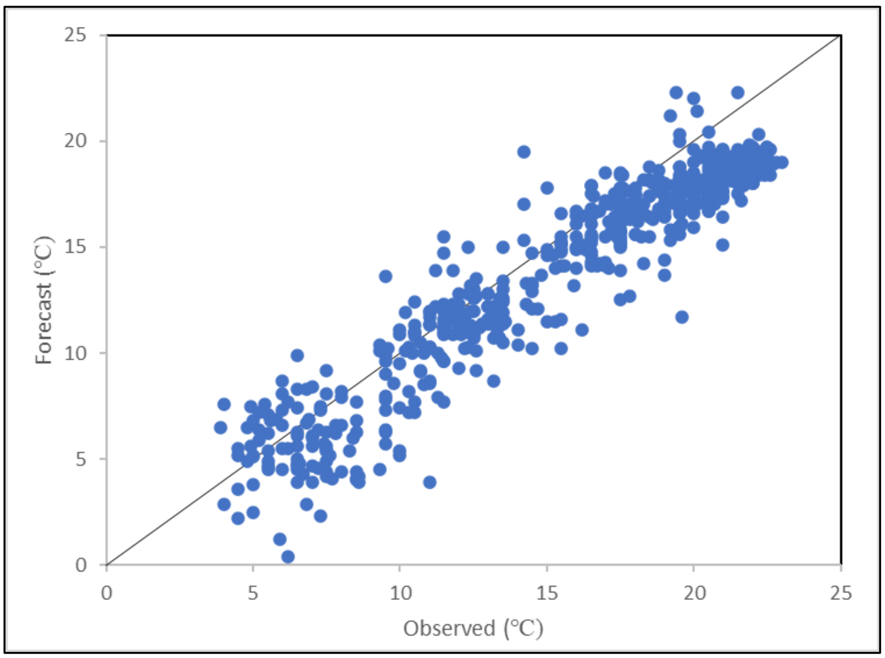

Figure 19: Inter comparison of three days weather forecast for Minimum temperature with Observed data during Jan-2021 to Dec-2022 at Khudibazar

Table 9: Accuracy of 3-day weather forecast in terms of statistical indices for maximum and minimum temperatures at Khudibazar

Index	Maximum Temperature	Minimum Temperature
Mean (Observed)	27.05	15.75
Mean (Predicted)	22.41	14.16
Root Mean Square Error (RMSE)	5.32	2.36
D-Index	0.74	0.95
Normalized RMSE	20%	15%
Mean absolute Percentage Error	18%	15%
R	0.84	0.95
Standard Deviation-Measured (SDm)	4.26	5.39
Standard Deviation-Estimated (SDe)	4.84	4.89

Hence the evaluation of 3-day forecast at selected locations in Nepal showed that, there is a bias in maximum and minimum temperature forecast in a range of 9-12% at Bhojpur and Karmaiya and 15-20% at Khudibazar.

3.4.3 Precipitation validation across the country

The annual cycle of the area-averaged (across all the grid points within the country) daily precipitation distribution of observed as well as WRF and WRF-DA simulated datasets are presented in Figure 20. Precipitation starts to increase from May and peak during July (~45 mm), however another peak after the monsoon is also observed during November (>50 mm). WRF and WRFDA simulated data closely follow the precipitation pattern until June (as during winter month received low precipitation). It is evident from Figure 5 that WRF-DA model largely over-estimated the precipitation amount during the monsoon season, while WRF model simulation exhibits consistent performance with observation. It is interesting to note that datasets from both the model versions captured the unusually high precipitation during October which are not recorded in observations. The average rainfall over Nepal for the year 2021 was estimated as 6.93 mm/day in observations, which is simulated as 6.06 mm/day and 8.67 mm/day in WRF and WRF-DA simulated datasets. Overall, WRF model under-estimated the annual mean precipitation while WRF-DA model over-estimated the annual mean precipitation amount. The daily high intensity rainfall averaged over Nepal during rainy season was grossly over-estimated in both the model simulations as compared to observations.

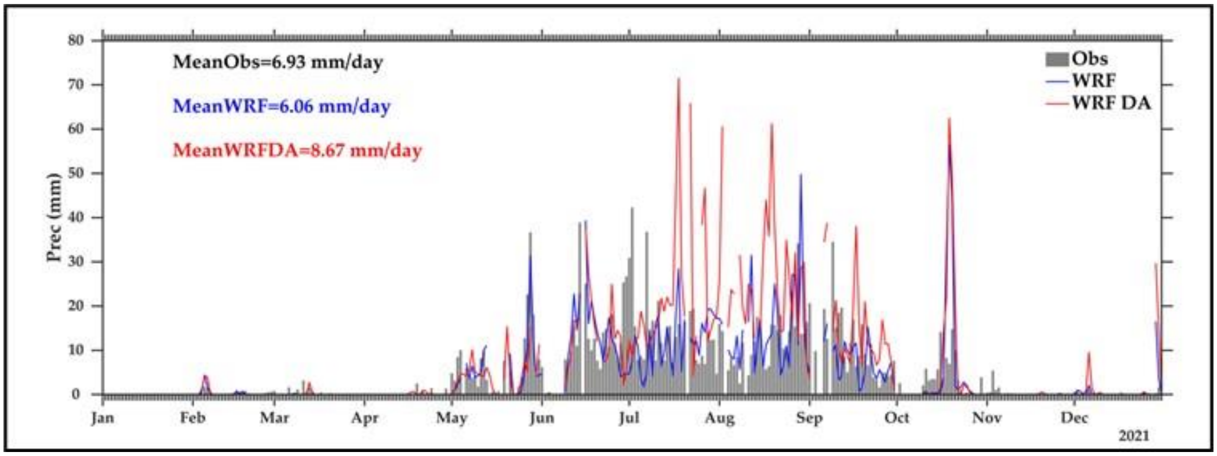

Figure 20: Daily distribution of observed, WRF and WRF-DA precipitation averaged over Nepal between January 24 to December 31, 2021. The Gray bar, Blue line and Red line represent the observed, WRF and WRF-DA datasets

The monthly total precipitation as calculated from observations and simulated in WRF and WRF-DA versions of the model from January 24 to December 31, 2021 is presented in Figure 21. The summer monsoon precipitation initially commences from June with peak in the month of July and then decreases from September to October (gradual monsoon withdrawal). The peak amount of precipitation occurred in July (480 mm) because of the very active summer monsoon in the observed records. The WRF and WRF-DA show the similar rain cycle during the monsoon season, however, both model version simulates peak precipitation during the month of August. The simulated June to September monsoon rainfall is underestimated in WRF while it is overestimated in WRF-DA simulation when compared with the observed precipitation. During winter and pre-monsoon season (during November to February and March to May) both the model versions underestimated the precipitation (comparatively low precipitation seasons). The highest monthly total precipitation in WRF and WRF-DA simulations is about 480 mm and 775 mm, respectively. The deviation in modelled monthly total forecast is much larger in the model after the assimilated input data is prescribed. This is likely if the observed monthly totals are missing the rainfall / snowfall amounts occurring in the remote data sparse regions and radar is not capable to capture this rainfall/snowfall beyond its range. The appropriately calibrated data from satellite also would need to be accounted for.

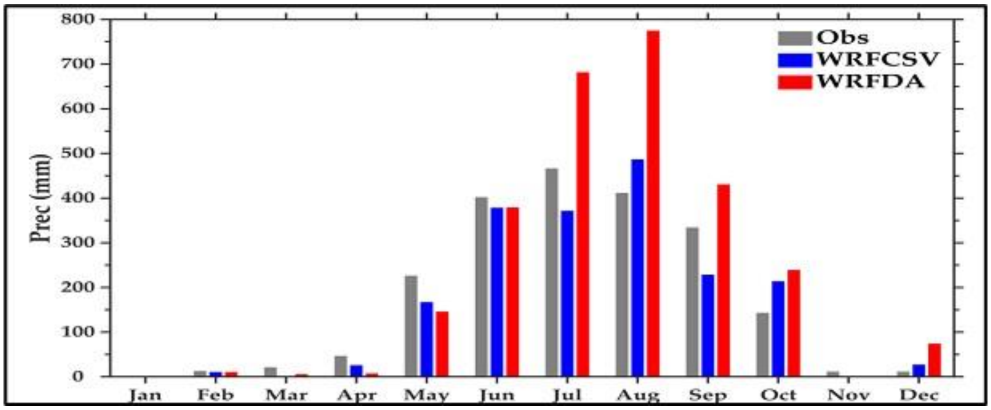

Figure 21: Validation of observed monthly total precipitation (mm) averaged over Nepal with those simulated in WRF and WRF-DA model versions

The observed precipitation during the January and February months is quite low (below 2 mm) as these months receive low precipitation. The statistical metrics of monthly precipitation prediction skill in Table 10 shows that the monthly precipitation amount simulated by WRF is close to observation (under-estimated, ME= -23.4 mm/month) than WRF-DA (over-estimated, ME=+46.53 mm/month). Similarly, WRF simulation also shows higher correlation (R=0.93) and lower RMSE (63.7) than WRFDA simulation (Table 3). Although, WRF simulated the monthly precipitation by a slightly under-estimated amount, it well represented the observed monthly precipitation pattern than in WRF-DA model simulation.

Table 10: Statistics of spatial distribution of monthly precipitation performance (mm) between observed and WRF and WRF-DA simulations

Datasets	Correlation Coefficient (R)	RMSE	Modelled Error (mm/month)	Mean Monthly Precipitation (mm)
Observation				182.70
WRF	0.93	63.7	-23.40	159.30
WRF-DA	0.92	136.03	+46.53	229.34

The spatial distribution of annual total precipitation (mm) between January 24, 2021 and December 31, 2021, as observed, as well as those simulated by WRF and WRF-DA model versions are illustrated in Figure 7(a), 4(b) and 4(c), respectively. The point scale mean precipitations are not spatially interpolated here due to error in accurate representation. The observation data shows large spatial variability of precipitation across the country as expected due to unique orography in Nepal. The highest mean precipitation amount (~4900 mm) was observed in the Lumle area (Gandaki province), whereas the lowest amount (<500 mm) in the high-elevation areas of the Central and Eastern region (Figure 7a). As is the observed spatial distribution, WRF and WRF-DA simulation datasets broadly exhibit the main characteristics, as the high precipitation occurs in Central Nepal (Gandaki Province) and high-elevation areas (Figures 7b and 7c). The WRF data generally under-estimates the annual total precipitation (by more than 500 mm at most of the stations) while, WRF-DA simulation over-estimates the observed precipitation over Nepal. WRF-DA simulated an over-estimate of the annual total precipitation by >500 mm at majority of stations, especially in the mid-elevation areas of the country (at higher altitudes, there are no stations to validate so this has not been critically validated). Further, statistical metrics for annual total precipitation at spatial scale are presented in Table 11 below. Overall metrics shows that WRF data better present the spatial patterns of observed precipitation with higher correlation (R) of 0.7, with smaller root mean square error (RMSE of 693.94) over Nepal.

Table 11: Statistics of spatial distribution of annual total precipitation (mm) between observed and WRF and WRF-DA simulations

Datasets	Correlation Coefficient (R)	RMSE	Modelled error	Annual Precipitation (mm)
OBS				1662.9
WRF	0.70	693.94	-236.59	1426.3
WRF-DA	0.58	756.77	+383.85	2046.8

For the seasonal analysis, only three seasons, namely, pre monsoon (March-May), monsoon (June-September), post-monsoon (October-November) are considered here, as for winter season, we would need data from 1st December 2020 to 28th February 2021. The performance of WRF and WRF-DA forecasted precipitation data relative to observations on seasonal timescale are illustrated in Figure 22. During the pre-monsoon, both WRF and WRF-DA simulated precipitation was under-estimated compared to observed precipitation at most of the stations (Figure 22a, Figure 23d). Under-estimation of precipitation by WRF-DA simulation is almost 32 mm higher than WRF simulated datasets (Figure 22a, Figure 22d). As monsoon season is the wettest season in the country, WRF simulated precipitation data exhibited under-estimation by ~153 mm, while WRF-DA simulated data over-estimated the observed precipitation by ~646 mm (Figure 22b, Figure 23e). WRF-DA simulation over-estimated the monsoon season precipitation mostly in mid- and high elevation areas, while over-estimation of monsoon season precipitation by WRF simulation was located at mid-elevation areas (Figure 22b, Figure 23e). Further, during the post-monsoon, WRF underestimation is higher than WRF-DA datasets (Figure 22c, Figure 23f). WRF underestimated the post-monsoon precipitation by ~43 mm, whereas WRF-DA underestimated observed precipitation by only ~17 mm across Nepal. Overall, WRF datasets exhibit more comparable performance during pre- and monsoon seasons while, WRF-DA datasets perform better in the post-monsoon season.

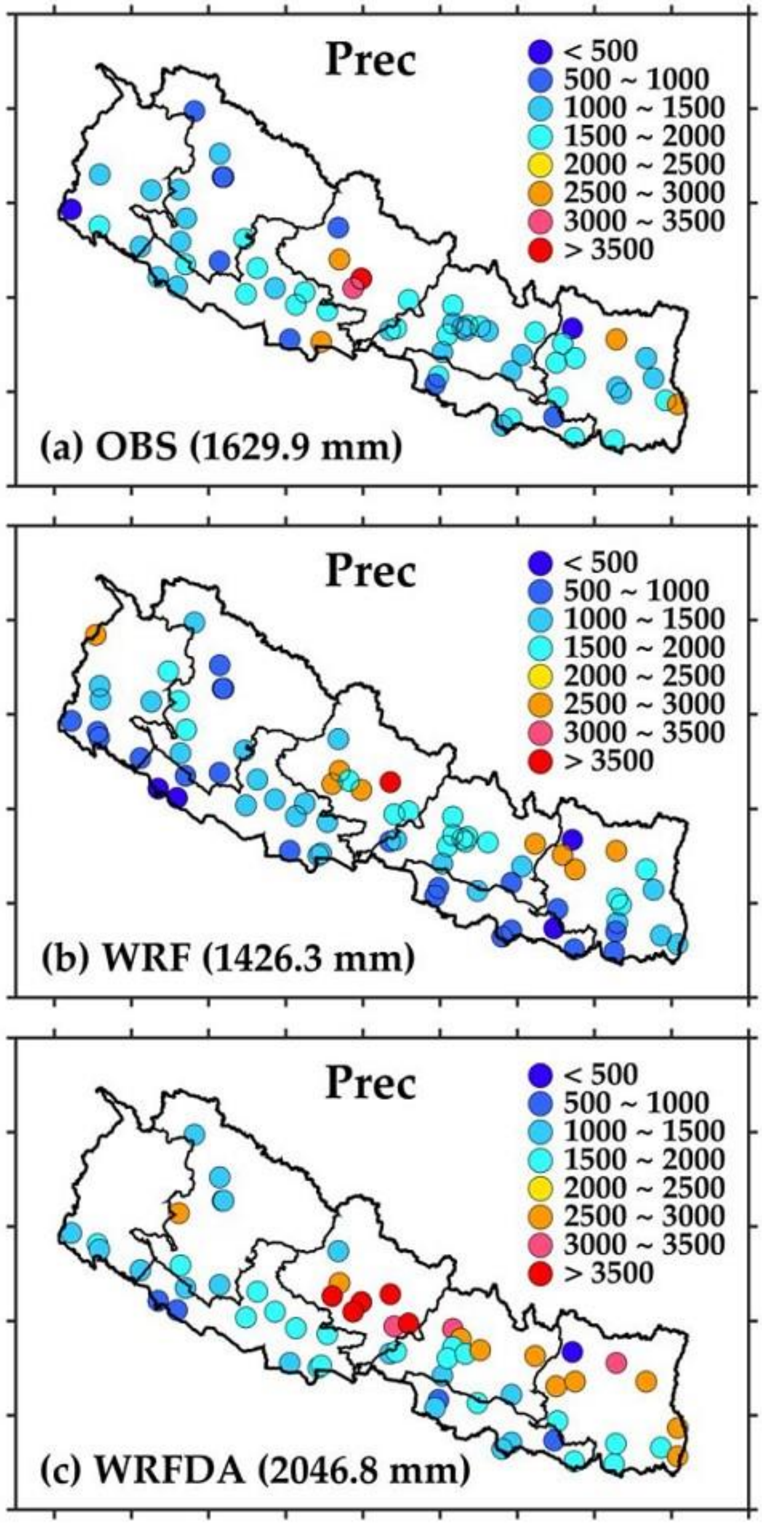

Figure 22: Spatial distribution of annual total precipitation as (a) observed and those simulated in (b) WRF and (c) WRF-DA experiments between 24 January and December 31, 2021 (area-averaged total rainfall / snowfall over Nepal is given in actual numbers here)

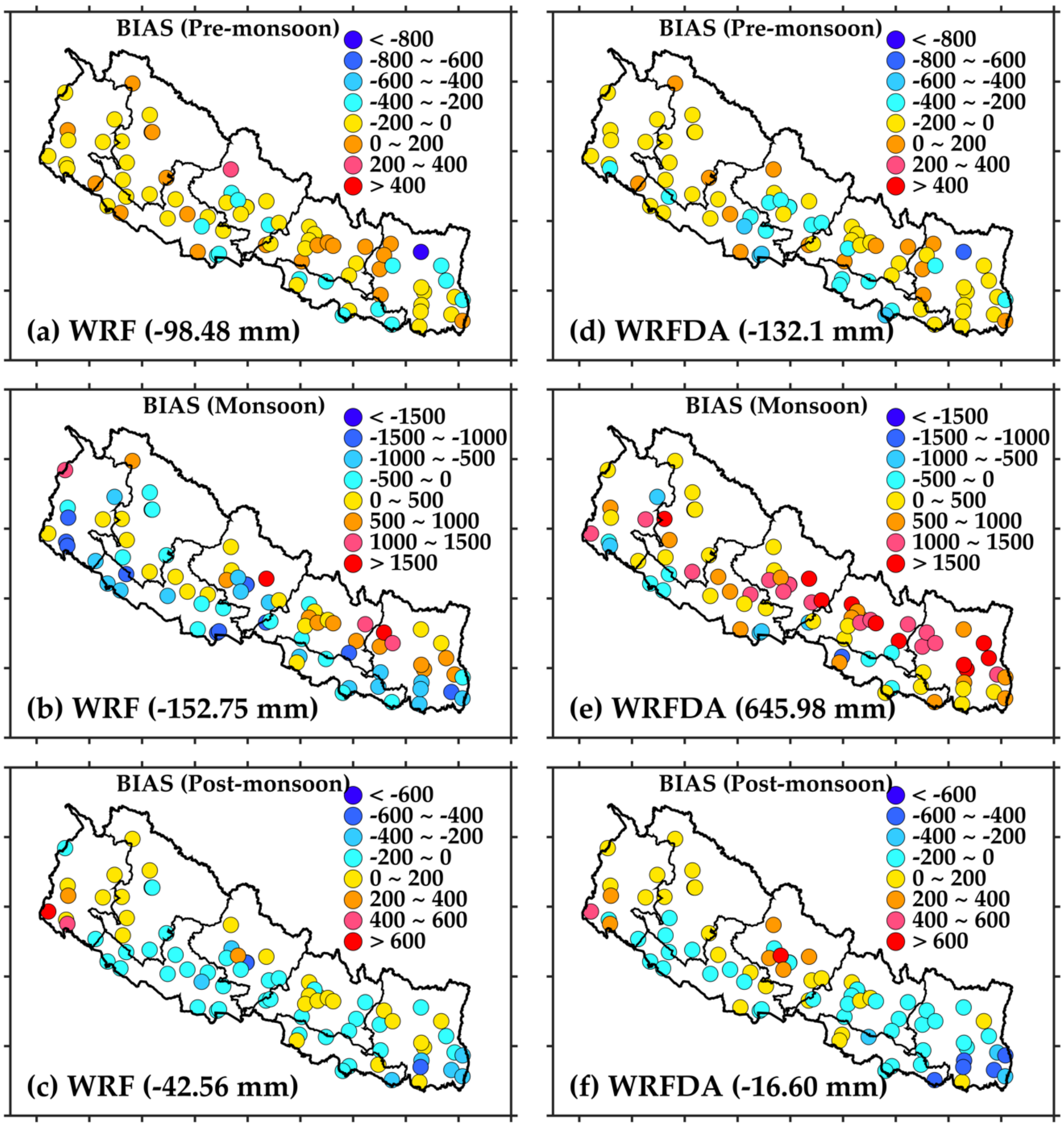

Figure 23: Spatial distribution of BIAS (WRF/WRF-DA – OBS) during (a, d) pre-monsoon, (b, e) monsoon, and (c, f) post-monsoon seasons over Nepal

A number of additional statistical tests e.g., Threat Score (TS, a metric that measures the skill of a precipitation forecast relative to chance) and Heidke Skill Score (HSS measures the fractional improvement over random chances) were performed on the datasets generated in WRF and WRF-DA simulations to further review the model's performance in simulating the precipitation across Nepal. The Threat score, and Heidke skill score at each of the stations in Nepal for both WRF and WRF-DA simulation datasets suggested that WRF simulation outputs exhibit slightly better performance than WRF-DA simulated datasets for detecting precipitation events or otherwise over Nepal during January 24, 2021 to December 31, 2021. Additionally, Skill Score was also calculated for each station for WRF and WRF-DA simulations using daily observations over Nepal (Figure 24). For the Skill Score, first, RMSE is calculated at each station, which is then divided by the Standard Deviation (SD) of the observed datasets. The ratio of RMSE and SD is finally subtracted by the perfect score (i.e., 1). The WRF datasets again exhibited better skill scores than the WRF-DA data sets. The Skill Scores at most of the station at mid-elevation showed more than 0.6 which is below 0.5 in WRF-DA datasets (Figure 24a, Figure 24b). It is also worth mentioning that, more stations show higher skill score in WRF datasets thus exhibiting better forecasting skill than WRF-DA simulation. This further re-iterates need for application of more appropriate the assimilation technique and include satellite-derived precipitation estimates for remote / data sparse regions of Nepal for improved precipitation forecast.

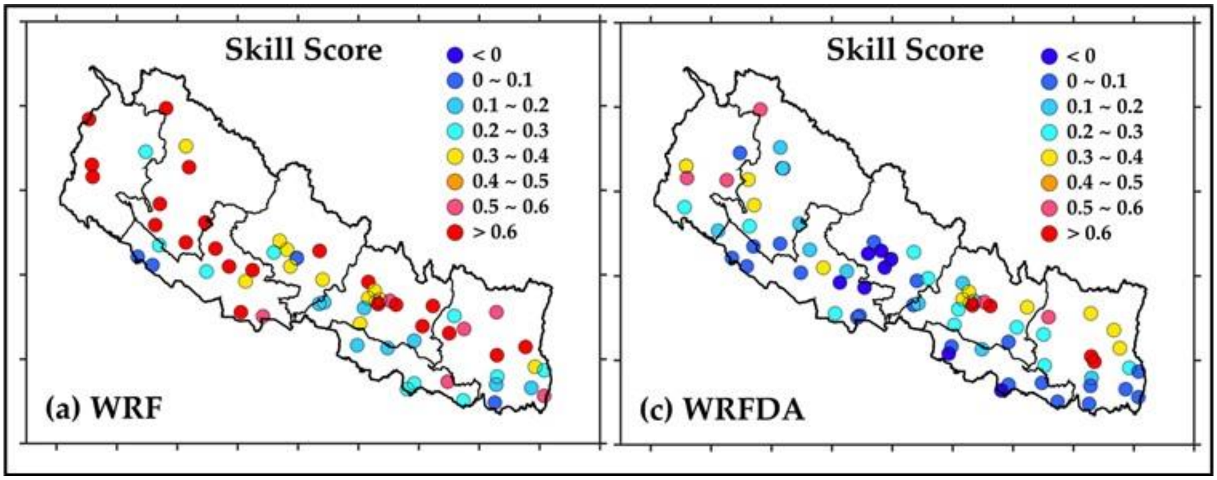

Figure 24: Skill score for forecasted precipitation in (a) WRF and (b) WRF-DA simulations

3.4.4 Precipitation validation at the selected three locations

The performance of monthly precipitation of WRF forecast against observed data during the SW monsoon period during the years 2021 and 2022 at the selected three locations are depicted from Figure 25 to Figure 27. From these graphs we can see that, there is a bias exists in WRF forecast in comparison with the observed data. The weather forecast overestimated the precipitation during all the months at Bhojpur. The forecasted values were higher than observed values during all the months except July at Karmaiya. However, at Khudibazar, the weather forecast was under estimated during June and overestimated during all the remaining months. From this analysis it was observed that, there is a significant bias exists in precipitation forecast, this forecast is due to the rugged topography of Nepal. Amid of the difficulty in collecting the weather data from remote areas of Nepal, the DHM is providing the best forecast services as per the available resources. The bias in the weather forecast can be reduced significantly and the quality of the weather forecast can be improved by adopting the bias correction techniques. We propose a bias correcting method to improve the quality of the forecast and it is described comprehensively in section 3.7 of this report.

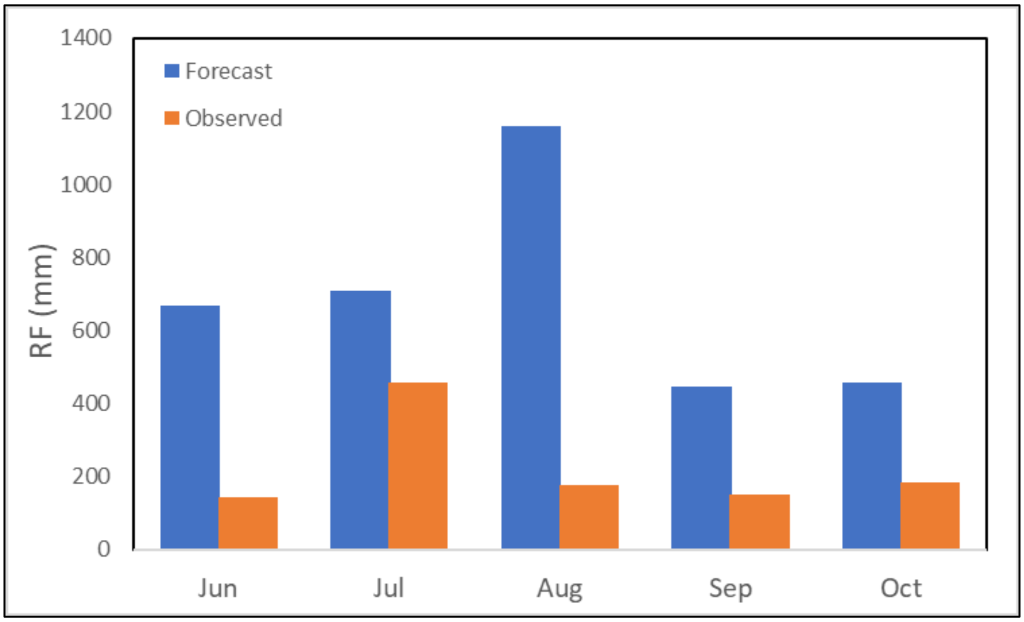

Figure 25: Monthly precipitation performance of WRF against observed data at Bhojpur

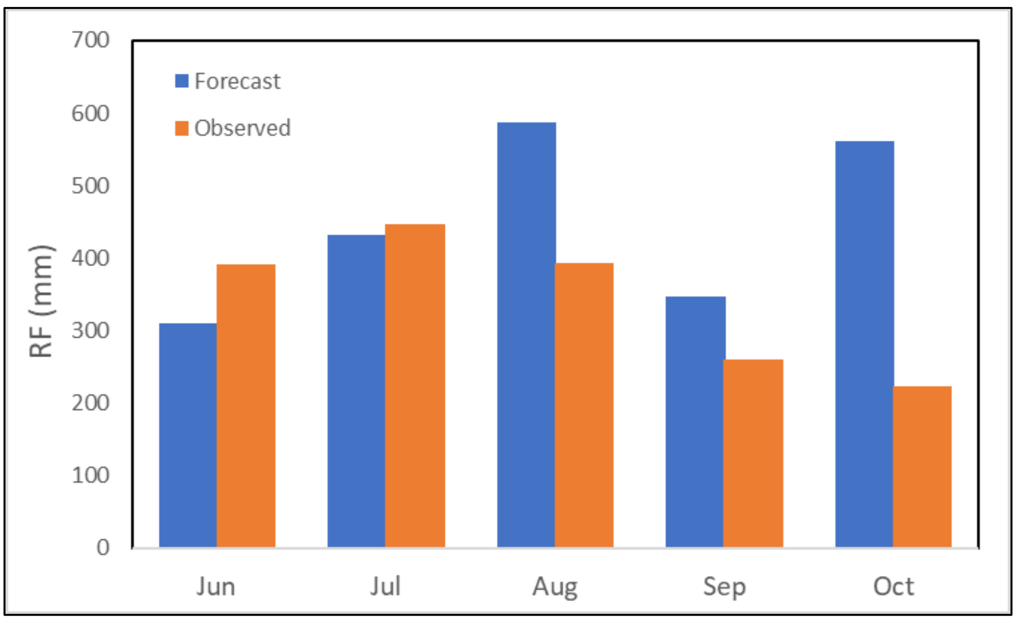

Figure 26: Monthly precipitation performance of WRF against observed data at Karmaiya

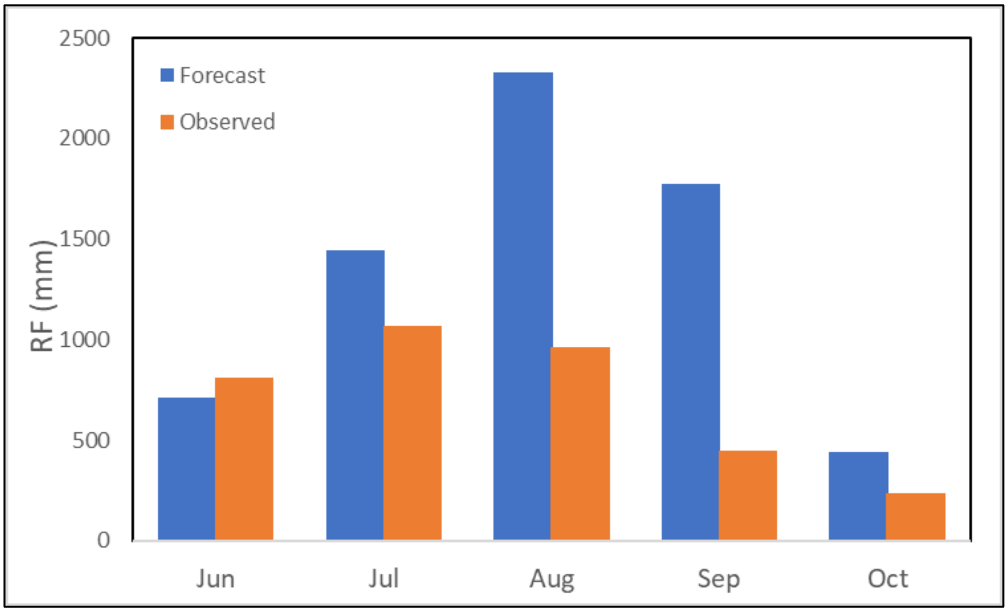

Figure 27: Monthly precipitation performance of WRF against observed data at Khudibazar

The evaluation of 3-day rainfall forecast against the observed rainfall during monsoon period (Jun-Oct) with the data of two years (2021 and 2022) has been performed in the present study in a dichotomous way. This analysis has been done on the basis of occurrence of moderate rainfall (>1 mm per day) in weather forecasts coincides with observed data. A dichotomous forecast says, "yes, an event will happen", or "no, the event will not happen" (Table 12). To verify this type of forecast a contingency table that shows the frequency of "yes" and "no" forecasts and occurrences can be used. The four combinations of forecasts (yes or no) and observations (yes or no), called the joint distribution are furnished in *Table 12*.

Table 12: Contingency table for forecast verification

		Observed		**Total**
		Yes	**No**	
Forecast	**Yes**	Hits	False Alarm	Forecast Yes
	No	Misses	Correct Negative	Forecast No
Total		Observed Yes	Observed No	Total

The criteria followed for evaluation of rainfall forecast over Nepal are described below.

Hit – When the observed (ERA-5) and WRF forecasted rainfall ≥ 1 mm

Miss – When the observed rainfall ≥ 1 mm and forecasted values < 1 mm

False Alarm - When the forecasted rainfall ≥ 1 mm and observed values < 1 mm

Correct Negative - When the observed (ERA-5) and WRF forecasted rainfall < 1 mm

The following indices based on this approach have been calculated.

3.4.5 Accuracy

It indicates the fraction of the forecasts were correct. It is simple and intuitive; however, it is heavily influenced by the most common category, usually "no event" in the case of rare weather. It is ranged between 0 to 1 and the perfect score is 1.

$$Accuracy = \frac{hits + correct\ negatives}{total}$$

3.4.6 Probability of detection (POD)

It indicates fraction of the observed "yes" events were correctly forecasted. It is sensitive to hit events but ignores false alarms. It is appropriate for rare and extreme weather events. It is also called as hit rate. It is ranged between 0 to 1 and the perfect score is 1.

$$POD = \frac{hits}{hits + misses}$$

3.4.7 Success Ratio

It indicates fraction of the forecast "yes" events were correctly observed. It is ranged between 0 to 1 and the perfect score is 1.

$$Success\ Ratio = \frac{Hits}{hits + False\ Alarm}$$

3.4.8 Threat Score

It indicates how well did the forecast "yes" events correspond to the observed "yes" events. It is ranged between 0 to 1 and the perfect score is 1.

$$Threat\ Score(TS) = \frac{Hits}{hits + Misses + False\ Alarm}$$

3.4.9 Results of the dichotomous forecast evaluation

The results of the present analysis say that, the accuracy of the 3-day weather forecast says that, more than 60% of the forecasts were correct in predicting rainy events (accuracy more than 0.63) at all the three selected locations (Table 13). However, this may be highly influenced by the occurrence of correct negatives. The POD says that the forecast is able to capture more than 90% of the rainy events. The success ratio was found highest in Khudibazar and lowest in Bhojpur. It indicates that, the occurrence of false alarms was highest in Bhojpur and lowest in Khudibazar. Due to this reason (occurrence of false alarms), there is significant variation was observed in threat score across these three locations. The threat score ranged between 0.57 at Bhojpur and 0.76 at Khudibazar and found intermediate at Karmaiya (0.61). As a whole, the present analysis indicates that, the success rate in predicting rainy event of the 3-day weather forecast among the selected locations was found highest at Khudibazar. The failure in predicting the occurrence of moderate rainy event (misses) was found highest in Karmaiya followed by Bhojpur. The occurrence of false alarms was found highest (Lowest success ratio) at Bhojpur followed by Karmaiya. As the combined influence of misses and false alarms (Threat Score), the efficiency of the 3-days weather forecast was found highest in Khudibazar followed by Bhojpur and Karmaiya. This analysis shows that, the weather forecast predicts most of the rainy event, however, there is a significant bias exists in predicting rainfall quantity. The month-wise deviation in this bias has been explained in section 3.4.4 of this report and in order to reduce this bias we propose to adopt the bias correction techniques explained in section 3.7 of this report.

Table 13: Evaluation of 3-day rainfall forecast during SW Monsoon period (Jun-Oct) at selected locations in Nepal

Index	Bhojpur	Karmaiya	Khudibazar
Accuracy	0.63	0.64	0.80
POD	0.98	0.90	0.94
Success Ratio	0.57	0.61	0.79
Threat Score	0.57	0.56	0.76

3.5 Evaluation of NWP Forecast disseminated through MFD website

The Meteorological Forecasting Division (MFD) of Department of Hydrology and Meteorology (DHM) is providing the meteorological analysis, weather conditions and forecast for rainfall, maximum and minimum temperatures on daily basis. The daily rainfall forecast has been provided in the format of rainfall probability (%) and the temperature (maximum and minimum) forecast is provided in the form of specific range of temperature (Eg: 34-36°C).

In the present study, the performance of daily rainfall and temperature forecast against the observed values has been analysed for selected locations in Nepal. The spatial distribution of selected 12 locations has been portrayed in Figure 28. These locations have been selected on the basis of continuous data availability and spatial distribution across the country. It was observed that, these locations are distributed more or less uniformly across the country and representing almost all the physiographic regions except high Himalayas. The daily data of observed and forecasted values for these locations were sourced from the website of MFD (www.mfd.gov.np). In the present study the daily weather forecast were compared against the observed values during the period of two years (April 2021 to March 2023).

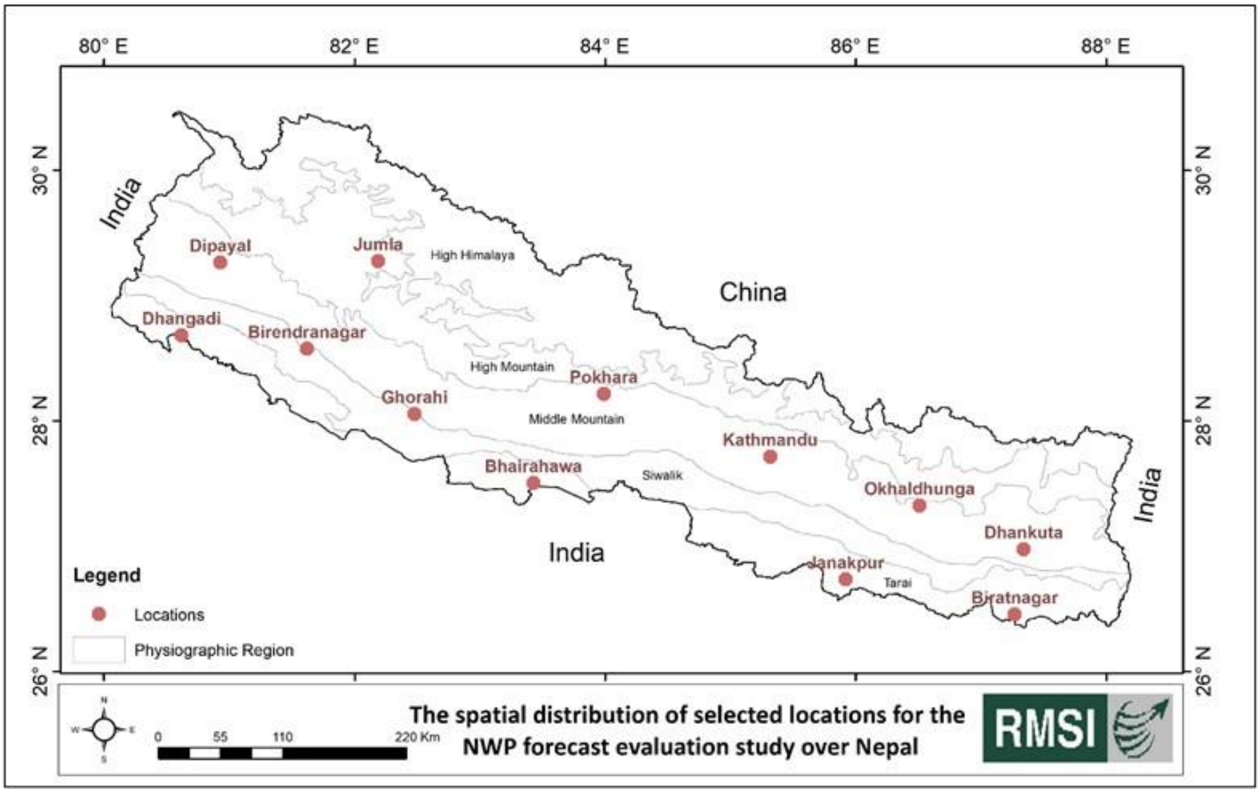

Figure 28: The spatial distribution of selected locations for the forecast evaluation analysis

In the case of evaluation of maximum and minimum temperature forecast it has been analysed whether the observed values are falling within the range of forecasted values. For example, if the observed maximum temperature is 35.6℃ and the forecast range is 36-38 ℃, the observed value if falling outside the forecasted range. Hence, there is only "hits" and "misses" and there is no "correct negatives" and "false alarms". Hence, only POD has been considered as the dichotomous forecast evaluation in the case of maximum and minimum temperatures.

In the present study, the total count of days with forecasted values of maximum and minimum temperatures which is higher and lower than the observed values have been estimated during the period April 2021 to March-2023. For this analysis, the middle value of the forecasted range has been considered to compare with the observed values. For example, if the forecasted maximum temperature range is 34-36℃ and the observed value is 33.7℃, then the forecasted value will be 35℃.

The criteria followed for evaluation of rainfall forecast over Nepal are described below.

Hit - Todays forecast for tomorrow's rainfall ≥ 50% probability and tomorrows observed rainfall ≥ 10 mm

Miss - Todays forecast for tomorrow's rainfall < 50% probability and tomorrows observed rainfall ≥ 10 mm

False Alarm - Todays forecast for tomorrow's rainfall ≥ 50% probability and tomorrows observed rainfall < 10 mm

Correct Negative - Todays forecast for tomorrow's rainfall < 50% probability and tomorrows observed rainfall < 10 mm

The indices such as POD and Threat Score have been computed for rainfall forecast based on this approach. The key findings of temperature and rainfall forecast evaluation have been explained in the following sections.

3.5.1 Evaluation of rainfall forecast

The POD of daily rainfall forecast in comparison with observed rainfall has been estimated for 12 selected locations in Nepal during the Southwest Monsoon Season (June-October) during the years 2021 and 2022. The Month wise POD in rainfall forecast from Jun to October during the years 2021 and 2022 have been over the selected locations in Nepal have been depicted from Figure 29 to Figure 38. These maps convey that the POD in rainfall forecast was higher in 2021 in comparison with 2022. During the month of June, the POD was above 0.61 over majority of the locations in 2021 (9 out of 12 locations), while it has been drastically declined in 2022 (Figure 29 and Figure 30). The POD was found as higher in the context of rainfall forecast in the month of July. All the locations exhibited a POD value of more than 0.61 in 2021, while during 2022, only 8 locations reached up to this level of accuracy (Figure 31 and Figure 32).

Similarly, during the month of August, 11 out of 12 locations exhibited a POD of more than 0.61 in daily rainfall forecast in 2021, while it has been drastically declined in 2022 (Figure 33 and Figure 34). The POD was found poor in the context of daily rainfall forecast in the month of September. Only 4 and 2 locations showed a POD value of more than 0.61 in 2021 and 2022, respectively (Figure 35 and Figure 36). However, the POD has been improved significantly during the month of October. Most of the locations in 2021 and all the locations in 2022 exhibited a POD value of more than 0.61 in daily rainfall forecast during the month of October (Figure 37 and Figure 38). During the whole SW monsoon season, majority of the locations (11 out of 12) exhibited a POD of more than 0.61, while in 2022 the rainfall forecast showed this level of accuracy.

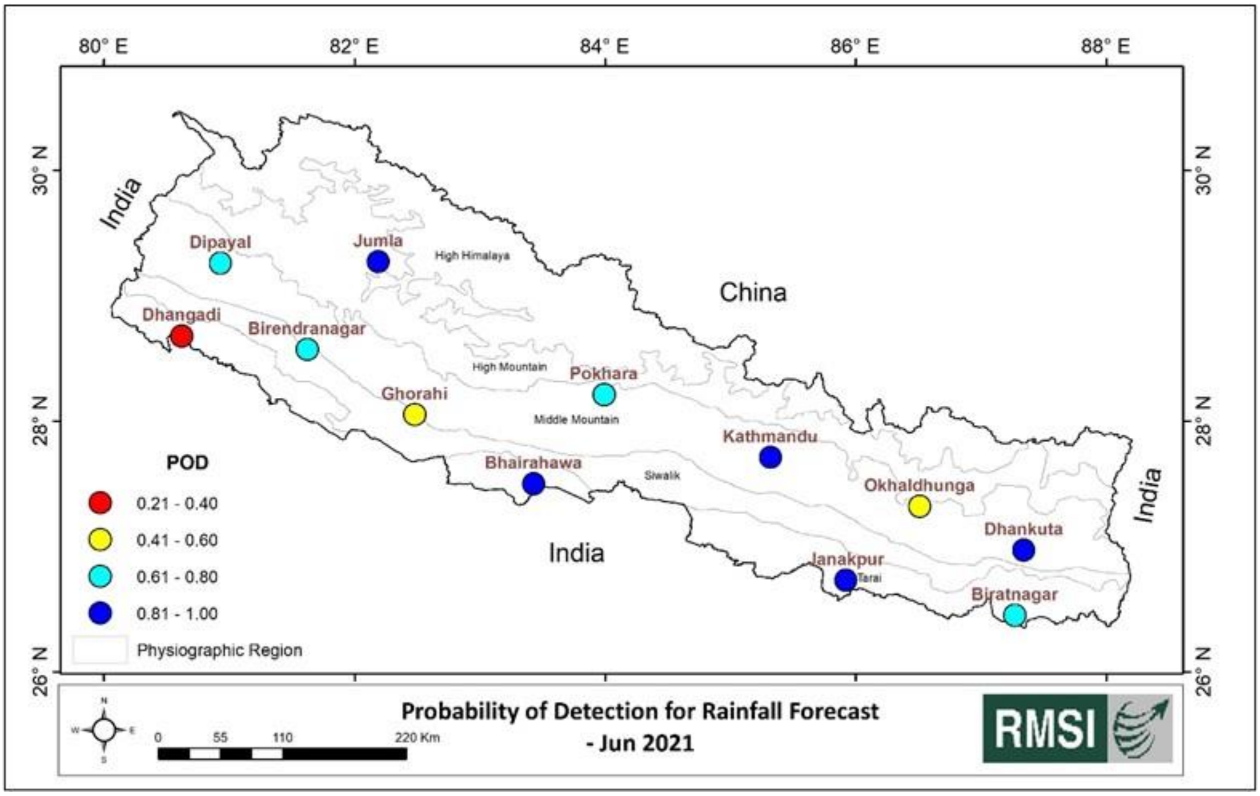

Figure 29: POD for Rainfall forecast over selected locations in Nepal during June 2021

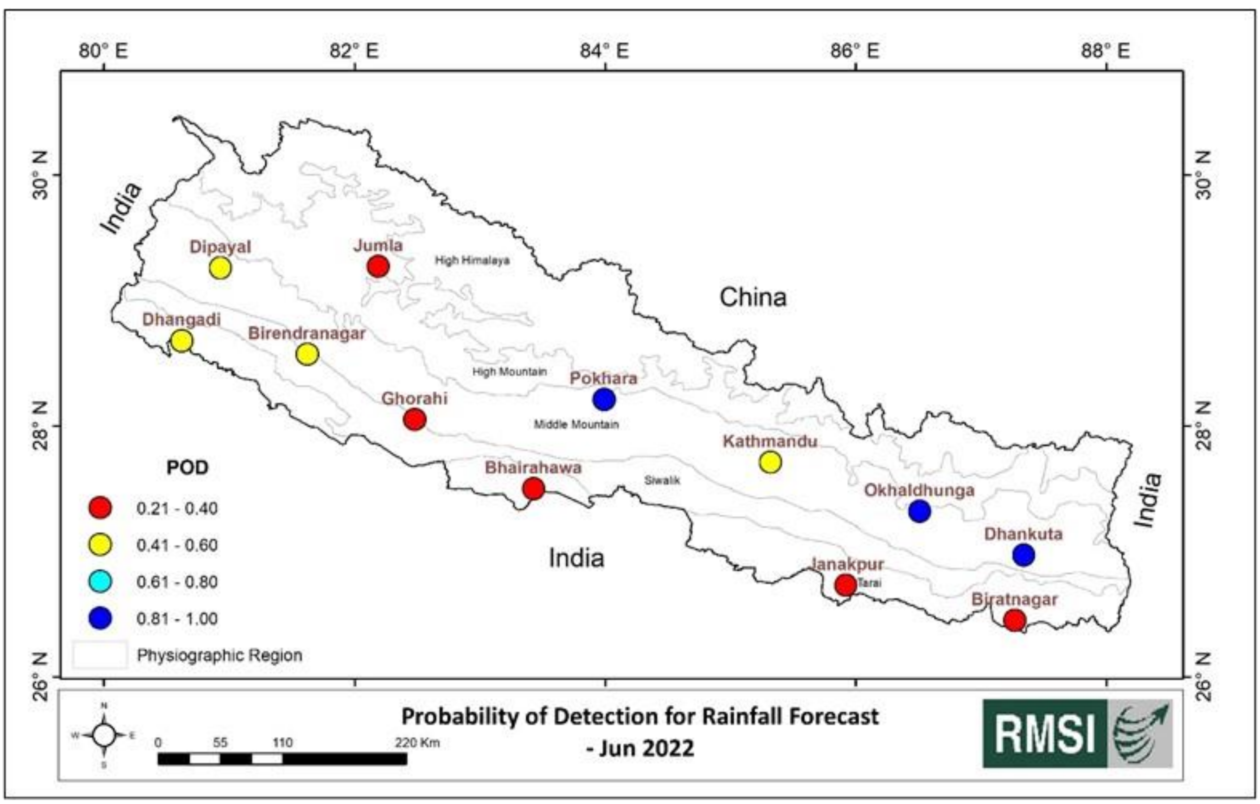

Figure 30: POD for Rainfall forecast over selected locations in Nepal during June 2022

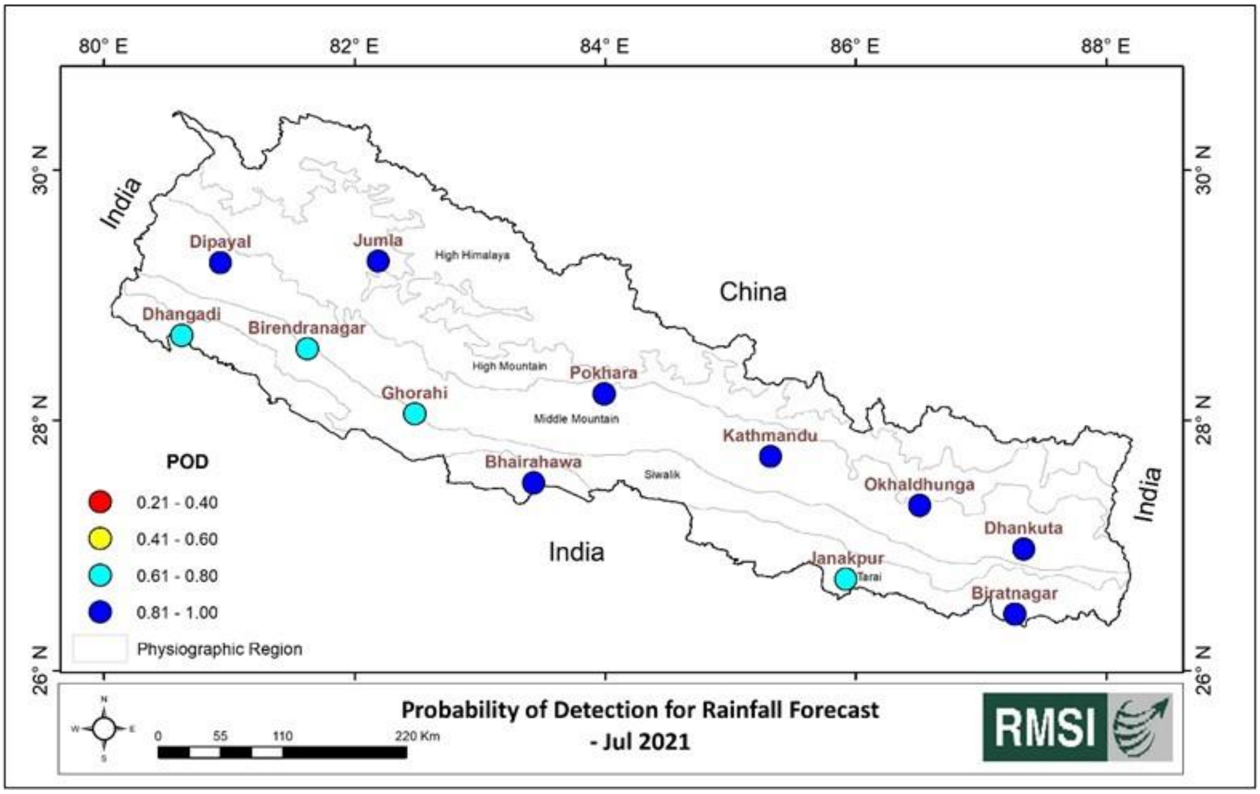

Figure 31: POD for Rainfall forecast over selected locations in Nepal during July 2021

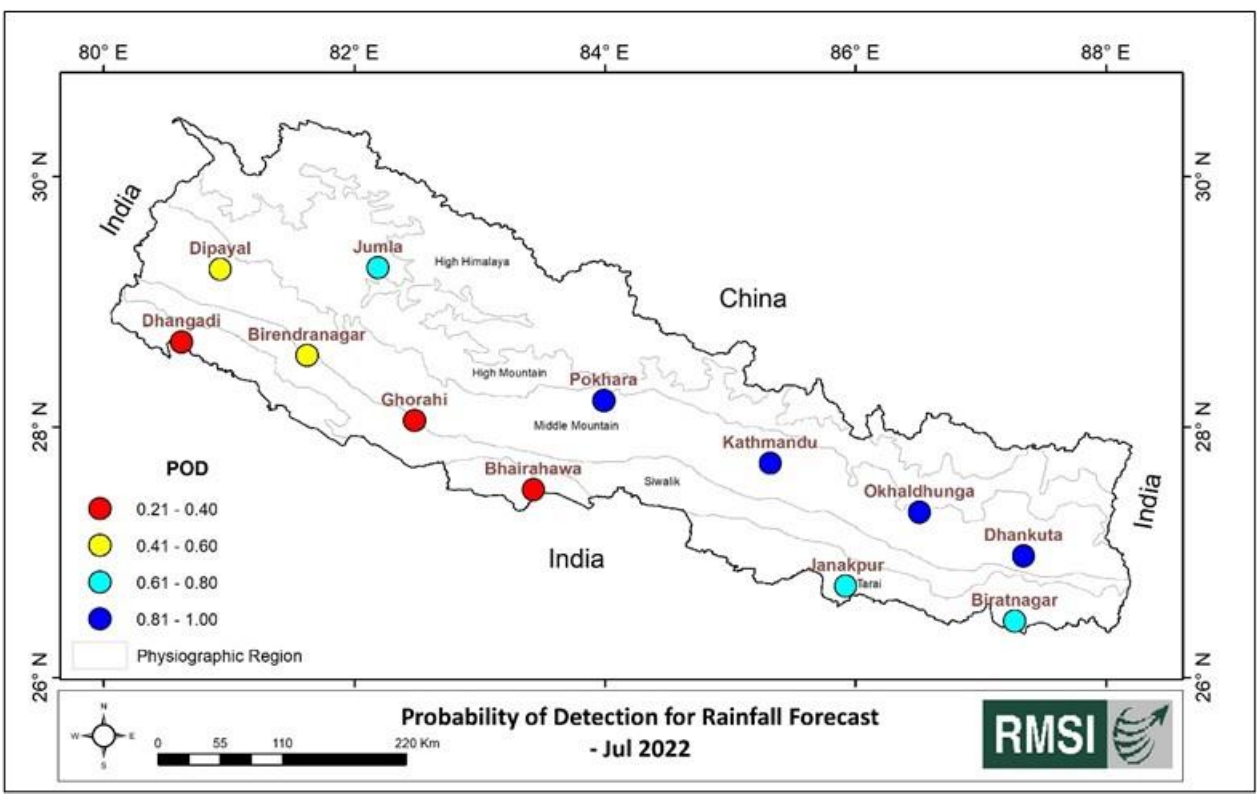

Figure 32: POD for Rainfall forecast over selected locations in Nepal during July 2022

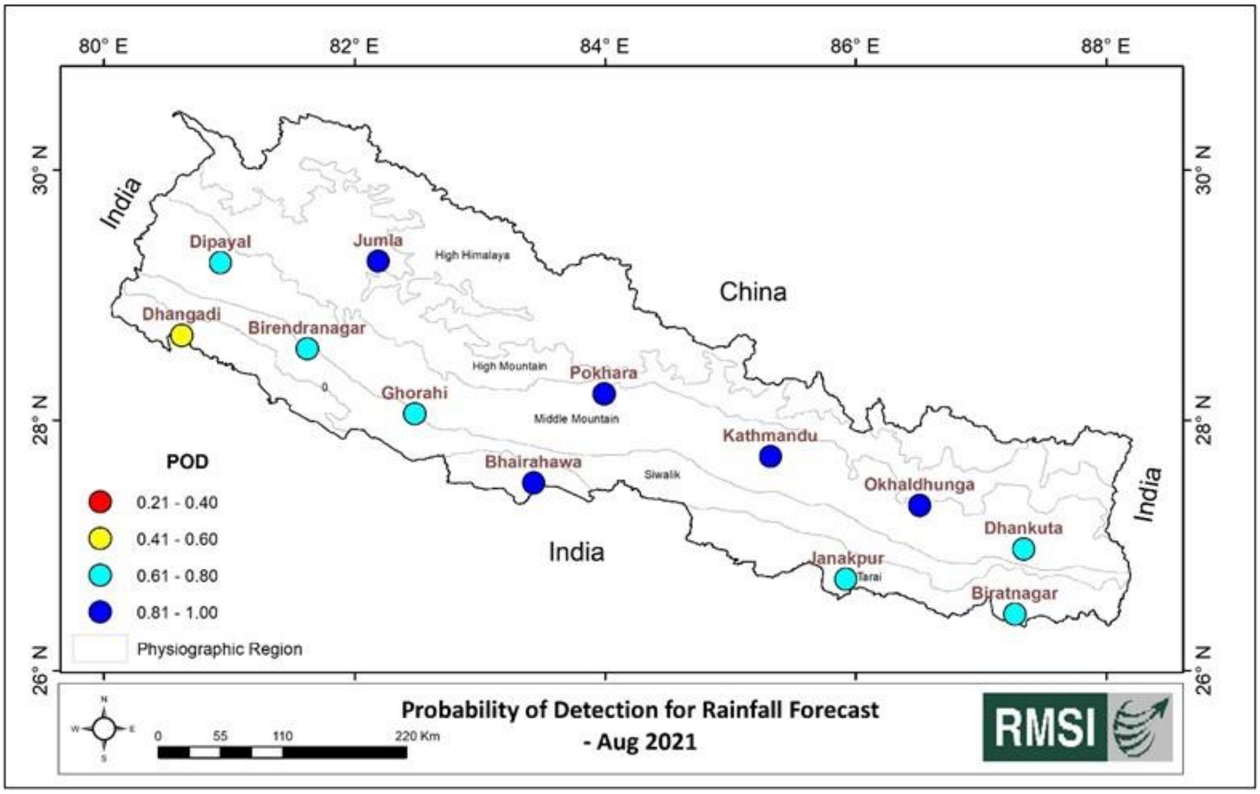

Figure 33: POD for Rainfall forecast over selected locations in Nepal during August 2021

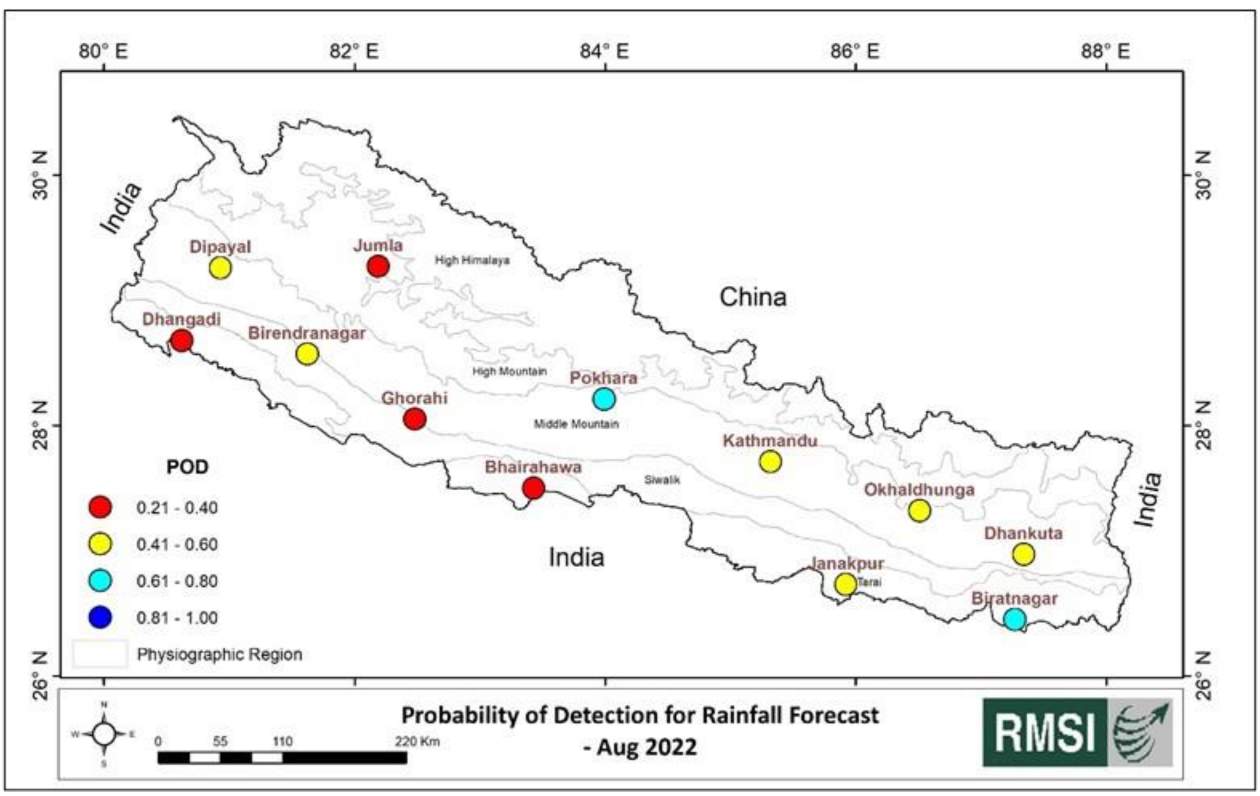

Figure 34: POD for Rainfall forecast over selected locations in Nepal during August 2022

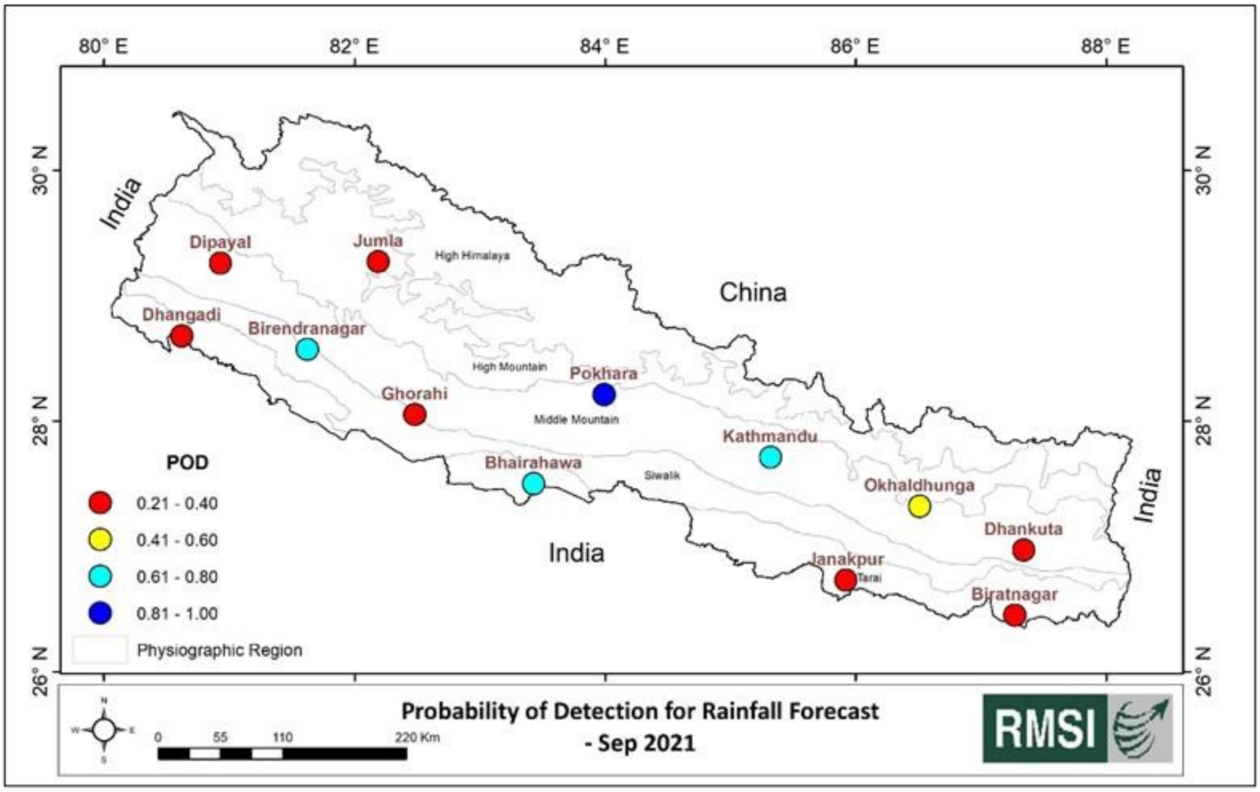

Figure 35: POD for Rainfall forecast over selected locations in Nepal during September 2021

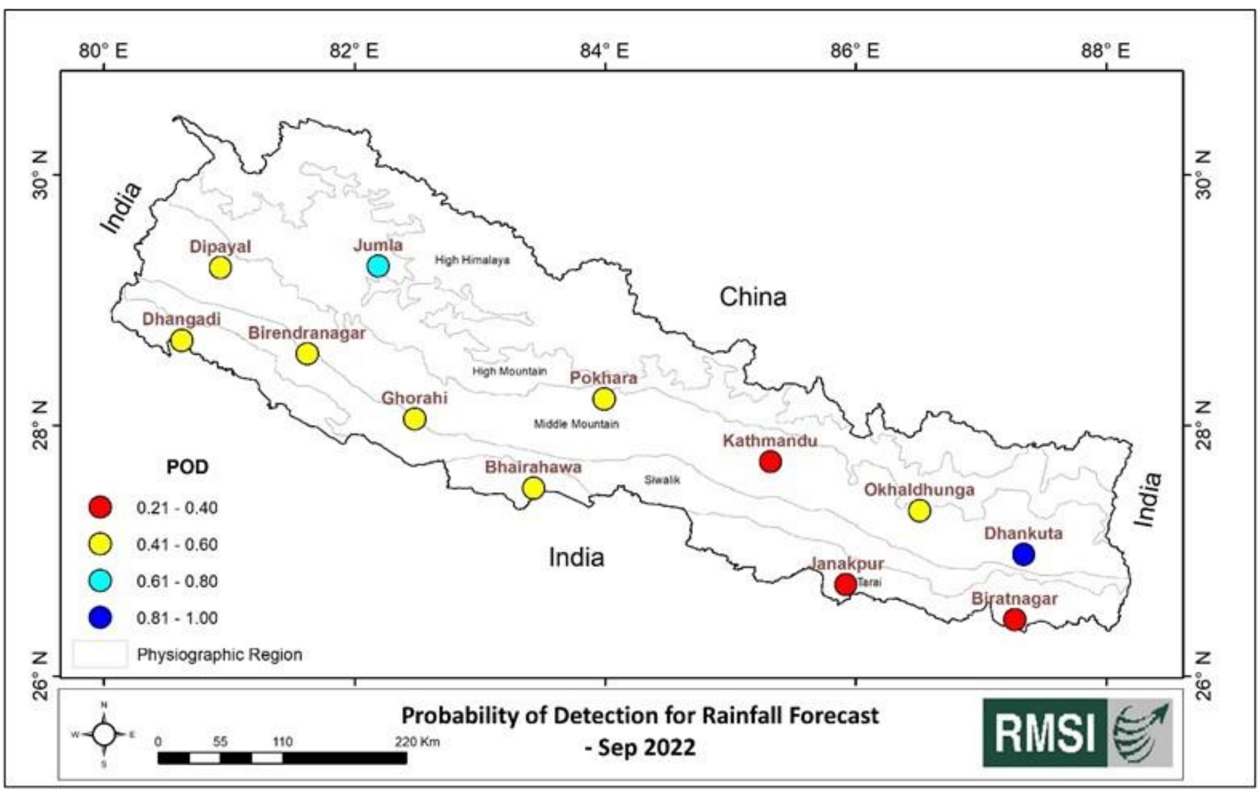

Figure 36: POD for Rainfall forecast over selected locations in Nepal during September 2022

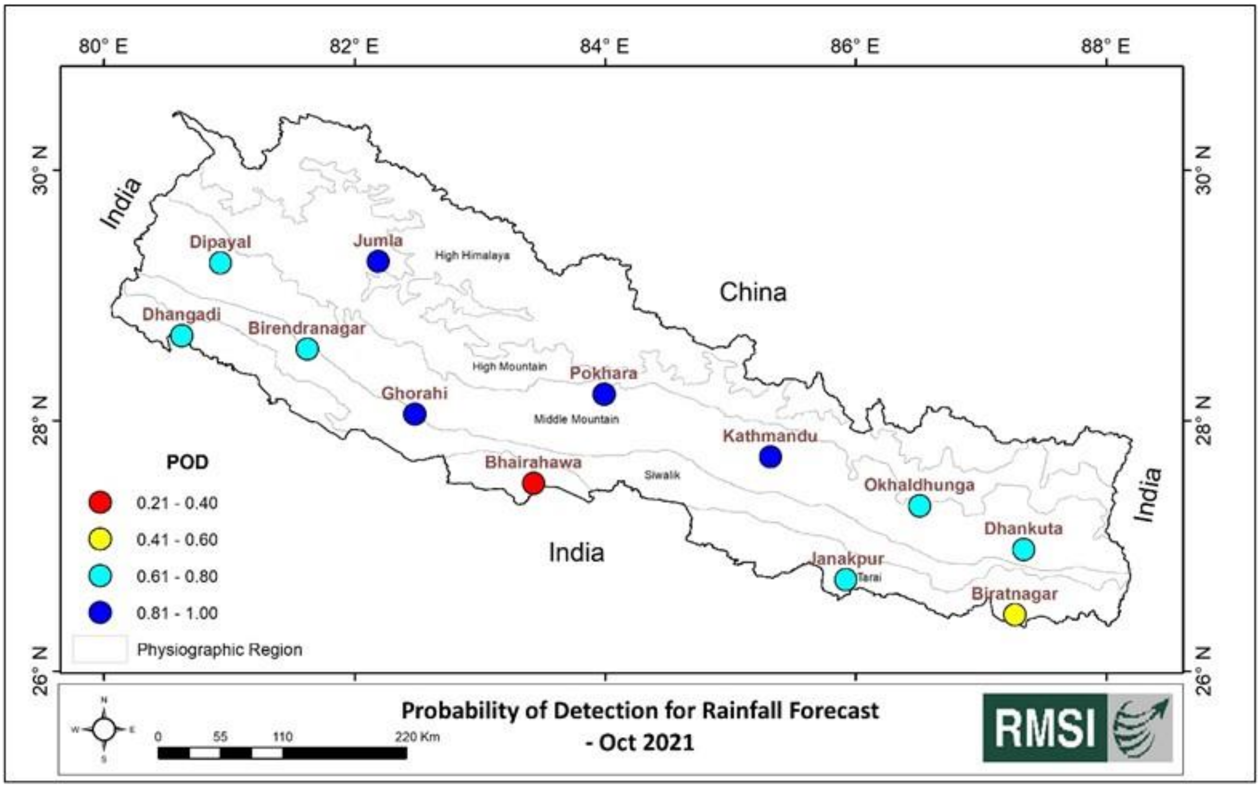

Figure 37: POD for Rainfall forecast over selected locations in Nepal during October 2021

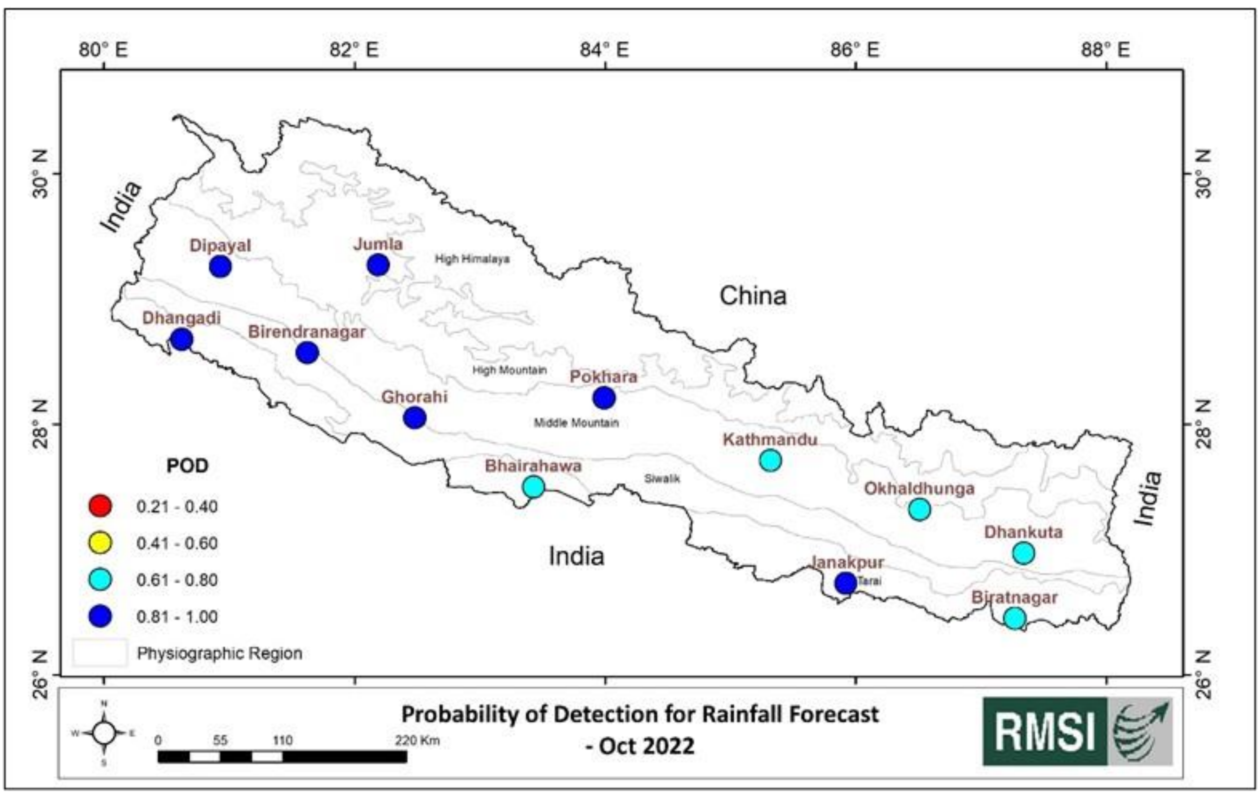

Figure 38: POD for Rainfall forecast over selected locations in Nepal during October 2022

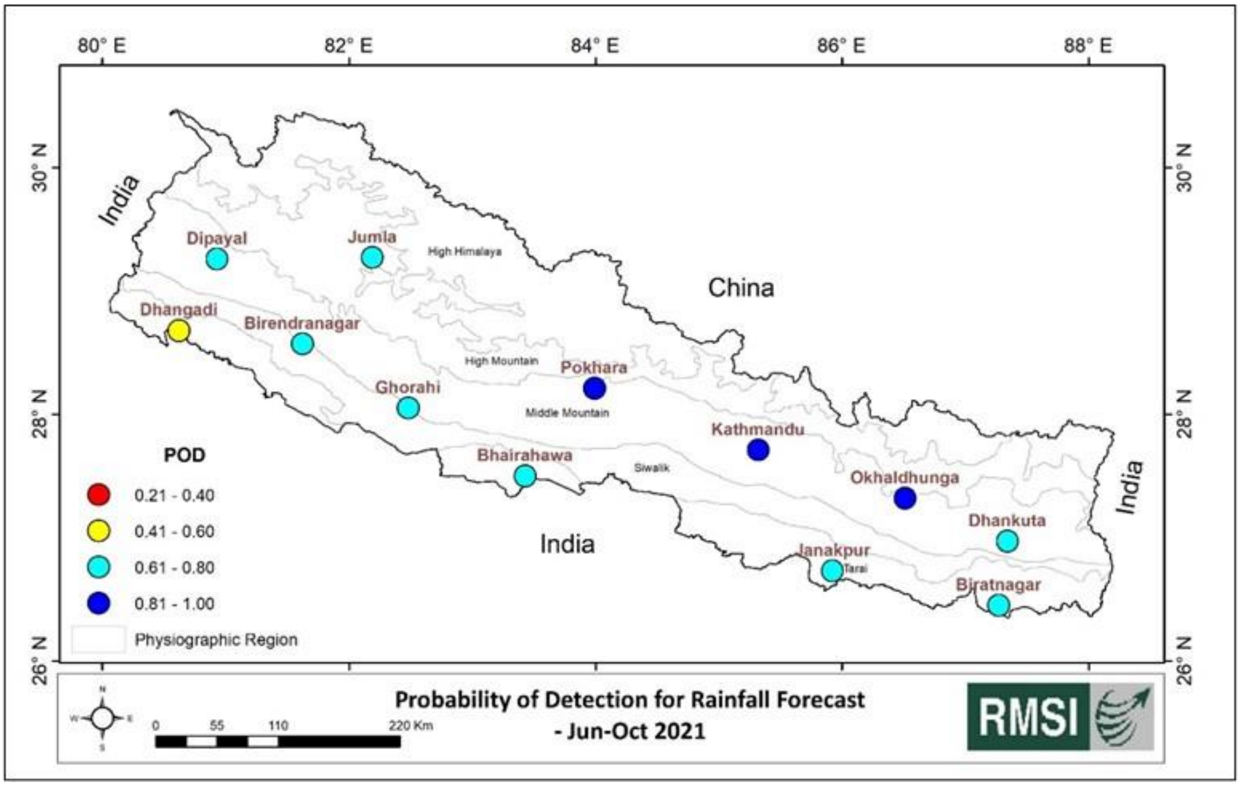

Figure 39: POD for Rainfall forecast over selected locations in Nepal during June-October 2021

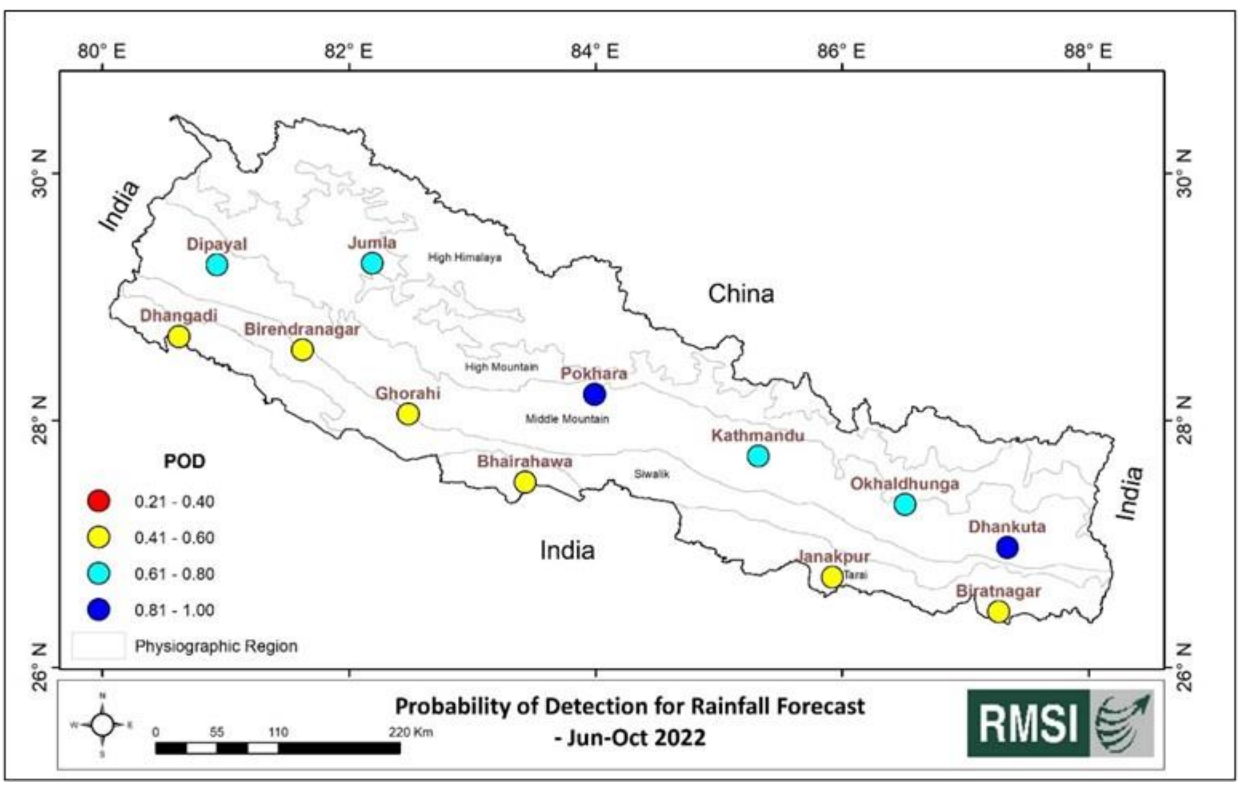

Figure 40: POD for Rainfall forecast over selected locations in Nepal during June-October 2022

The accuracy of rainfall forecast has further reduced in terms of threat score across all the locations, since the threat score will also account "false alarms" along with "hits" and "misses". The threat score was found less than 0.6 across majority of the locations in monthly scale as well as the whole SW Monsoon season (June-October) during both the years of 2021 and 2022 (Figure 41 to Figure 52). However, the treat score was found above 0.8 over few locations in the western parts of the country in October during the year 2022 (Figure 50).

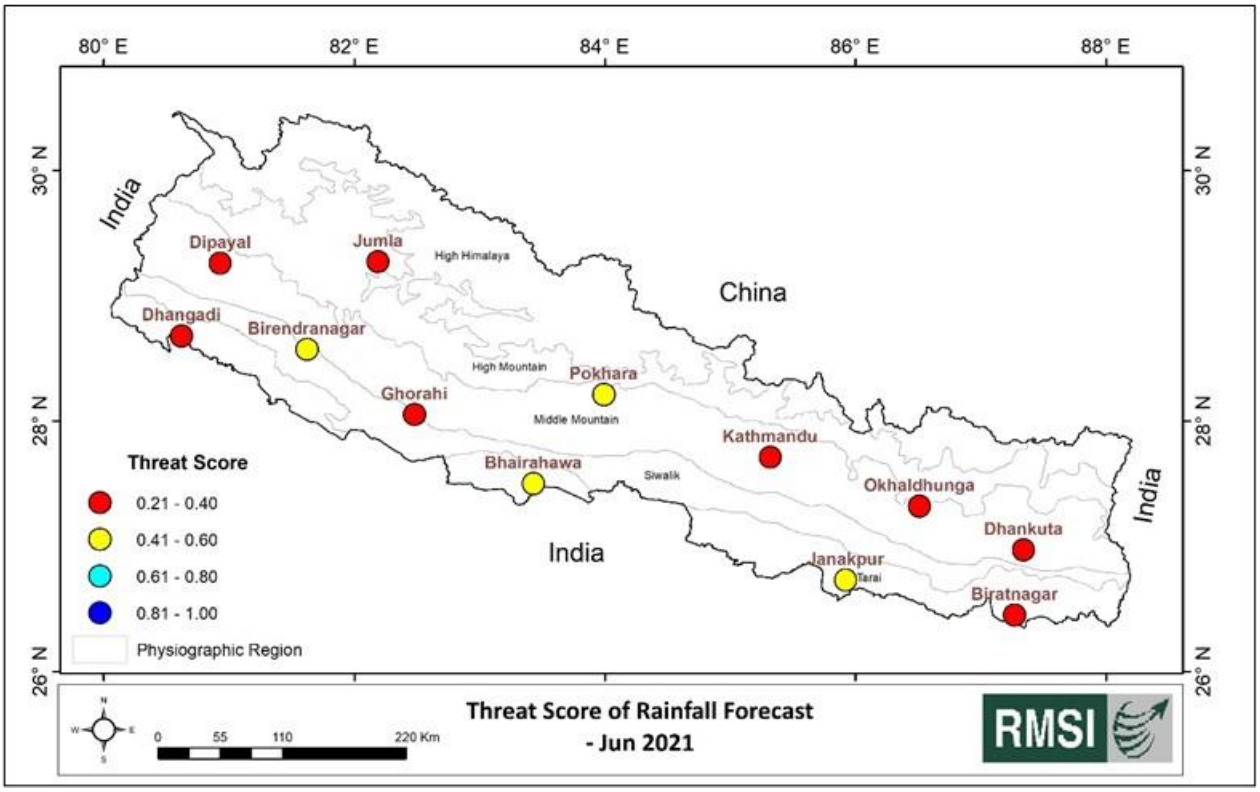

Figure 41: Threat score of Rainfall forecast over selected locations in Nepal during June 2021

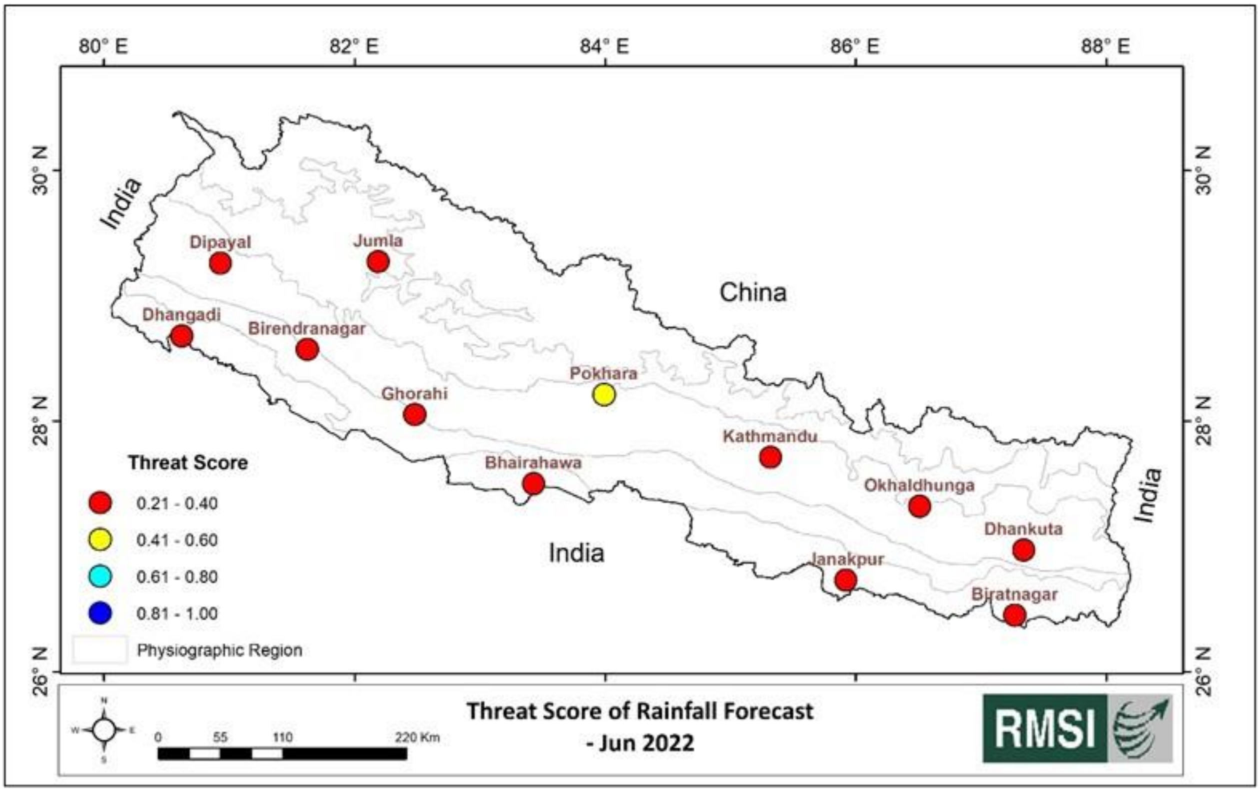

Figure 42: Threat score of Rainfall forecast over selected locations in Nepal during June 2022

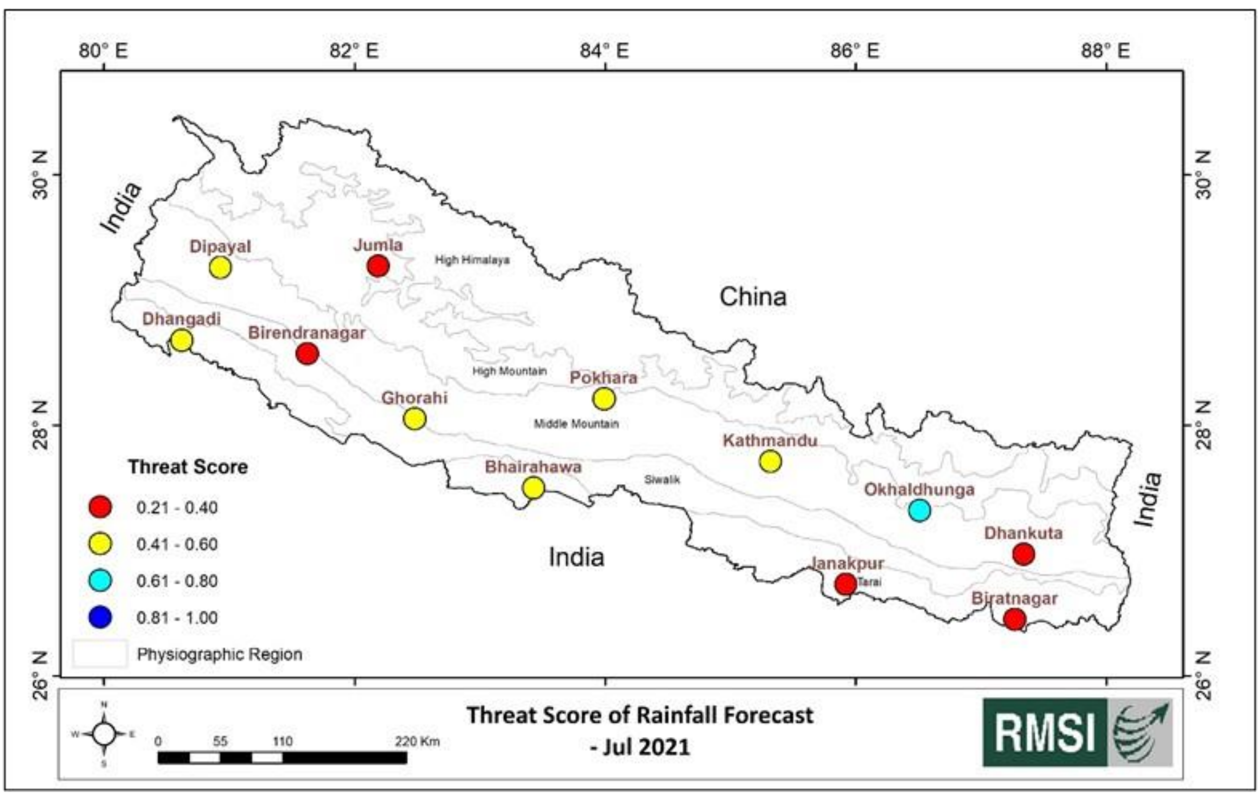

Figure 43: Threat score of Rainfall forecast over selected locations in Nepal during July 2021

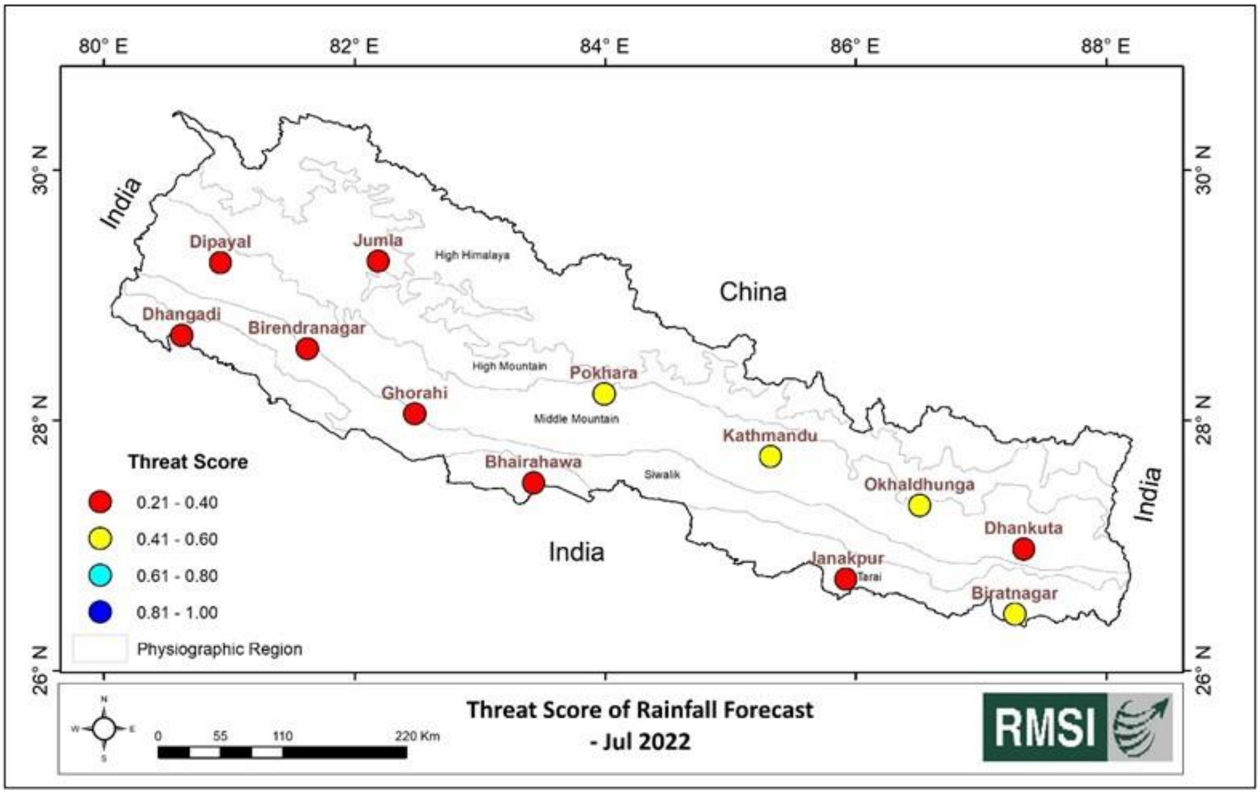

Figure 44: Threat score of Rainfall forecast over selected locations in Nepal during July 2022

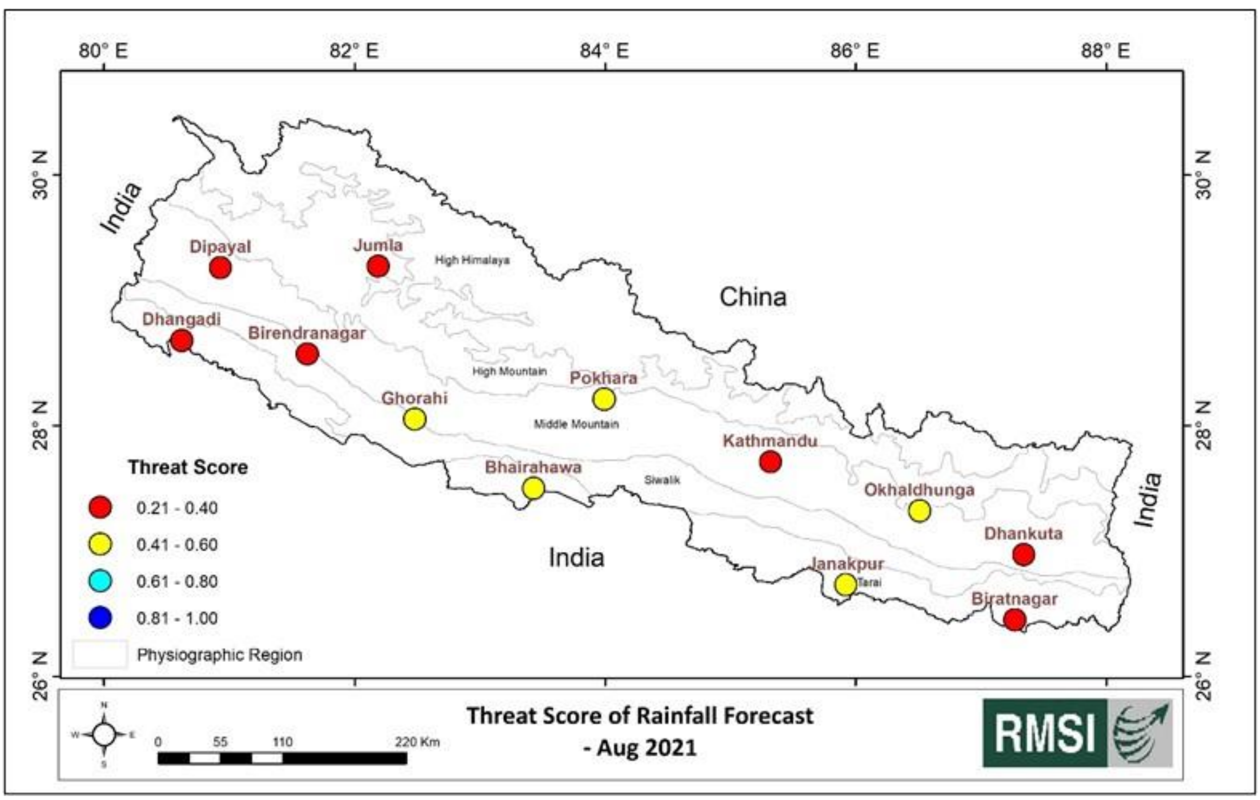

Figure 45: Threat score of Rainfall forecast over selected locations in Nepal during August 2021

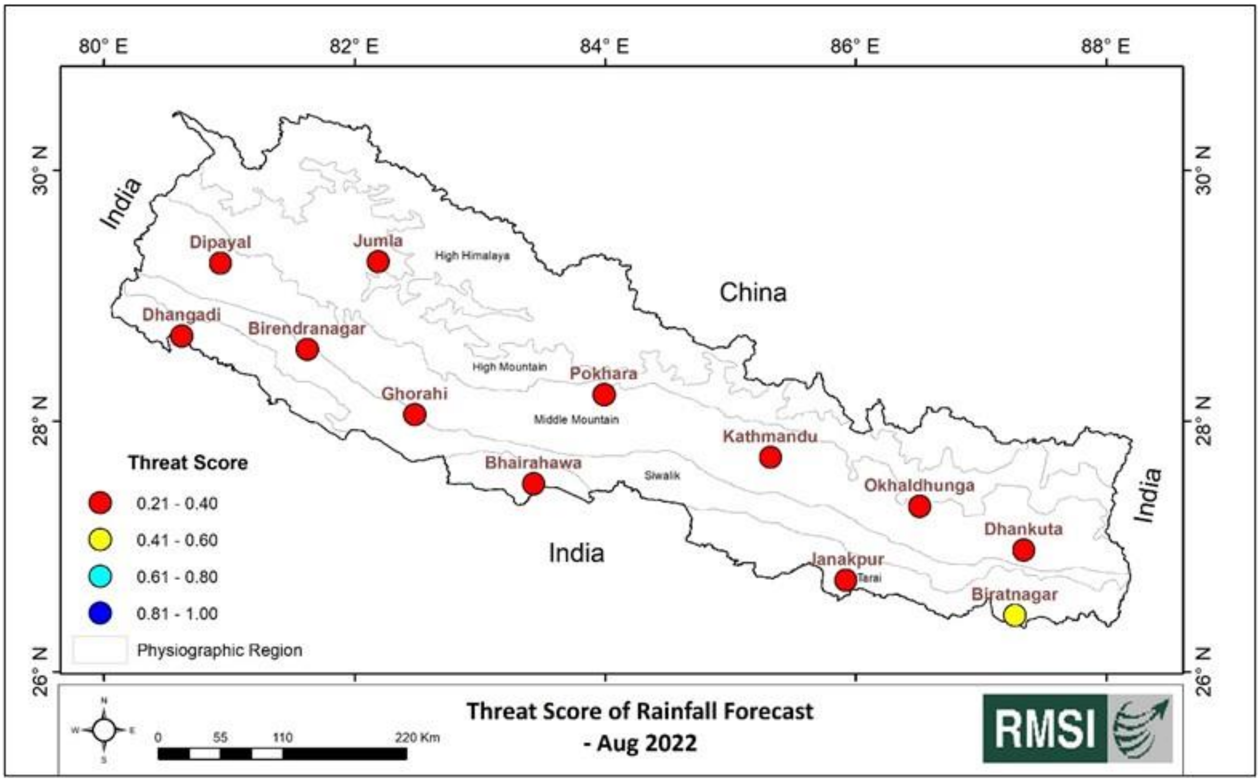

Figure 46: Threat score of Rainfall forecast over selected locations in Nepal during August 2022

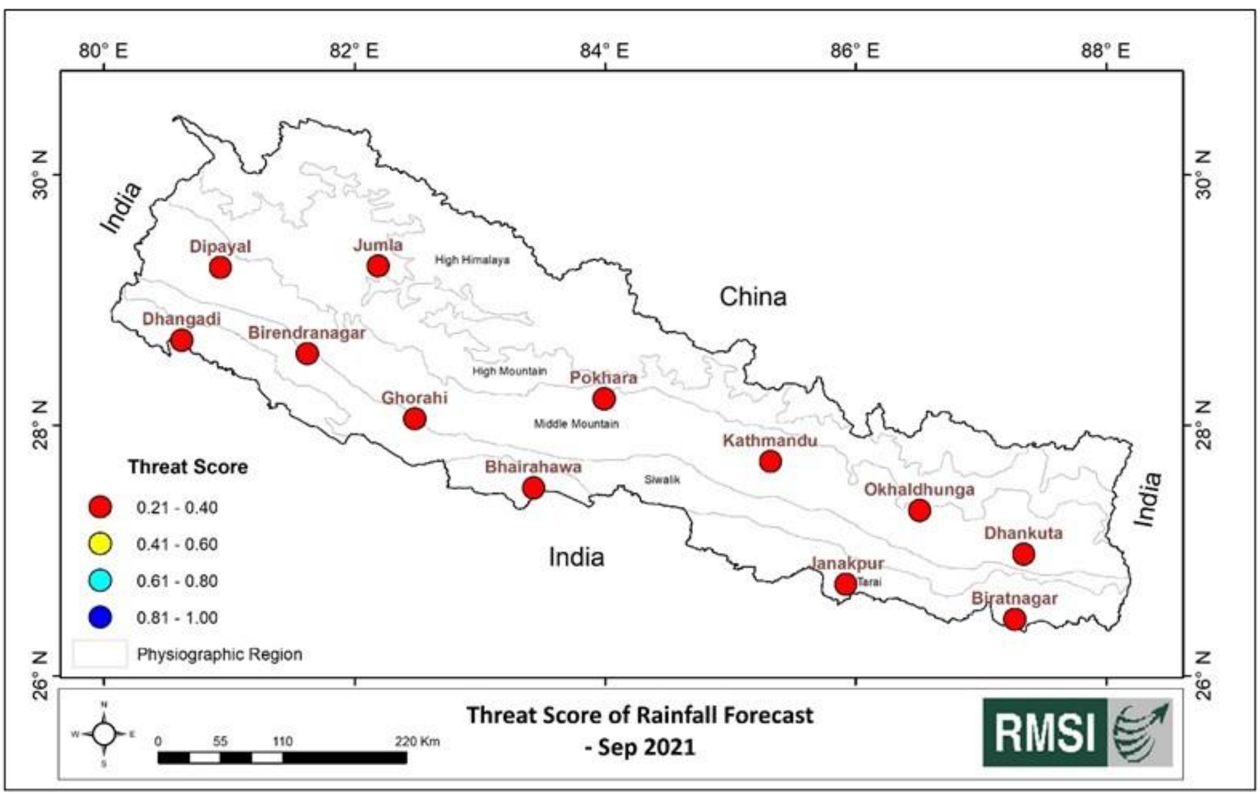

Figure 47: Threat score of Rainfall forecast over selected locations in Nepal during September 2021

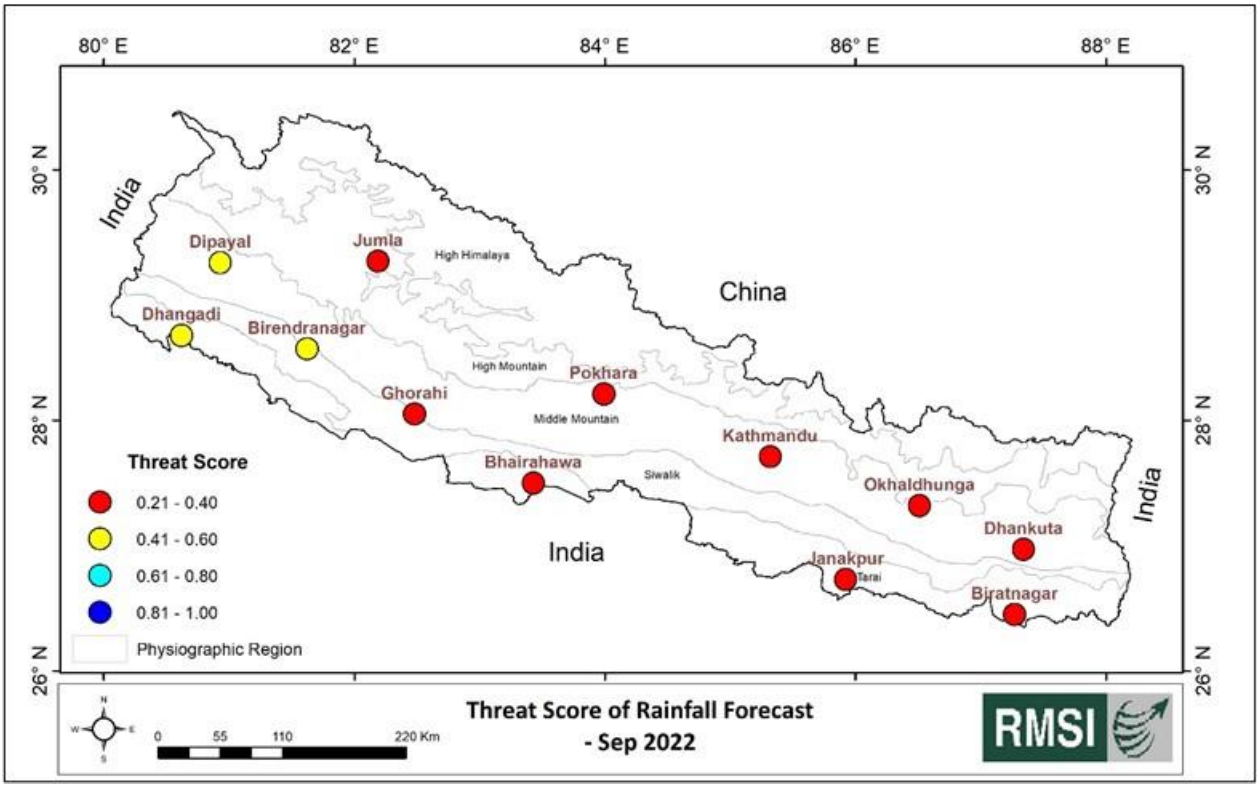

Figure 48: Threat score of Rainfall forecast over selected locations in Nepal during September 2022

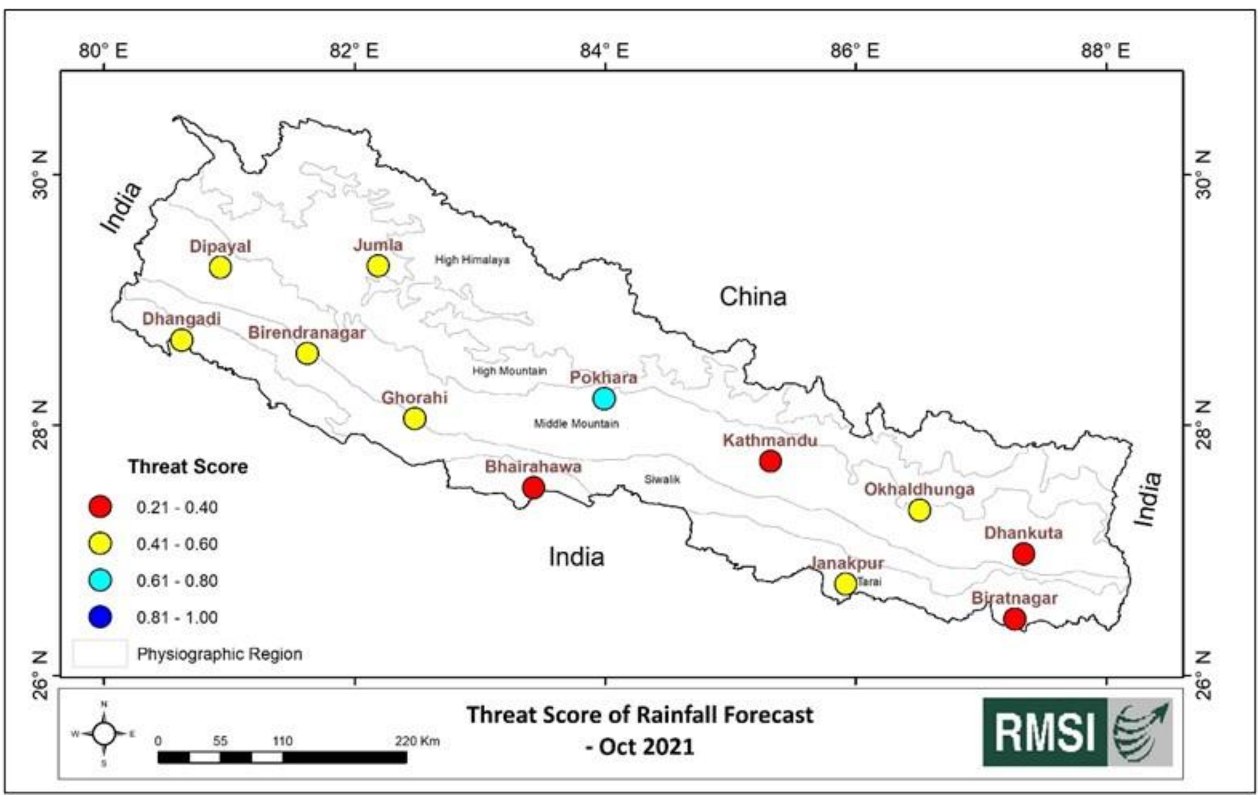

Figure 49: Threat score of Rainfall forecast over selected locations in Nepal during October 2021

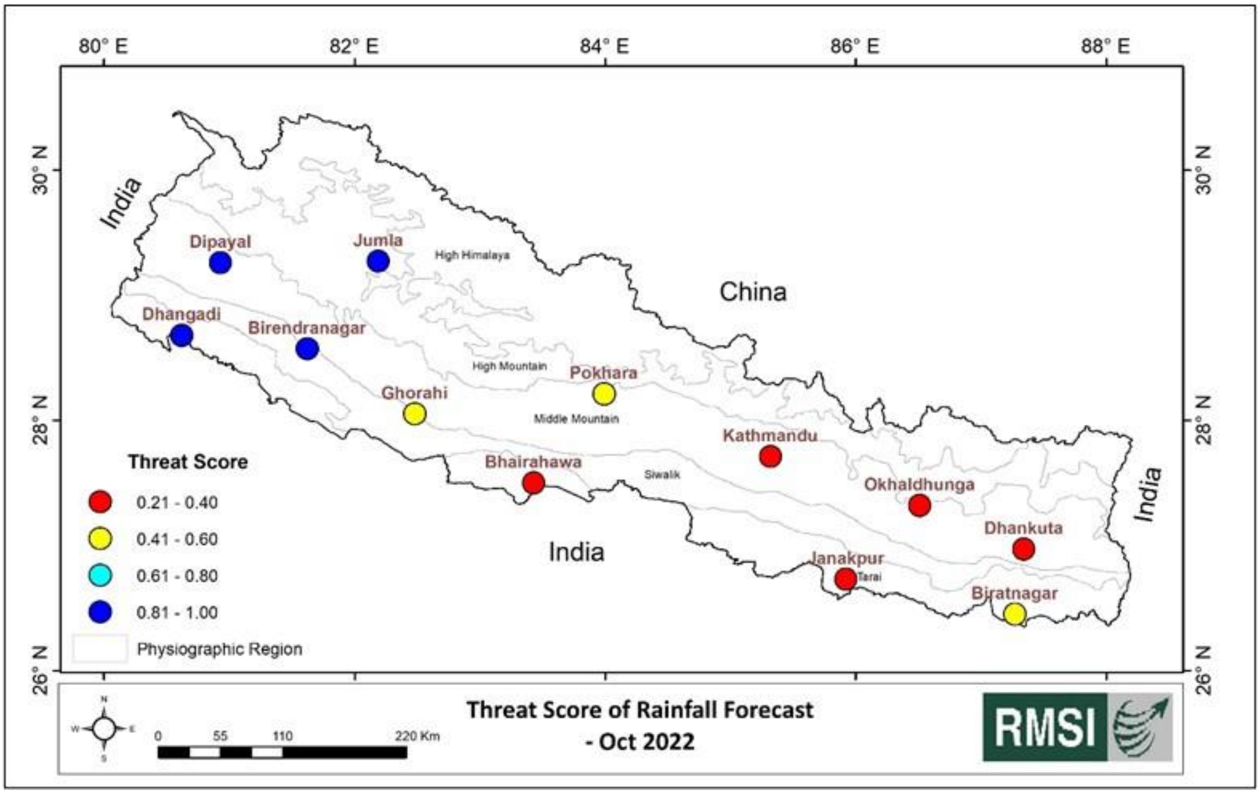

Figure 50: Threat score of Rainfall forecast over selected locations in Nepal during October 2022

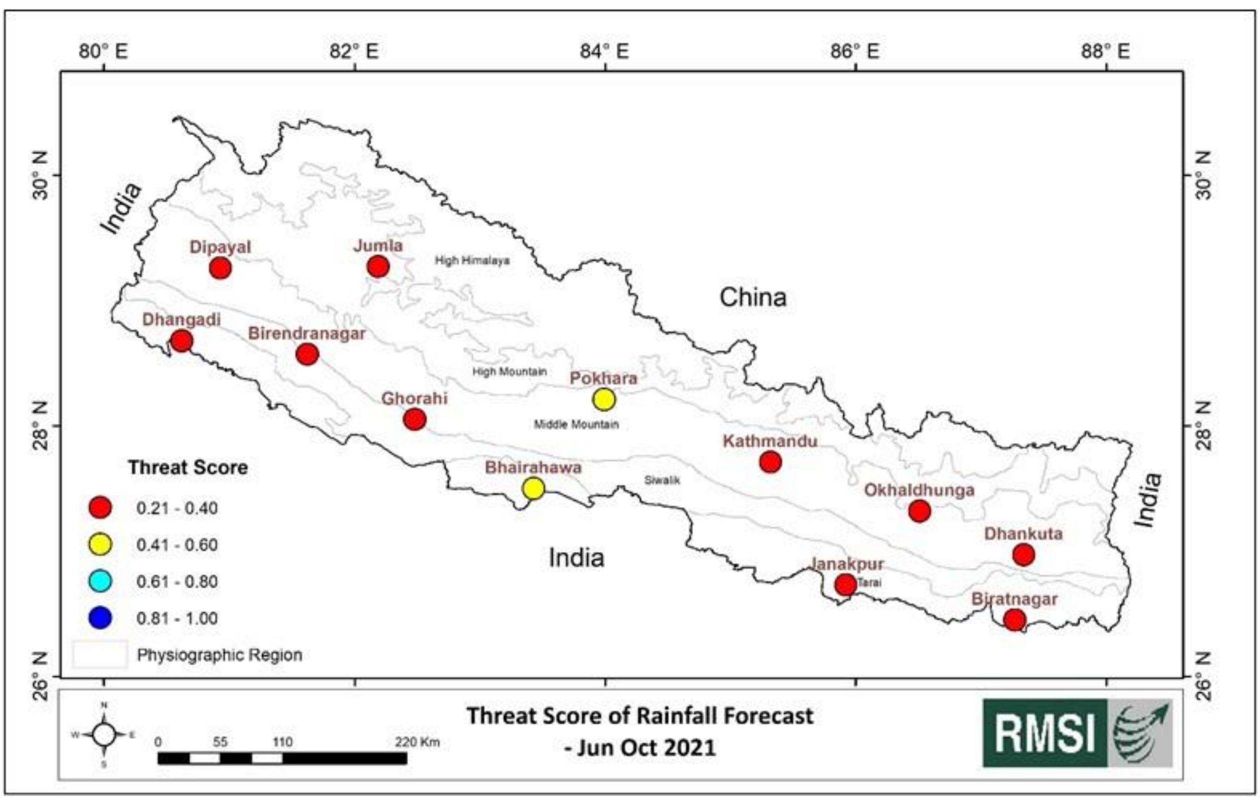

Figure 51: Threat score of Rainfall forecast over selected locations in Nepal during June-October 2021

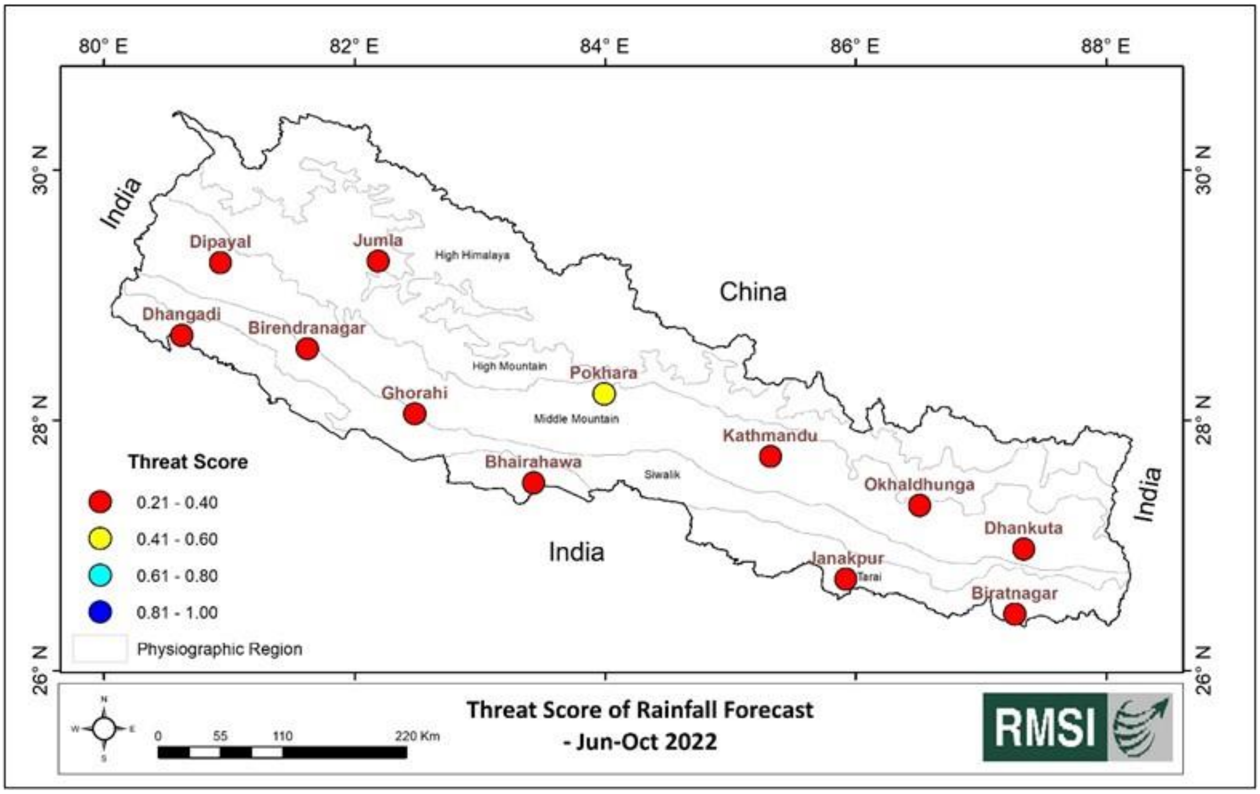

Figure 52: Threat score of Rainfall forecast over selected locations in Nepal during June-October 2022

The month wise and seasonal POD of monsoon season (Jun-Oct) rainfall forecast during 2021-23 over selected locations in Nepal has been furnished in Table 14. In the case of total season, the highest and lowest POD has been observed at Pokhara (0.86) and Dhangadi (0.48), respectively. The average POD during the season across all the locations has been estimated as 0.65. It indicates that, the daily forecast predicts almost 65% of the occurrence of rainy events in Nepal. The month wise average POD across all the stations says that, the highest POD has been observed in October (0.81) followed by July (0.75). The average PODs during June and August were found as intermediate (0.63), while during the month of September it was found as low (0.46).

Table 14: POD of Monsoon Season Rainfall forecast over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jun	0.61	0.58	0.60	0.33	1.00	0.65	0.46	0.56	0.43	0.77	0.74	0.83
Jul	0.55	0.77	0.61	0.46	0.87	0.69	0.59	0.76	0.77	0.97	0.97	0.94
Aug	0.56	0.78	0.58	0.45	0.63	0.70	0.32	0.63	0.58	0.66	0.76	0.85
Sep	0.65	0.29	0.63	0.27	0.50	0.28	0.35	0.30	0.53	0.50	0.46	0.75
Oct	0.46	0.63	0.83	0.88	0.67	0.88	1.00	0.83	1.00	0.88	0.73	0.91

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Season	0.57	0.61	0.65	0.48	0.73	0.64	0.54	0.62	0.66	0.76	0.73	0.86

The month wise and seasonal Threat Score of monsoon season (Jun-Oct) rainfall forecast during 2021-23 over selected locations in Nepal has been furnished in Table 15. In comparison with POD, the Threat Score will account false alarm as well along with hits and misses. Hence, it was found that the efficiency of rainfall forecast further reduces while considering false alarms. The average threat score for the whole season (Jun-Oct) across all the selected locations in Nepal during 2021-23 has been estimated as 0.34. The highest and lowest threat score has been observed over Pokhara (0.49) and Dhankuta (0.2), respectively. Similar to the POD, the month wise average threat score was found highest in October (0.49) followed by July (0.38). The average threat score during June and August were found as 0.3, the lowest value of threat score has been observed during September (0.2).

Table 15: Threat Score of Monsoon Season Rainfall forecast over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jun	0.35	0.29	0.38	0.25	0.16	0.31	0.34	0.32	0.19	0.31	0.21	0.56
Jul	0.30	0.40	0.28	0.32	0.31	0.38	0.33	0.30	0.28	0.51	0.58	0.55
Aug	0.32	0.43	0.32	0.31	0.21	0.27	0.20	0.37	0.16	0.24	0.30	0.45
Sep	0.34	0.11	0.36	0.23	0.03	0.21	0.20	0.12	0.21	0.23	0.19	0.33
Oct	0.28	0.36	0.75	0.72	0.29	0.80	0.50	0.35	0.67	0.27	0.35	0.57
Season	0.32	0.32	0.42	0.37	0.20	0.39	0.31	0.29	0.30	0.31	0.33	0.49

3.5.2 Evaluation of temperature forecast

The POD of daily maximum temperature forecast during the years of 2021 and 2022 in annual and SW monsoon season (Jun-Oct) has been depicted from Figure 53 to Figure 56. It was observed that, The POD in maximum temperature was found less than 0.6 over majority of the locations during these years. The POD of daily minimum temperature forecast during these has been depicted from Figure 57 to Figure 60. The results convey that, the POD for minimum temperature forecast was observed better in comparison with the maximum temperature forecast especially during SW monsoon season. Majority of the locations showed a POD value of more than 0.6 in minimum temperature forecast during SW monsoon season.

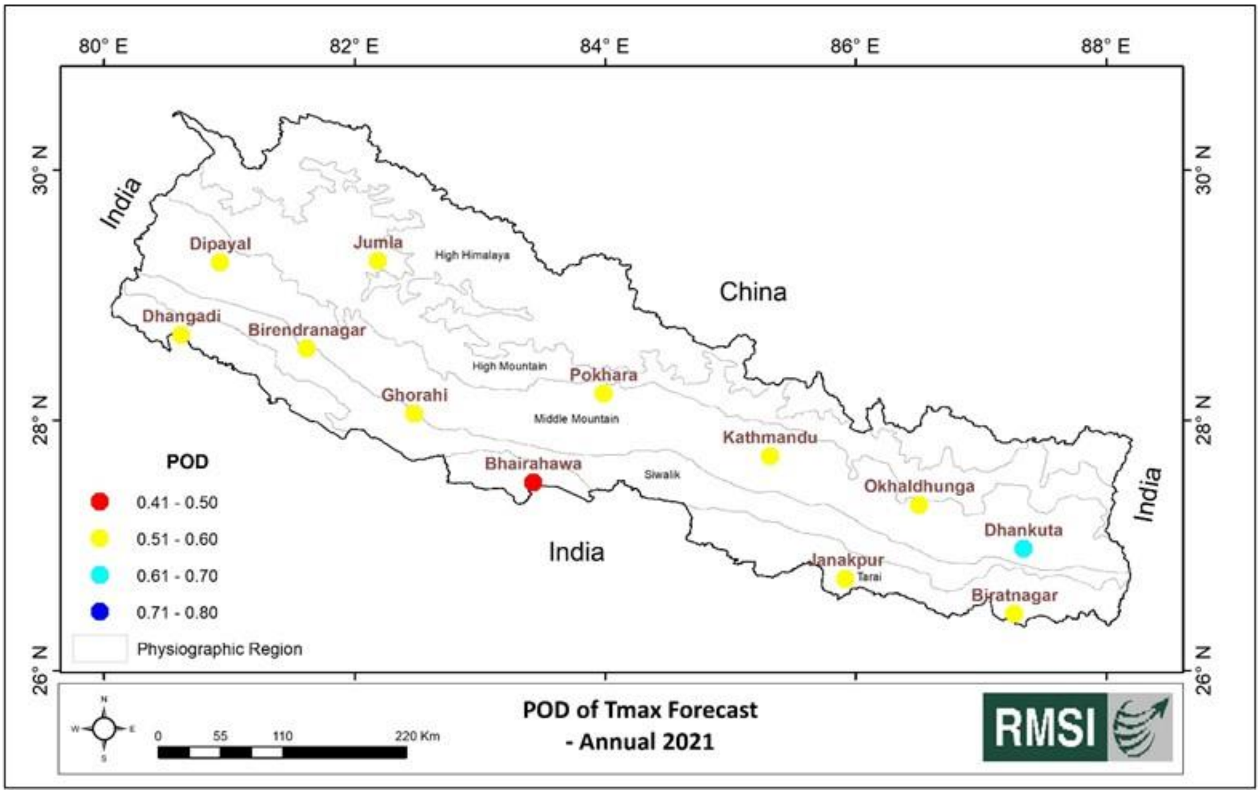

Figure 53: POD for daily Tmax forecast over selected locations in Nepal during 2021

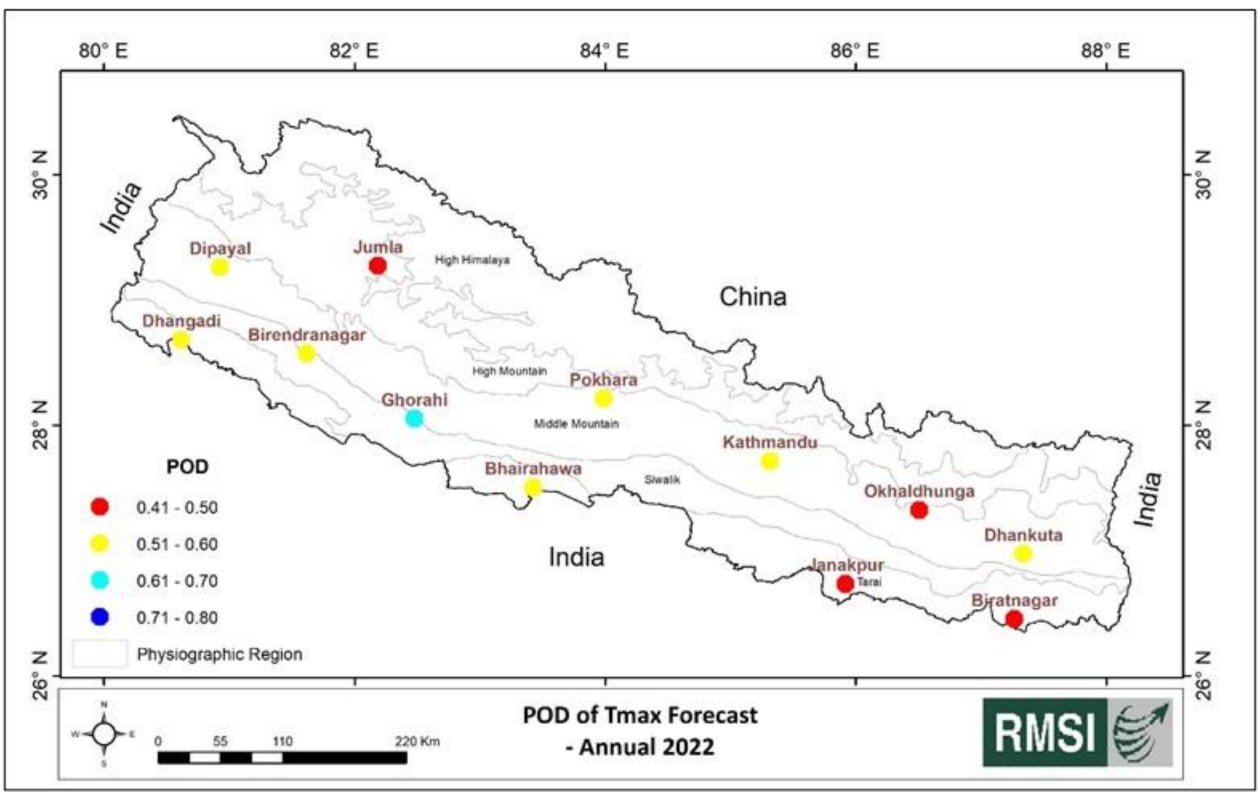

Figure 54: POD for daily Tmax forecast over selected locations in Nepal during 2022

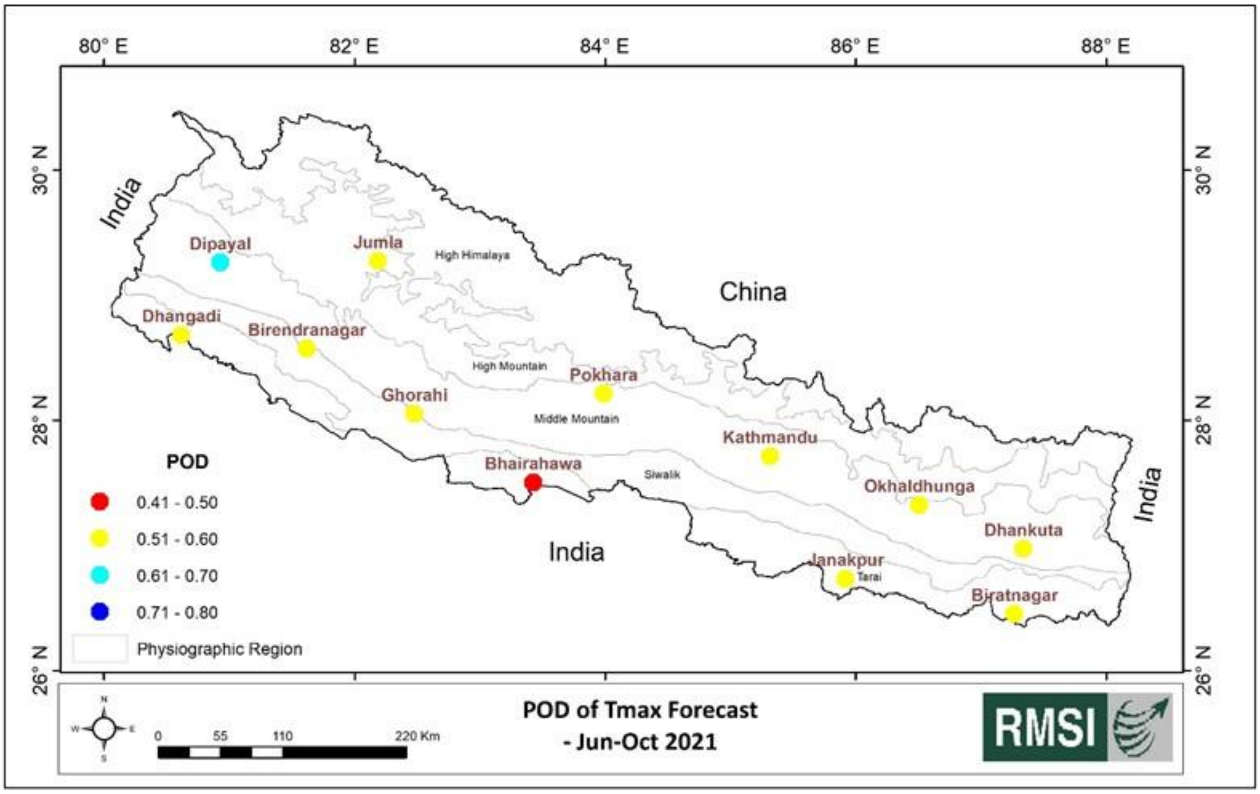

Figure 55: POD for daily Tmax forecast over selected locations in Nepal during Jun-Oct 2021

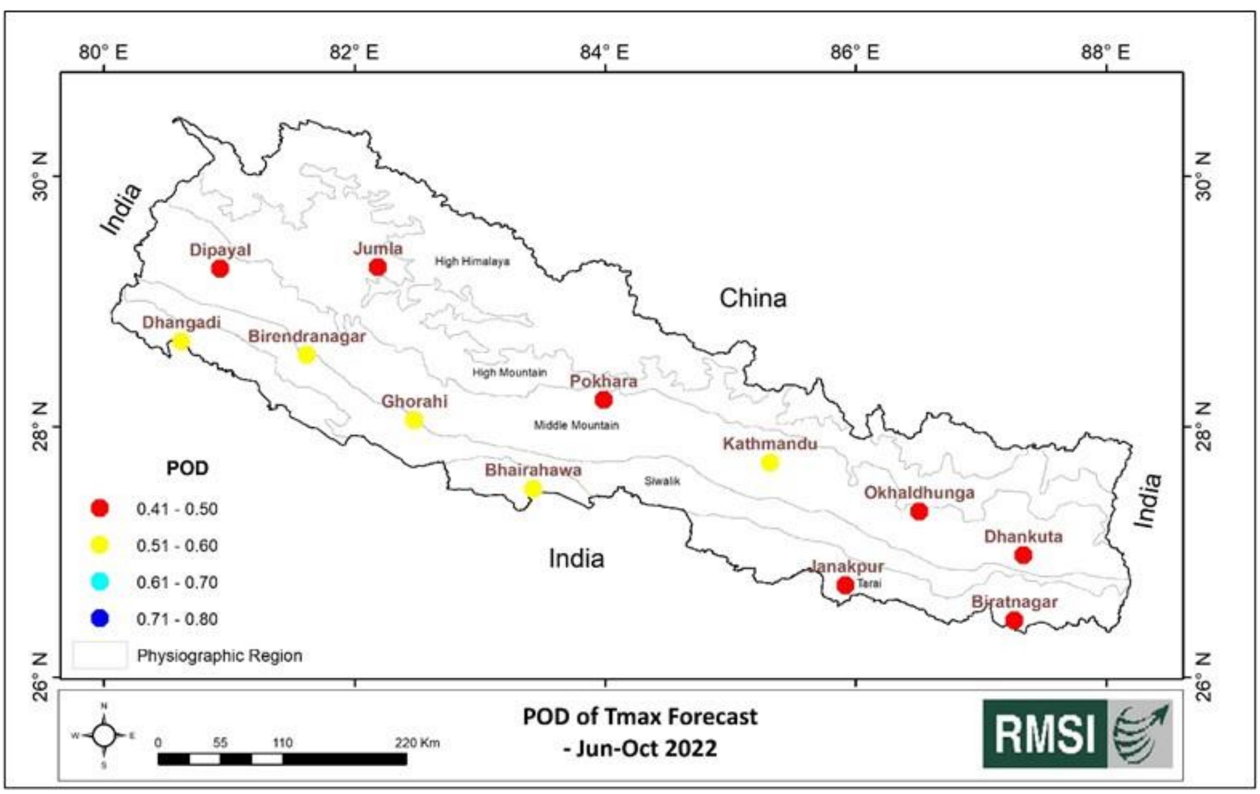

Figure 56: POD for daily Tmax forecast over selected locations in Nepal during Jun-Oct 2022

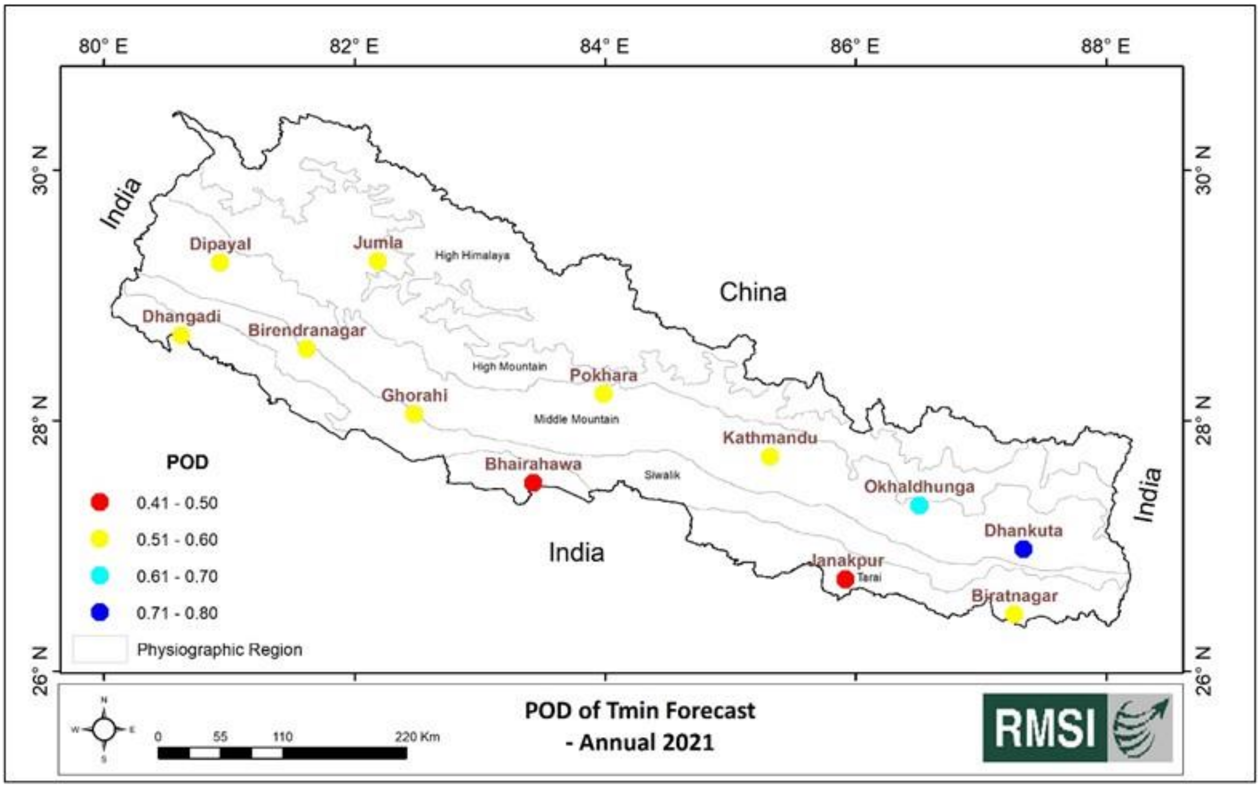

Figure 57: POD for daily Tmin forecast over selected locations in Nepal during 2021

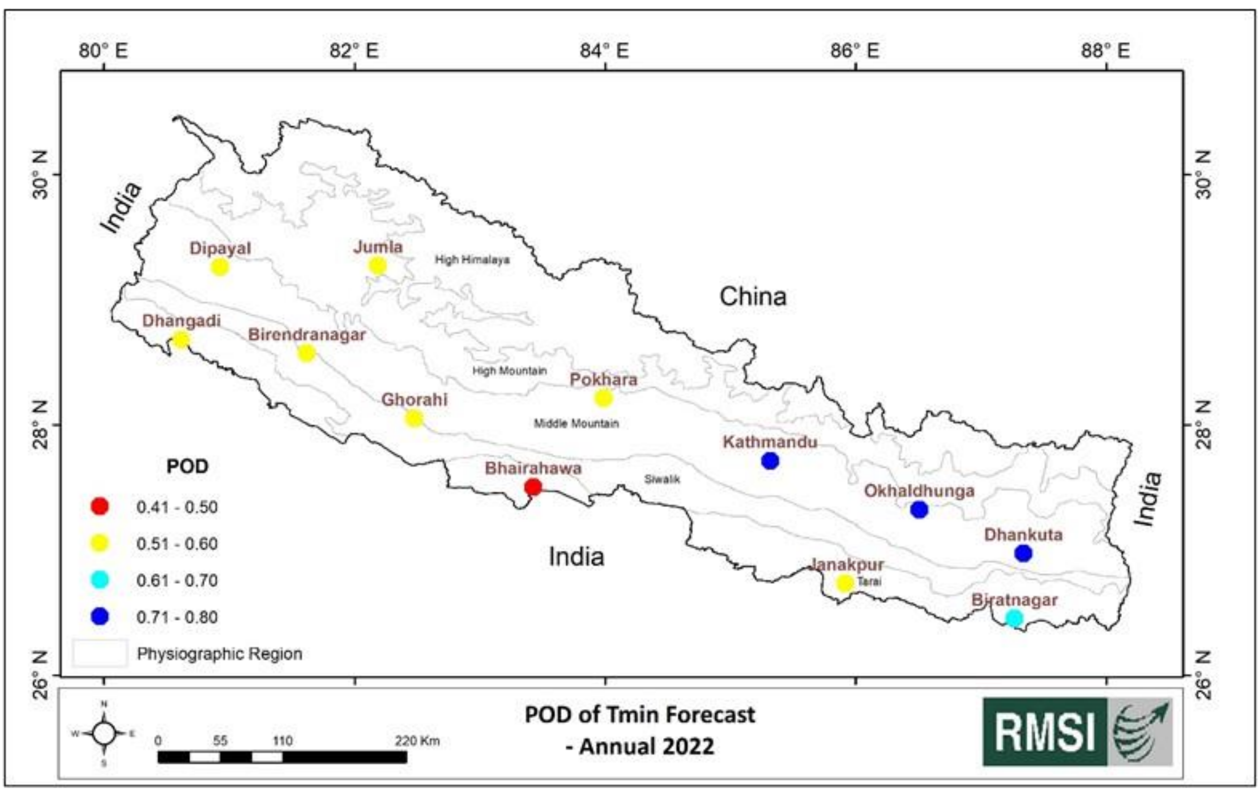

Figure 58: POD for daily Tmin forecast over selected locations in Nepal during 2022

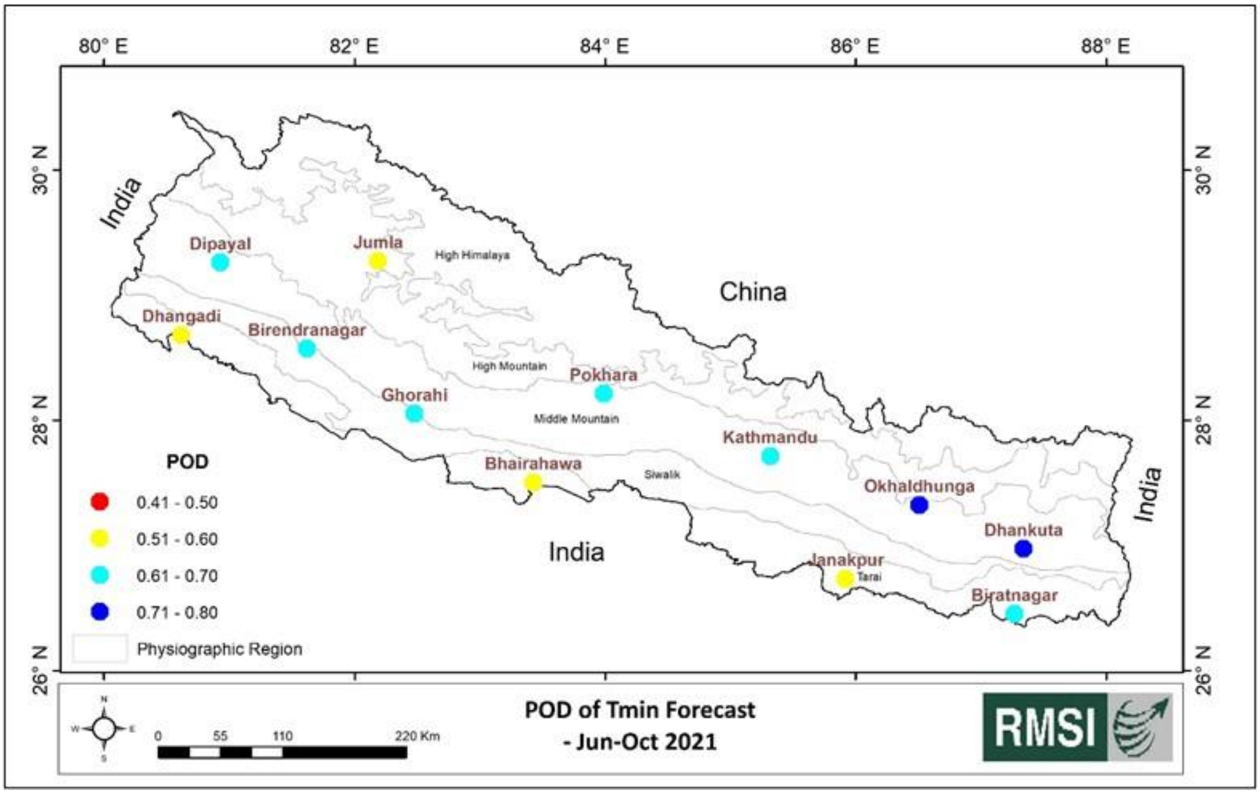

Figure 59: POD for daily Tmin forecast over selected locations in Nepal during Jun-Oct 2021

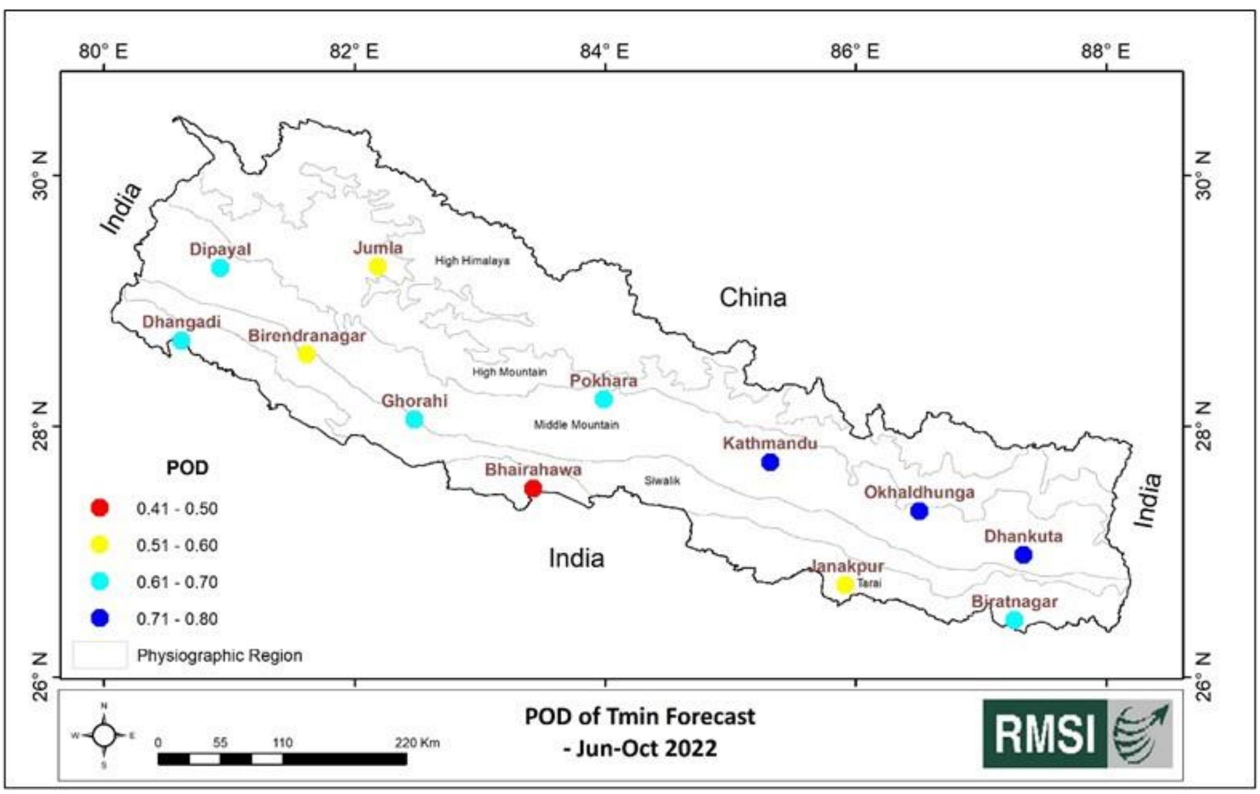

Figure 60: POD for daily Tmin forecast over selected locations in Nepal during Jun-Oct 2022

The number of days with forecasted maximum and minimum temperature value is higher/less than the observed values has been estimated for all the selected locations in Nepal. The fraction of total days (%) with over estimation in maximum and minimum temperature forecast in annual and SW monsoon seasonal (Jun-Oct) during the years 2021-22 and 2022-23 have been portrayed from

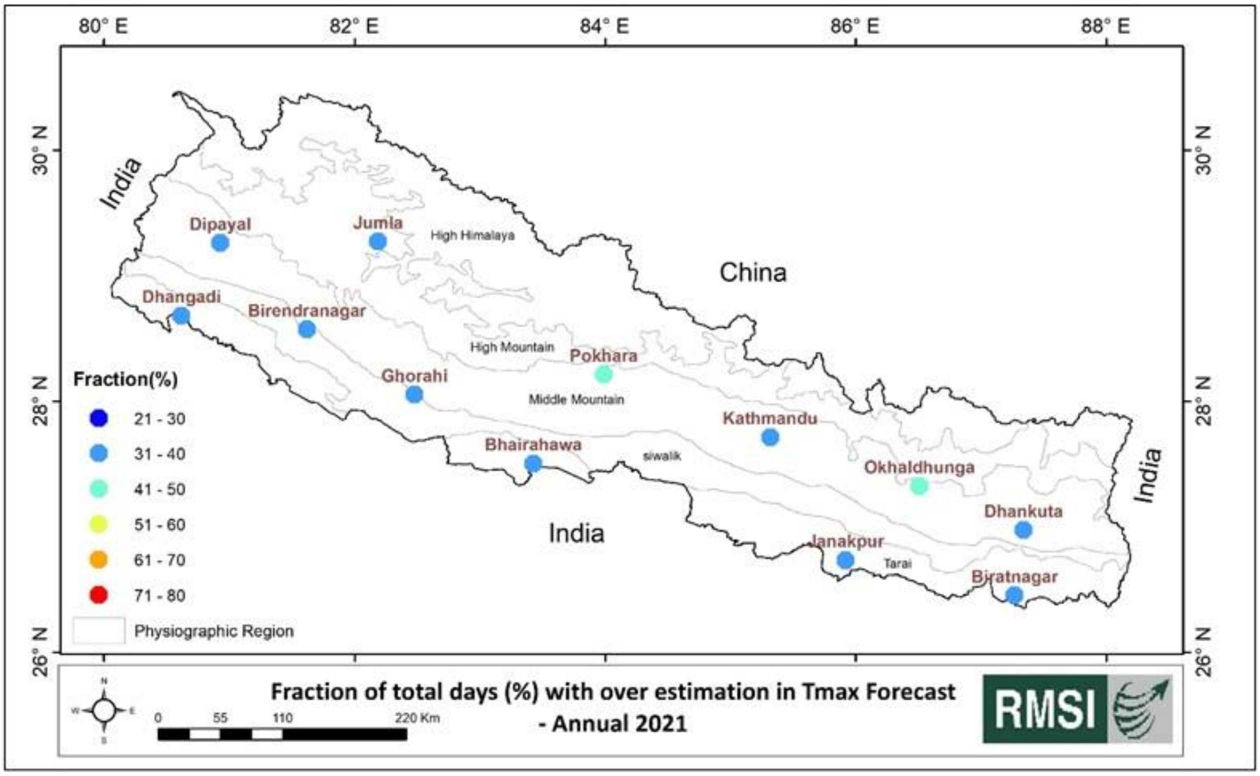

Figure 61 to Figure 68. It has been observed that across all the locations, the number of days with over estimation in temperature forecast was observed during less than 50% of total days in annual and seasonal scale. It indicates that more than half of the total days in an year and SW monsoon season, the temperature forecast value is less than (under estimating) the observed values (Figure 69 to Figure 76).

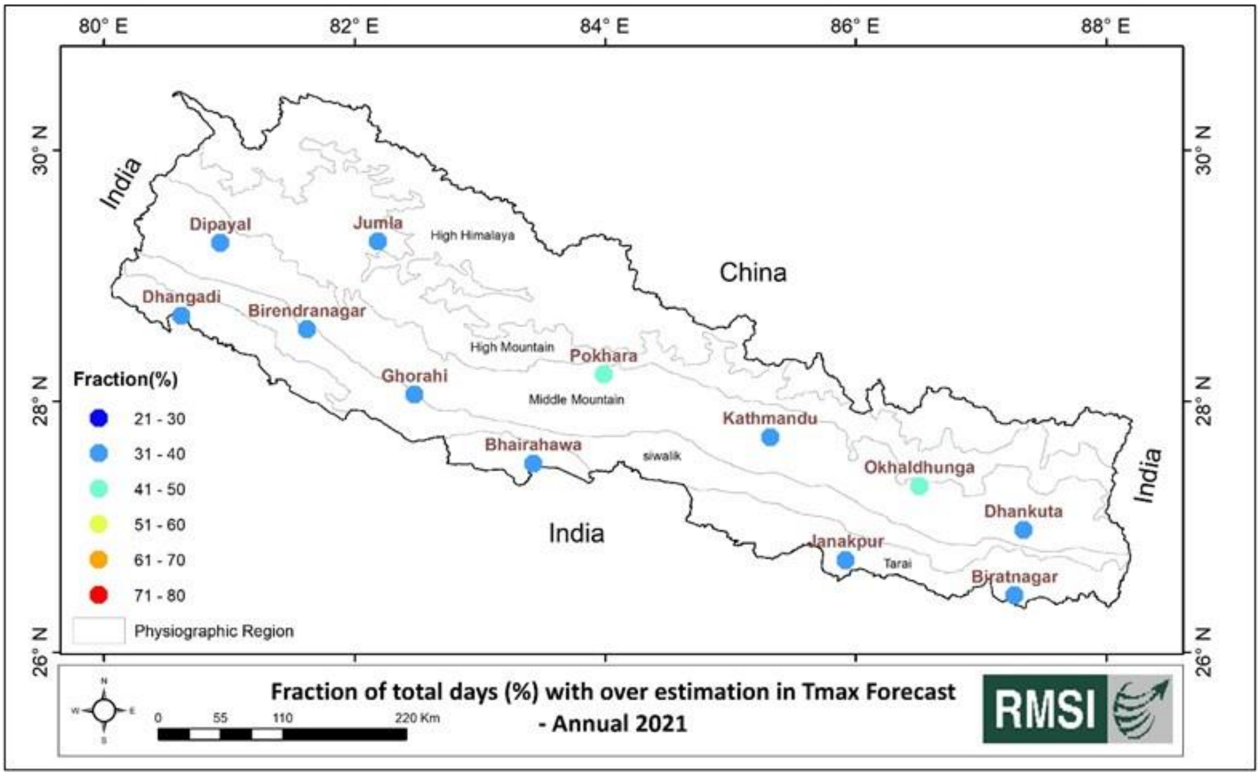

Figure 61: Fraction of total days (%) with over estimation in Tmax forecast across selected locations in Nepal during 2021

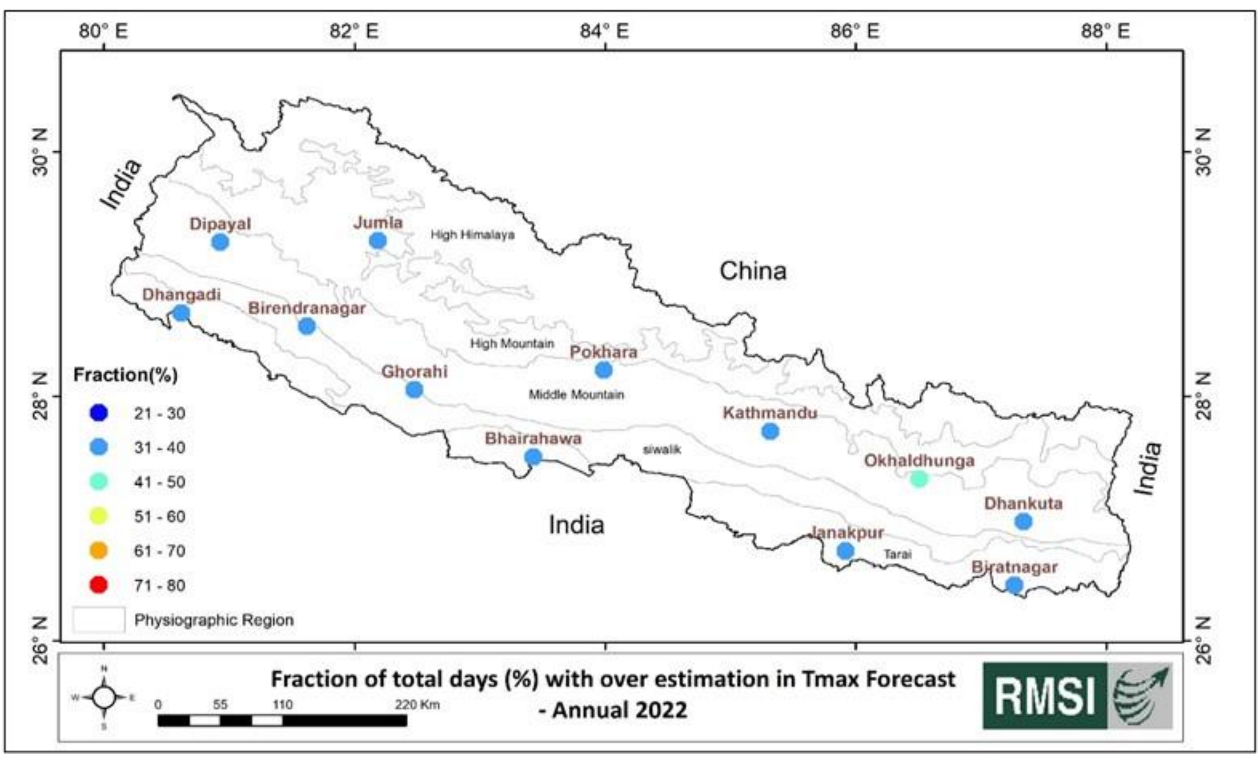

Figure 62: Fraction of total days (%) with over estimation in Tmax forecast across selected locations in Nepal during 2022

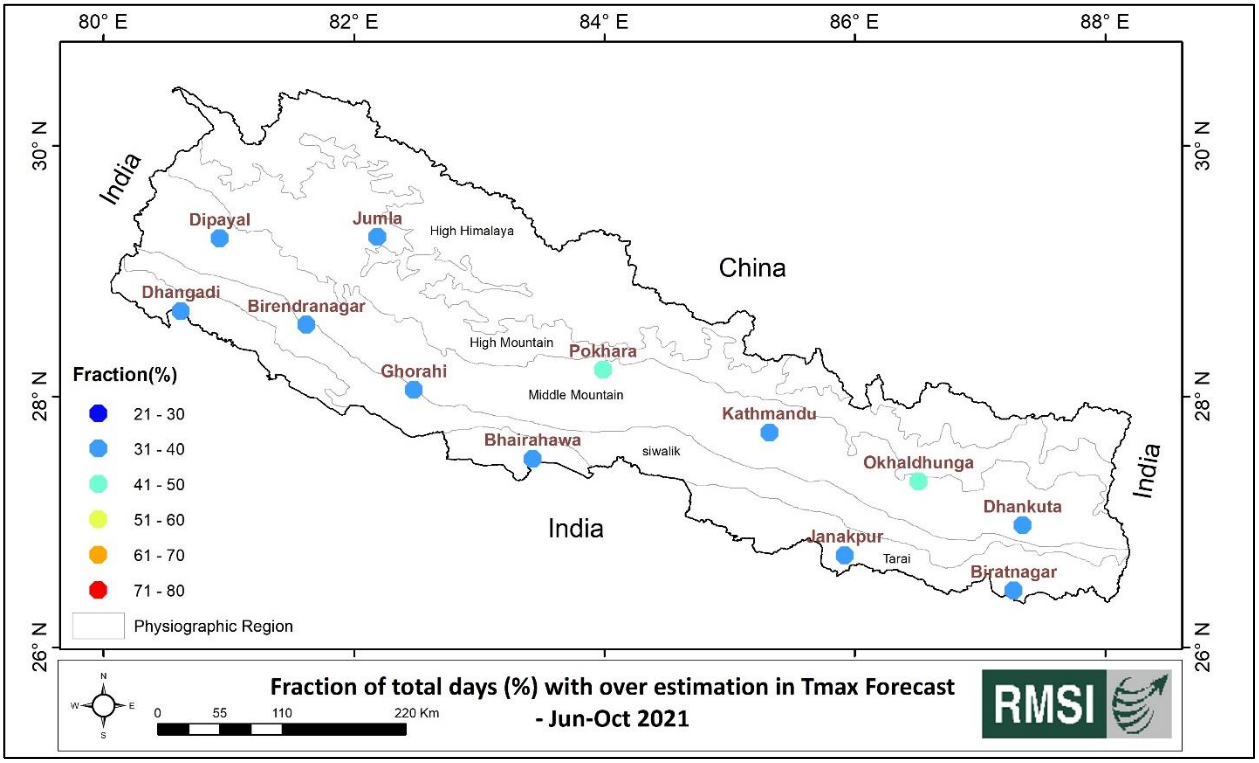

Figure 63: Fraction of total days (%) with over estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2021

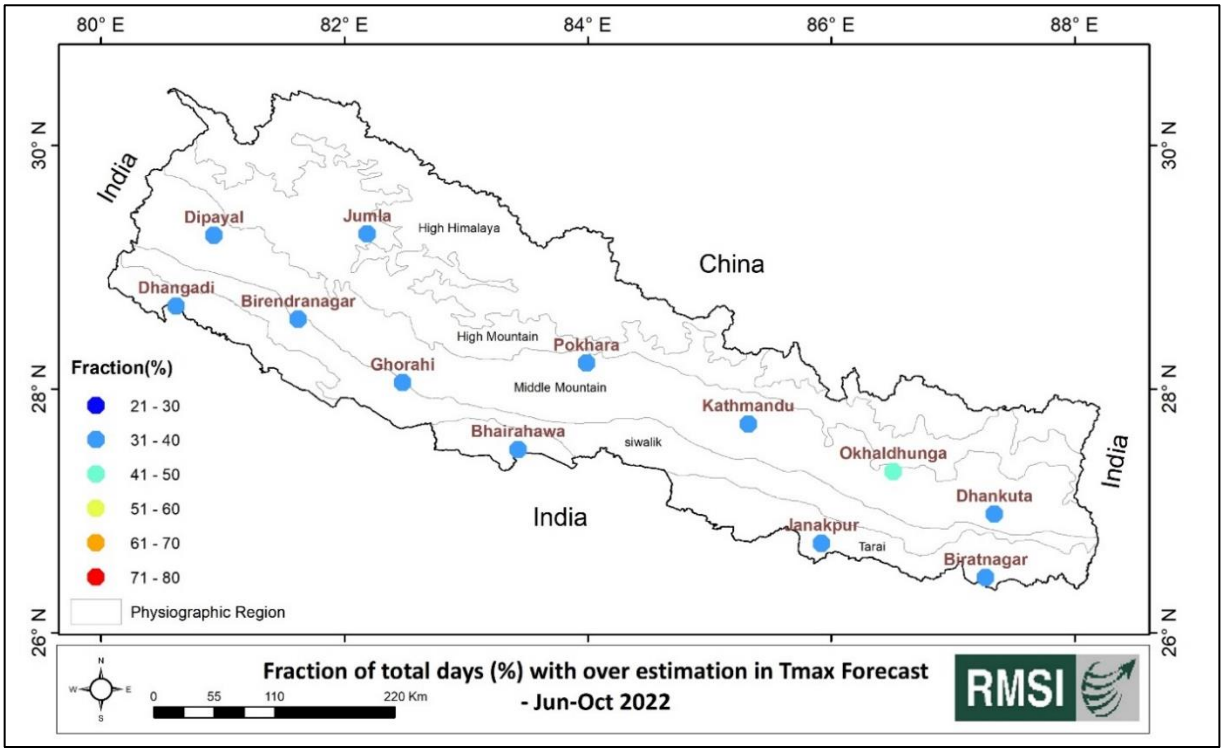

Figure 64: Fraction of total days (%) with over estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2022

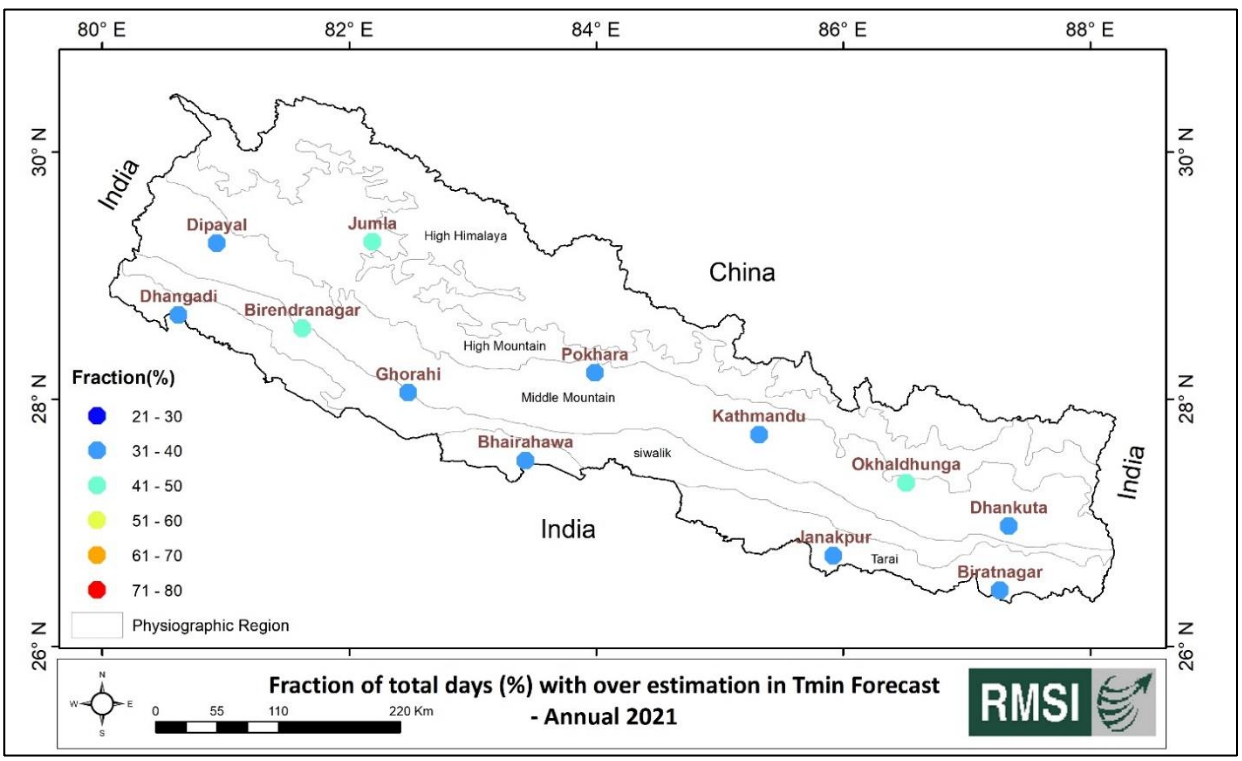

Figure 65: Fraction of total days (%) with over estimation in Tmin forecast across selected locations in Nepal during 2021

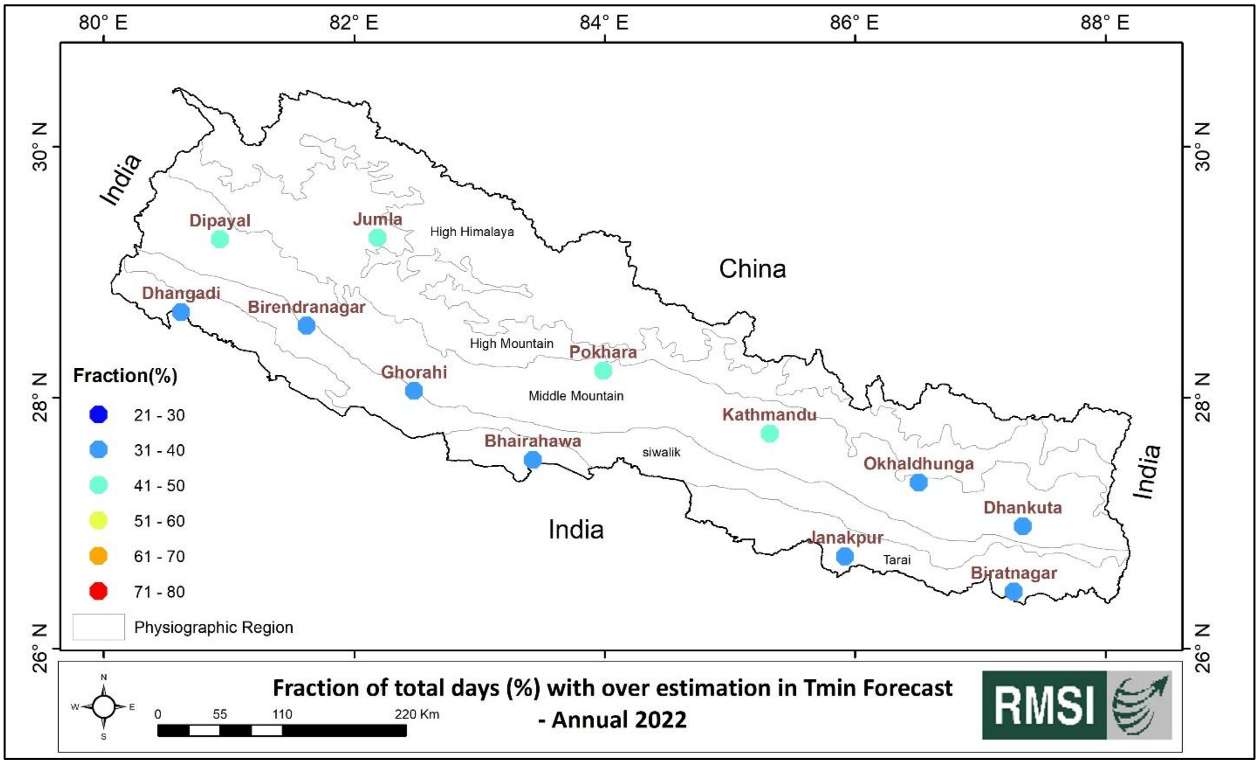

Figure 66: Fraction of total days (%) with over estimation in Tmin forecast across selected locations in Nepal during 2022

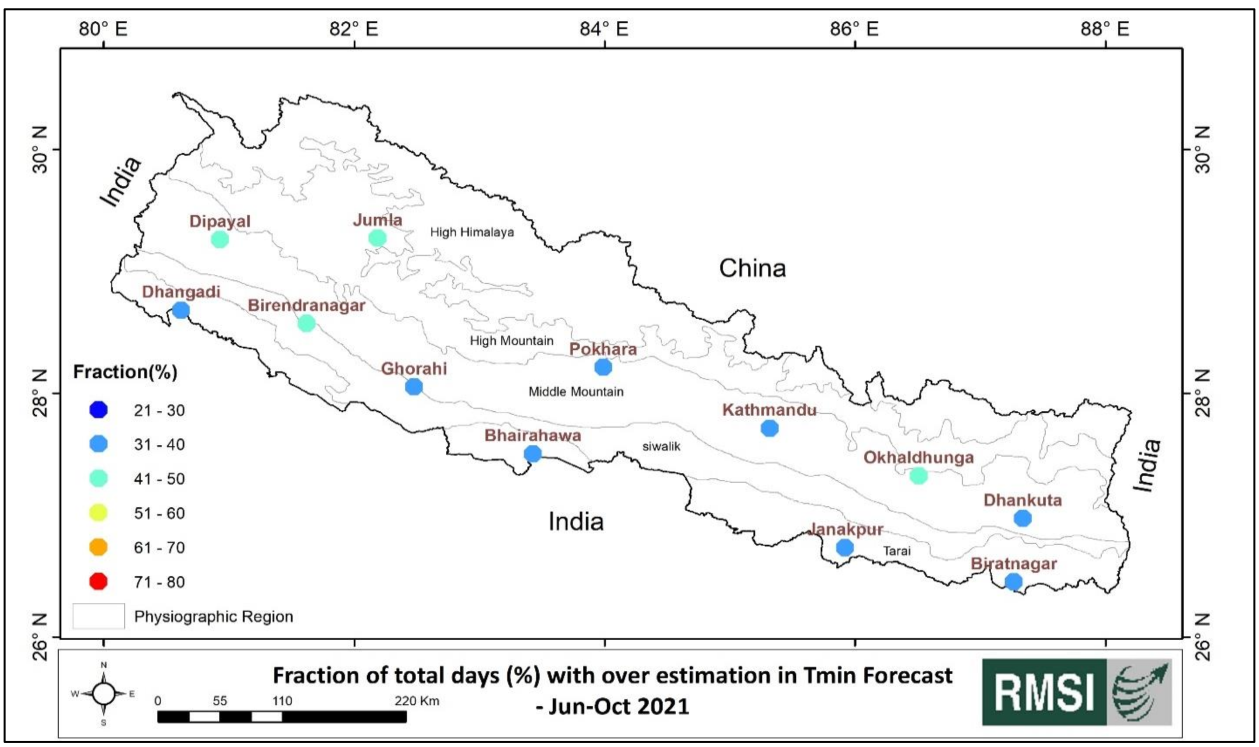

Figure 67: Fraction of total days (%) with over estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2021

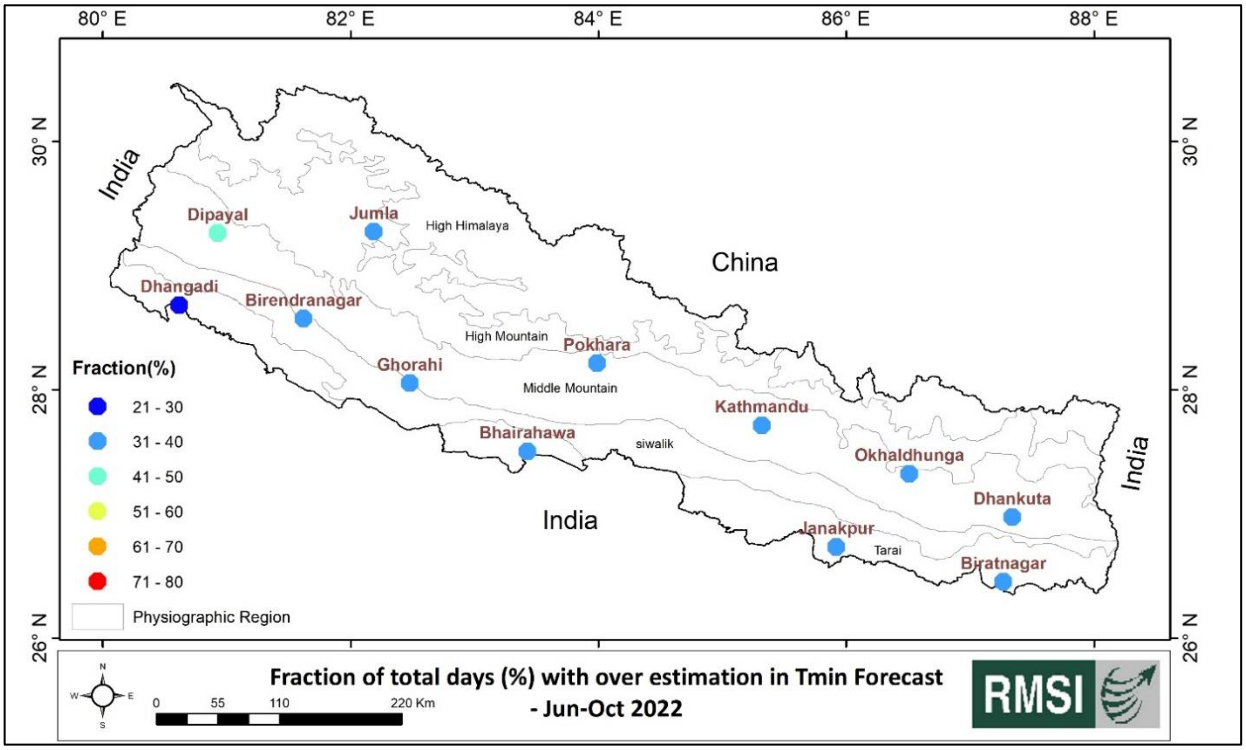

Figure 68: Fraction of total days (%) with over estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2022

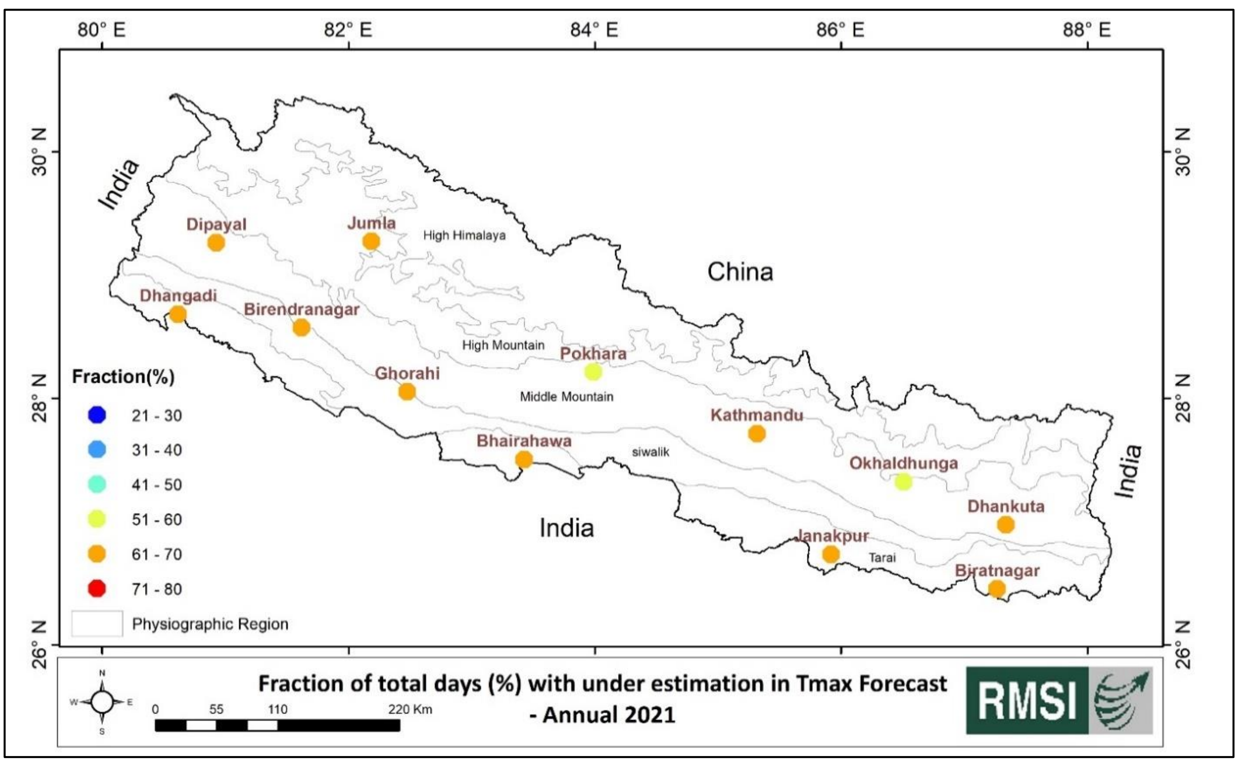

Figure 69: Fraction of total days (%) with under estimation in Tmax forecast across selected locations in Nepal during 2021

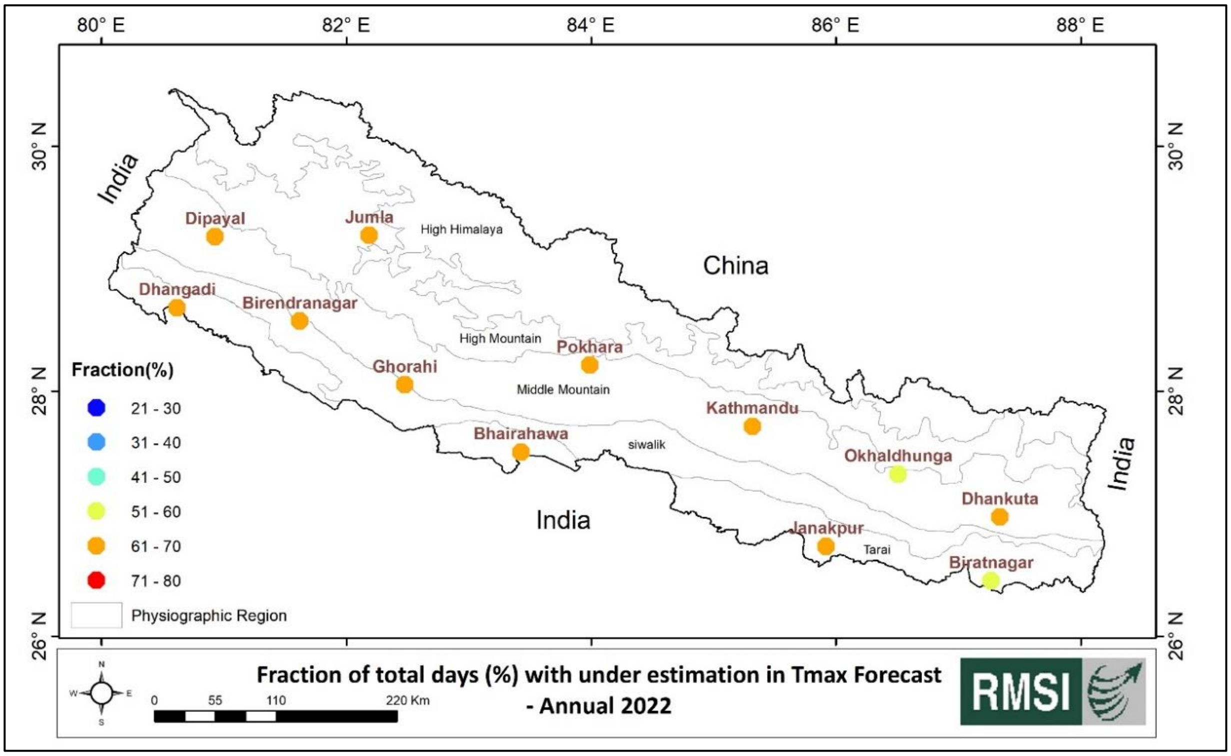

Figure 70: Fraction of total days (%) with under estimation in Tmax forecast across selected locations in Nepal during 2022

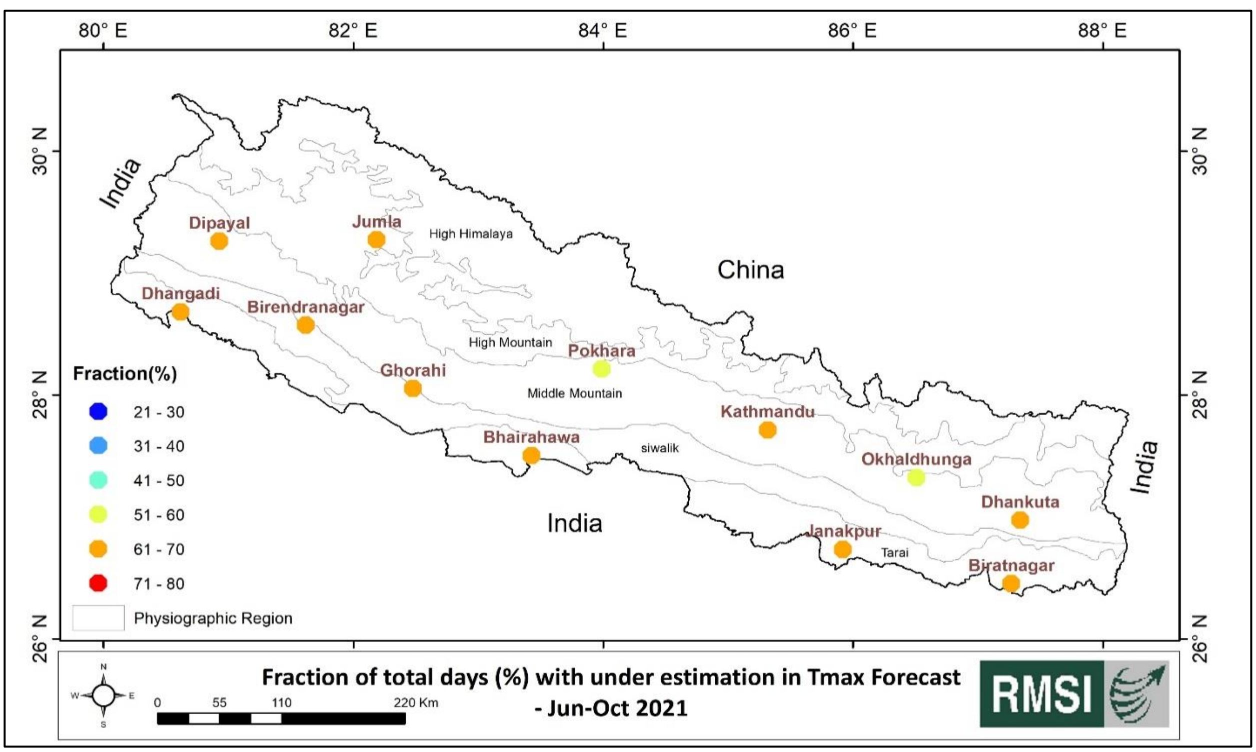

Figure 71: Fraction of total days (%) with under estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2021

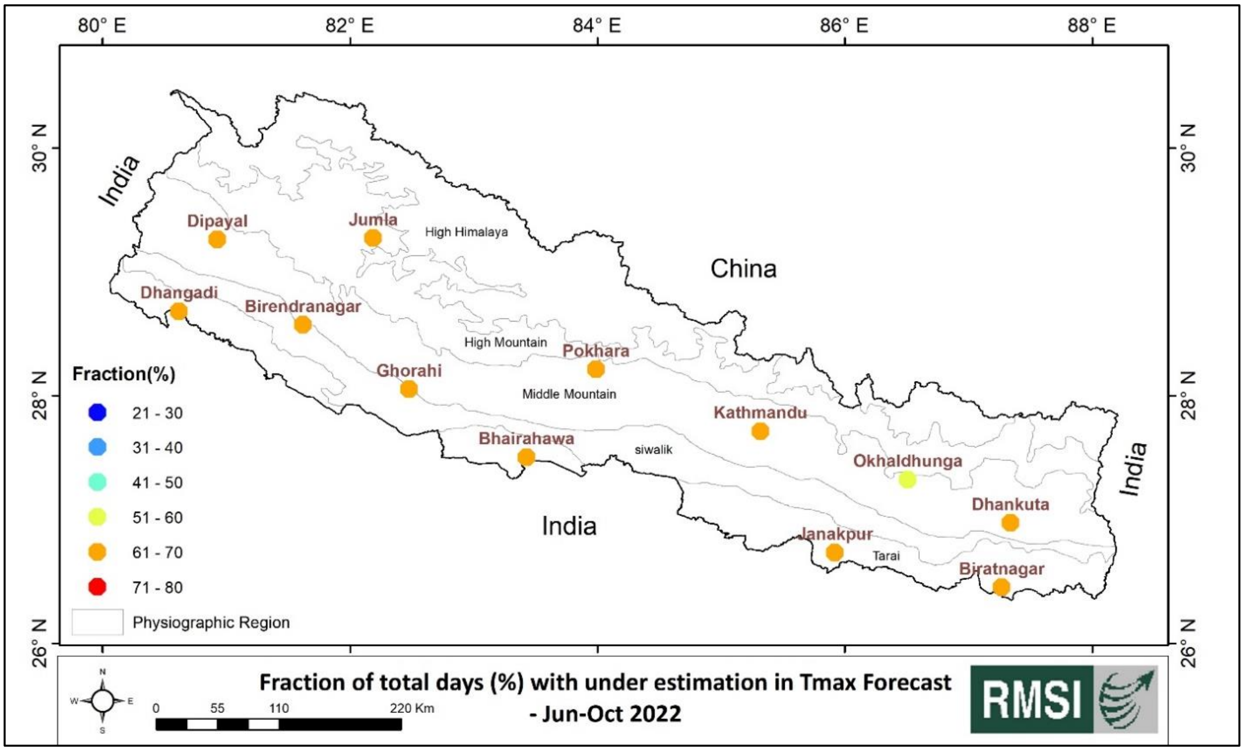

Figure 72: Fraction of total days (%) with under estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2022

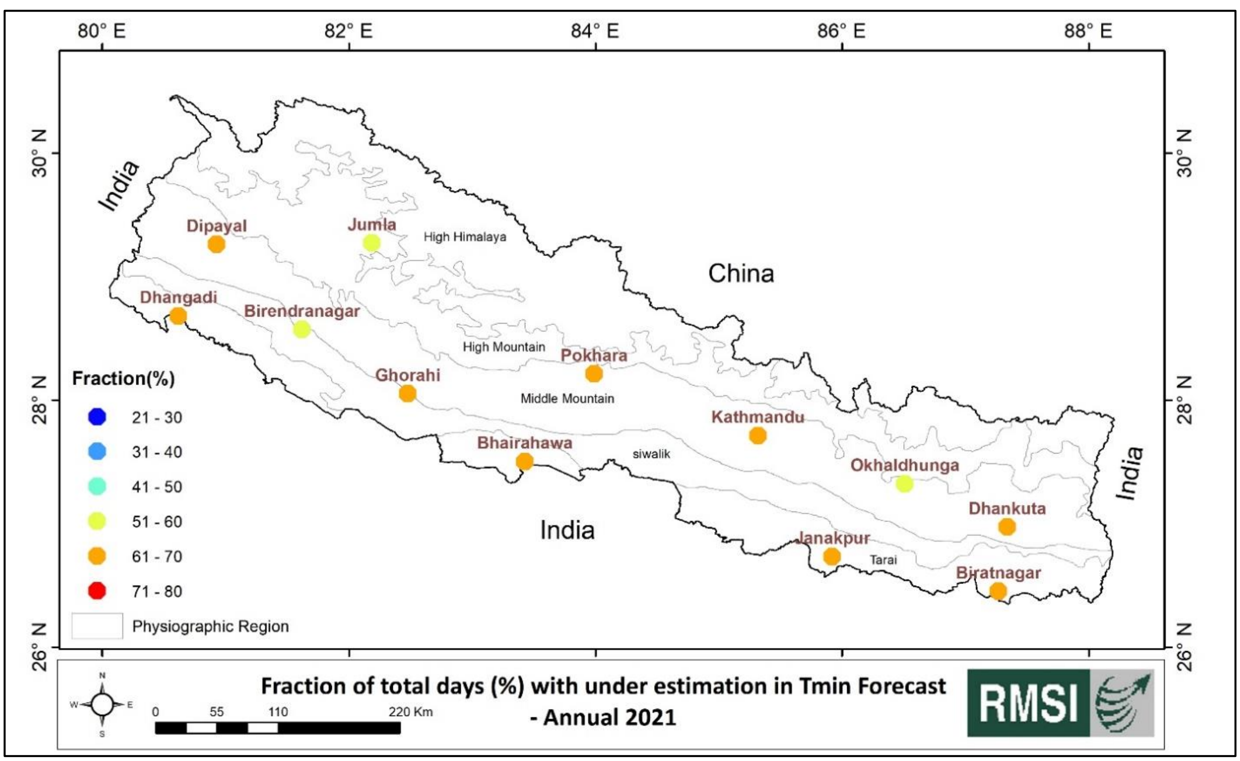

Figure 73: Fraction of total days (%) with under estimation in Tmin forecast across selected locations in Nepal during 2021

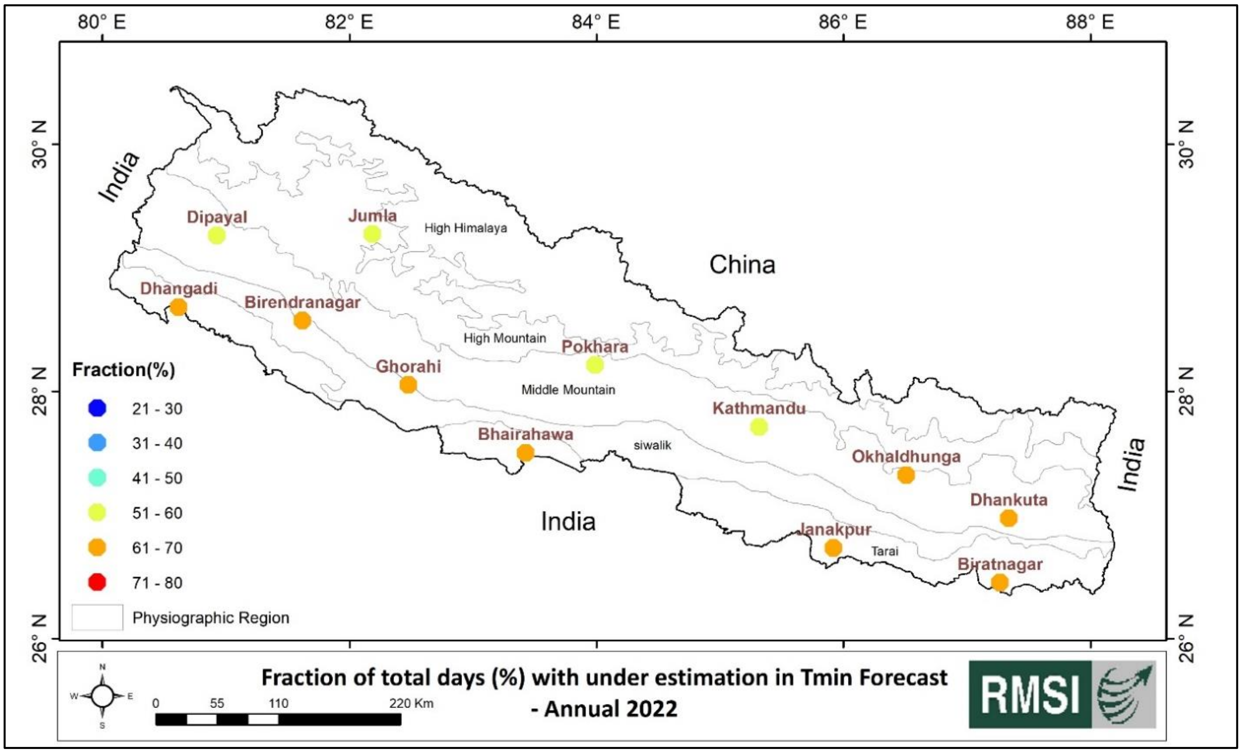

Figure 74: Fraction of total days (%) with under estimation in Tmin forecast across selected locations in Nepal during 2022

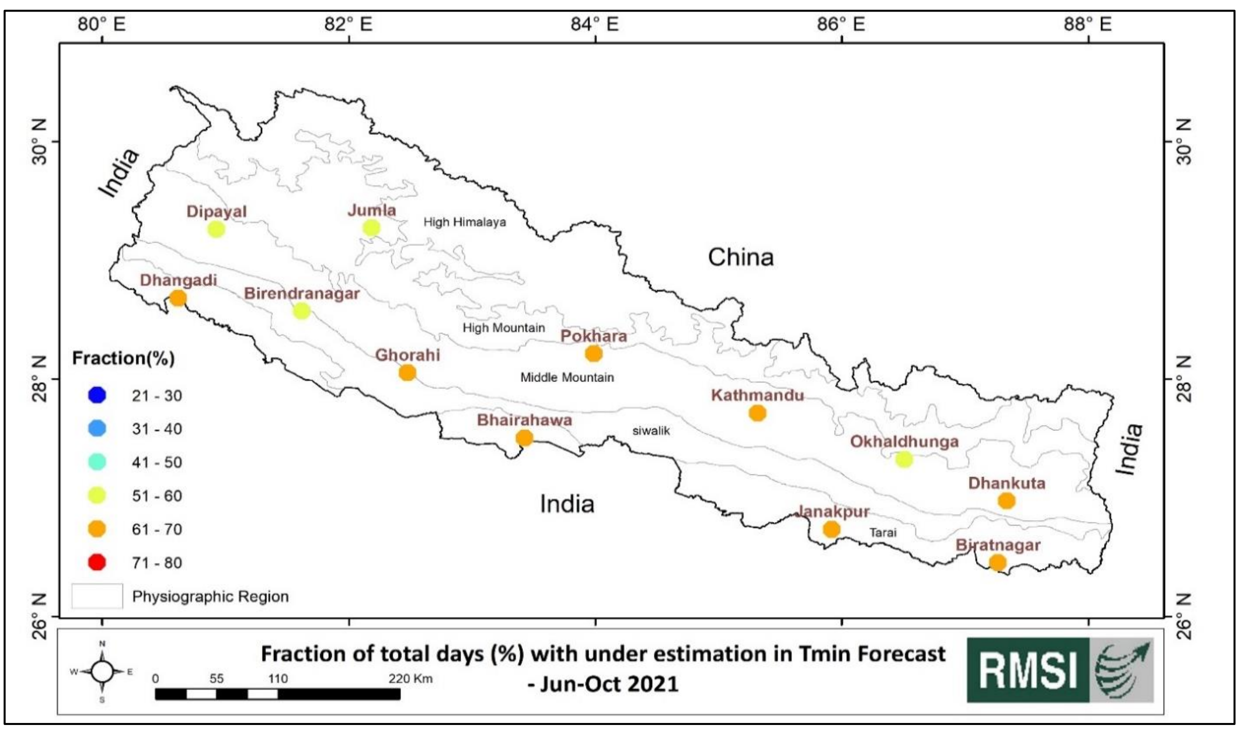

Figure 75: Fraction of total days (%) with under estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2021

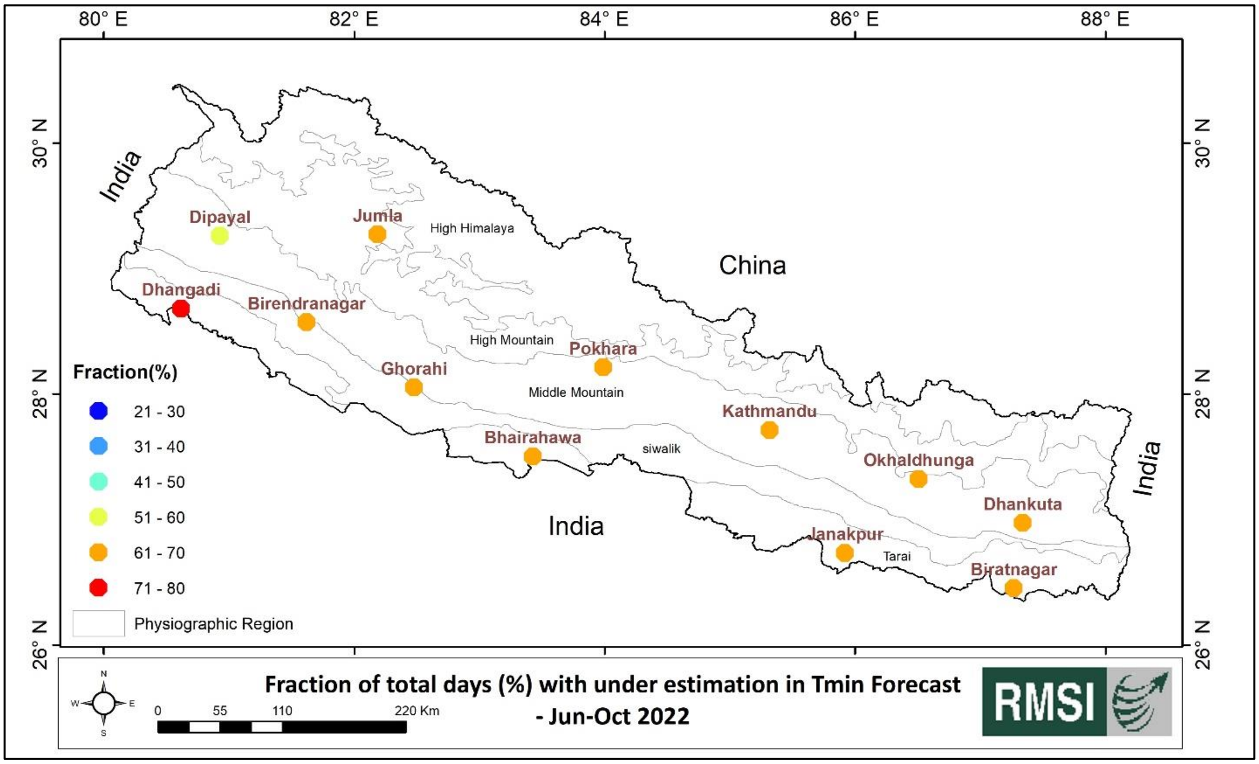

Figure 76: Fraction of total days (%) with under estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2022

The average deviation of temperature in °C during the days of over/under estimation in maximum temperature forecast has been estimated in the present study. The distribution of average difference of forecasted values from observed values during the days of over estimation in maximum and minimum temperature forecast across the selected locations in Nepal in annual and SW monsoon seasons during the years 2021-22 and 2022-23 have been depicted from

Figure 77 to Figure 84. In the case of maximum temperature, it was observed that, the average deviation is greater than 1.5℃ over majority locations during the both of the years in annual and seasonal scale. However, in the context of minimum temperature, the average deviation of the forecasted values from the observed values is higher than 1.5℃ during 2021-22 over majority of the locations, while in this difference has been drastically reduced in the year 2022-23.

The distribution of average difference of forecasted values from observed values during the days of under estimation in maximum and minimum temperature forecast across the selected locations in Nepal in annual and SW monsoon seasons during the years 2021-22 and 2022-23 have been depicted from

Figure 85 to Figure 92. In the case of maximum temperature, it was observed that, the average deviation is ranged between -2.5 to -1.5℃ over majority locations during the both of the years in annual and seasonal scale. While, in the context of minimum temperature, the difference is ranged between -1.5 to -0.5℃ over all the locations during both years.

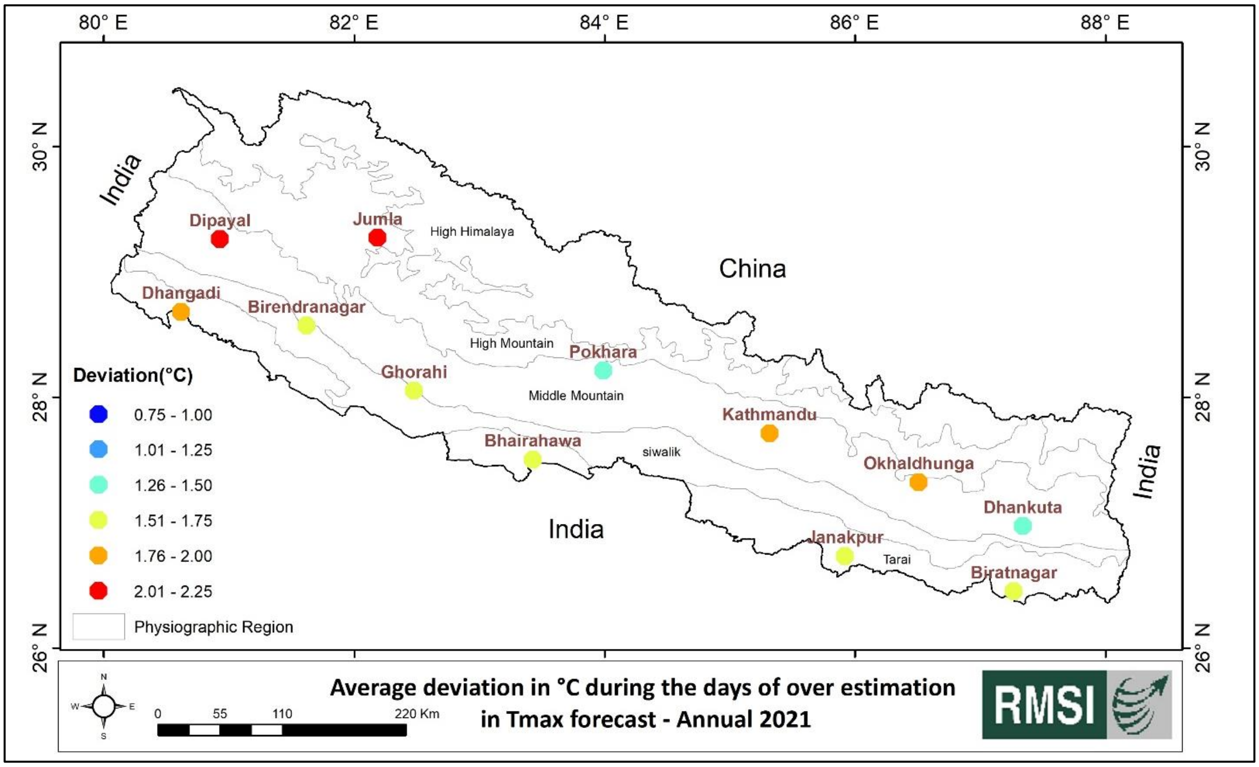

Figure 77: Average deviation in °C from observed values for the days with over estimation in Tmax forecast across selected locations in Nepal during 2021

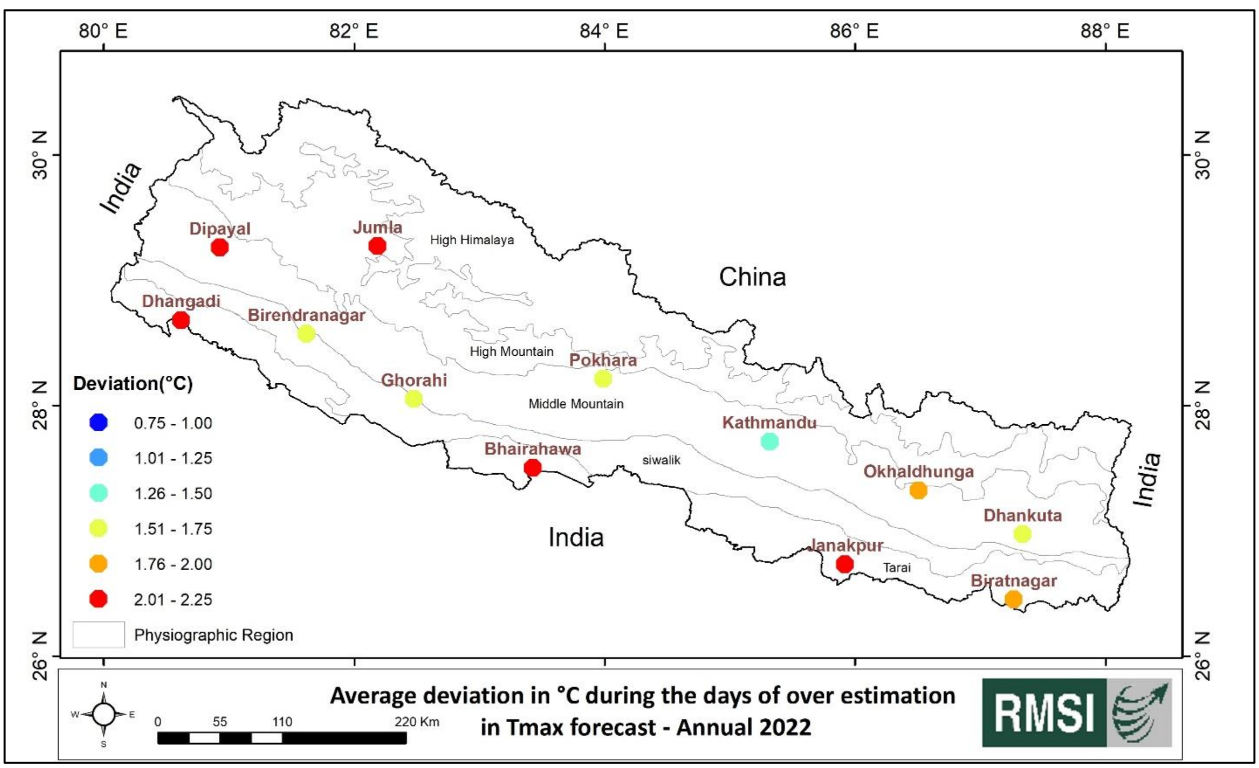

Figure 78: Average deviation in °C from observed values for the days with over estimation in Tmax forecast across selected locations in Nepal during 2022

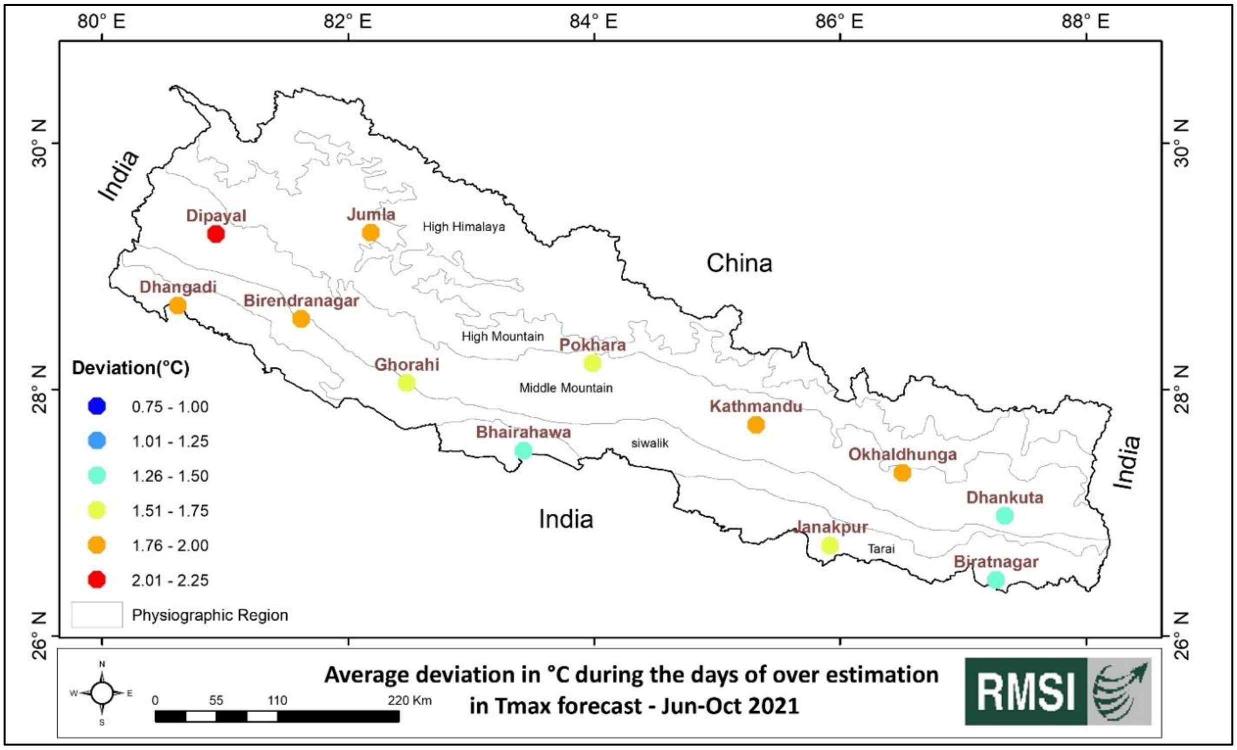

Figure 79: Average deviation in °C from observed values for the days with over estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2021

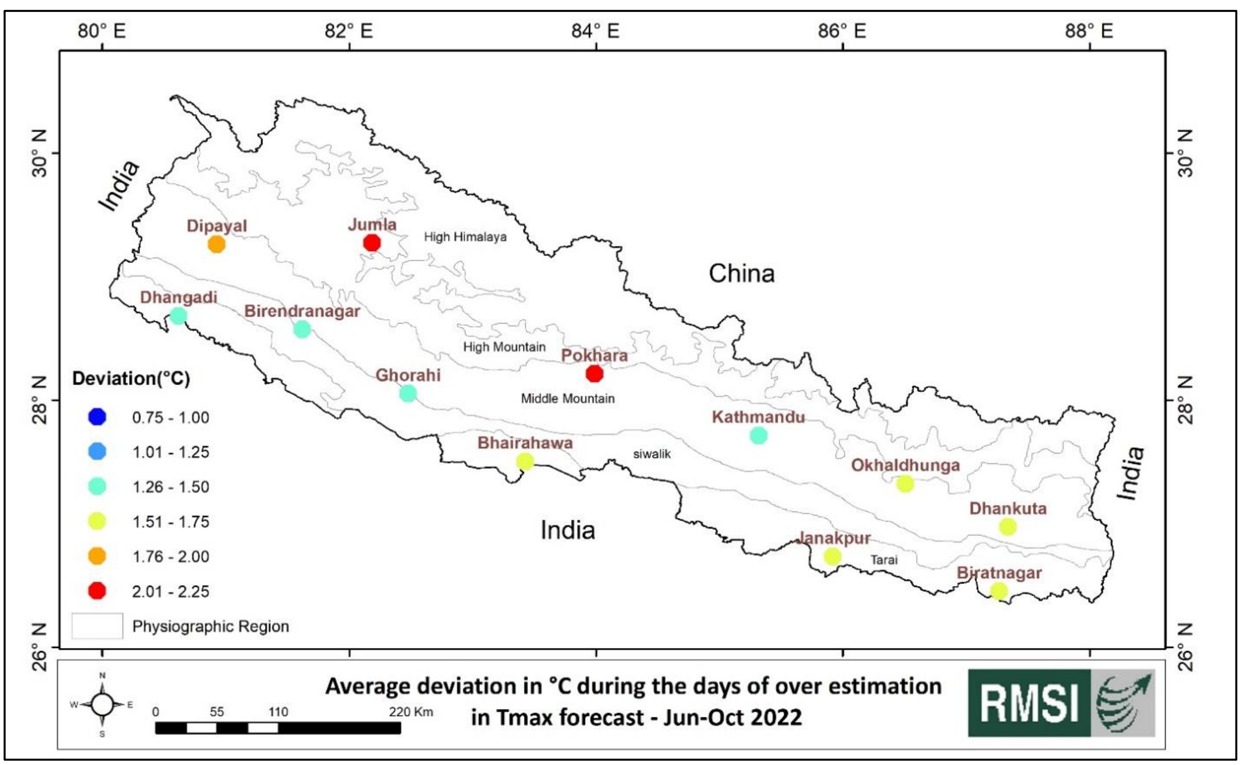

Figure 80: Average deviation in °C from observed values for the days with over estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2022

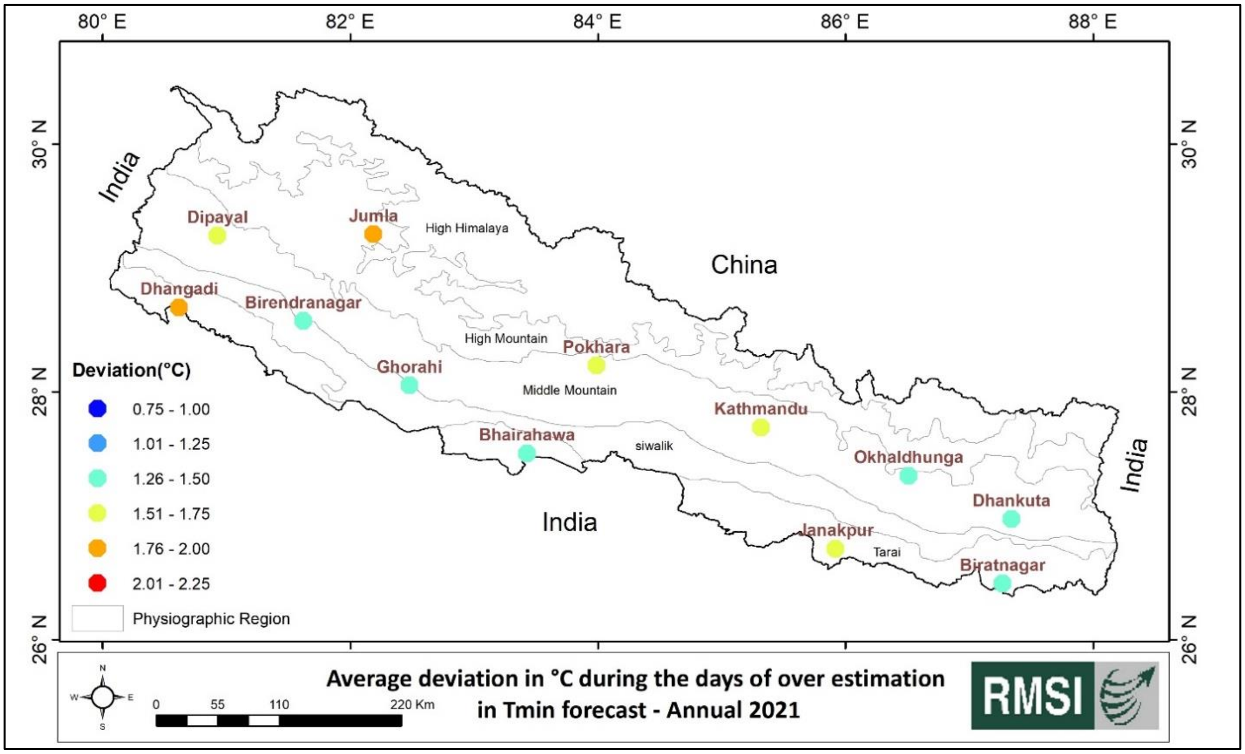

Figure 81: Average deviation in °C from observed values for the days with over estimation in Tmin forecast across selected locations in Nepal during 2021

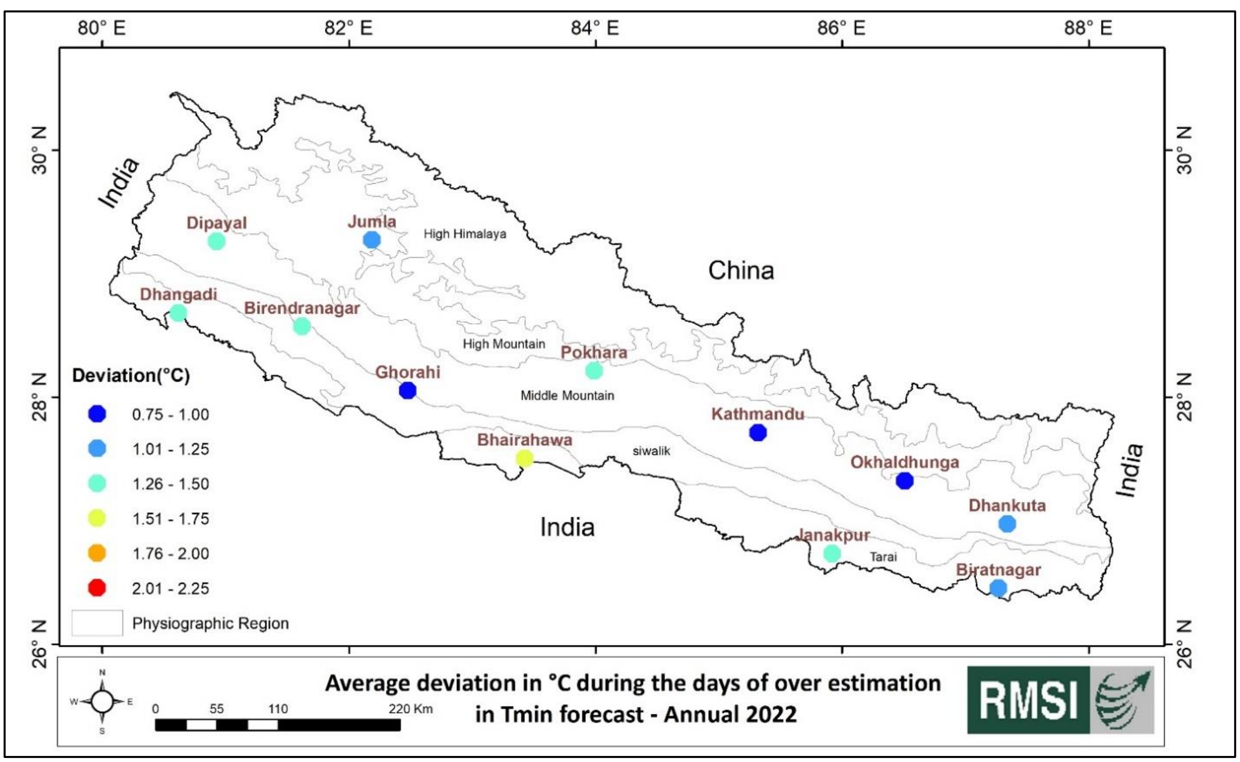

Figure 82: Average deviation in °C from observed values for the days with over estimation in Tmin forecast across selected locations in Nepal during 2022

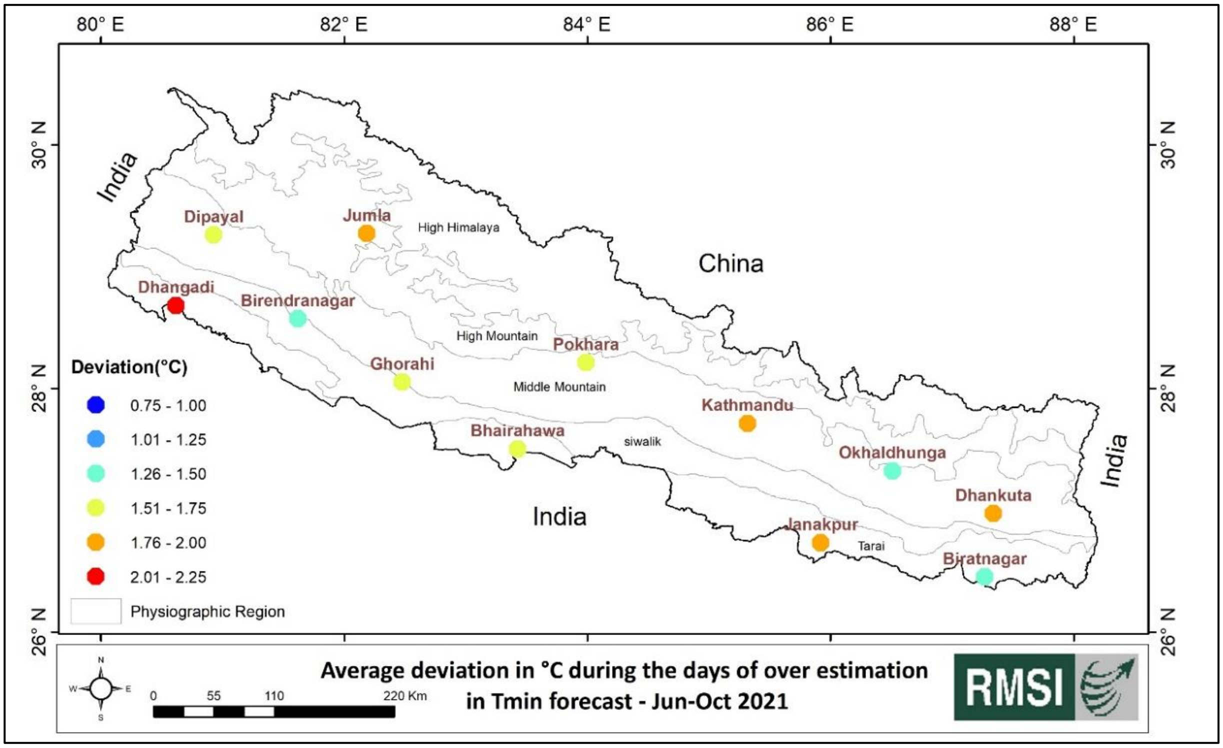

Figure 83: Average deviation in °C from observed values for the days with over estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2021

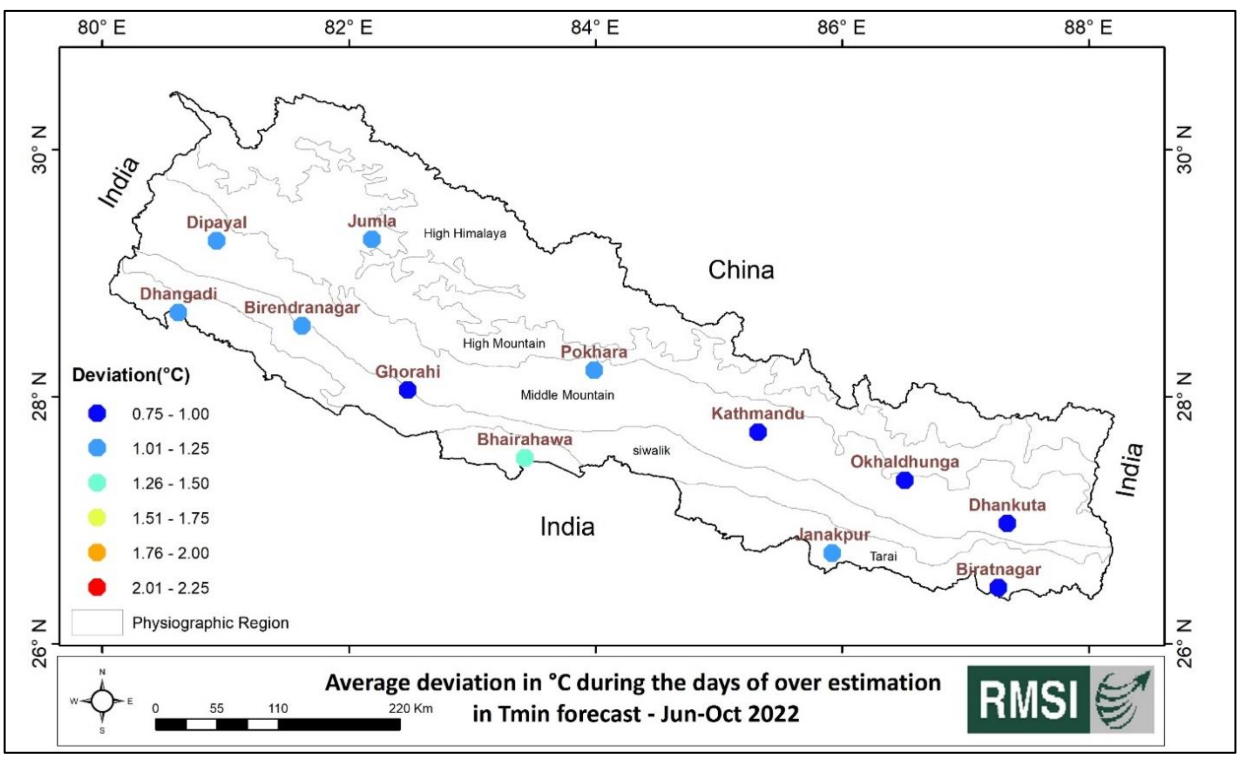

Figure 84: Average deviation in °C from observed values for the days with over estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2022

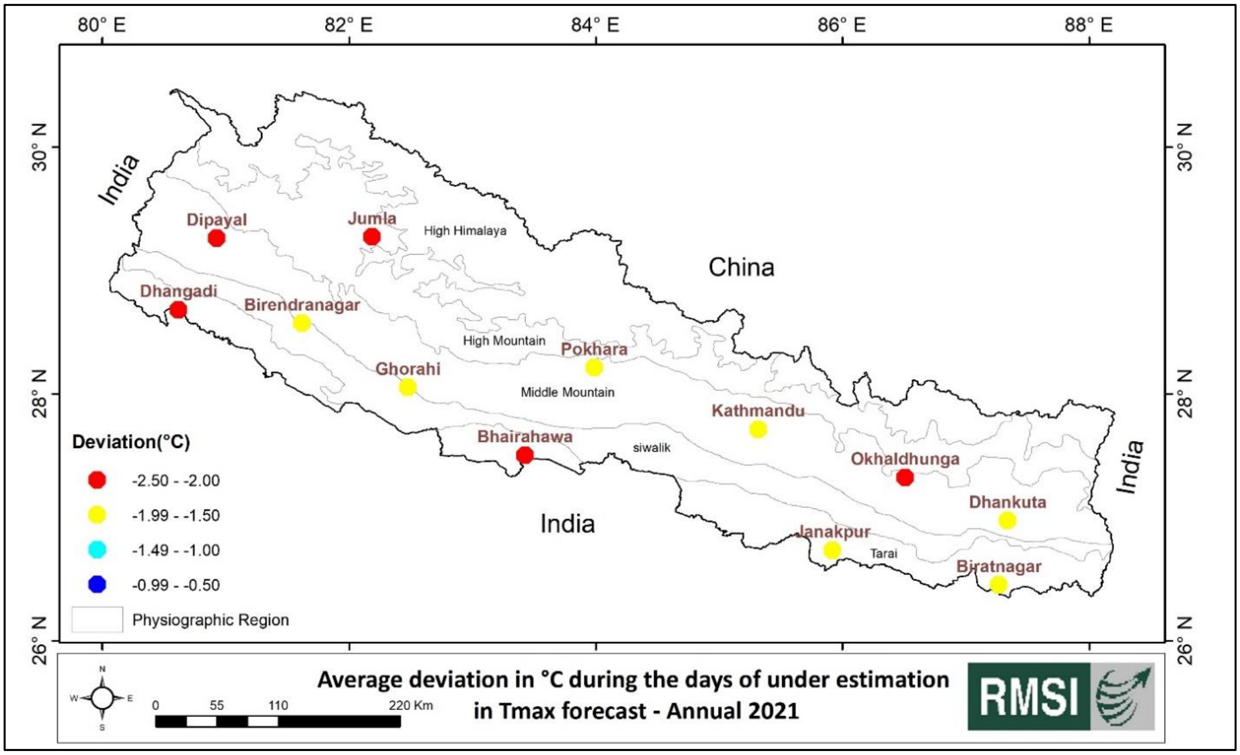

Figure 85: Average deviation in °C from observed values for the days with under estimation in Tmax forecast across selected locations in Nepal during 2021

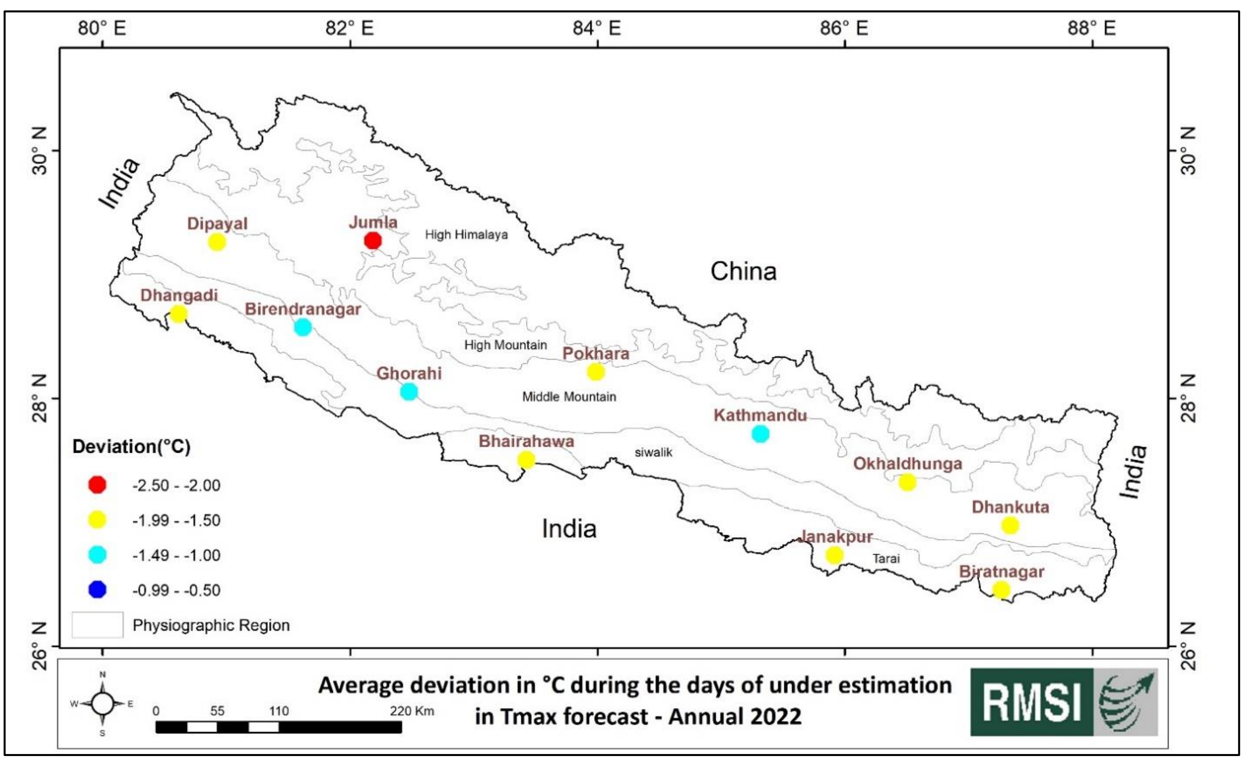

Figure 86: Average deviation in °C from observed values for the days with under estimation in Tmax forecast across selected locations in Nepal during 2022

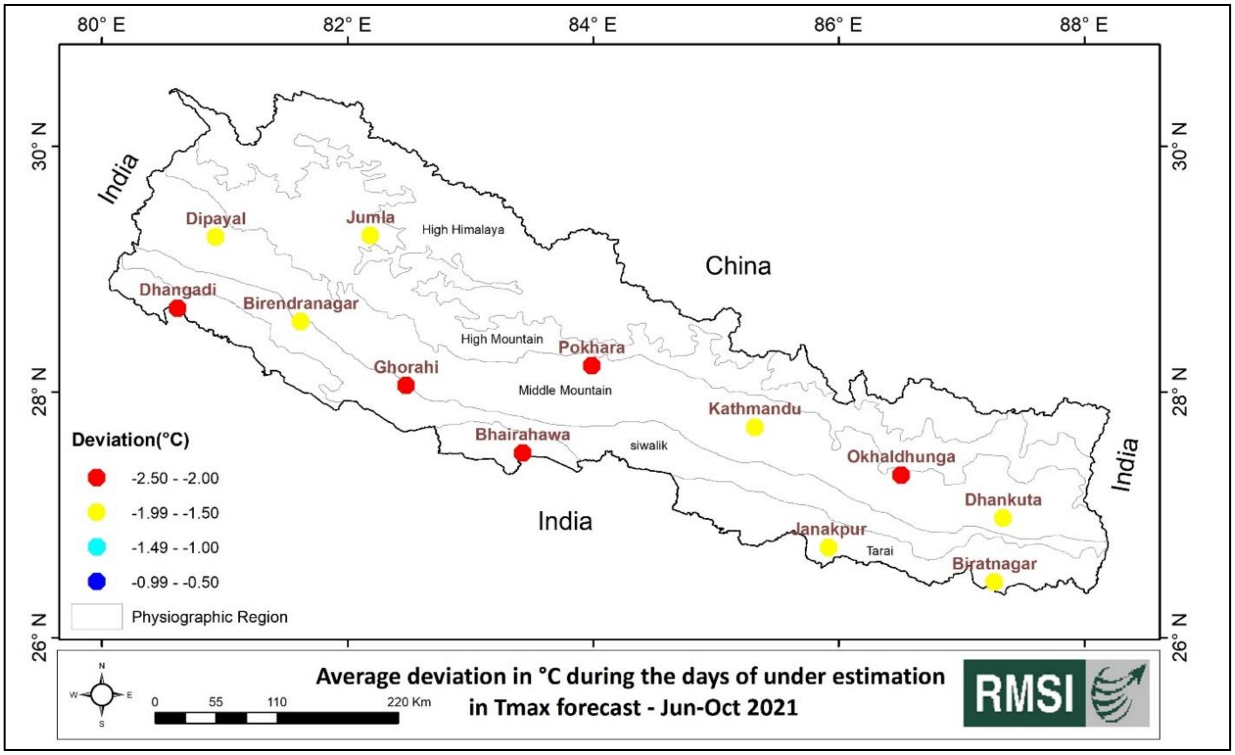

Figure 87: Average deviation in °C from observed values for the days with under estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2021

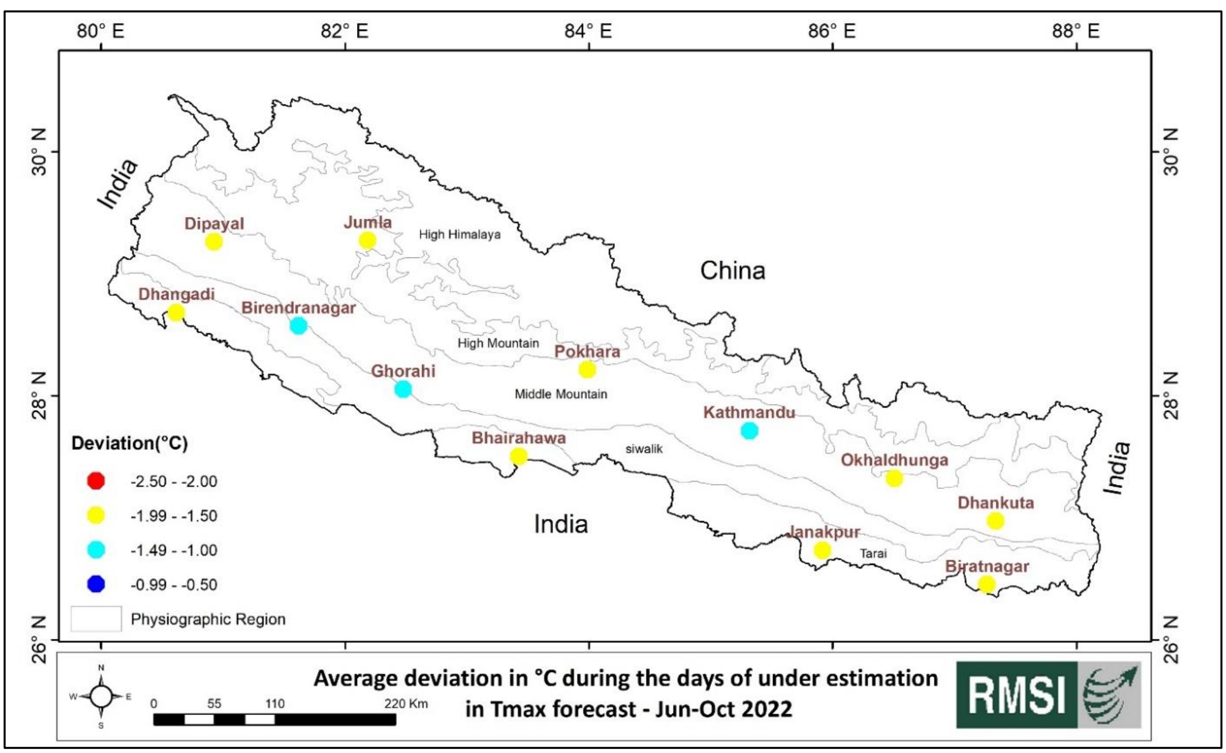

Figure 88: Average deviation in °C from observed values for the days with under estimation in Tmax forecast across selected locations in Nepal during Jun-Oct 2022

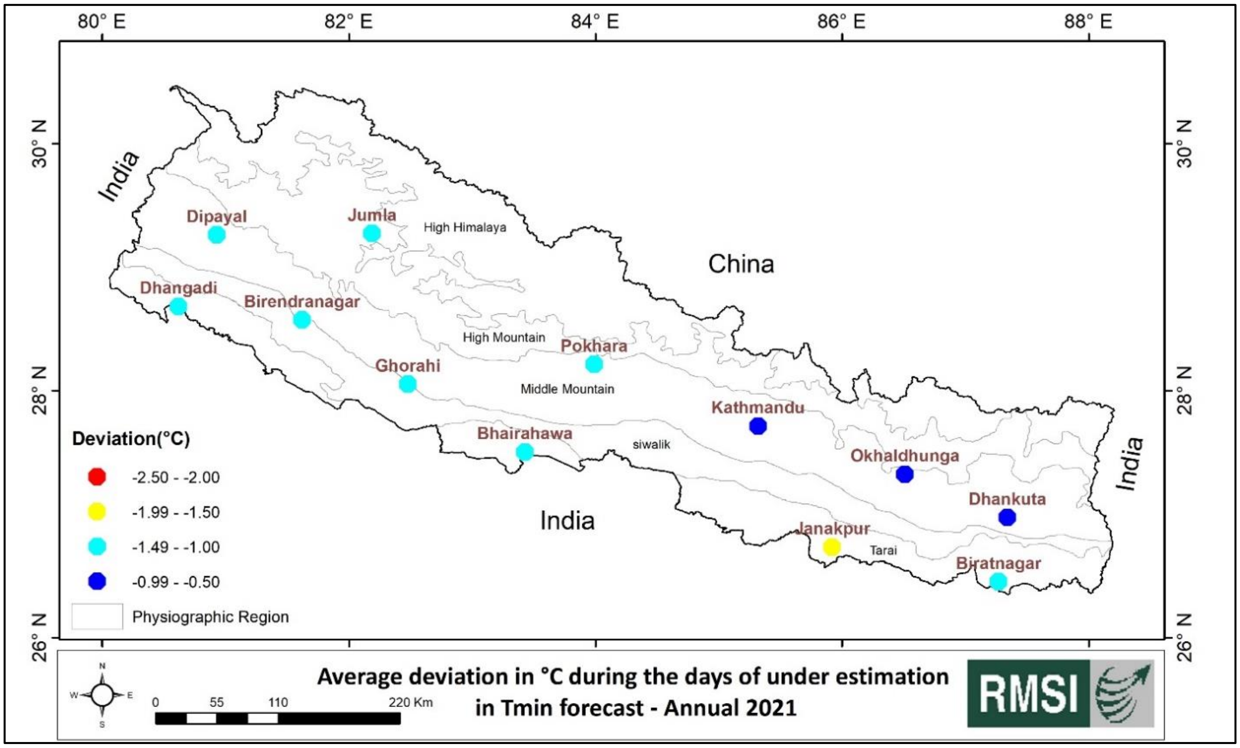

Figure 89: Average deviation in °C from observed values for the days with under estimation in Tmin forecast across selected locations in Nepal during 2021

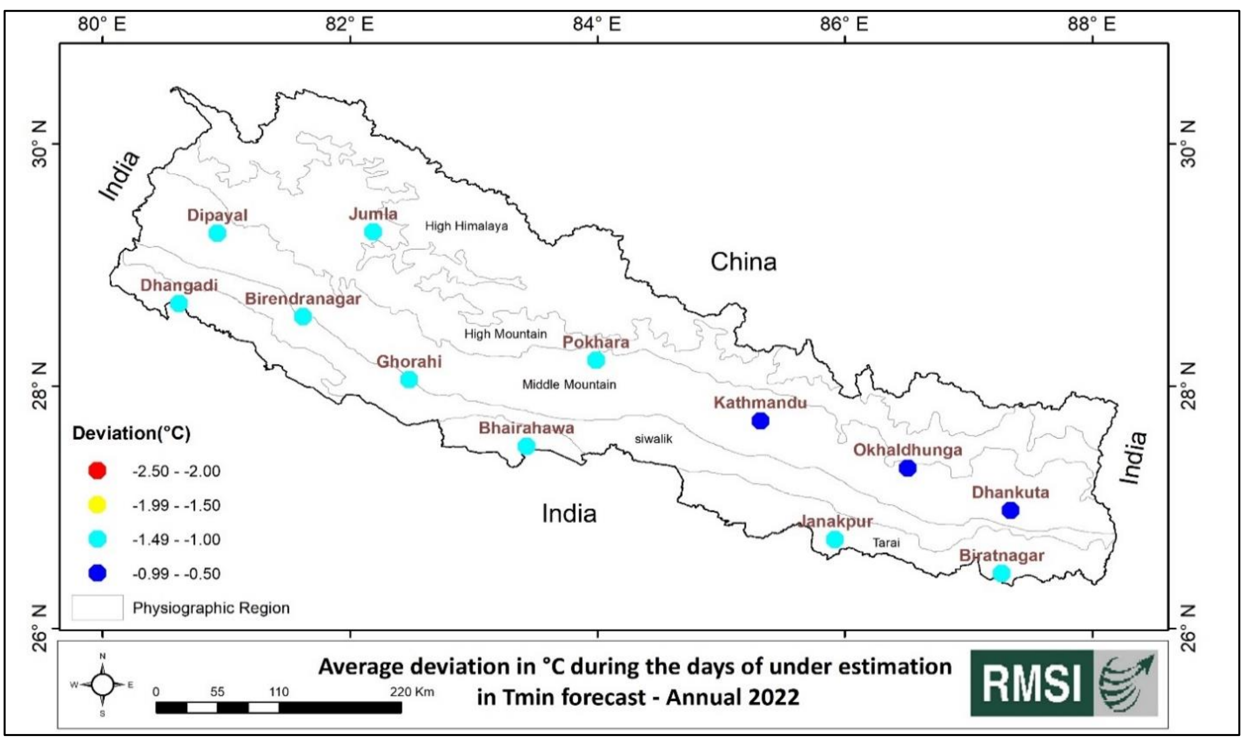

Figure 90: Average deviation in °C from observed values for the days with under estimation in Tmin forecast across selected locations in Nepal during 2022

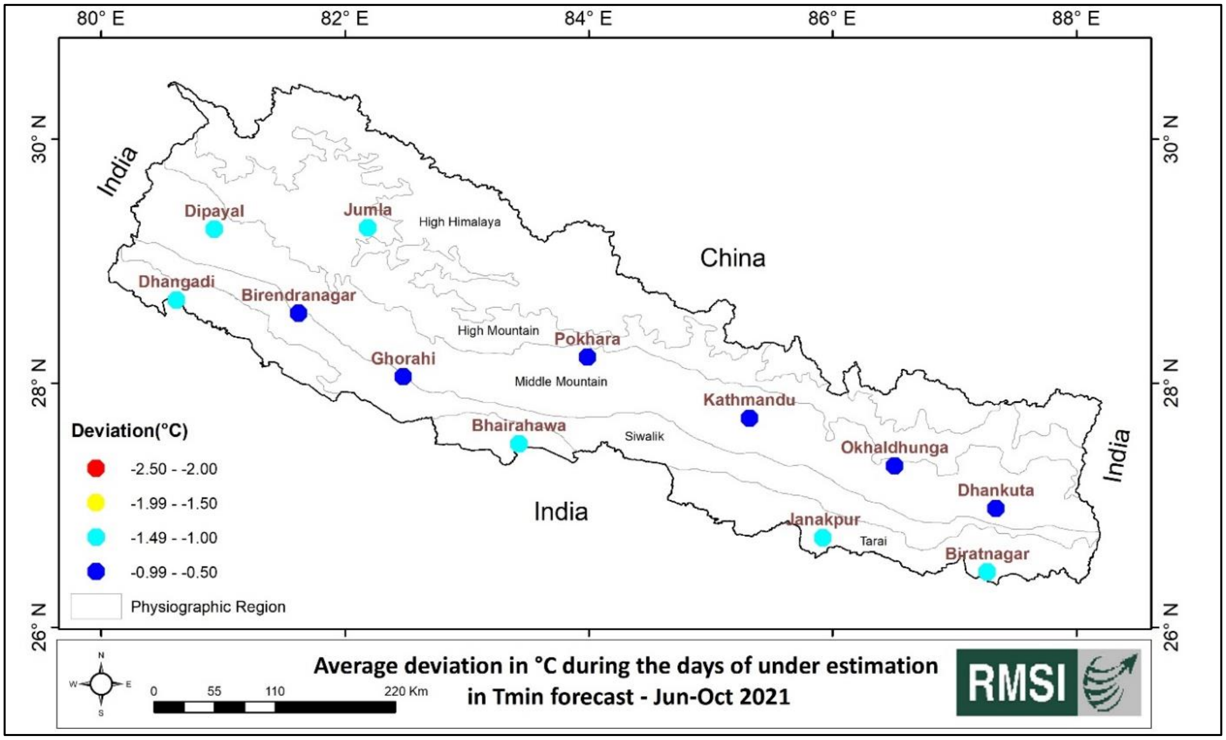

Figure 91: Average deviation in °C from observed values for the days with under estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2021

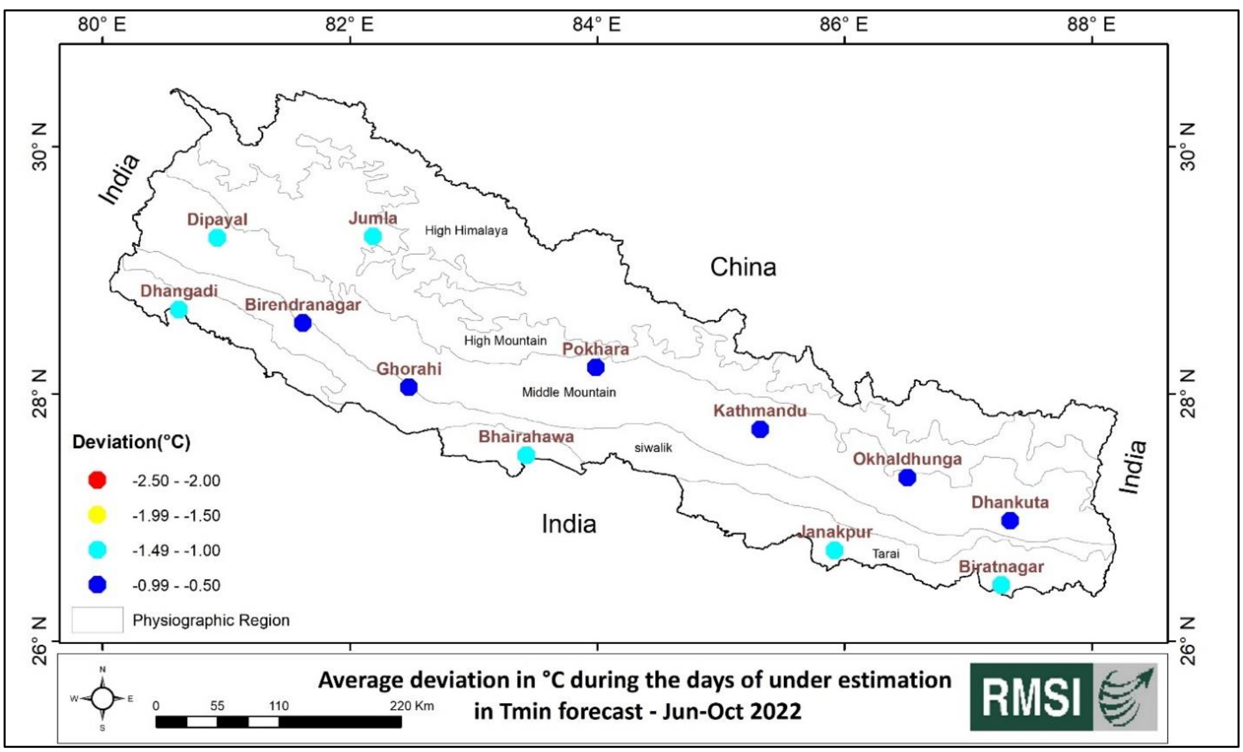

Figure 92: Average deviation in °C from observed values for the days with under estimation in Tmin forecast across selected locations in Nepal during Jun-Oct 2022

The month wise POD of maximum temperature forecast over selected locations in Nepal during the period 2021-23 has been furnished in Table 16. The average POD of maximum temperature forecast is ranged between 0.5 at Bhairahawa and 0.57 at Ghorahi. The average POD during annual and monsoon season (Jun-Oct) for all the stations has been estimated as 0.54 and 0.52, respectively. It indicates that, more than half of the daily observed values are falling within the forecasted ranges during a year. As the average of all the stations, the highest POD has been observed during the month of November (0.63), followed by December and April (0.6). The POD was found low during the months of January (0.44) and July (0.49).

Table 16: POD of Maximum Temperature forecast over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	0.34	0.37	0.45	0.37	0.50	0.39	0.48	0.34	0.45	0.53	0.47	0.60
Feb	0.61	0.57	0.57	0.50	0.57	0.48	0.64	0.55	0.48	0.55	0.54	0.64
Mar	0.55	0.58	0.58	0.55	0.42	0.47	0.63	0.55	0.50	0.45	0.53	0.61
Apr	0.53	0.52	0.72	0.60	0.65	0.53	0.65	0.58	0.53	0.60	0.60	0.68
May	0.47	0.39	0.53	0.53	0.60	0.56	0.53	0.47	0.44	0.61	0.45	0.52
Jun	0.45	0.50	0.65	0.60	0.53	0.60	0.58	0.52	0.58	0.50	0.60	0.55
Jul	0.52	0.52	0.47	0.55	0.55	0.47	0.48	0.48	0.44	0.50	0.45	0.44
Aug	0.55	0.53	0.50	0.53	0.52	0.55	0.55	0.52	0.40	0.58	0.50	0.37
Sep	0.50	0.53	0.58	0.47	0.45	0.48	0.52	0.53	0.43	0.53	0.53	0.55
Oct	0.40	0.48	0.55	0.63	0.53	0.65	0.58	0.48	0.60	0.69	0.42	0.55
Nov	0.67	0.58	0.62	0.63	0.73	0.67	0.62	0.70	0.58	0.63	0.43	0.65
Dec	0.47	0.66	0.60	0.55	0.74	0.66	0.63	0.55	0.53	0.69	0.47	0.61
Annual	0.50	0.52	0.57	0.54	0.57	0.54	0.57	0.52	0.50	0.57	0.50	0.56
Jun-Oct	0.48	0.51	0.55	0.56	0.52	0.55	0.54	0.51	0.49	0.56	0.50	0.49

The month wise POD of minimum temperature forecast over selected locations in Nepal during the period 2021-23 has been furnished in Table 17. The average POD of minimum temperature forecast is ranged between 0.49 at Bhairahawa and 0.72 at Dhankuta. The average POD during annual and monsoon season (Jun-Oct) for all the stations has been estimated as 0.58 and 0.62, respectively. It indicates that, more than half of the daily observed values are falling within the forecasted ranges during a year. As the average of all the stations, the highest POD has been observed during the month of September (0.68), followed by November (0.67) and December & August (0.65). The POD was found low during the months of April (0.42) and May (0.46).

Table 17: POD of Minimum Temperature forecast over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	0.55	0.58	0.53	0.48	0.82	0.50	0.56	0.39	0.55	0.58	0.74	0.58
Feb	0.55	0.50	0.64	0.52	0.64	0.55	0.52	0.43	0.57	0.59	0.66	0.59
Mar	0.48	0.60	0.58	0.55	0.61	0.40	0.48	0.48	0.60	0.65	0.68	0.44
Apr	0.35	0.30	0.48	0.45	0.50	0.35	0.40	0.45	0.45	0.47	0.40	0.40
May	0.27	0.63	0.47	0.48	0.52	0.42	0.44	0.27	0.40	0.56	0.61	0.47
Jun	0.42	0.55	0.55	0.47	0.72	0.55	0.52	0.53	0.52	0.72	0.87	0.67
Jul	0.35	0.45	0.60	0.47	0.74	0.58	0.55	0.47	0.61	0.66	0.68	0.69
Aug	0.56	0.79	0.63	0.68	0.74	0.60	0.58	0.55	0.65	0.69	0.71	0.61
Sep	0.57	0.63	0.65	0.60	0.82	0.73	0.77	0.60	0.53	0.80	0.82	0.65
Oct	0.55	0.69	0.66	0.68	0.69	0.56	0.77	0.63	0.47	0.61	0.69	0.45
Nov	0.65	0.82	0.65	0.63	0.90	0.63	0.72	0.70	0.43	0.67	0.62	0.57
Dec	0.53	0.73	0.63	0.58	0.89	0.73	0.52	0.48	0.55	0.77	0.74	0.63
Annual	0.49	0.61	0.59	0.55	0.72	0.55	0.57	0.50	0.53	0.65	0.68	0.56
Jun-Oct	0.49	0.62	0.62	0.58	0.74	0.61	0.64	0.56	0.56	0.70	0.75	0.61

The average fraction of total number of days in percentage with forecasted value greater than observed values of Maximum Temperature over the selected locations in Nepal during 2021-23 are furnished in **Table 18**. It has been observed that as the average of all the stations, the forecasted value is higher than observed values during 37% of the total number of days during the aforementioned period. It means that, the maximum temperature forecast is over estimating compared to observed values around one-third fraction of total days in a year. Among the different stations, it is ranged from 32% at Dhankuta and 43% at Okhaldunga. Among the different months, as an average of all the stations, the total count of days with over estimation in maximum temperature forecast is ranged from 29% in March to 41% in May.

Table 18: Average fraction (%) of total number of days with forecasted value is greater than observed values of Maximum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	45	42	32	58	29	29	32	42	45	39	48	35
Feb	36	39	36	36	36	36	39	36	43	36	43	43
Mar	23	32	35	19	19	29	29	23	29	32	39	35
Apr	43	47	40	30	33	37	33	47	50	40	40	43
May	42	39	42	35	35	48	48	39	42	35	45	42
Jun	37	43	40	43	30	47	37	40	33	37	43	40

Jul	35	32	35	32	32	35	35	29	32	35	39	32
Aug	45	39	42	52	29	29	42	35	35	32	48	42
Sep	37	33	40	33	37	40	37	37	43	37	53	37
Oct	23	39	35	32	35	32	39	29	29	45	42	35
Nov	33	37	43	37	37	33	47	37	37	43	40	43
Dec	45	45	35	39	42	39	42	45	39	32	42	48
Annual	36	39	37	36	32	35	38	35	38	36	43	39
Jun-Oct	35	37	38	38	33	36	37	33	34	36	44	37

Similar to the number of days of over estimation in maximum temperature forecast, the fraction (%) of total number of days with forecasted value is less than observed values of maximum temperature over the selected locations in Nepal during 2021-23 has been listed in Table 19. As the average of all the stations the forecasted value of maximum temperature is less than the observed value during 63% of total days in the year. It is ranged between 57% in Okhaldunga to 68% in Dhankuta. Among the different months, as the average of all the days, the total count of days with under estimation in maximum temperature forecast is ranged from 59% in May to 71% in March. It indicates that, the maximum temperature forecast is under estimating in comparison with the observed values during two-third fraction of total number of days in a year.

Table 19: Average fraction (%) of total number of days with forecasted value is less than observed values of Maximum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	55	58	68	42	71	71	68	58	55	61	52	65
Feb	64	61	64	64	64	64	61	64	57	64	57	57
Mar	77	68	65	81	81	71	71	77	71	68	61	65
Apr	57	53	60	70	67	63	67	53	50	60	60	57
May	58	61	58	65	65	52	52	61	58	65	55	58
Jun	63	57	60	57	70	53	63	60	67	63	57	60
Jul	65	68	65	68	68	65	65	71	68	65	61	68
Aug	55	61	58	48	71	71	58	65	65	68	52	58
Sep	63	67	60	67	63	60	63	63	57	63	47	63
Oct	77	61	65	68	65	68	61	71	71	55	58	65
Nov	67	63	57	63	63	67	53	63	63	57	60	57
Dec	55	55	65	61	58	61	58	55	61	68	58	52
Annual	64	61	63	64	68	65	62	65	62	64	57	61
Jun-Oct	65	62	61	61	67	63	62	66	65	63	55	62

The average fraction of total number of days in percentage with forecasted value greater than observed values of minimum temperature over the selected locations in Nepal during 2021-23 are furnished in Table 20. Similar to maximum temperature, as the average of all the stations, the forecasted value is higher than observed values during 38% of the total number of days during a year. Among the different stations, it is ranged from 33% at Dhangadi and 49% at Jumla. Among the different months, as an average of all the stations, the total count of days with over estimation in minimum temperature forecast is ranged from 30% in August to 48% in October.

Table 20: Average number of days with forecasted value greater than observed values of Minimum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	45	35	45	39	32	45	55	39	52	42	32	42
Feb	29	36	50	32	29	46	39	36	68	39	39	39
Mar	19	35	29	29	29	32	29	26	45	32	32	32
Apr	53	50	43	43	43	37	43	40	47	43	40	43
May	35	35	39	39	29	45	35	45	45	48	39	42
Jun	40	43	40	30	37	47	33	33	43	33	30	43
Jul	32	32	35	26	29	42	29	29	39	29	35	29
Aug	23	26	32	26	29	32	35	26	29	35	32	32
Sep	43	40	43	30	43	47	40	33	47	37	40	40
Oct	45	42	48	45	48	45	48	39	55	55	58	48
Nov	30	33	47	30	27	23	23	37	63	43	33	40
Dec	39	42	58	39	39	42	52	35	71	48	45	35
Annual	35	37	41	33	34	40	38	34	49	39	38	38
Jun-Oct	36	37	39	31	37	42	37	31	41	37	39	38

The fraction (%) of total number of days with forecasted value is less than observed values of minimum temperature over the selected locations in Nepal during 2021-23 has been listed in Table 21. As the average of all the stations the forecasted value of minimum temperature is less than the observed value during 62% of total days in the year. It is ranged between 51% in Jumla to 67% in Dhangadi. Among the different months, as the average of all the days, the total count of days with under estimation in minimum temperature forecast is ranged from 52% in October to 70% in August. It also indicates that, the minimum temperature forecast is under estimating in comparison with the observed values during two-third fraction of total number of days in a year.

Table 21: Average number of days with forecasted value less than observed values of Minimum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	55	65	55	61	68	55	45	61	48	58	68	58
Feb	71	64	50	68	71	54	61	64	32	61	61	61
Mar	81	65	71	71	71	68	71	74	55	68	68	68
Apr	47	50	57	57	57	63	57	60	53	57	60	57
May	65	65	61	61	71	55	65	55	55	52	61	58
Jun	60	57	60	70	63	53	67	67	57	67	70	57
Jul	68	68	65	74	71	58	71	71	61	71	65	71
Aug	77	74	68	74	71	68	65	74	71	65	68	68
Sep	57	60	57	70	57	53	60	67	53	63	60	60
Oct	55	58	52	55	52	55	52	61	45	45	42	52
Nov	70	67	53	70	73	77	77	63	37	57	67	60
Dec	61	58	42	61	61	58	48	65	29	52	55	65
Annual	65	63	59	67	66	60	62	66	51	61	62	62
Jun-Oct	63	63	61	69	62	58	63	68	58	63	61	61

The month wise average deviation of temperature in °C during the days when forecasted value is greater than the observed values of maximum temperature during April 2021 to March 2023 has been furnished in Table 22. The average deviation between forecasted and observed values for all the stations during the days with over estimation in maximum temperature in annual and monsoon season (Jun-Oct) has been estimated as 1.8°C and 1.7°C, respectively. The highest deviation was observed over Dhangadi and Dipayal (>2°C) followed by Bhairahawa and Janakpur. This deviation is found higher (more than 2°C) in the months of January, April and May and the lowest deviation (1°C) has been observed in November. During the remaining months its value has been ranged between 1.5-2°C.

Table 22: Average deviation in °C during the days with forecasted value greater than observed values of Maximum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	3.4	2.7	2.4	3.2	1.0	2.5	2.0	3.9	2.4	1.4	1.9	1.3
Feb	2.0	1.2	1.5	2.3	1.1	2.3	1.5	1.5	2.2	1.0	2.2	1.1
Mar	1.5	1.6	1.2	1.3	1.9	1.7	1.2	2.2	2.4	1.4	1.3	1.4
Apr	2.5	3.3	2.1	2.8	2.5	3.2	2.3	2.4	2.4	2.6	2.4	1.9
May	1.9	2.4	2.0	2.3	2.2	2.2	1.7	2.4	2.5	2.5	2.1	1.6
Jun	1.6	1.8	2.0	1.8	1.4	2.2	1.7	1.6	1.4	1.8	1.5	1.5
Jul	1.0	1.2	1.6	1.8	1.4	1.7	1.2	1.2	1.6	1.6	1.6	1.6

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Aug	1.4	1.5	1.2	1.6	1.7	1.4	1.3	1.6	1.7	1.7	1.6	2.5
Sep	1.7	1.5	2.0	1.7	1.3	2.2	1.6	1.2	2.3	1.6	1.5	1.5
Oct	2.0	1.3	1.8	1.5	1.8	2.7	1.7	2.1	2.7	1.5	2.4	1.8
Nov	1.0	0.7	1.1	0.8	0.8	1.0	1.1	0.8	1.3	1.2	1.7	1.0
Dec	2.3	1.4	1.4	2.6	1.1	1.4	1.5	2.3	2.2	1.5	1.6	1.2
Annual	1.9	1.7	1.7	2.0	1.5	2.0	1.6	1.9	2.1	1.6	1.8	1.5
Jun-Oct	1.5	1.5	1.7	1.7	1.5	2.0	1.5	1.6	1.9	1.6	1.7	1.8

The average deviation of temperature in °C during the days when forecasted value is less than the observed values of maximum temperature has been furnished in Table 23. The average deviation from forecasted and observed values for all the stations during the days with under estimation in maximum temperature has been estimated as -1.8°C for both annual and monsoon season (Jun-Oct). The highest deviation was observed over Jumla and Dipayal (<-2°C) followed by Okhaldunga and Dhangadi. As the average of all the stations, this deviation was found highest during May (-2.3°C) followed by January and July (-2.2°C). The lowest deviation has been estimated in March (-1.4°C). During the remaining months its value has been ranged between -2 to -1.5°C.

Table 23: Average deviation in °C during the days with forecasted value less than observed values of Maximum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	-2.7	-1.7	-1.8	-3.5	-1.7	-2.8	-1.9	-2.2	-2.4	-1.6	-2.1	-1.5
Feb	-1.5	-1.2	-1.4	-1.8	-1.5	-2.0	-1.2	-1.2	-2.4	-1.3	-1.7	-1.1
Mar	-1.2	-1.5	-1.6	-1.2	-1.5	-1.8	-1.0	-1.2	-1.7	-1.4	-1.7	-1.1
Apr	-1.8	-1.6	-1.1	-1.7	-1.2	-1.6	-1.4	-1.8	-2.5	-1.4	-1.4	-1.6
May	-2.4	-2.3	-2.6	-2.2	-1.7	-2.8	-1.7	-2.8	-2.6	-2.2	-2.3	-2.1
Jun	-1.7	-2.1	-1.4	-1.9	-1.6	-2.3	-1.7	-2.1	-1.6	-1.6	-1.6	-1.8
Jul	-2.2	-2.1	-2.1	-2.3	-1.7	-2.4	-2.0	-2.3	-2.4	-2.2	-2.3	-2.6
Aug	-1.4	-1.3	-1.3	-1.7	-1.5	-1.4	-1.3	-1.5	-1.7	-1.2	-1.8	-2.2
Sep	-2.1	-1.7	-2.1	-2.0	-1.9	-2.2	-1.9	-1.9	-2.5	-1.7	-2.3	-2.0
Oct	-1.9	-1.8	-1.7	-1.5	-1.7	-1.3	-1.6	-1.5	-1.4	-1.1	-2.0	-1.4
Nov	-1.2	-1.5	-1.3	-1.6	-1.5	-1.5	-1.3	-1.5	-1.8	-1.5	-1.9	-1.2
Dec	-2.0	-1.3	-1.6	-1.8	-1.3	-2.4	-1.3	-1.8	-2.1	-1.2	-2.3	-1.7
Annual	-1.8	-1.7	-1.7	-1.9	-1.6	-2.0	-1.5	-1.8	-2.1	-1.5	-1.9	-1.7
Jun-Oct	-1.9	-1.8	-1.7	-1.9	-1.7	-1.9	-1.7	-1.9	-1.9	-1.6	-2.0	-2.0

The month wise average deviation of temperature in °C during the days when forecasted value is greater than the observed values of minimum temperature during April 2021 to March 2023 has been furnished in Table 24. The average deviation between forecasted and observed values for all the stations during the days with over estimation in minimum temperature in annual and monsoon season (Jun-Oct) has been estimated as 1.4°C and 1.3°C, respectively. The highest deviation was observed over Dhangadi (1.6°C) followed by Bhairahawa, Dipayal, Jumla and Janakpur (1.5°C). Among the different months, the average deviation for all the stations has been found highest in April (1.9°C) and July (1.8°C). The lowest deviation (1°C) has been observed in August and November. During the remaining months its value has been ranged between 1.2-1.6°C.

Table 24: Average deviation in °C during the days with forecasted value greater than observed values of Minimum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Jan	1.3	1.7	1.3	2.1	0.9	1.4	1.0	1.5	1.4	1.1	0.8	1.1
Feb	1.7	1.1	1.2	1.7	1.2	1.3	1.2	1.8	1.5	1.1	1.2	1.4
Mar	1.2	1.1	1.4	1.2	0.9	2.2	0.9	1.1	1.2	0.9	0.8	1.4
Apr	1.7	2.0	1.8	1.9	1.6	2.0	1.4	2.0	2.4	1.8	1.5	2.1
May	2.2	1.3	1.7	1.8	1.6	1.9	1.5	1.8	1.5	1.0	1.6	1.7
Jun	1.5	1.1	1.3	1.4	0.9	1.3	1.2	1.2	1.1	1.3	0.6	1.1
Jul	2.3	1.5	1.4	2.4	2.1	1.7	1.6	1.9	1.9	1.7	1.6	1.7
Aug	1.2	0.7	1.1	1.2	0.9	1.0	1.0	1.1	0.8	0.8	0.9	0.9
Sep	1.5	1.5	1.6	1.8	1.7	1.4	1.3	1.6	1.8	1.9	1.2	1.6
Oct	1.2	1.1	1.2	1.2	1.0	1.4	0.8	1.6	1.7	1.2	1.1	1.5
Nov	0.9	1.0	1.2	1.1	0.6	1.4	1.0	0.7	1.4	1.0	0.9	1.2
Dec	1.4	1.0	1.3	1.4	1.2	0.8	1.3	1.3	1.2	1.1	0.8	1.3
Annual	1.5	1.3	1.4	1.6	1.2	1.5	1.2	1.5	1.5	1.2	1.1	1.4
Jun-Oct	1.3	1.3	1.3	1.5	1.1	1.3	1.1	1.3	1.5	1.3	1.0	1.3

The average deviation of temperature in °C during the days when forecasted value is less than the observed values of minimum temperature has been furnished in Table 25. The average deviation from forecasted and observed values for all the stations during the days with under estimation in minimum temperature has been estimated as -1.2°C and -1.0°C for annual and monsoon season (Jun-Oct), respectively. The highest deviation was observed over Bhairahawa followed by Janakpur. As the average of all the stations, this deviation was found highest during January (-1.7°C) followed by May (-1.6°C). The lowest deviation has been estimated in September to November (-0.9°C). During the remaining months its value has been ranged between -1 to -1.6°C.

Table 25: Average deviation in °C during the days with forecasted value less than observed values of Minimum Temperature over the selected locations in Nepal during 2021-23

Month	Bhairahawa	Biratnagar	Birendranagar	Dhangadi	Dhankuta	Dipayal	Ghorahi	Janakpur	Jumla	Kathmandu	Okhaldhunga	Pokhara
Apr	-2.3	-2.3	-1.8	-2.1	-1.2	-1.7	-1.8	-1.7	-1.5	-1.0	-1.3	-1.4
Jan	-1.5	-1.1	-1.3	-1.5	-0.8	-1.4	-1.5	-1.6	-1.4	-1.0	-0.8	-1.3
Feb	-1.4	-1.3	-1.0	-1.3	-1.1	-1.3	-1.3	-1.5	-1.0	-1.0	-0.8	-1.1
Mar	-1.3	-1.4	-1.1	-1.5	-1.1	-1.6	-1.3	-1.5	-1.0	-1.0	-1.0	-1.4
May	-2.1	-1.3	-1.4	-1.5	-1.5	-1.8	-1.5	-2.2	-1.6	-1.3	-1.3	-1.5
Jun	-1.9	-1.3	-1.2	-1.5	-0.8	-1.4	-1.2	-1.5	-1.5	-0.8	-0.6	-0.9
Jul	-1.8	-1.4	-1.2	-1.4	-0.8	-1.4	-1.1	-1.4	-1.1	-0.9	-0.9	-0.9
Aug	-1.1	-0.8	-0.9	-0.9	-0.6	-1.1	-1.1	-1.1	-1.1	-0.9	-0.8	-1.0
Sep	-1.1	-0.9	-0.8	-1.4	-0.5	-0.9	-0.6	-1.4	-1.1	-0.8	-0.6	-0.9
Oct	-0.9	-0.8	-0.7	-0.7	-0.8	-0.9	-0.7	-0.9	-1.7	-0.9	-0.6	-1.2
Nov	-1.0	-0.7	-0.9	-1.1	-0.5	-1.0	-0.7	-0.9	-1.5	-0.8	-0.9	-1.2
Dec	-1.2	-0.8	-1.0	-1.1	-0.5	-0.8	-1.1	-1.4	-1.3	-0.7	-0.8	-0.7
Annual	-1.5	-1.2	-1.1	-1.3	-0.9	-1.3	-1.2	-1.4	-1.3	-0.9	-0.9	-1.1
Jun-Oct	-1.1	-0.9	-1.0	-1.2	-0.6	-1.0	-0.9	-1.2	-1.4	-0.8	-0.7	-1.1

3.5.3 Key findings of the evaluation of NWP forecast disseminated through MFD website

The present study pointing out that, the daily rainfall forecast predicts almost 65% of the occurrence of rainy events during monsoon seasons in Nepal by means of POD. On this basis among different months, the highest success rate was observed in October followed by July (more than 75%). The success rate during June and August were found as intermediate (>60%), while during the month of September it was found as low (less than 50%). However, there is a significant fraction of false alarms in the rainfall forecast and the efficiency of the rainfall forecast was found decreasing drastically after considering false alarms.

The temperature forecast evaluation conveys that, around 40-45% of the observed values during a year are not falling within the range of maximum and minimum temperature forecast over Nepal. It is also observed that, as the average of all the selected locations, around two-third fraction of total number of days in a year are experienced with under estimation in maximum and minimum temperature forecasts, while the remaining one-third fraction experiences over estimation. The average deviation of forecast from the observed values during the days with over and under estimation in maximum temperature forecast are 1.8°C and -1.8°C, respectively. In the context of minimum temperature forecast, the average deviation of forecast from the observed values during the days with over and under estimation are 1.4°C and -1.2°C, respectively. From the count of total number of days in a year it can be concluded that, the temperature forecast is found as under estimating in comparison with observed values over all of the selected locations in Nepal.

3.6 Recommendations for improvement in forecasting skill in Nepal

WRF, as a modelling environment, has been exploited for a wide range of applications, ranging from air quality to hydrology (Powers et al., 2017)[11]. WRF is also well connected to UHI research, the nocturnal warming caused by the built environment, through coupling with several urban models (Chen et al., 2011)[12]. Many WRF model applications for short-range weather forecasting including those at DHM in Nepal have been using this model to generate weather forecasts based on a single model run using available surface observations without or with additional data assimilation for initial conditions without addressing any form of uncertainty.

The inaccuracy of forecasting is due to the chaotic nature of the atmosphere, the massive computational power required to solve the equations that describe the atmosphere, the land, and the ocean, the error involved in measuring the initial conditions, and an incomplete understanding of atmospheric and related processes. Hence, forecasts become less accurate as the difference between current time and the time for which the forecast is being made (the *range* of the forecast) increases. Uncertainty from perturbing initial conditions, which generates internal model variability (IMV), also must be considered. This can be achieved through modifying initial conditions (i.e., simply changing start times) while keeping model configuration (i.e., parameters and physics) and lateral boundary conditions constant.

It may be noted here that fast-moving boundary conditions, that is, a high-pressure system through flow of weather driven by large-scale circulations, will cause conditions within the WRF domain to be more strongly forced by these external inputs (Giorgi & Bi, 2000[13]; Laprise et al., 2012[14]). However, if conditions at the domain boundaries are not active, like persistent high pressure, WRF will have more freedom to generate its own weather: Hence, there will be a higher IMV as the model is more sensitive to initial conditions. The use of ensembles and model consensus helps narrow the error and provide confidence in the robust performance in leveraging the prediction ability and computational efficiency of the prediction of heavy precipitation.

Short-term rainfall prediction relies on mesoscale numerical weather prediction (NWP) models. The deterministic predictions from the WRF model incorporate relatively large errors due to numerical discretization, inaccuracies in initial/boundary conditions and parameterizations, etc. Among them, the

[11] Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., et al. (2017): The weather research and forecasting model: Overview, system efforts, and future directions. *Bulletin of the American Meteorological Society*, *98*(8), 1717–1737. https://doi.org/ 10.1175/BAMS-D-15-00308.1

[12] Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmond, C. S. B., Grossman-Clarke, S., et al. (2011): The integrated WRF/urban modelling system: Development, evaluation, and applications to urban environmental problems. *International Journal of Climatology*, *31*(2), 273–288. https://doi.org/10.1002/joc.2158

[13] Giorgi, F., & Bi, X. (2000): A study of internal variability of a regional climate model. *Journal of Geophysical Research*, *105*(D24), 29,503–29,521. https://doi.org/10.1029/2000JD900269

[14] Laprise, R., Kornic, D., Rapaić, M., Šeparović, L., Leduc, M., Nikiema, O., et al. (2012): Considerations of domain size and large-scale driving for nested regional climate models: Impact on internal variability and ability at developing small-scale details. In A. Berger, F. Mesinger, & D. Sijacki (Eds.), *Climate change* (pp. 181–199). Vienna: Springer Vienna. https://doi.org/10.1007/978-3-7091-0973-1_14

uncertainties in parameterization schemes have a huge impact on the forecasting skill of rainfalls, especially over the mountainous terrains in the north of Nepal. Through assimilating quality-controlled observations and adopting advanced numerical discretization methods, the prediction of the WRF model can be highly improved, physical parameterization also has significant impact on the WRF model's forecasts.

Precipitation and cloud microphysical processes in numerical weather prediction systems pose one of the major forecasting challenges. Predicting the sub-grid scale phenomena such as clouds and precipitation, with some degree of accuracy, is still an ongoing ambitious project. Advances in computational resources have boosted the use of more sophisticated physics schemes incorporated into models with higher resolutions grids. The choice of the proper combination of such schemes is, still, a challenging task especially in case of high impact weather in which the forecast errors are expected to be large. To overcome the use of a single deterministic run, that represents the future state of atmosphere, one can use several runs from the same numerical weather prediction model but with different physical formulations. The uncertainty associated to the physical parameterizations of the forecast can then be assessed by the range of the different forecasts produced.

To figure out the impact of various parameterization schemes and their interactions on rainfall predictions over the complex topography in Nepal, the Global Forecast System data and ECMWF Reanalysis v5 (ERA5) are generally used as the initial/boundary conditions for the WRF model and a number of ensemble tests need to be conducted based on different combinations of microphysical (MP) schemes, planetary boundary layer (PBL) schemes, and cumulus (CU) schemes, for selected rainfall cases during monsoon season. It should be noted that CU parameterization schemes are not used in the nested domain with a resolution of 3 km because CU parameterization is theoretically only valid for a coarser grid size (e.g., greater than 5 km). Considering that rainfalls may have a diurnal cycle that is sensitive to different physical schemes, except for evaluating the 24-h accumulated precipitation, we also need to split the 24 h forecasts into two parts, i.e., night-time and day-time, to calculate the evaluation metrics, respectively.

The numerical prediction model to be used to generate a representative sample of the possible future states of the dynamical system should be the Weather Research Forecast model with the Advanced Research Weather (WRF-ARW) dynamical core. An ensemble with sixteen forecasts members should be created with WRF-ARW by using different physical parameterizations, available in WRF-ARW version 3.2 or higher. The ensemble forecast can be evaluated in terms of the ensemble members average concerning the precipitation variable, as well as their degree of dispersion represented by their overall spread. A Principal Component Analysis should be performed to infer the space variability of the monthly precipitation accounted within the Terai region of Nepal. This procedure should enable us to find the daily series that best represents the variance of the precipitation within the Terai region of Nepal.

Meso-scale numerical weather prediction models have proven to give satisfactory first estimates of the wind fields and can be used to locate sites with frequent wind gusts and also promising sites with respect to wind power. WRF is a widely used and tested model and can provide fairly reasonable results in agreement with observations. However, near-surface wind modelling remains challenging, especially when it comes to accurately reproducing the wind field in a complex terrain. Several studies reported in literature have evaluated the performance of WRF with a special focus on the model's ability to reproduce the wind speed[15,16]. A good agreement between the WRF model simulations and wind speed measurements for areas characterized by a complex terrain, are reported[17, 18]. Typically for these studies are low biases between the observed wind speeds and the simulated wind speed. When also the temporal simultaneity is considered, the deviation is larger. It is also found that the WRF model tend to overestimate the low wind speed and underestimate the higher wind speeds. It may be noted here that the distribution of the wind speeds is as important as is the wind direction. To gain a better understanding of the WRF model's ability to reproduce the magnitude of the wind speed and direction in complex terrains of Nepal, a comprehensive study on validation and verification of wind speed and direction must be undertaken by DHM, Nepal.

3.7 Method to perform the Bias Correction for 3-day weather forecast

The bias correction of three-day weather forecast issued by DHM can be done by using Linear Scaling method. We propose this method as it is a simple and robust method to perform this action and widely accepted.

3.7.1 Bias correction of Maximum and Minimum temperatures

The steps to do the bias correction for three-day weather forecast of maximum and minimum temperatures are given below.

Step-1: Procure the observed data during the last 15 days for a specific location

Step-2: Procure the three-day weather forecast for the same location

Step-3: Calculate the anomaly between the observed and forecasted value for each day for these 15 days as shown in Table 26.

[15] El-Samra R, Bou-Zeid E and El-Fadel M (2018): What Model Resolution is required in Climatological Downscaling over Complex Terrain? Atmospheric Research, 203, 68 – 82, ISSN 0169-8095 URL http://www.sciencedirect.com/science/article/pii/S0169809516305798

[16] Giannaros T M, Melas D and Ziomas I (2017): Performance evaluation of the Weather Research and Forecasting (WRF) model for assessing wind resource in Greece, Renewable Energy, 102, 190–198 URL http://dx.doi.org/10.1016/j.renene.2016.10.033

[17] Jim ́enez P A and Dudhia J (2013): On the Ability of the WRF Model to Reproduce the Surface Wind Direction over Complex Terrain, Journal of Applied Meteorology and Climatology, 52, 1610 URL https://journals.ametsoc.org/doi/10.1175/JAMC-D-12-0266.1

18 Ferna ́ndez-Gonza ́lez S, Mart ́ın M L, Garc ́ıa-Ortega E, Merino A, Lorenzana J, Sa ́nchez J L, Valero F and Rodrigo J S (2018): Sensitivity Analysis of the WRF Model: Wind-Resource Assessment for Complex Terrain, Journal of Applied Meteorology and Climatology, 57, 733–753 (Preprint https://doi.org/10.1175/JAMC-D-17-0121.1) URL https://doi.org/10.1175/JAMC-D-17-0121.1

Table 26: Observed and forecasted values during the past 15 days for the bias correction of maximum and minimum temperatures

Day	Date	Observed Value (°C)	Forecast (°C)			Bias in Forecast (°C)		
			Day-1	Day-2	Day-3	Day-1	Day-2	Day-3
		A	B	C	D	E=A(Day1)-B	F=A (Day-2)-C	G=A(Day-3)-D
1	17-Dec-23	23.00	22.15	22.24	22.81	-0.09	-0.12	0.07
2	18-Dec-23	22.06	22.27	22.22	22.92	-0.15	0.66	-0.79
3	19-Dec-23	22.12	22.19	22.92	22.11	0.69	-0.79	0.22
4	20-Dec-23	22.88	23.61	22.61	22.19	-1.48	-0.28	1.51
5	21-Dec-23	22.13	22.07	22.53	22.31	0.26	1.17	0.86
6	22-Dec-23	22.33	22.79	22.01	23.31	0.91	1.16	-0.6
7	23-Dec-23	23.70	22.72	23.44	23.58	0.45	-0.73	-0.17
8	24-Dec-23	23.17	22.3	23.29	23.56	0.41	0.12	-1.41
9	25-Dec-23	22.71	23.33	23.91	23.02	0.08	-1.76	-0.11
10	26-Dec-23	23.41	23.46	22.26	22.13	-1.31	0.65	0.92
11	27-Dec-23	22.15	23.45	22.26	23.73	-0.54	0.79	-0.49
12	28-Dec-23	22.91	22.87	23.46	22.46	0.18	-0.22	-0.39
13	29-Dec-23	23.05	23.19	22.56	23.99	0.05	-0.49	
14	30-Dec-23	23.24	23.67	23.36	23.68	-1.60		
15	31-Dec-23	22.07	23.38	22.61	22.3			

Step-4: Calculate the anomaly for the forecasts of Day-1, Day-2 and Day-3, Separately (Table 26).

Step-5: Calculate the average of these anomalies during the past 15 days for Day-1, Day-2 and Day-3 forecasts as indicated in Table 27.

Table 27: Estimate the average bias during the past 15 days for the bias correction of maximum and minimum temperatures

Day-1 (°C)	Day-2 (°C)	Day-3 (°C)
H=Mean(E)	I=Mean(F)	J=Mean(G)
-0.15	0.01	-0.03

Step-6: Add/subtract this calculated bias (anomaly) to today's forecast as indicated in Table 28.

Table 28: Correct today's forecast using the average anomaly for the bias correction of maximum and minimum temperatures

Date	Forecast (°C)			Corrected Forecast (°C)		
	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3
	K	L	M	N=K+H	O=L+I	P=M+J
01-Jan-24	24.05	24.56	24.61	23.90	24.57	24.58

Please note that the aforementioned methodology can be applied for both maximum and minimum temperatures. This method should be applied in repetitive cycles. For example, to correct the forecast for 02-Jan-24, use the observed and past forecast values during 18-Dec-23 to 01-Jan-24, and, to correct the forecast for 03-Jan-24, use the observed and past forecast during 19-Dec-23 to 02-Jan-24 and so on.

3.7.2 Bias Correction of Rainfall

The steps to do the bias correction for three-day weather forecast of daily rainfall are given below.

Step-1: Procure the observed data during the last 15 days for a specific location

Step-2: Procure the three-day weather forecast for the same location

Step-3: Calculate the multiplication factor by dividing forecasted value from observed value for each day for these 15 days as shown in Table 29. In the context of rainfall, we use multiplication factor instead of addition factor because rainfall values can be "0".

Table 29: Observed and forecasted values during the past 15 days for the bias correction of daily rainfall

Day	Date	Observed Value (mm)	Forecast (mm)			Bias in Forecast		
			Day-1	Day-2	Day-3	Day-1	Day-2	Day-3
		A	B	C	D	E=A(Day-1)/B	F=A (Day-2)/C	G=A (Day3)/D
1	17-Dec-23	1.984	4.744	3.425	2.412	0.32	0.77	0.50
2	18-Dec-23	1.501	3.449	1.891	1.65	0.76	0.64	2.77
3	19-Dec-23	2.633	3.164	4.781	4.501	0.38	0.96	0.41
4	20-Dec-23	1.205	4.097	4.031	4.799	1.12	0.45	1.03
5	21-Dec-23	4.573	3.29	1.878	4.572	0.56	2.64	0.36
6	22-Dec-23	1.829	4.83	3.988	2.943	1.03	0.41	1.41
7	23-Dec-23	4.961	2.589	2.309	2.217	0.64	1.80	0.62
8	24-Dec-23	1.647	2.573	2.451	4.078	1.61	0.56	0.66
9	25-Dec-23	4.148	2.603	4.068	4.77	0.53	0.66	0.66
10	26-Dec-23	1.372	4.718	2.766	2.623	0.57	1.13	1.56
11	27-Dec-23	2.687	3.808	3.96	4.539	0.82	1.03	0.67
12	28-Dec-23	3.126	3.618	1.585	3.675	1.13	1.92	0.95
13	29-Dec-23	4.084	1.811	2.517	4.05	1.68	1.39	
14	30-Dec-23	3.037	1.91	4.089	1.268	1.83		
15	31-Dec-23	3.504	3.211	3.002	4.18			

Step-4: Calculate the multiplication factor for the forecasts of Day-1, Day-2 and Day-3, Separately (Table 29).

Step-5: Calculate the average of these multiplication factors during the past 15 days for Day-1, Day-2 and Day-3 forecasts as indicated in Table 30.

Table 30: Estimate the average multiplication factor during the past 15 days for the bias correction of maximum and minimum temperatures

Day-1	Day-2	Day-3
H=Mean(E)	I=Mean(F)	J=Mean(G)
0.93	1.10	0.97

Step-6: Multiply the calculated multiplication factor with today's forecast as indicated in Table 31.

Table 31: Correct today's forecast using the multiplication factor for the bias correction of daily rainfall

Date	Forecast			Corrected Forecast		
	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3
	K	L	M	N=K*H	O=L*I	P=M*J
01-Jan-24	2.05	4.56	4.61	1.90	5.04	4.45

Similar to the bias correction of temperature, rainfall bias correction also performed in repetitive cycles. For example, to correct the forecast for 02-Jan-24, use the observed and past forecast values during 18-Dec-23 to 01-Jan-24, and, to correct the forecast for 03-Jan-24, use the observed and past forecast during 19-Dec-23 to 02-Jan-24 and so on.

4 Assessment of the users' needs for the weather forecast and advisories

Nepal's unique geography and varying climatic effects, social and economic conditions require an integrated climate action with a multi-faceted approach would best suit Nepal in addressing the current situation. Weather forecast and agro-meteorological information plays a major role before and during the agricultural season and if provided in advance can be helpful in inspiring the farmer to organize and activate their own resources in order to reap the benefits. Despite several efforts in improving climate information services, weather forecasts produced by national bodies have limited dissemination in rural and remote areas thereby hindering the agriculture systems to be climate-smart and more productive. Hence, there is need to engage all the relevant actors so that a better understanding of the sensitivity of farming practices can be developed and more relevant information can be produced. The assessment of users need for the agro-meteorological information and products is an important task to prepare recommendations for improvement of the Agro-meteorological Advisory Services capacity in Nepal. In order to work towards recommendations, the user needs assessment could focus on the following types of user needs:

1. Services Currently used for decision making.
2. Required needs (the gap between what is currently used and what is needed for the decision-making process).
3. Opportunities (things that would be very useful to have and can assist in improved and more effective/efficient decision making).
4. Future (looking at the users' long-term vision/ambitions/plans there are future demands to be defined.

The project team conducted a user needs assessment to understand requirements for weather forecast and agro-meteorological services by the users using structured questionnaire (refer Annexure – 1). The team also conducted an analysis of level of user access for these services. This has been executed through an interactive survey using a structured questionnaire.

4.1 Approach

This study primarily focused on the required user needs and opportunities on the below given aspects.

- The organization of the weather forecast and agro-meteorological services users and respective sectors.
- Importance of weather forecast and agro-meteorological services for selected communities.
- Current source and dissemination system of weather forecast and agro-met services.
- Requirement of climatic data and weather forecast for their organization.
- Types of weather forecast and agro-meteorological information services currently used by them for their operations or activities and its efficiency and effectiveness based on the following aspects.
    - Lead times and Frequency of updates
    - Spatial Coverage and Resolution
    - Accuracy
    - Presentation
    - Availability
    - Ease of Interpretation
    - Overall rating
- Type of weather forecast and agro-meteorological parameters that are important for their organization's uninterrupted operation operations and activities.
- Magnitude of the consequences of inaccurate weather forecast and agro-meteorological information services and its past examples.
- Modes to access the weather forecast and agro-meteorological services.
- Tasks that cannot be performed due to the lack of sufficient weather forecast and agro-meteorological information services.
- Ideal way to receive and format of weather forecast and agro-meteorological services.
- Recommendations and strategies for better dissemination of weather forecast and agro-meteorological services.

At first, project team identified relevant weather forecast and agro-meteorological services users and then structured questionnaire was sent to them for their inputs. It should be noted that after sending the questionnaire to the identified stakeholders project team either visited their office or call them to explain the questions and expectations from them while responding to the questions. This gave the opportunity for the users to articulate their demand for weather forecast and agro-meteorological services and in particular their specific tailored products that are user and location specific. The list of weather forecast and agro-meteorological services users participated in this has been furnished in Table 32. A total of 16 participants from potential governmental organizations who uses weather forecast and agro-meteorological services.

Table 32: List of identified users of weather forecast and agro-meteorological services in Nepal

Sr. No	Name of organization
1	Agriculture Knowledge centre, Achham
2	Agriculture Knowledge Center, Baitadi
3	Agriculture Knowledge Center, Bajura
4	Agriculture Knowledge Center, Bagmati Province Government, Chitwan
5	Agriculture Knowledge Center, Dadeldhura
6	Agriculture Knowledge Centre Darchula
7	Directorate of Agricultural Development
8	Prime Minister Agriculture Modernization Project, PIU, Jajarkot
9	Agriculture Knowledge Centre, Jhapa
10	Agriculture Knowledge Center, Kailali
11	Agriculture Business Promotion Support and Training Center, Gandaki
12	Agriculture Knowledge Center, Lamjung
13	Temperate Horticulture Development Centre, Marpha, Mustang
14	Prime Minister Agriculture Modernization Project, PIU Sindhuli
15	Agriculture Knowledge Centre Salleri, Solukhumbu
16	Agriculture Knowledge Centre, Kanchanpur

4.2 Results of the weather forecast and agro-met services user need assessment

The major findings of the weather forecast and agro-meteorological services user need assessment are discussed in detail in the below given sub-sections.

4.2.1 Importance of different weather forecast and agro-met services

The Figure 93 shows the fraction of the participants on the basis of response on the relative importance of weather forecast and agro-meteorological services to their organization. The Early Warning Service for cyclone induced rainfall & wind speed, drought, and flood has been identified as the most important service, which was followed by Medium Range Forecast and Weekly level agro-meteorological services. However, all the weather forecast and agro-meteorological services which are considered for this study were recognized as either very important or important by the majority of the participants in the survey.

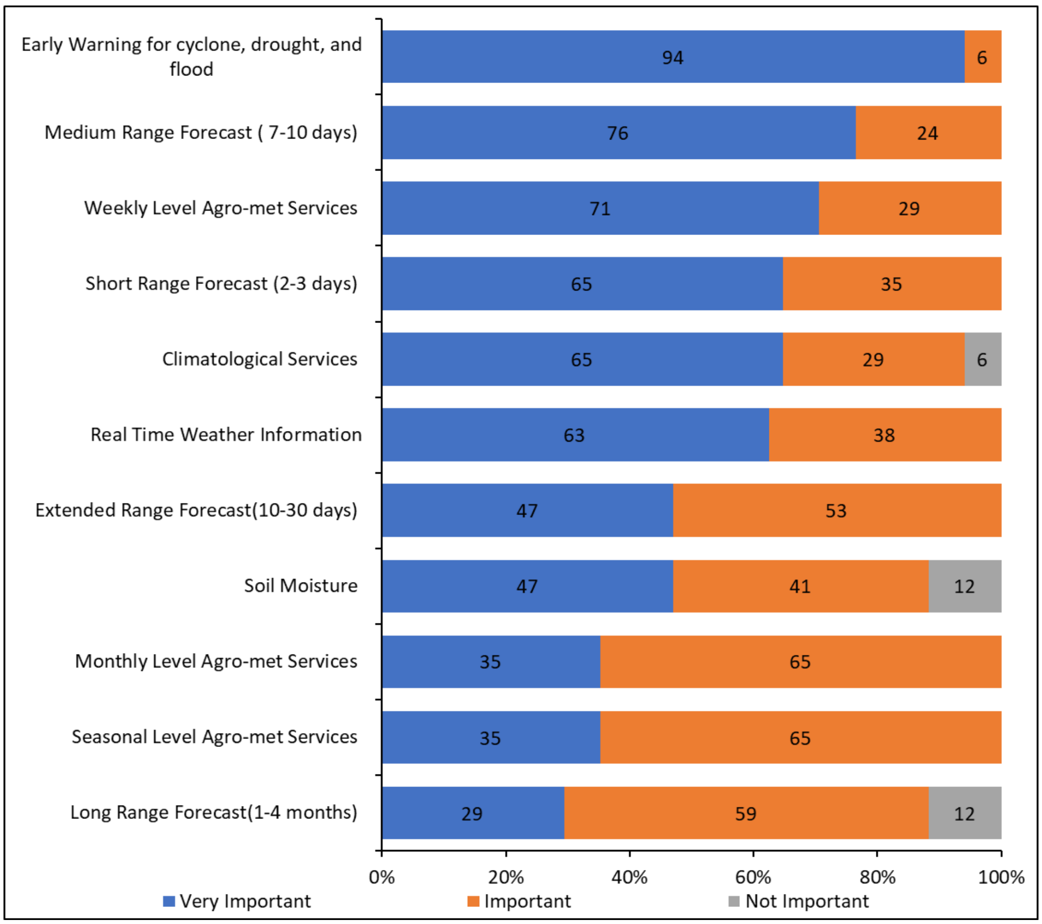

Figure 93: Fraction of the participants (%) based on the response on relative importance of different weather forecast and agro-meteorological services to their organization.

4.2.2 Source of service and service delivery agreement

According to the response from the participants, the Department of Hydrology and Meteorology (DHM) is the major source for weather forecast and agro-meteorological services (Figure 94). Few participants also receive these services from Nepal Agriculture Research Council (NARC) Province emergency operation Center (PEOC) and Department of Water Resources and Irrigation (DWRI. Only few participants (13%) receive these services through mutual agreement with the service provider (DHM&NARC) (Figure 95). All the participants receive these services as free of cost. The many types of contracts with varying conditions suggests that there is no consistent, standardized, and overarching cost and pricing policy for the agro-meteorological services which could be implemented uniformly across the end users

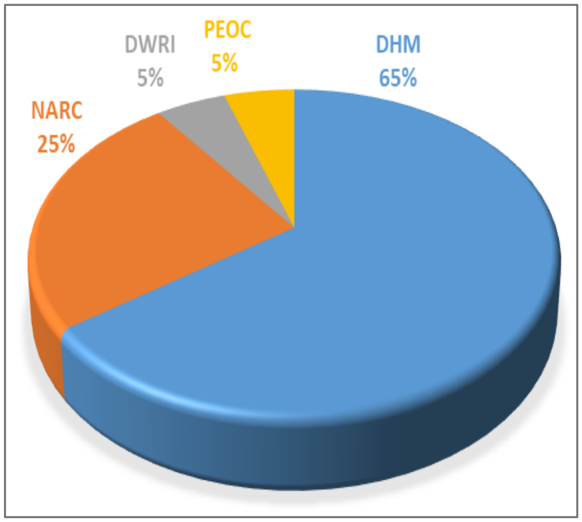

Figure 94: Fraction of the participants (%) based on the source of weather forecast and agro-meteorological services

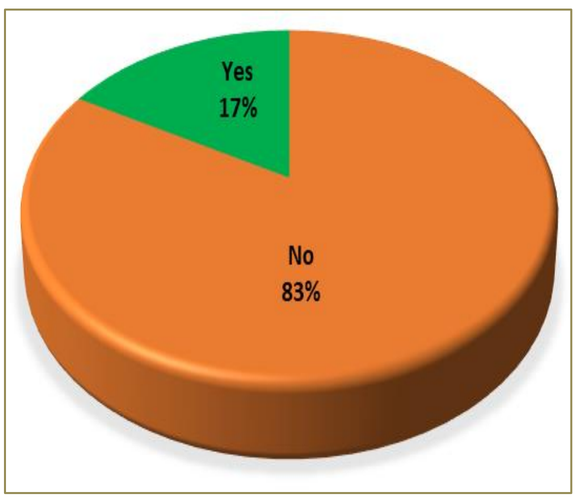

Figure 95: Fraction of the participants (%) having mutual agreement with service provider for weather forecast agro-meteorological services.

4.2.3 Service delivery assessment

The participants rated the different features of weather forecast and agro-meteorological products and the results are presented in Table 33. On the basis of majority of the response from the participants, it can be concluded that all the features of agro-met advisory services, weather forecasting services were observed as satisfactory, while all the features of Climatological Services and Early Warning Services were found as rudimentary. The Real Time Weather Services was found as satisfactory in terms of lead time, spatial resolution, and availability while the accuracy, presentation, and ease to interpretation of this service were observed as rudimentary. The features such as spatial resolution, accuracy and availability of soil moisture service were found as rudimentary while the remaining features of this service were observed as satisfactory. In the context of overall rating, the agro-advisory services, real time weather service and weather forecast were observed as satisfactory, while the climatological service, early warning services and soil moisture service were observed as rudimentary.

- The analysis on the rating by the participants says that there should be a significant improvement in all the features of climatological and early warning services.
- The two aforementioned services and the soil moisture service should be improved in term of spatial resolution. Hence, these services should be expanded to a greater number of locations representing all the geographical and agro ecological regions of the country.
- The accuracy of real time weather services can be improved by timely calibration and repair of sensors.
- Improving the presentation and ease to interpretation of weather forecast and agrometeorological services involves making the information more accessible, visually appealing, and user-friendly. To achieve it, following approaches can be adopted.
    1. Use visuals: Weather data is inherently visual, so it's important to use graphics and images to help convey the information. Use maps, charts, and other graphics to show temperature, precipitation, and other weather patterns.
    2. Simplify the language: Weather data can be complex and difficult to understand for people without a background in meteorology. Use simple and clear language, avoiding scientific terms.
    3. Use color-coding: Use color-coding to quickly convey information. For example, use green for clear skies, yellow for partly cloudy, and red for severe weather.
    4. Offer customization: Allow users to customize the information they receive based on their location and specific needs. For example, allow users to set alerts for specific weather conditions or choose to receive information in Celsius or Fahrenheit.
    5. Provide context: Give context to the weather data by explaining what it means and how it might impact people's daily activities. For example, explain how a heavy rainfall event will affect agricultural activities.
    6. Offer multiple platforms: Make sure the weather service is available across multiple platforms, such as desktop, mobile devices, and media, to ensure that users can access the information wherever they are.
    7. Be timely: Ensure that the weather information is updated regularly and in real-time so that users have the most accurate information available.

Table 33: Participants response on rating of different features of weather forecast and agro-meteorological services

Categories	Lead times	Spatial Resolution	Accuracy	Presentation	Availability	Ease of Interpretation	Overall rating
Agro-Advisories Services	Green	Green	Green	Green	Green	Green	Green
Climatological Services	Yellow	Yellow	Red	Red	Yellow	Yellow	Yellow
Early Warning Services	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Real-time Weather Services	Green	Green	Yellow	Yellow	Green	Yellow	Green
Soil Moisture Service	Green	Red	Yellow	Green	Yellow	Green	Red
Weather forecasting Services	Green	Green	Green	Green	Green	Green	Green

0 (Red)	• End-users' needs are not met and operations/activities cannot be performed.
1 (Yellow)	• End-users' operations/activities can only be performed on a very rudimentary level.
2 (Green)	• End-users' operations/activities can be performed on a satisfactory level.
3 (Dark green)	• End-users' needs are fully met.

4.2.4 Requirement of agro-meteorological parameters

The participants were asked to list of most critical agro-meteorological parameters that would drive or guide their decision-making processes. All of 16 participants stated that the temperature, rainfall and solar radiation are important for them and majority of them need information on wind, relative humidity and soil moisture too (Figure 96). A minor fraction (2 each) of them conveyed that, they require the data of evaporation and air pressure. All the participants also conveyed that they require this information at least on district level. The required temporal resolution of these data set is at least daily level. Along with the raw text format, they also wish to receive this information in the form of properly arranged tables, comparison graphs and spatial maps.

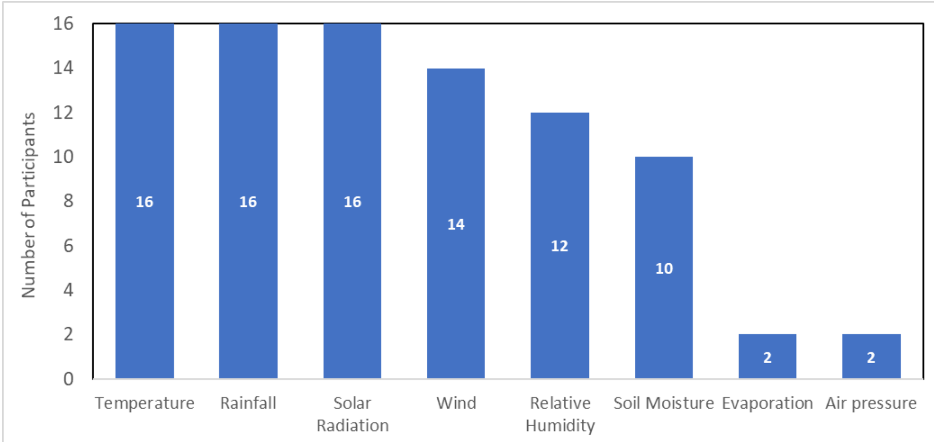

Figure 96: Requirement of agro-meteorological parameters by the participants

4.2.5 Consequences of inaccurate weather forecast and agro-met services

The participants mentioned that there are huge negative consequences on their organizations if the weather forecast and agro-meteorological services are inaccurate, not timely or are not location specific. These consequences are summarized below.

- If the advisory goes wrong, it will reduce the reliability of the office and the users will be reluctant to use the advisory in future.
- Wastage of fertilizers and damage the agriculture commodities.
- Wrong advisory leads to wrong agricultural practices. For example, harvested crops cannot be transported to safer place. Wrong advisory for sowing and transplantation leads to poor crop development.
- Wrong advisory on landslide, flood, and cyclones reduces the available time to react and causes human casualties with crop damage.
- Damage of seedlings just after transplantation by hailstones and high rainfall.
- Occurrence of Pest and Diseases due to inaccurate advisory for the application of pesticides.
- Crop failure due to inadequate irrigation during drought and water logging during flood conditions.

4.2.6 Past examples for consequences of inaccurate weather forecast and agro-met advisory services

The participants conveyed their response on the query regarding any task which could not be performed by them in the past due to insufficient weather forecast and agro-met advisory services and are summarized below.

- Heavy rainfall occurred during the harvesting time of paddy caused huge loss of harvested paddy and thereby food insecurity over the entire Far Eastern Province during the year 2018/19.

- Unavailability of advisory on hailstorms and wind storms causing heavy loss of banana due to wind and heavy loss of vegetables due to hailstorms.
- The unpredictable rainfall occurred during October, 2021 caused heavy loss of agricultural commodities.
- A banana farm was destroyed by hailstones and strong winds that hit Chitwan district on May 6, 2018.
- Over western Nepal, 85,580 hectares of paddy land was submerged due to the heavy rainfall happened on 17 October 2022.
- Over 12 bigha of vegetable land over Sisahaniya was destroyed due to heavy rainfall and hailstorm occurred on 18 April 2018.
- Heavy loss on rice during nursery and transplantation stages due to poor monsoon forecast every year.

4.2.7 Mode to access the weather forecast and agro-met services

The participants ranked the preferred mode of service delivery on a scale of 1 to 10; 1 being the most used mode and 10 being the least preferred mode. The SMS & IVRS system is the most preferred delivery channel followed by email, mobile app, internet, print and electronic media (such as newspaper & TV news), social media such as Facebook, and personal contact. Hence, in order to have efficient service delivery through the internet, a comprehensive, robust, and interactive website can help to further automate and facilitate tailor made product delivery to the end-users Figure 97.

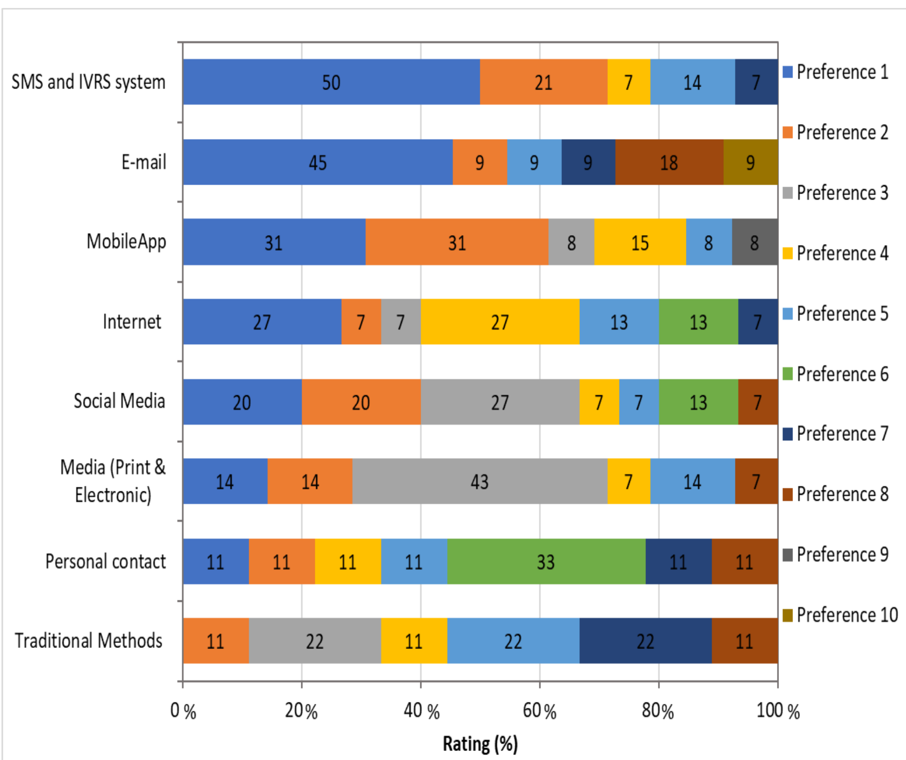

Figure 97: Preferred modes of agro-met service dissemination mode

4.2.8 Tasks could not perform due to insufficient weather forecast and agro-met services

The participants responded to the query regarding any task which could not be performed by them due to insufficient weather forecast and agro-met advisory services and are summarized below.

- Protective measures for crops against natural disaster such as floods, landslides, hails, and storms and against pest and diseases cannot be done due to the lack of sufficient weather forecast and agro-met services.
- Agricultural insurance scheme cannot be popularized amongst farmers as it is difficult to motivate farmers in lack of such data.
- Choice of crops, irrigation and intercultural operations etc. cannot be performed due to lack of sufficient weather forecast and agro-met services.
- Weather based insurance service is not in practice in Nepal in major crops like paddy and maize. The provision of area specific agro-meteorological service could be useful in developing the index-based crop insurance practice for the farmers.
- Recommending Plantation, intercultural operations and harvest time.

4.2.9 Proposal of new weather forecast and agro-met services

The participants also proposed new weather forecast and agro-met services and those are summarized below.

- Index based insurance scheme for principal crops.
- Mobile friendly weather forecast dissemination system.
- More number of Automatic Weather Stations at farmers' fields.
- Information on heat and cold waves, greenhouse gas concentration, moisture content, chemical concentration of soil, infestation of pest and diseases. etc.
- Develop more crop specific, user specific products and location specific products.

4.2.10 Recommendations for better dissemination of weather forecast and agro-met information services

The participants proposed several recommendations and strategies for better dissemination of weather forecast and agro-meteorological services which will enhance the needs of their organization and are summarized below.

- A reliable, authentic service delivered through a common platform that can be accessed through many websites so that it could be easily broadcasted through media, shared through social media.

- Regularly update these services according to the latest available technology to make it faster and more effective.
- Provide access to information farmers will help to make best possible use of resources and services.
- Regular dissemination of information to the farmers through media and internet platforms.
- The services should be directly accessible at field level.
- Capacity building of technical staff and public.
- Access to Micro-meteorological information to agro service providers like Agriculture Knowledge Centre could help in determining suitable package of practices of crops, farm advisory services and disease pest forecasting.

4.2.11 Key findings on the user need assessment

Based on the analysis of the requirement of the user communities in Nepal, the following conclusions were made:

- The Early Warning Service for cyclone induced rainfall & wind speed, drought and flood has been identified as the most important service on the basis of response from the participants of the survey, which was followed by medium range weather forecast and weekly level agro-meteorological services.
- The Department of Hydrology and Meteorology (DHM) and Nepal Agriculture Research Council is (NARC) are the major source for weather forecast and agro-meteorological services.
- All the participants receive these services free of cost and majority of them receive these services without any mutual agreement with the service provider.
- All the participants stated that the temperature, rainfall, and solar radiation are important for them and majority of them need information on wind, relative humidity and soil moisture and a minor fraction of them need air pressure and evaporation data.
- The SMS & IVRS system is the most preferred delivery channel followed by email, mobile app, internet, print and electronic media (such as newspaper & TV news), social media such as Facebook, and personal contact.
- All the participants also stated that they require this information on district level. Along with the raw text format, they also wish to receive this information in the form of properly arranged tables, comparison graphs and spatial maps.
- If these services are inaccurate, not timely or are not location specific, there will be several negative consequences including the reduction in the reliability of the organization, wastage of fertilizers and damage the agriculture commodities, wrong agricultural practices, reduction in available time to react to the catastrophes, damage of seedlings just after transplantation, occurrence of pest and diseases and damage of crops due to inadequate irrigation.

- The participants stated that, they already experienced losses in the past such as damage of paddy, maize, banana, vegetables, etc. along with household and property damages due to inaccurate weather forecast and agro-meteorological services.
- The participants stated that due to insufficient weather forecast and agro-meteorological services they could not perform are several tasks including protective measures towards weather and natural hazards as well as against pest and diseases, choice of crops, popularization of agricultural insurance schemes, recommending Plantation, intercultural operations and harvest time.
- They also proposed new weather forecast and agro-meteorological services including, index-based insurance scheme for principal crops, mobile friendly weather forecast dissemination system, a greater number of Automatic Weather Stations at farmers' fields, information on heat and cold waves, greenhouse gas concentration, moisture content, chemical concentration of soil, infestation of pest and diseases and develop more crop specific, user specific products and location specific products.
- The participants also proposed several recommendations and strategies for better dissemination of weather forecast and agro-meteorological services including a mechanism of a reliable, authentic service delivered regularly through media, update by employing latest available technology, provide access to information farmers, services should be directly accessible at field level, capacity building of technical staff and public and access to Micro-meteorological information to the service providers like Agriculture Knowledge Centers.

5 Existing agro-meteorological information system of Nepal

5.1 Significance of agro-met advisories in Nepal

The anticipated modernization and notable accomplishments in Nepal's agricultural sector are poised to sustain the growing population. Weather, a pivotal factor affecting agricultural productivity, plays a critical role in shaping decision-making systems for agricultural planning, optimizing resources for farmers, and mitigating weather-related agricultural risks (Arunkumar et al. 2015[19], Jagadeesha et al. 2010[20]). Being a sector that employs a large proportion of the workforce, weather-impacts on Nepalese agriculture sector can affect the overall economic growth and wellbeing of the Nepalese farmers (Timilsina, 2019[21]).

Approximately 47% of arable land remains rainfed, leading to irregularities in agricultural output (Pradhan et al., 2017[22]). These fluctuations can be attributed to shifts in temperature, precipitation levels, and relative humidity. Weather forecasts play a crucial role in mitigating risks and losses in agricultural production, enhancing crop and water utilization efficiency, and ultimately boosting overall agricultural productivity (Hansen et al., 2011[23]). One key approach to minimizing agricultural losses due to adverse weather conditions is to select suitable crops and implement corresponding management practices tailored to expected weather patterns (Kenkel and Norris, 1995[24]). Consequently, the integration of meteorological data with agricultural information, forming an agro-meteorological advisory, bridges the gap between farmers and scientists in the agricultural sector (Zuma and Stigter, 2016[25]).

Agro-meteorological advisory services serve as a crucial bridge between agriculture and weather information, facilitating the efficient management of farm resources, agricultural practices, and natural assets. The primary objective of these advisory services is to optimize farm productivity and resource utilization by harnessing the advantages and mitigating the adverse effects of impending weather conditions. The adoption of agro-meteorological advisories is gaining traction worldwide, with numerous

[19]Arunkumar, N., Solaimalai, A., Jawahar, D., Veeraputhiran, R. and Rao, V. U. M. (2015). Economic Use of Agro Meteorological Advisory Bulletins (Aabs) At Farmer's Holding for Chilli in Southern Agroclimatic Zone of Tamil Nadu. International Journal of Agriculture Sciences, 7(14), 879-882.

[20]Jagadeesha, N., Ravindrababu, B.T., Pankaja, H.K. and Rajegowda, M.B. (2010). Adoption of agro met advisory services (AAS) for improving livelihood of rural farmers. International Journal of Agricultural Sciences, 6(2), 584-586.

[21]Timilsina, A. P., Shrestha, A., Gautam, A. K., Gaire, A., Malla, G., Paudel, B. P., Rimal, R., Upadhyay, K. P. and Bhandari, H. L. (2019). A practice of agro-met advisory service in Nepal. Journal of Bioscience and Agriculture Research, 21(02), 1778-1785.

[22] Pradhan P, Parajuli UN, Khanal RC. (2017). Framework for effectiveness and resilience of small- and medium-scale irrigation systems in Nepal. https://cdkn.org/sites/default/files/files/Framework-for-effectiveness-and-resilience-of-small-and-medium-scale-irrigation-systems-in-nepal.pdf.

[23]Hansen, J. W., Mason, S. J., Sun, L. and Tall, A. (2011). Review of seasonal climate forecasting for agriculture in Sub Saharan Africa. Experimental Agriculture, 47(2), 205-240.

[24]Kenkel, P. L. and Norris, P. E. (1995). Agricultural producer's willingness to pay for real-time mesoscale weather information. Journal of Agricultural and Resource Economics, 20 (2), 356-372

[25]Zuma-Netshiukhwi, G. N. C. and Stigter, C. J. (2016). An extension approach to close the gap between suppliers and users of agro meteorological services in the South-Western Free State of South Africa. South African Journal of Agricultural Extension, 44, 84–98.

success stories emerging (Jagadeesha et al., 2010[26]). However, it is in countries with lower agricultural productivity levels and a heightened risk of food insecurity that the true value of these advisories becomes apparent (Weiss et al., 2000[27]).

In this context, countries like Nepal, which are particularly vulnerable to the repercussions of climate change and facing declining crop yields, stand to benefit immensely from agro-meteorological advisory services (CBS, 2016[28]). The erratic nature of weather patterns, including unpredictable rainfall and extreme weather events like heavy precipitation, droughts, and floods, underscores the critical importance of such advisories. Additionally, monitoring short-term changes in weather parameters can empower farmers to establish meaningful correlations between these parameters and crop and farm activities, allowing them to proactively mitigate potential weather-related challenges.

This study examines how weekly Agro-met Advisory Bulletins (AAB) are being prepared by (Nepal Agricultural Research Council) NARC & Department of Hydrology and Meteorology (DHM) at the regional level and the mechanism of dissemination of this information to the public.

5.2 Development of agro-met advisory bulletins (AAB)

The procedure of preparation of AAB in Nepal has been depicted in Figure 98. The DHM provides the weather statistics across the country during the past week (Saturday-Friday) which was prepared from the observed weather data collected from a network of weather stations. These weather statistics primarily includes the spatial distribution of rainfall, maximum temperature, minimum temperature and relative humidity across the country. The DHM supplies the weather forecast also for the next one week from Friday onwards. The derived variables such as deviation from weekly normal, number of rainy days, number of days having maximum Temperature >30°C in the past week and number of days having maximum Temperature <10°C in the past week are also will be used to prepare the advisory. The crop and livestock condition and statistics will be collected from NARC centres, Agricultural Knowledge Centres (AKC) and Veterinary Hospital and Livestock Service Expert Center (VHLEC) centres. By combining these weather statistics, weather forecast and crop and livestock statistics, the experts from DHM, NARC and Agriculture Information and Training Center (AITC) will conduct a brainstorming session and thereby the weekly AABs will be prepared.

[26] Jagadeesha, N., Ravindrababu, B.T., Pankaja, H.K. and Rajegowda, M.B. (2010). Adoption of agromet advisory services (AAS) for improving livelihood of rural farmers. International Journal of Agricultural Sciences, 6(2), 584-586.
[27] Weiss, A., Van Crowder, L. and Bernardi, M. (2000). Communicating agro meteorological information to farming communities. Agricultural and Forest Meteorology, 103(1), 185–196.
[28] CBS (2017). National climate change impact survey 2016: a statistical report. A Statistical Report. Central Bureau of Statistics, Kathmandu, Nepal.

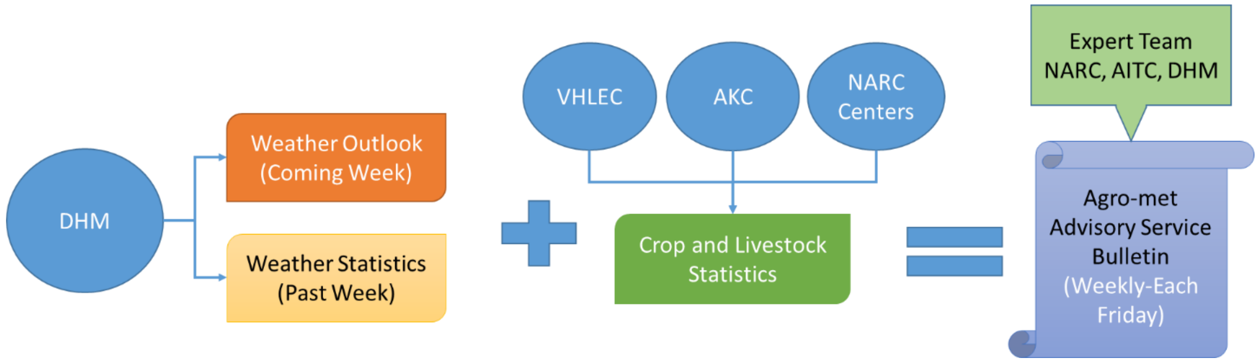

Figure 98: Preparation of AAB in Nepal

5.3 Contents of AAB

The contents of AAB are depicted in Figure 99. The AAB includes the information on the time of land preparation, seed rate, fertilizer dose, the probability of pests & diseases infestation, chances of water stress/excess, mulching practices, use of machineries, heat stress/cold stroke in cattle, weather induced disease and other information related to the fisheries and so on. The AAB has been issued weekly level and this service not available in monthly and seasonal scales. Currently, this service is available in national and provincial levels.

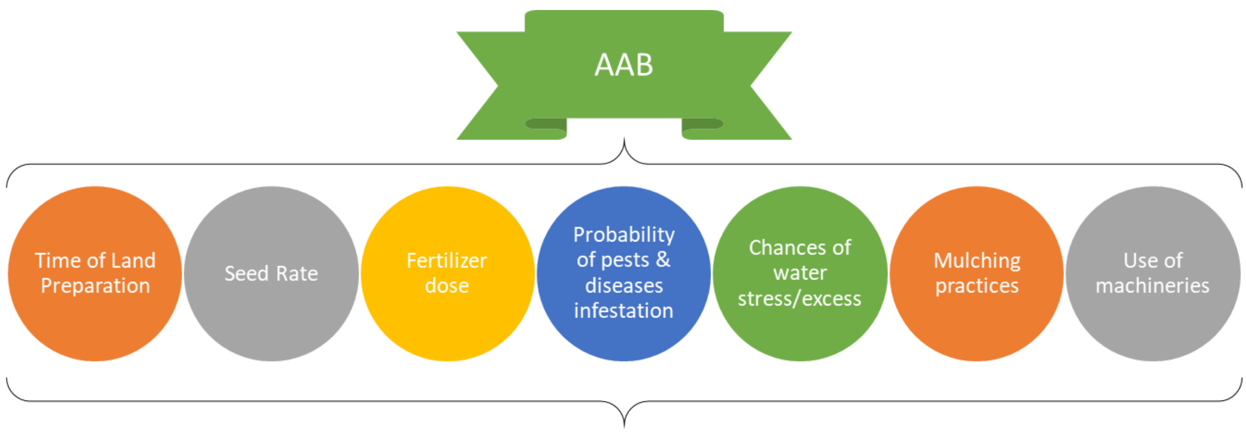

Figure 99: Contents of AAB in Nepal

5.4 Dissemination of AAB

The dissemination of AAB in Nepal has been depicted in Figure 98. It has been uploaded to the website of NARC and NAMIS on every Friday. In addition to that, the AAB is being disseminated through Email groups, bulk SMSs, mobile apps (Hamro Krishi and NARC Krishi Apps), National Television and google group of NARC agro services. The major users of these are farmers, agricultural enterprises, agricultural technicians and other relevant stakeholders. The AAB service providers will take regular feedback from these stakeholders and make necessary revisions and modifications on the basis of user feedback.

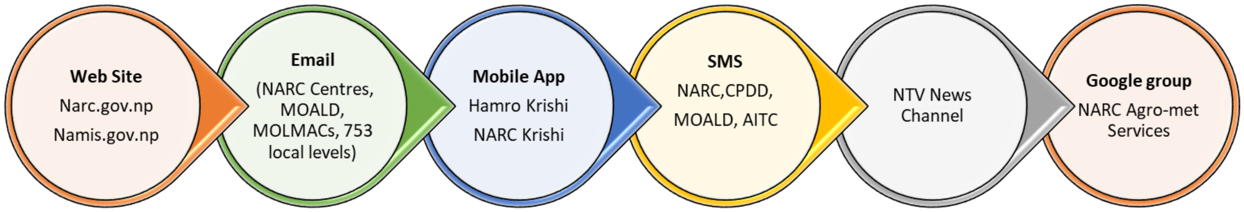

Figure 100: Dissemination of AAB in Nepal

5.5 Current challenges faced by NARC for the dissemination of AAB

The uneven topography of Nepal creates numerous microclimates. Hence, the field level data such as crop and livestock status, disease/pest infestation and crop phenology are essential for the generation of AAB. Since NARC does not have mandate on agricultural extension, there is no institutional mechanism to reach to the farmers and collect field level data.

- The number of recipient farmers for AAB is very limited.
- Unavailability of two-way communication system between the service providers and users.
- The AAB service is not available at district/sub-district levels.
- Unavailability of agro climatic zonation of the country for the generation of AAB based on agroclimatic zones.

5.6 Recommendations on the development of AAB

5.6.1 Generations of Agro-climatic zones of Nepal

Different agroclimatic zones have different climatic regimes such as varying temperature ranges, precipitation levels, and soil types. Agroclimatic zones help in understanding the specific climatic conditions and environmental factors that prevail in different regions of the country. It helps farmers to choose the most suitable crops, livestock, and agricultural practices for their area. It also helps to optimize agricultural production and resource allocation. Hence, it helps to reduce the risk of crop failure due to unfavorable conditions. By understanding the rainfall patterns and water availability in different zones, the efficient irrigation systems and water management strategies can be developed for these respective zones.

Agroclimatic zones help in identifying areas at higher risk for particular pests and diseases. This information can be used to develop targeted pest and disease control strategies, reducing the need for broad-spectrum pesticides and minimizing environmental impact. Hence, agroclimatic zoning is a crucial tool for sustainable agriculture. It helps maximize agricultural productivity, conserve resources, adapt to changing climate conditions, and support the livelihoods of farmers while minimizing the negative environmental and economic impacts of agriculture.

5.6.2 Crop weather calendars

The crop weather calendar is a comprehensive guide for farmers that provides information on average weather of every week, planting, sowing and harvesting periods of locally adapted crops in a specific agro-ecological zone. Further, stage-wise pest disease infestation information can also be added. It can also contain the adverse weather condition that cause crop failure. Nepalese agriculture largely depends on the agro-ecological zones, climate, and irrigation facilities (Rimal et al., 2018[29]). Rice, wheat and maize in Tarai region, maize and wheat in hill, region, and maize and potato in mountain region are predominantly produced. A general crop weather calendar for Nepal has been depicted in Figure 101.

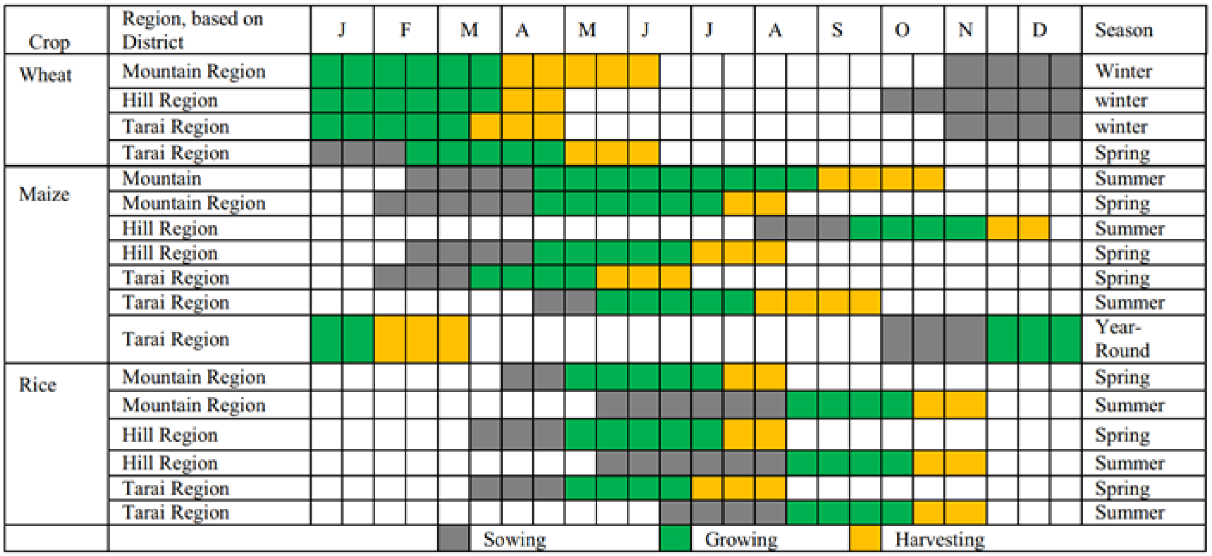

Figure 101: General crop weather calendar for Nepal (Source: Rimal et. al., 2018[29])

The crop weather calendars primarily contain the optimum timing of major crop stages for a particular crop in a region or agro climatic zones. Crop stage information from sowing to maturity should be arranged on a weekly basis. Main 'stages like sowing, germination / emergence, transplanting (in case of rice), vegetative growth, flowering, grain formation and maturity can be tabulated as per the Standard Meteorological Weeks. In addition to that, information on the favorable meteorological conditions for the crop which lead to high yield can be tabulated. The congenial weather conditions for the occurrence of pest and diseases also should be included. A sample structure of crop weather calendar is depicted in Figure 102. A sample of crop weather calendar with favorable weather condition for optimum crop growth along with information on unfavorable weather condition that cause 50% and 100% crop failure has been depicted in Figure 103.

[29] Rimal B, Zhang L and Rijal S (2018). Crop Cycles and Crop Land Classification in Nepal Using MODIS NDVI. Remote Sensing in Earth Systems Sciences. https://doi.org/10.1007/s41976-018-0002-4.

CROP WEATHER CALENDAR

Crop: Rainfed Sali Rice | Duration: Long (145-162 days) | State: Assam | District: Jorhat

Climatic Normals	June					July				August					September				October				November			
Std Week	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Tmax (°C)	31	32	32	32	32	32	32	32	32	33	33	33	32	33	32	32	32	31	31	31	30	30	30	29	28	27
Tmin (°C)	24	24	24	25	25	25	25	25	25	25	25	25	25	25	25	24	24	24	23	23	22	20	19	17	16	14
RHm (%)	88	89	90	90	90	90	91	91	90	91	90	90	92	91	92	92	92	92	92	93	93	93	93	93	94	94
RHe (%)	73	74	75	76	75	76	77	77	76	75	74	75	77	75	76	76	76	77	77	75	74	71	68	68	67	67
BSS (hr/day)	5	5	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	6	6	7	7	7	7	7
Rain (mm/wk)	48	62	70	76	69	84	95	79	71	60	75	63	78	68	57	73	49	43	43	32	25	15	8	8	5	5


Phenophase wise weather for better yield							
Phenophase	Emergence	Seedling	Tillering	Panicle Initiation	Flowering	Grain Filling	Physiological Maturity
Duration (days)	(5-7)	(7-28)	(28-30)	(9-10)	(12-13)	(10-12)	(15-17)
Tmax (°C)	30-34	28-32	28-34	30-35	28-33	28-31	26-30
Tmin (°C)	23-25	24-27	24-25	24-26	24-25	21-23	15-21
RHm (%)	88-95	89-96	90-95	89-93	90-94	90-95	91-98
RHe (%)	70-88	71-88	68-84	74-84	75-85	73-87	67-78
BSS (hr/day)	1-6	1-7	2-7	2-7	2-6	2-7	3-9
Rain (mm/wk)	9-84	13-116	10-114	13-163	6-124	7-142	3-39

Congenial weather for pest/disease	
Bacterial Blight	Tmax 28-30 °C & RHm 80-90%
Blast of rice	Tmax 25-28 °C & RHm 98-100%
Brown leaf spot	Tmax 27-30 °C & RH m > 90%

Figure 102: Sample format of a Crop Weather Calendar (Rao et. al., 2015[30])

Station Name: Surat | Crop: Kharif Sorghum | Cultivar: CSH-16
Latitude: 21.17 N | Longitude 72.83 E | Elevation: 13 m
Climatlogical Features
Annual Rainfall 1145 mm | Annual Rainy Days 110
SWM Rainfall 1030 mm | SWM Rainy Days 103

Note: the limits of Tmax, Tmin and RF has been determined by sensitivity analysis using DSSAT CERES-Sorghum
However, the same limits can be determined either by using regression analysis of weather & yield data or by gathering info. From farmers/ extension/ subject matter specialists

NORMAL WEEKLY WEATHER

Month	June	July				August					September				October		
Week	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
MAXT(C)	31.8	30.9	30.7	30.4	30.3	30	29.5	29.7	30.2	30	30.4	31.1	32.1	32.4	33.4	34.4	34.7
MINT (C)	25.2	24.9	24.7	24.7	24.7	24.5	24.4	24.3	24.2	24.2	23.9	23.7	23.9	24	23.5	23.2	22.1
RH1(%)	85	90	91	92	92	92	94	92	92	92	91	89	88	89	84	81	76
RH2 (%)	68	72	74	75	75	75	77	75	73	74	71	67	65	66	59	55	49
WS (kmph)	8.4	8.4	8.4	8.5	8.5	7.9	8	8.1	7.3	7.3	7	6.5	5.8	5.5	5.1	4.7	4.8
RF (mm)	67.7	84.6	78.2	101.3	128.6	80.1	89.8	86.1	56.4	24.9	21.6	29.2	30.4	57.2	15	11.9	0.8
SS (hr/ day)	8.4	7.1	7.4	7.6	7.2	7.7	7.6	7.8	7.9	8.1	8	8.3	8.2	8.4	8.3	8.4	8.2

Favourable weather condition for kharif sorghum at Surat

Crop Stage	Sowing to Emergence	5 leaf stage	Panicle Initiation	Flag Leaf	50% Flowering	Soft Dough	Hard Dough	Maturity
MAXT(C)	30 - 34	29 - 33	28 - 33	29 - 34	27 - 32	29 - 33	31 - 35	32 - 35
MINT (C)	23 - 28	24 - 27	22 - 26	22 - 27	23 - 27	23 - 26	23 -28	21 - 25
RH1(%)	80 -90	86 - 90	88 - 94	89 - 93	86 - 92	85 - 91	78 - 86	75 - 79
RH2 (%)	65 -75	71 - 76	73 - 78	70 - 76	64 - 72	65 - 69	58 - 66	50 - 58
WS (kmph)	6.5 - 8.5	7.3 - 9.2	7.3 - 8.5	6.9 - 7.7	7.2 - 8.7	7.4 - 8.5	7.1 - 8.3	7.6 -8.6
Rainfall (mm)	60 - 165	105 - 195	165 - 335	175 - 255	85 - 115	65 - 80	10 - 20	0
SS (hr/ day)	6.6 - 8.7	6.9 - 9	6.8 - 8.4	7 - 9.3	7.3 - 9.4	7.6 - 9.4	7.9 - 9.2	8 - 9.3

Unfavourable weather condition for Kharif sorghum at Surat

Month	June	July				August					September				October		
Week	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
100% crop loss																	
MAXT	-	-	> 41 °C for continous 21 or more days					> 39 °C for continous 18 or more days					-	-	-	-	-
MINT	-	-	> 28 °C for continous 23 or more days					> 29 °C for continous 26 or more days					-	-	-	-	-
Rainfall	-	> 19 days dry spell			> 20 days dry spell			> 20 days dry spell			> 25 days dry spell				-	-	-
50% crop loss																	
MAXT	> 37 °C for continous 18 or more days				> 36 °C for continous 15 or more days			> 37 °C for continous 16 or more days			> 36 °C for continous 15 or more days				-	-	-
MINT	> 29 °C for continous 20 or more days				> 28 °C for continous 16 or more days			> 28 °C for continous 15 or more days			> 29 °C for continous 17 or more days				-	-	-
Rainfall	-	> 14 days dry spell			> 15 days dry spell			> 16 days dry spell			> 19 days dry spell				-	-	-

Figure 103: A sample of crop weather calendar (Source: Sandeep VM, IMD[31])

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[30] V.U.M. Rao, A.V.M. Subba Rao, M.A. Sarath Chandran, Prabhjyot Kaur, P. Vijaya Kumar, B. Bapuji Rao, I.R. Khandgond and Ch. Srinivasa Rao. (2015). District Level Crop Weather Calendars of Major Crops in India. Central Research Institute for Dryland Agriculture, Hyderabad – 500 059, 40 pp.

[31] Sandeep VM (2020). Crop Weather Calendar for Kharif Sorghum for Surat, Gujarat. India Meteorological Department. Unpublished.

The agro-met advisory bulletin combined with crop weather calendars of agro climatic zones will be a powerful tool to support farmers due to the following reasons.

- It will align the agro-met advisory service to the specific needs of farmers in different agroclimatic zones. Use the crop weather calendar as a foundation for creating location-specific advisories that take into account local weather patterns and the growth stages of various crops.
- It ensures the agro-met advisories are timely and location-specific. Farmers should receive information relevant to their particular region, and the advisories should be delivered well in advance of critical agricultural activities such as planting, irrigation, and harvesting.
- The crop weather calendar helps farmers to make decisions about which crops to plant based on the expected weather conditions throughout the growing season. Provide guidance on suitable crop varieties for each season and location.
- It alerts farmers about potential pest and disease outbreaks and recommend preventive measures or treatments at specific growth stages of crops.

By effectively combining agro-met advisory services with a crop weather calendar and implementing these recommendations, agricultural practices can become more sustainable, productive, and resilient, ultimately benefiting both farmers and the broader agricultural sector.

Annexure 1: Questionnaire for the weather forecast and agro-meteorological information users

A. Introduction

Weather forecast and agro-meteorological information plays a major role before and during the agricultural season and if provided in advance can be helpful in inspiring the farmer to organize and activate their own resources in order to reap the benefits. However, currently there is weak system in place to better translate raw weather and climate information into accessible forms by all stakeholders and particularly the farmers that are understandable and relevant to make decisions.

Hence, assessment of users need for the agro-meteorological information and products is a first step to prepare recommendations for improvement of the Agro-meteorological Advisory Services capacity in Nepal. This includes needs assessment of different types of Agro-meteorological Monitoring and Forecasting Products and Advisory Services in Nepal with respect to temporal resolutions (short range, medium range, and long range) and spatial resolutions (national/ regional/ district/ local level) and to design and agree a list of agro-meteorological products and services for the users.

In the light of this the overall goal of this assignment is to strengthen agro-meteorological monitoring & forecasting products and advisory services in Nepal so that weather forecast based agro-met information and tailor-made advisories can be disseminated in advance to the concerned stakeholders particularly the farming community on decisions linked to weather forecasts during cropping seasons.

One of example of agro-met information and advisory is likely impacts due to weather forecasted climatic hazards (e.g., drought and flood) and associated appropriate measures to minimize the impacts. This will help for disaster preparedness at all levels so that adverse impacts can be avoided/minimized at greater extent.

In order to work towards recommendations, the user needs assessment could focus on the following types of user needs:

5. Services Currently used for decision making;
6. Required needs (the gap between what is currently used and what actually is needed for the decision-making process);
7. Opportunities (things that would be very useful to have and can assist in improved and more effective/efficient decision making); and
8. Future (looking at the users' long-term vision/ambitions/plans there are future demands to be defined.

It is suggested that the user needs assessment will primarily focus on the current and required needs. Secondary focus would be the Opportunities. Future needs are only captured in a general way.

We understand that in some way or other agricultural sector is using agro-met information to deal with the impacts and minimize the damages caused by weather induced Natural Hazards. Understanding your organization's role and responsibilities is crucial to assess for what reason, who needs what type of agro-met information, where and at what moment in time. Understanding your needs will allow us to prepare recommendations for improvement of the agro-met services in Nepal.

Therefore, we would like to invite you to fill in this questionnaire as this will help us to identify what are your current and required needs for agro-met information. In case you have any questions with regards to the contents of this questionnaire you can contact:

- Dr. Rajendra Uprety (upretyr@hotmail.com; Mobile: +977-9842050835)
- Dr. Sujata Tamang (sujutamang@gmail.com; Mobile: +977-9841444353)
- Dr. Uttam Singh (uttam.singh@rmsi.com; Mobile: +91-9968179986)

B. PART A: INSTITUTIONAL PROFILE

Name of organization	
Type of organization (Governmental, non-government, private, association, educational, international, etc.)	
Address	
Telephone	
Fax	
E-mail	
Website	
Mandate of the organization (include responsibilities/duties/Authority and any Regulatory Requirements (Laws)	
As a user, which is your area of utilization of agro-met information products and services? Please mark (✓) as appropriate.	☐ Agricultural ☐ Others

C. PART B: CURRENT AND REQUIRED USER NEEDS

1. How important do you consider the following category and types weather forecast and agro-meteorological services for your organization?

Rank:
1 = Very Important,
2 = Important,
3 = Not important.

Category and Type	Rank
Short Range (i.e., 2-3 days) Weather Forecast Services for the weather parameters - rainfall, maximum temperature, minimum temperature, and relative humidity.	
Medium Range (i.e., 7-10 days) Weather Forecast Services for the weather parameters - rainfall, maximum temperature, minimum temperature, and relative humidity.	
Extended Range (i.e., 10-30 days) Weather Forecast Services for the weather parameters - rainfall, maximum temperature, minimum temperature, and relative humidity.	
Long Range (i.e., 1-4 months) Weather Forecast Services for the weather parameters - rainfall, maximum temperature, minimum temperature, and relative humidity.	
Real Time Weather Information	
Early Warning for cyclone, drought, and flood.	
Climatological Services such as normal values of weather parameters - rainfall, maximum temperature, minimum temperature, relative humidity and wind speed.	
Weekly Level Agro-meteorological Services - agro-met outlook and crop yield forecast	
Monthly Level Agro-meteorological Services - agro-met outlook and crop yield forecast	
Seasonal Level Agro-meteorological - agro-met outlook and crop yield forecast	
Soil moisture content information.	
Any other Information Services	

2. From whom you receive weather forecast /agro-met forecasting and warning products and services? (Include any National/Regional/District/Local level agencies) and indicate whether there is an agreement or not.

Sr. #	Name of Provider	Service Delivery Agreement (Bilateral/MoU/Other)
1		
2		
3		
4		

3. Types of weather forecast and agro-meteorological services you currently use for your agricultural operations/activities?

In this section we would like you to describe the meteorological and agro-met services you currently receive from a particular service provider. We would like you to list details on the meteorological services within the following categories:

A. Weather forecasting services

B. Early warning services

C. Agro-advisories related services

D. Real-time weather-related services

E. Climatological related services

F. Soil moisture content related service

G. Any other type of services

Please be as specific as possible about the type of service!!

Furthermore, we are interested for what operational activities you use the specific meteorological/agro-met service. Furthermore, we would like you to provide details on your current experiences with the provided service and if it fits your needs in order to efficiently and effectively perform your operational activities. We would like to know to what extend your user needs are met for the following subjects:

1. **Lead times / Frequency of updates:** Is the service provided at the right times and with the right frequency? Or do you need information earlier and/or more frequent?
2. **Spatial Coverage / Resolution:** Is the service providing you with information at the right locations/area? And is the resolution (number of locations) good enough?
3. **Accuracy:** Based on your experience with the services delivered in the past, is the information provided to you accurate enough, is it correct?
4. **Presentation:** Is the format in which the information is provided to you okay, or do you want information presented in a different way (e.g. a map or a graph)?
5. **Availability:** Is the information easily accessible, or should the dissemination of the information be organized differently?
6. **Ease of Interpretation:** Is the information provided easy to use, or should it be more concise, more detailed, and easier to read?
7. **Overall rating:** Provide an overall rating for the service you receive.

For the above listed subjects, we would like you to rate each service by using the following grading scheme:

0: End-User needs are not met and operations/activities cannot be performed.

1: End-User operations/activities can only be performed on a very rudimentary level,

2: End-users operations/activities can be performed on a satisfactory level,

3: End-users needs are fully met.

So please fill for each subject what is applicable: 0, 1, 2 or 3.

We would also like to know from who you receive the service (**Source**) and if you need to **Pay** for the service or not?

Service Type *(Please be as specific as possible on the type of service you currently use. For example: Daily weather forecast, or Streamflow in a specific river, or water level forecast/warning, etc.)*	**For what operational activities do you use this service**	**Current Service Delivery Assessment** *(Please fill in 0, 1, 2 or 3: see explanation of grading scheme on previous page)*							**Source**	**Paid/ Free**
		Lead times / Frequency of updates	**Spatial Coverage / Resolution**	**Accuracy**	**Presentation**	**Availability**	**Ease of Interpretation**	**Overall rating**		

4. Type of agro-met Parameters that are important for your organization operations/activities?

In this section we would like to describe what type of **agro-met parameters are important** for your organization's operations. Please list all the critical parameters that would drive or guide your decision-making process. Examples of agro-met parameters are: rainfall, maximum temperature, minimum temperature, soil moisture content, sunshine hour, wind speed, relative humidity, weather forecast based agro-advisory, etc.

We would like to know why and how (**Purpose**) this parameter is used in your operational activities. Are certain triggers used for decision making?

Furthermore, we would like to know for each of these parameters:

1. If you use observation data, forecasts and/or warnings
2. What are the most important locations/Areas for which you would need information for this parameter
3. What is the required frequency basis you need to receive updated information?
4. What would be the best format for you to receive this information
5. Do you currently use any verification/calibration metrics in order to check how accurate an observation, forecast or warning is? Is this type of accuracy information used in your decision-making process?

Please fill in the table below and keep in mind that these should reflect your **required** needs. It's important for us to know what you **really need in order to best perform your operational activities**!! If for example a parameter is currently not forecasted in a location that would be useful or important for you, this table allows you to indicate those areas.

Important agro-met parameters **(Please be as specific locations)**	**Purpose**	**For this parameter do you use observations, forecasts, warnings**	**Important Locations/ Areas**	**Required Frequency of updates**	**Format**	**Verification** **Calibration information required?**
		Observations Forecasts Warnings		Daily Weekly Monthly Seasonal Annual Other: Please specify	Text Graph Tabular Map Other: please specify	

5. a: If weather forecast and agro-met services are inaccurate, not on time, or not in the right place, what is the magnitude of the consequences for you as a user organization?

b: Can you give examples from the past (if any) where inaccurate forecasts lead to problems?

6. Which of the modes do you use/prefer to use to access the weather forecast and agro-met services for your operational activities? Starting with 1 as the most preferred one and 10 the least preference mode?

No.	Mode of dissemination	Rank and observations
1	Internet such as DHM website	
2	Telephone such as SMS and IVRS system	
3	E-mail	
4	MobileApp	
5	Media such as newspaper and TV news	
6	Social media such as Facebook	
7	Traditional Methods (e.g., bells, sirens, speakers, flags, and beacons)	
8	Personal contact/Communication	
9	Others	

D. PART C: HOW TO IMPROVE WEAHTER FORECAST AND AGROMET SERVICES

1. **Is there any task that you cannot (or only partly) be performed due to the lack of sufficient weather forecast and agro-met services? If Yes: please describe the reason why your agency cannot perform this task.**

2. **What weather forecast and agro-met services would you like to receive in order to improve your agency's performance?**

3. **Please provide any recommendations and strategy for better dissemination of weather forecast and agro-met information to better serve the needs for your organization.**

4. **Do you foresee any new activity for your Agency in the future that requires "NEW" weather forecast and agro-met services/products? If yes, please provide a description of both the process/tasks and Agro-met Service/Products.**

5. **In your opinion how would you like (in an IDEAL world) to receive weather forecast and agro-met services/products (please describe the type of service/product, format, frequency, etc.)**

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