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Research Article

INTENSIFYING HAZE AND DISAPPEARING DENSE FOG IN WINTER AT TRIBHUVAN INTERNATIONAL AIRPORT, KATHMANDU: IMPACTS IN AVIATION

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ABSTRACT

In winter, Tribhuvan International Airport (TIA) in Kathmandu, Nepal, is badly affected by poor visibility conditions due to the occurrence of thick haze and dense fog. In this study, we examined the microclimatic behaviors (e.g., consecutive duration and onset/dispersal) of the winter fog. Alongside, we analyzed the trend in the occurrence of fog, dense fog, and winter haze in TIA from a historic global hourly climatological dataset (1976–2022) from TIA. We found that radiation fog in the valley is mostly short spells having a consecutive duration of less than an hour (~86% of fog, ~95% of dense fog). The onset of fog starts most favorably in the early morning (05:45–09:00 am) and disperses mostly before noon. To ascertain the synergetic effect of enhanced natural and anthropogenic forcing, urbanization, and meteorological changes on winter haze and fog, we assessed their trend for the same period. There was a marked change in visibility around the year 2000 together with important changes in humidity and dew point depression. We observed an upward trend of winter haze frequency (2.36% day/year, at 0.001 level of significance (a)) and fog frequency (0.46% day/year, at a = 0.05) in regime-I (1976–2000). Whereas the trend of winter haze flattened to 0.36% day/year (at a = 0.05) and dense fog declined at the rate of −1.28% day per annum (at a = 0.01) in regime-II (2001–2022). By careful examination of all plausible climatological drivers of the change (relative humidity, temperature, wind speed, and dew point depression), we found strong evidence of decreasing humidity and increasing dew point depression after the year 2000. Effective air pollution and urbanization control measures are imminent to lessen the adverse impact of the increased frequency of haze and fog at the country's major international airport, TIA.

Keywords: Aviation, fog, haze, Kathmandu, visibility

INTRODUCTION

Haze and fog over an airport reduce visibility, making it difficult for pilots to land an aircraft visually (Hanesiak & Wang, 2005). Resulted from the suspension of aerosols in the atmosphere, haze reduces visibility to lower than 5 km under a relatively dry atmosphere (Du *et al.*, 2013; Kathayat *et al.*, 2023; Vautard *et al.*, 2009; Wu, 2006). Whereas, fog and dense fog—obscurity caused by the suspension of water droplets near the surface layer of the atmosphere—reduces visibility to lower than 1 km and 200 m respectively (Jenamani, 2007; Kathayat *et al.*, 2023; Vautard *et al.*, 2009; Wu, 2006). Such low visibility events at the airport affect the safety, timeliness, and efficiency of flight operations as well as add extra financial burden (Gultepe *et al.*, 2007; Jenamani & Kumar, 2013; Kulkarni *et al.*, 2019; Morisset & Odoni, 2011). Like elsewhere (Jenamani & Kumar, 2013), low visibility contributed many aviation accidents and incidents in Nepal (Kathayat *et al.*, 2023; Regmi *et al.*, 2020). Typical evidence of such occurrence in Nepal is a runway excursion after the landing of Turkish Airlines wide-body aircraft (TC-JOC, Airbus-A330) at Tribhuvan International Airport (TIA) in Kathmandu (KTM) under very dense-fog conditions over the airport (AIC, 2015).

Atmospheric constituents (gaseous molecules, aerosols, and water vapor) attenuate incoming solar radiation by scattering and absorption, leading to visibility reduction (Y. Chen & Xie, 2013; Malm, 1999; Vautard *et al.*, 2009; Zhang *et al.*, 2010) in the form of haze. Many past studies have reported a decline in visibility in global (e.g., Wang *et al.*, 2009) and regional scale (Y. Chen & Xie, 2013; Fu *et al.*, 2016; Jaswal *et al.*, 2013; A. Singh & Dey, 2012). On the contrary, there has been an improvement in visibility in regions like Europe, the USA, and Canada (Inhaber, 1976; Munn, 1973; Stjern *et al.*, 2011; Streets *et al.*, 2006; Vautard *et al.*, 2009).

The occurrence of fog—a complex and interesting boundary layer phenomenon—depends on several factors, such as meteorology, air pollution, land use, terrain, and topography (Gultepe *et al.*, 2007; Hunova *et al.*, 2020, 2021; Kim *et al.*, 2019; Safai *et al.*, 2019). Because of the high damage potential of fog to general aviation, developing an intensity and duration-based fog microclimatic information system using long-term data is highly advantageous benefiting forecasters, air traffic controllers (ATC), airlines, and pilots (Jenamani, 2012). Various researchers studied various aspects of fog occurrences in different places in India (Bhushan *et al.*, 2003; Jenamani, 2007; J. Singh *et al.*, 2007; Srivastava *et al.*, 2016) and elsewhere (Hameed *et al.*, 2000; Hunova *et al.*, 2020; Liu *et al.*, 2012; Vautard *et al.*, 2009). Because of the severity of the fog problem, most of the fog studies in our region focus on the occurrence of fog in cities and airports of Indo Gangetic Plains (IGP)—a region stretching more than 2000 km across northern South Asia including eastern Pakistan, northern and eastern India, southern Nepal and large parts of Bangladesh. The region has experienced a notable increase in fog events over the years (Saikawa *et al.*, 2019; Srivastava *et al.*, 2016; Syed *et al.*, 2012). Through the analysis of climatological data at Indira Gandhi International Airport (IGI) in New Delhi, India, Jenamani (2007) reported an alarming rise and persistence of fog at the airport. Another comprehensive study conducted by Ghude *et al.* (2017) at the same airport also supported it by finding that dense fog hours doubled over the last three decades.

Nevertheless, our country lacks dedicated studies of haze and fog despite their significance in various sectors; most of these studies are localized within the IGP section of Nepal (Kathayat *et al.*, 2023; Manandhar, 2006; Shrestha *et al.*, 2018, 2023). Analyzing multi-decadal meteorological data, we (Kathayat *et al.*, 2023) also found almost a doubling of winter fog days and a substantial uptrend in other fog parameters at Gautam Buddha International Airport (GBIA) at BWA—an airport located in the IGP section of Nepal. In this paper, we also highlighted the impact of low visibility (caused by haze and fog) on aviation. In KTM, a handful of studies have occurred regarding haze and fog occurrence (e.g., Larssen *et al.*, 1997; Nakajima *et al.*, 1980; B. Sapkota, 2002; B. K. Sapkota, 1996; Sharma, 1997). Using photographs and meteorological data, Nakajima *et al.* (1980) investigated the mechanism of fog formation in KTM. On the onset and dispersal timing of winter fog over the valley, Sharma (1997) reported that fog covering the valley basin usually restricts visibility until 10 or 11 am. Larssen *et al.* (1997) reported increased fog and the largest decline in visibility in winter. A study by Sapkota (2002) reported declining visibility (1.58 km year^{-1}) using three years of data (1996, 1998, and 1999). Most of the papers are quite old; various factors affecting haze and fog including undeniable increase in regional air pollution level and possibly some meteorological changes could have happened ever since. To cater for this research gap, this paper uses a multi-decadal dataset to investigate the long-term trend of haze and fog in winter at TIA. We also aim to shed light on the microclimatic behavior of fog and its implication on flight operations.

MATERIALS AND METHODS

In this study, we used meteorological data (Jan 1976–Feb 2023) obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) for Tribhuvan International Airport in Kathmandu (NOAA station ID: 444540, 27° 41' 49.1994" N, 85° 21' 32.3994", elevation: 1338.1 m). Our data includes 3-hourly synoptic records until 1996, one-hourly until 2015, and half-hourly onwards Meteorological Weather Report (METAR) records—used especially for aviation use. Such historic and long-term global hourly data are archived and publicly distributed (https://www.ncei.noaa.gov/maps/hourly). Each of them includes the measurement of surface air temperature, dew point temperature, visibility, wind speed, wind direction, and present weather among many other meteorological parameters. The present weather code gives observed weather phenomena like rain, fog, hail, thunder, etc. during the time of measurement. The station reports fog according to the definition of WMO (WMO, 1992). Although records in the years 2013 and 2014 were completely missing from this dataset, more than 45 years of data were used in this study. This dataset does not include a direct measurement of relative humidity (RH), thus, we computed one using the following equation (Chang *et al.*, 2009; J. Chen *et al.*, 2012).

$$RH \approx 100\left(\frac{112-0.1T+T_d}{112+0.9\,T}\right)^8 \qquad (1)$$

Where T & T_d denote air temperature and dew point temperature respectively.

Similar to previous studies (Du *et al.*, 2013; Kathayat *et al.*, 2023; Vautard *et al.*, 2009; Wu, 2006), we classified weather types based on a threshold of observed visibility, RH, and precipitation. This study considers only haze and fog among different weather types. They have been defined according to the following classification scheme:

1. Haze: precipitation = 0 , visibility ≤ 5 km & RH ≤ 90%
2. Fog: precipitation = 0, visibility ≤ 1 km & RH ≥ 90%
3. Dense-fog: precipitation = 0, visibility ≤ 200 m & RH ≥ 90%

Microclimatic properties of fog: consecutive duration, onset, and dispersal

To gain a better insight into fog occurrence timing and its duration in winter at TIA, this paper examines two important microclimatic properties, namely consecutive duration and onset/ dispersal of fog episodes. Because of the coarse and uneven time resolution of our dataset, we assumed that if a fog event were detected in a record, it would have persisted from half of the period (time resolution) before and after the timestamp of observation. For example, if the fog were observed in a half-hourly observation, it would have persisted from 15 minutes before to 15 minutes after the observation time. Consecutive duration of fog is the cumulative period when a fog event of a given intensity continuously occurs. According to our previous assumption, an isolated fog observation could last for a period equal to or less than the time resolution of data during that period. On that basis, if we observe another same-intensity fog, then consecutive duration is the cumulative duration lasting less than double the time resolution, and so on. Its occurrence frequency (percentage) is the percentage of the total number of days with a given consecutive duration to a total of all fog days.

A fog observed in a record could have started any time before. When the same intensity fog is observed in the next record, the onset of the fog should be the first instance when it was recorded. Similarly, if a fog event were recorded earlier but not in the successive measurement, it could have dispersed anytime in between. Their occurrence frequency is the ratio of the number of fog onset/dispersal during the period to total onset/dispersal in the whole of the study period.

Long-term change in haze and fog

In this study, we have defined a day as having haze/fog/dense fog, if at least one record of the day fulfills the respective criteria as mentioned above. Since our data is not uniform across our study period, in terms of time resolution and annual measurement frequency, we opted to use percentage occurrence frequency rather than number frequency similar to the work of Hu *et al.* (2017) and Kathayat *et al.* (2023). Where occurrence frequency (percentage) of haze/fog/dense fog in a year is the number of days with respective weather types to the total number of days of available data in the winter season (DJF) of that year. To detect and quantify the long-term trend in the occurrence of the weather type in the subject, we used Mann-Kendell Test (MK Test) and Sen's Slope Estimator (Sen's Slope) similar to many previous studies (e.g., Kathayat *et al.*, 2023; Shrestha *et al.*, 2018; Yue & Wang, 2004). These two non-parametric tests are particularly preferred statistical tools to detect the trend in climatic and hydrological time series when the data is inhomogeneous and/or bears some errors and outliers (Sen, 1968) as our data does. In the Mann-Kendall test, the null hypothesis (H_0) is that there is no trend in the subjected parameter over the considered period. Following are the governing equations of the Mann-Kendall test.

Mann-Kendall Statistics (*S*):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sig(X_j - X_i) \tag{2}$$

$$sig(X_j - X_i) = \begin{cases} +1 \; if (X_j - X_i) > 0 \\ 0 \; if (X_j - X_i) = 0 \\ -1 \; if (X_j - X_i) < 0 \end{cases} \tag{3}$$

The variance of MK statistics:

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} tp\,(t_p - 1)(2t_p + 5)\right] \tag{4}$$

Standardized test statistics (Z_{MK}):

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if\; S > 0 \\ 0 & if\; S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if\; S < 0 \end{cases} \tag{5}$$

Where *n* is the length of the considered time series, X_j and X_i are time series observations (in chronological order), t_p is the number of ties for the p_{th} value and *q* is the number of tied values. Zero, positive, and negative values of *Z* respectively indicate none, upward, negative trend. We reject H_0 when $p < a$ (the significance level) or, $|Z_{MK}| > Z_{1-\alpha/2}$ indicating statistically significant trend value. From the standard normal table, the critical value, $Z_{1-\alpha/2}$, at $a = 0.05$ is 1.96.

Similarly, the trend line equation of Sen's slope (Sen, 1968) is given by

$$f(t) = Qt + B \tag{6}$$

Here, *Q* is the slope and *B* represents the intercept.

In a time series, the slope of the *i*th value pair x_j and x_k observed at time *j* and *k*, respectively (in chronological order) is

$$Q_i = \frac{x_j - x_k}{j - k} \tag{7}$$

The median value of all such Q_i gives the Sen's slope estimator *Q* such that:

$$Q = \begin{cases} Q_{\frac{N+1}{2}} & when, \quad N \; is \; odd \\ \frac{1}{2}\left(Q_{(N)/2} + Q_{(N+2)/2}\right) & when, \quad N \; is \; even \end{cases} \tag{8}$$

It may take zero, negative, or positive values representing none, positive and negative trends, respectively.

RESULTS AND DISCUSSION

Microclimatic properties of fog: Consecutive duration, onset, and dispersal

Figure 1 shows the occurrence frequency of fog (dense-fog) days having witnessed fog of a certain duration at a stretch and intensity. We observed that most of the fog (~86% of fog days) and dense fog (~95% of dense fog days) at TIA lasted a very brief period (< 1 hour). Only ~6% (~3%) of fog (dense-fog) days witness fog lasting up to two hours. ~4% (~1%) of fog (dense fog) lasted for up to 3 hours. Although there were some days having fog continuously occurring for up to 6 hours, these were very rare for dense fog.

Winter fog onset and dispersal timing are shown in Figure 2. In December, fog usually starts to form as early as 04:45 am local time (LT) until 09:45 am in and around TIA. A very small percentage of fog occurrences were even recorded at 11:00 pm too. The most favorable time was 05:15 am when about 23% of all fog onsets occurred. Whereas fog onset takes place between 03:15 am to 09:45 in January with the most favorable onset time being 06:45 am when more than 16% of all onsets happen.

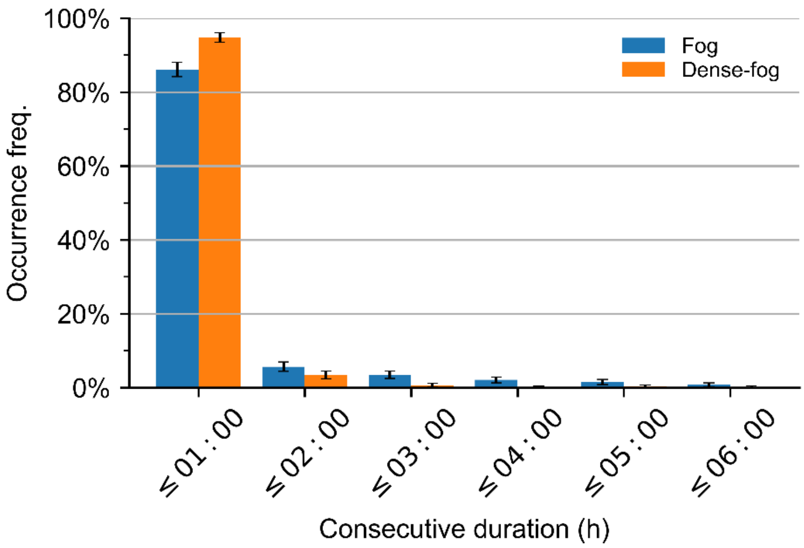

Figure 1. Consecutive duration of fog and dense fog in winter (DJF) at Tribhuvan international airport, Kathmandu from 1976 through 2023. The error bars represent a 95% confidence interval of a single proportion

The fog onset window is narrow in February; it occurs between 04:45 am and 09:15 am, with the highest onset at 06:45 am. Regarding dispersion of fog, it occurs during 05:45–10:45 LT in Dec, 04:45–12:15 LT in Jan, and 05:45–10:15 in Feb. The most favorable times of dispersion of fog are 06:15 LT in Dec and 07:45 LT in January and February. Likewise, the onset and dispersal time of dense fog during winter at TIA has been shown in Figure 3. Dense-fog onset usually occurs in 03:45–08:45 am in Dec, 02:15–09:15 am in Jan, and 05:15–08:15 am in Feb. Most of the dense fog onset occurs at 05:15 and 08:15 am in all three months. Dispersal timings are 04:45–09:45, 03:45–10:15, and 06:15–09:45 am in Dec, Jan, and Feb respectively. Most of the dense fog dispersal takes place at 06:15 and 09:15 am in all three winter months. This is in line with previous observations of the highest percentage of dense-fog onset at 05:15 and 08:15 am.

Our investigation of the consecutive duration of winter fog in Kathmandu revealed that the maximum percentage of fog (dense fog) events in Kathmandu do not last long—less than one hour. Only very few days witnessed fog (dense fog) lasting up to 6 h (2 h). Fog in Kathmandu exhibits a sharp contrast to fog in the IGP region. Jenamani (2012) reported having a higher duration fog up to 18 hours over Indira Gandhi International Airport (IGI) in Delhi.

Persistent fog spells (also called '*seetlahar*') lasting up to a few days in a stretch is a common phenomenon in the IGP region, including in the Terai plains of Nepal, during December and January. We found that the onset of fog in the valley occurs in the early morning and dispersal occurs before noon. The onset of fog usually takes a longer duration, as the ambient temperature gradually falls overnight and reaches dew point temperature before the fog starts forming. However, the dispersal takes a shorter duration as the increase in ambient temperature occurs faster when the sun passes overhead, or the wind becomes stronger (Jenamani, 2012).

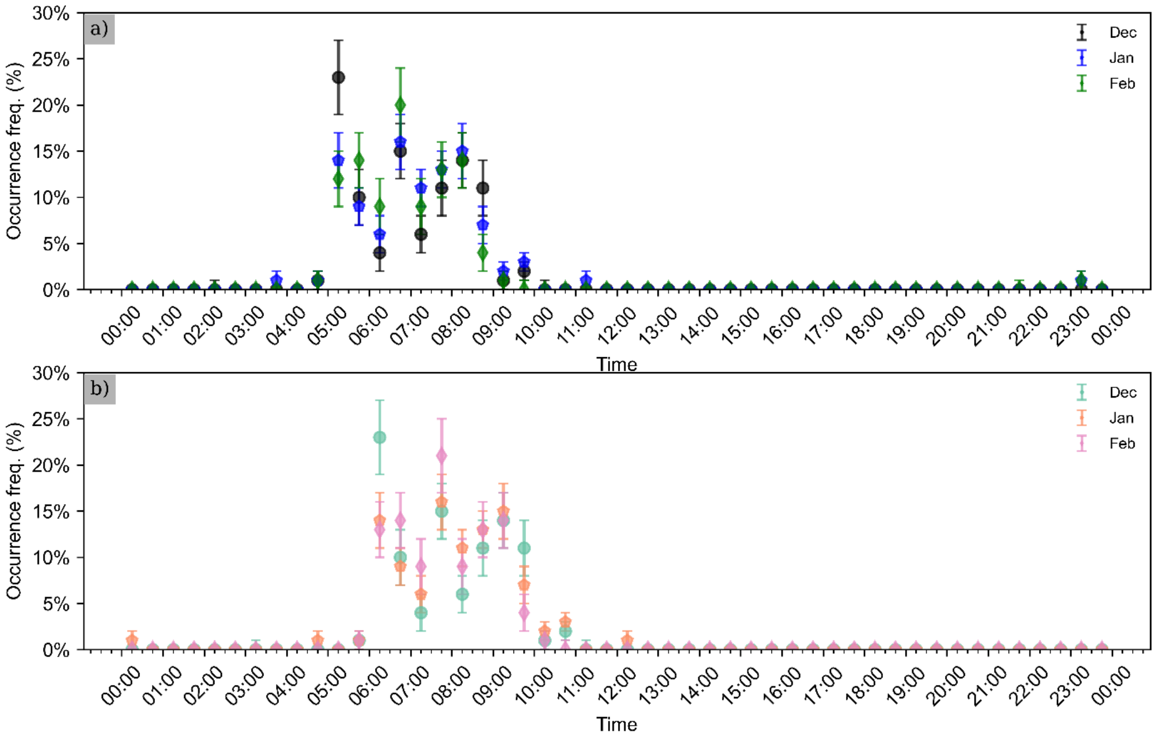

Figure 2. Occurrence frequency of: (a) onset, and (b) dispersal of winter fog (general) in Tribhuvan International Airport (TIA), Kathmandu, from 1976 to 2023. The error bars represent a 95% confidence interval of a single proportion

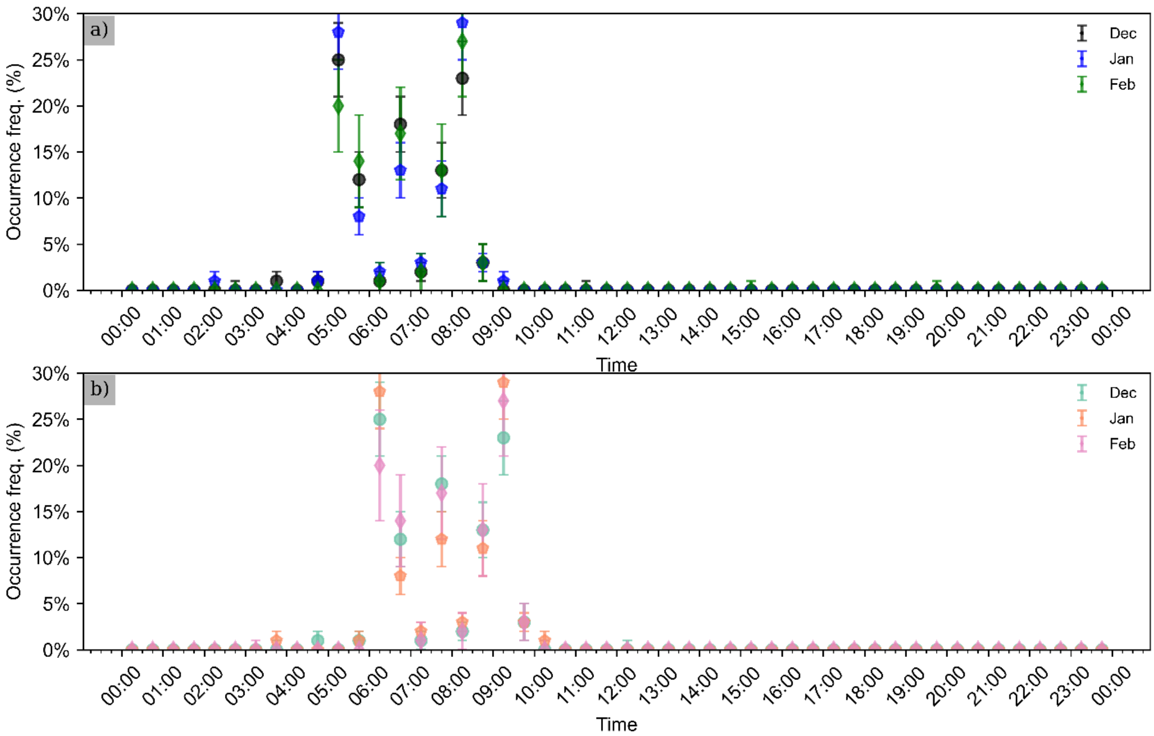

Figure 3. Occurrence frequency of: (a) onset, and (b) dispersal of winter dense fog in Tribhuvan International Airport, Kathmandu, from 1976 to 2023. The error bars represent a 95% confidence interval of a single proportion

Long-term change in haze and fog

Interannual variation of frequency of haze during winter (DJF) over the study period (Figure 4a) reveals that haze occurrence in TIA atmosphere was very little (< 30% of winter days) up until the year 1990. This suggests Kathmandu had a clear sky with good visibility. The haze frequency gradually rose, attaining a value (< 60%) about double the preceding period until the year 2000. The year 2000 marks a sudden jump in haze frequency near its saturation (~ 100% of winter days). It has remained more or less the same (max number of haze days) since the year 2000.

Thus, we have divided the whole data into two periods 1976–2000 (regime-I) and 2001–2022 (regime-II), and further analyzed. Trend results in Table 1 also reveal a definitive increase in haze day frequency for our study period (2.36% day yr^{-1}, a = 0.001 before the year 2000 and 0.36% day yr^{-1} at a = 0.05 after the year 2000). However, the frequency of winter fog in TIA (Figure 4b) remained mostly below 20% until the year 1998, which rose up to 66% in the year 2001, and again declined to 13% in the year 2006. It displayed a secondary peak value (57%) in the year 2015 and started declining. Surprisingly, only 2 days out of 88 winter days (data available) during the winter of 2020 witnessed fog. It rose to 17% in the year 2021. Again, in the winter of 2022, we observed only four foggy days out of 90 days. Trend result of fog days revealed an upward trend (0.46% day yr^{-1} at a = 0.05) in regime-I. Although the yearly relative frequency of fog days is usually higher than in the previous period, there is no such significant trend in regime II (Table 1). On the contrary, the relative frequency of dense-fog days showed no trend in the previous period but a declining trend (−1.28% day yr^{-1} at a = 0.01) in regime II.

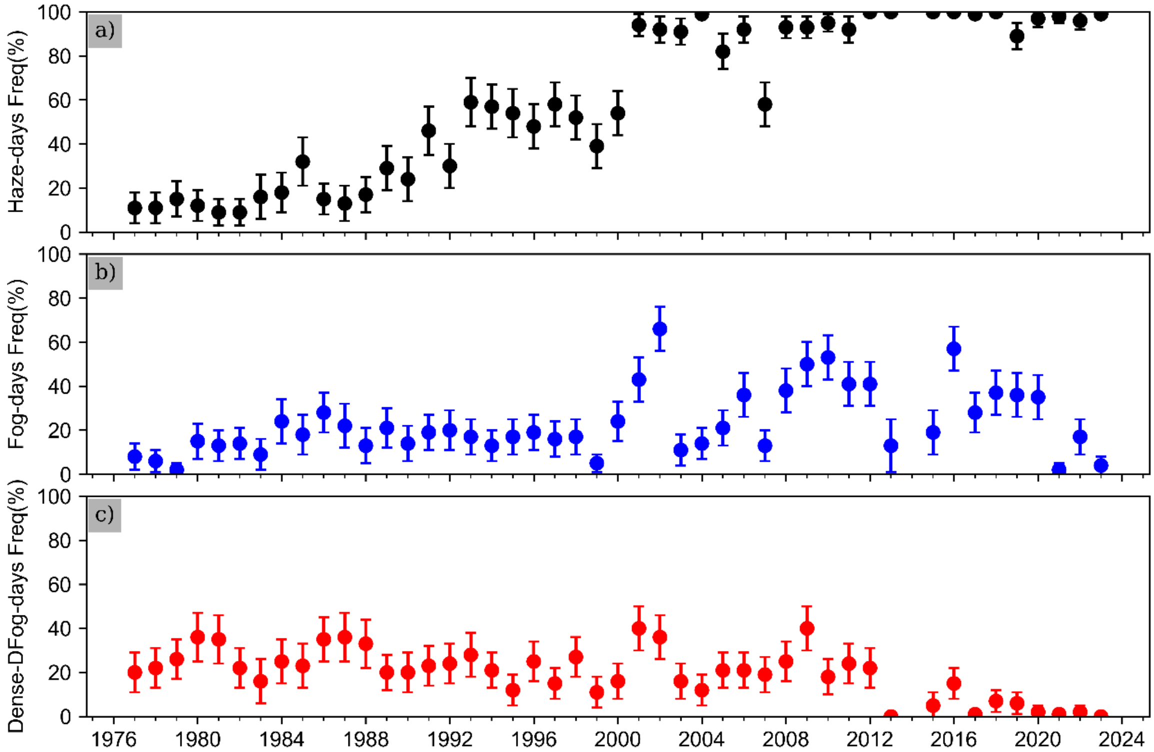

Figure 4. Time evolution in the percentage frequency of: (a) haze days, (b) fog days, and (c) dense-fog days in the winter season (DJF) at Tribhuvan International Airport (TIA), Kathmandu, from 1976 to 2023. The error bars indicate the Margin of Error (MoE)

There was little variation (variance = 0.6%) in occurrence frequency up until the year 2011 (Figure 4c). In this period, the lowest number of dense-fog episodes (11 % of available winter days) were observed in the year 1998 and the highest (40%) in the year 2000. Dense fog events were below 10% after the year 2016. We observed dense fog in only one day in the winter of 2020, two days in 2021, and none in the year 2022. Likewise, the annual fog and dense fog days over the study period have been shown in **Figure S.1** (Supplementary material).

Several previous research works (e.g., De & Dandekar, 2001; Saikawa *et al.*, 2019; Sarkar *et al.*, 2006; Syed *et al.*, 2012) also reported increased regional haze and fog episodes over the years elsewhere in Hindu Kush Himalayan (HKH)—where the KTM valley lies. Kathmandu Valley is highly vulnerable to air pollution due to its unique bowl-shaped topography (Panday *et al.*, 2009), atmospheric conditions (Becker *et al.*, 2021), and increased sources of local emissions (Mool *et al.*, 2020). During winter, the valley's atmosphere experiences the highest levels of ground-level air pollution (Aryal *et al.*, 2008; Becker *et al.*, 2021; Putero *et al.*, 2015) that makes KTM Valley occasionally rank as having the worst particulate air pollution levels worldwide (Becker *et al.*, 2021). Near-surface temperature and wind speed in KTM are the lowest in the winter months (Supplementary material, Table S.1). In winter, strong nighttime inversions form cold air pool above the valley basin (Panday *et al.*, 2009; Panday & Prinn, 2009) resulting in lower Mixing Layer Height (Mues *et al.*, 2017) that suppresses buoyant vertical transport of air pollutants. Rain scarcely occurs in the valley during winter—making precipitation scavenging a rare seasonal phenomenon. All of the above factors—air pollution emissions and meteorological—contribute to the intensification of winter haze.

Table 1. Trend results of occurrence frequency of haze, fog, and dense fog days in winter (DJF) at Tribhuvan International Airport (TIA) in Kathmandu from 1976 to 2022 using Mann-Kendall and Sen's slope estimator. CI denotes the confidence interval

	Period	Mann-Kendall		Sen's slope	
		Z_{MK}	p–value	Trend Q (%yr^{-1})	CI %
Occurrence frequency of haze days (%)	1976–2000	4.79	< 0.001	2.36*	[1.00, 3.69]
	2001–2022	2.01	0.044	0.36†	[-0.12,1.75]
	1976–2022	7.34	< 0.001	2.34*	[1.79,3.00]
Occurrence frequency of fog days (%)	1976–2000	1.92	0.055	0.46†	[-0.45, 1.25]
	2001–2022	-0.91	0.364	-0.56^{ns}	[-2.78, 3.83]
	1976–2022	2.52	0.012	0.46†	[-0.06, 1.04]
Occurrence frequency of dense-fog-days (%)	1976–2000	-0.89	0.374	-0.25^{ns}	[-0.75, 0.25]
	2001–2022	-3.23	0.001	-1.28**	[-1.84, 0.13]
	1976–2022	-4.07	< 0.001	-0.53*	[-0.79, 0.00]

*- 0.001, ** - 0.01, and † – 0 .05 level of significance ; ns – non significant

Through the analysis of Copernicus Atmosphere Monitoring Services (CAMS)-PM2.5 reanalysis data of Kathmandu for 2003–2019, Becker *et al.* (2021) revealed that the winter season witnessed the highest increase in PM2.5 levels (~ $2\,\mu g\,m^{-3}$) annually. Considering visibility as a proxy of air pollution, our present study using multi-decadal data, also suggests similar deteriorating winter air quality in the valley. Possible reasons could be either an increase in wintertime-air-pollution-activities—local and/or transboundary—or a meteorological impact. We could see a slight upward trend (0.28% /year at a = 0.05) of RH in regime-I (supplementary material, Table S.2), which might have played a contributory role in haze enhancement. In regime II, RH reversed the trend (−0.46 %/year at a = 0.01); already a higher level of air pollution should have outplayed the role of RH in this period. Though little, slowing down of the wind since 2000 (-0.02 m/s/year at a = 0.05) might have contributed to the intensification of winter haze in Kathmandu in regime II. Detailed analysis of the increase in air pollution emission is beyond the framework of the current study. However, it is reasonable to mainly link the seen intensification of winter haze to the significant increase in anthropogenic air pollution sources in KTM ranging from road/air traffic, and industrial activities, to refuse burnings—commensurate with the rapid increase in population (~ 4% per annum) (Timsina *et al.*, 2020) of the valley. Intensification of haze in the IGP region during the same period has been reported in tens of papers (e.g., De & Dandekar, 2001; Kathayat *et al.*, 2023; Saikawa *et al.*, 2019; Sarkar *et al.*, 2006). Thus, the observed haze uptrend in KTM can also be attributed to the transboundary transport of IGP haze into the valley.

Tens of papers have reported increasing frequency of both fog types (fog and dense-fog) elsewhere in the IGP region (e.g., Ghude *et al.*, 2017; Jenamani, 2007; Kathayat *et al.*, 2023; Shrestha *et al.*, 2018; Syed *et al.*, 2012) as well as central and eastern China (Niu *et al.*, 2010). Many (e.g., Kathayat *et al.*, 2023; Niu *et al.*, 2010; Sarkar *et al.*, 2006; Syed *et al.*, 2012) have attributed this to the increase in air pollution and thus abundance of CCN, resulting in more water droplets with higher optical depth (Syed *et al.*, 2012). Yan *et al.* (2020) suggested that aerosols promote fog by increasing Liquid Water Content (LWC) and droplet concentration while decreasing effective droplet size. Some works of literature have also pointed out the possible change in land cover use and irrigation area (Kathayat *et al.*, 2023; Shrestha *et al.*, 2018) and regional meteorological change (Niu *et al.*, 2010).

In addition to the looking at trend of plausible parameters (e.g., RH and WS), we also estimated the trend in Dew-point Depression (T_{dep})—the difference between ambient temperature (T) and dew-point temperature (T_d)—similar to the work of Kutty *et al.* (2020). If dew point depression is low, the saturation of air is more likely, and hence the fog formation, provided other conditions be met. In addition to elevated air pollution, declining nighttime T_{dep} (−0.03 ℃/year at a = 0.05) (Supplementary material, Table S.3) might have contributed to the observed increased trend of fog during 1976–2000. Whereas the decreased RH (−0.70 % /year at a = 0.001) and increase in T_{dep} (0.13 ℃ /year at a = 0.001) should have contributed to the decline in dense fog occurrence since 2000. We also observed an increase in average nighttime temperature (0.14 ℃ /year at a = 0.01) in the later period (2001–2022).

Kathmandu Valley is one of the fastest-growing metro cities in South Asia (Timsina *et al.*, 2020). Because of the increased population, agricultural land and other vegetation land coverage have shrunk considerably in later periods. This can be visible in satellite imagery of Kathmandu taken 60 years apart (Supplementary material, Figure S.2). This vast change in land cover use led to a diminished source of moisture—one of the most important ingredients for the genesis of fog—as evidenced by a decrement in RH. Decreased moisture content in the atmosphere results in decreased dew point temperature and increased dew point depression as seen above. This may explain the reduced occurrence of dense fog in the later period.

CONCLUSIONS

In the present study, we considered over four and half decades of climatological data measured at the TIA in Kathmandu focusing on the occurrence of haze and fog in winter that usually impair winter visibility at the airport making it difficult for flight operations. We studied the two important properties of fog, namely, consecutive duration and onset/dispersal timing of winter fog at the airport. We found that ~ 86% (~95%) of fog (dense fog) days witnessed fog lasting not more than one hour. Dense fog exceedingly more than two hours is rare in TIA while some fog events lasted up to 6 hours. The onset of fog occurs in the early morning—usually between 05:00 to 09:45 am—in all three winter months and disperses before noon. The most favorable onset times for fog are 05:15 am in December and 06:45 am in January and February while the dense fog onset window is between 05:00 and 09:00 am. The highest percentage of dense fog onset occurs at 05:15 and 08:15 am and dissipates at 06:15 and 09:15 am.

Haze intensifies during winter in the TIA owing to the intensified air pollution, weaker air-pollution-dispersion-mechanism (colder air, slower wind, shallow boundary layer, and no rain), and unique topography of the valley. This has increased exceedingly over the study period mainly because of increased local air pollution. Increased RH in the winter season in regime and slowing down of wind in regime II could have partly contributed to the intensification of winter haze over the years.

Fog events have increased in the TIA, though little, due to the effect of enhanced aerosols (more Cloud Condensation Nuclei (CCN)) in the air. However, it appears that dense fog may have disappeared largely in the recent period (regime II) because of a reduction in agricultural land and vegetation cover and increased dew point depression in Kathmandu.

Increased haze and fog adversely affect aviation at TIA because of the reduced visibility they cause. It shall be a serious concern to aviation service at the country's major international airport. Effective measures are imminent to control air pollution emissions in winter and urbanization of the valley. We require further investigation into the mechanism of winter fog in Kathmandu Valley by using models and the effect of Urban Heat Island (UHI) on fog.

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AUTHOR CONTRIBUTIONS

B. Kathayat: Conceptualization, methodology, software, formal analysis, investigation, data curation, writing original draft, and visualization; A.K. Panday: Conceptualization, validation, supervision, writing, review, and editing; B. Pokharel: Validation, supervision, writing, review, and editing; N.P. Chapagain: Supervision, writing, review, and editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data used in this study are publicly available at https://www.ncei.noaa.gov/maps/hourly/.

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