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Abstract. Atmospheric visibility, a measure of horizontal distance one can distinctly see with unaided eye, is affected by the scattering and absorption of visible light by the tiny particles (aerosols), or different gases present in the atmosphere. Thus, visibility is commonly considered a proxy for ambient air quality. The long-term trend of visibility may reflect the change in the air quality of a place over the period. In our study, we have analyzed historic climatological data (1977-2020) from the National Oceanic and Atmospheric Administration (NOAA) global hourly archive, for the two cities of west Nepal, namely, Bhairahawa (BWA, 27.506N, 83.416 E) and Surkhet (SKH, 28.6 N, and 81.617 E). We have found that both of the synoptic stations exhibited persistent degraded visibility. BWA had poorer visibility conditions (poor air quality) than that of SKH since the beginning of the study period. Since 2014, the 'annual good day' (V10 km) at BWA is steadily near 0%, and the 'annual bad day' (V<5 km) is 60 %, suggesting a degraded air quality. Similarly, we observed a notable decline in the 50th percentile of visibility in the mid-1980s at SKH, and a sharp decline of 'good day' since 2011. Meteorology modifies the optical properties of aerosol/ gaseous in the atmosphere, thereby, resulting in a change in visibility. In our study, we have investigated the influence of relative humidity (RH) on prevailing visibility. Although the relationship between them exists in both of the stations, it is more distinctly visible at BWA. We observed lower visibility conditions (V 3 km) occurring at an RH level as low as 50% at BWA. This indicates an abundance of specific hygroscopic aerosols, whose light extinction thresholds are as low. At BWA, the impact of RH is evident during the dry season. In contrast, the threshold value of RH is quite high (80%) at SKH and the relationship is prominent during the wet season. This alarmingly poor air quality at both stations requires a serious concern because of its adverse impact on various sectors like aviation, tourism, and public health.

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Keywords: air pollution, meteorology, relative humidity, trend, visibility.

INTRODUCTION

Atmospheric visibility is a key element in meteorological observation. Very good atmospheric visibility (up to > 100 km) can be observed in unpolluted circumstances in clear sky conditions [1, 2]. Whereas, the low visibility is observed when there is heavy air pollution in the atmosphere and, or bad meteorological conditions [1, 3]. Thus, the status of atmospheric visibility, good or bad, is an important indicator of the status of atmospheric optics [4, 5, 6, 7, 8, 9, 10, 11, 12]. This makes visibility an important proxy for particulate matter pollution [13, 14]. Atmospheric visibility can decrease because of the scattering and absorption of visible light by particles and gases present in the atmosphere [10, 15, 16]. Several studies in the past have confirmed that visibility extinction is related to fine particles PM2.5, and PM10, especially particles with a diameter of less than 1 mm [10]. The total light extinction resulting from atmospheric particles can be apportioned to the major components of particles, which includes sulfate, nitrate, organic carbon (OC), black carbon (BC), soil, and the coarse mass fraction (PM10 and PM2.5) [17]. Several studies have shown that countries like the United States, China, and India having vast territories, large populations and giant economies have faced problems of poor visibility conditions and hence the poor air quality in different periods because of industrial revolutions [18]. Serious sulfur and organics pollution in the mid-eastern and western urban regions [6, 17, 19, 20] were attributed to the poor air quality in the US during those periods. Population and economic explosions in their mega-cities, and the associated air pollution are attributed as the reason behind the significant decline in visibility in India [18, 21, 22, 23, 24] and China [1, 3, 12, 25, 26, 27, 28, 29, 30, 31, 32, 33]. Meteorological factors, especially relative humidity (RH), have a great influence on visibility [17, 34, 35]. As the RH increases, hygroscopic particles progressively uptake ambient water vapor leading to increased scattering cross-sections and hence refractive index. For instance, the scattering cross-section of ammonium sulfate could be increased by a factor of five or more above that of dry particles when RH increases above 90% [17]. This very property, hygroscopicity; inevitably affects the light radiation in the horizontal direction; and influences atmospheric visibility [4, 11, 36]. This is how; the understanding of the mechanism of visibility variations plays a key role in air pollution, emergency response, and regional air quality management. In this study, we have investigated the long-term variation of visibility in two cities Bhairahawa and Surkhet. The variations in visibility were investigated using 43 years of data collected from the National Climatic Data Center (NCDC). Two different statistical approaches have been adopted for the investigation of the trend: (a) trend of 50th, 90th, and 10th percentile and (b) annual percentage of good and bad days. Lastly, we have attempted to study the dependence of visibility on RH.

DATA AND METHODS

Bhairahawa (BWA) and Surkhet (SKH), two cities in the western region of Nepal (Figure.1; Table I), have contrasting geographic and meteorological features and were chosen as the representative sites for the investigation. Bhairahawa, a municipal city is an administrative headquarter of the Rupandehi district, lies in the outer flat plains of Nepal, 265 km west of the capital city, Kathmandu. This city borders India towards the south. The nearest mountain foothill to the city lies about 25 km north. The city is highly urbanized, and among the major industrial powerhouse in the country influencing major economic aspects of Nepal. In contrast, Surkhet station (28.6 N, 81.617 E; elevation: 720 m) lies in the valley of Surkhet, about 600 km west of Kathmandu. It is surrounded all around by hills. Surkhet is a comparatively less populated city and it lags Bhairahawa in terms of industrial establishments.

TABLE I. Details of the selected synoptic station in West Nepal

Station	Lat.(°)	Lon.(°)	Elev.(m)	Available data duration
ine Bhairahawa(BWA)	27.506 N	83.416 E	109.1	1977-2020
Surkhet (SKH)	28.6 N	81.617 E	720	1976-2020

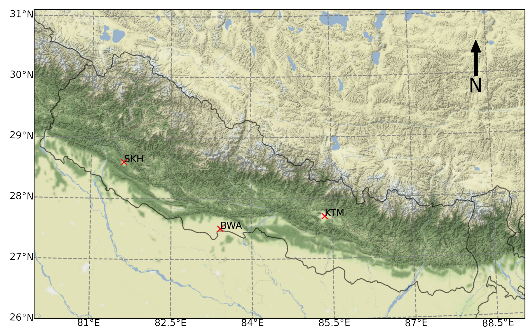

FIGURE 1. Bhairahawa and Surkhet stations, in country map of Nepal and their relative position w.r.t. Kathmandu (KTM), the capital city of Nepal

Visibility and other key meteorological parameters like wind speed, wind direction, air temperature, and dew-point temperature of these two sites with at least 3 hr. intervals from 1977 to 2020 were collected from the online repository of the National Climate Data Center (NCDC)(source: https://www7.ncdc.noaa.gov/CDO//cdoselect.cmd). NCDC is an authentic data source, used by many researchers as the main data source. It archives historical climatological datasets on a global scale. The data has been subjected to extensive automated quality control to correctly decode as much synoptic data as possible and to eliminate many of the random errors found in the original data. A series of processes were performed to get quality-controlled data that could accurately reflect the relationship between visibility and air pollution. Relative humidity (RH) was calculated through the equation [37]:

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

Where T (°C) represents the air temperature and T_d (°C) represents the dew point temperature.

Visibility trend analysis

Naturally, the low visibility observations may occur because of specific weather conditions such as mist, precipitation, and fog, which have high relative humidity (RH). In this study, we have narrowed down our purpose of trend analysis to detect any inadvertent alteration of air quality resulting from human activities only, rather than the synergetic effect of human activities and natural influences. Similar to the work of many other researchers like [7, 11, 25], we have made a minor attempt to offset meteorological factors while carrying out the trend analysis. As all of these specific weather conditions bear one property in common, i.e. high moisture content (RH), we have removed all visibility observations when relative humidity (RH) equals or exceeds 90%. This is how; we have screened our data for precipitation, fog, and mist. In addition, we have screened the data for the time of day, i.e. data between 00:00 to 12:15 UTC (5:45-18:00 LT). Using visibility observation from 1980 to 2019 (inclusive), we have used two common statistical methods as described in the following sections.

Trend analysis by cumulative percentile

The observed visibility is the lower limit to prevailing visibility. The trend of a particular percentile of visibility can reflect the change in visibility level [11] over a long period. The Nth cumulative percentile of a visibility distribution is the visibility that equaled or exceeded N percent of the time according to [7, 8] . Usually, the fiftieth percentile is compared to establish the trend of visibility observation at a place. For a continuous and widespread frequency distribution, the 50th percentile would correspond to a median, a familiar concept. However, when applied to the visibility data, the 50th percentile need not necessarily correspond to the median, rather it represents the visibility one may expect to be equal to or exceed half of the considered period. Many researchers (e.g. [11]) have used other percentile levels, like the 10th percentile and 90th percentile to establish the trend in visibility data, since these percentile levels are inherently more representative of optical air quality compared to the 50th percentile. Here, the 10th percentile of visibility represents ‘good visibility’ and the 90th percentile represents “poor visibility”. We also have attempted to report a trend in these percentile levels in our study. It is worthwhile to note here that the notion of percentile in this analysis follows reverse order to the statistical meaning of percentile of a continuous and widely spread frequency distribution because of the definition of visibility itself ([7, 8]). In this method, we also have grouped the visibility data into non-overlapping five-year periods to lessen the effect of large seasonal fluctuation in a given year.

Annual good and bad day percentage

The original dataset contains a combination of data from two different standard methods of measurement: SYNOP (Surface Synoptic Observations) and METAR (Meteorological Terminal Air Report). The major difference between these two methods is the recording time of their observations and observation standard. METAR data are encoded by automated airport weather stations (AWS) and SYNOP data are encoded by both manned and automated weather stations. The upper limit of METAR is 10 miles (or,10 km) whereas that of SYNOP could reach 30 miles or higher ([38]). Additionally, the time resolution of SYNOP is 3 hr, and METAR is 1 hr or half an hour. Thus, measurements of percentile, averages, etc. from the mixed data may not reflect the actual picture. Our dataset is mixed-type and primarily occupied by METAR in the later stages of recordings. This may lead to a sharp decrease in percentile values. Thus, a conclusion drawn based only on the analytical method described in the above section may not accurately reflect the actual status of visibility. To compensate for the influences caused by METAR records, we have adopted a more stringent analysis. In this method, we define a ‘good day’ as a day having daily average visibility equaled or exceeded the 10 km visibility threshold and a ‘bad day’ as one having daily average visibility of less than 5 km. We have calculated bad visibility frequency directly based on the data points rather than daily mean visibility values similar to the work of [18]. Finally, we have calculated the annual percentage of good and bad days for the entire period at both locations. According to [11, 18, 39] this method can more accurately indicate a long-term variation of air pollution status in a place.

RESULTS AND DISCUSSION

The 50th, 90th, and 10th cumulative percentiles of visibility

The long-term trends of visibility differed between the measurement locations as we can see from the grouped percentile charts (Figure.2) in three different percentiles levels. It is to be noted that the maximum value of visibility reported in our observation is 75.5 km. At the beginning of the five-year interval (1980 –1984), a very high 50th percentile of visibility nearing a maximum reported (75.5 km) was observed (Figure.2 [a]) in SKH. We observe an initially sharp (1985-1989) followed by a gradual decline in visibility until the end of our study period. Thus, the deterioration of general visibility is witnessed at SKH since the mid-80s. Figure 2[a] also depicts BWA having far less 50th percentile i.e., visibility observed during half of the considered period, in comparison to that of SKH, the difference being appreciable initially. The 50th percentile and 10th percentile values of visibility at SKH (Figure.2 [b]) are both 75.5 km at the beginning period indicating excellent visibility conditions. In contrast, only 10% of the time during the period BWA witnessed that excellent visibility. We witness a decline in good visibility condition abruptly since mid- 90s at SKH and as early as mid - 80s in BWA. We also can see strong evidence of deterioration of visibility in SKH (Figure.2 [c]). Visibility used to be more than 10 km, 90% of the time before the year 2010, which is reduced to as low as 4 km in the later interval. The marked difference in studied percentile levels at these two sites suggests the regionality of the atmospheric aerosols. The typical poor visibility is reflected by the trend of the 90th percentile, as discussed. These plots show that visibility in SKH is much higher than that of BWA. All of these percentile levels display an overall marked declining trend of visibility indicating a worsening of air quality at both locations.

Percentage of annual good days and bad days

Figure 3 depicts that more than 55% of annual days witness good visibility before the year 1985 at BWA in line with our observation of the high value of the 50th percentile in Figure (2[a]). It exhibits gradual decline until reaching nil annual good day percentage since the year 2014. There is no recovery ever since it dropped to its lowest. Meanwhile, except for one year since 1980, all years before the year 2007 witnessed good visibility conditions, with a good day percentage of over 85%. It has recently reached the lowest after 2018. Annual bad day percentages at BWA are higher throughout, in comparison to SKH. It displayed a gradual rise from 20% (in 1980) to 60% (in 2014), and remained steady ever since with minor fluctuation. These findings suggest long periods of “general good visibility” in SKH compared to BWA. This method too clearly indicates a notable declining trend of visibility at both locations. SKH witnessed a better overall visibility condition throughout. A marked decline in the annual good day percentage is seen in the year 2011. Since our analysis has screened the influence of specific meteorological phenomena, any change in visibility should be a direct manifestation of the extent of air pollutants content in the atmosphere. Hence, we can certainly view visibility as a proxy for air pollution. Our findings, thus, imply a cleaner atmosphere in SKH. This can be attributed to the combined effect of lesser local-air-pollution-emission and/or diminished influence of trans-boundary air pollution, which agrees with its location and rural settings relative to BWA.

Influence of relative humidity on Visibility

Water vapor in the atmosphere does not have any direct effect on visibility since it does not scatter or absorb visible light by itself. The effect of RH on visibility results from the hygroscopic growth or shrink of atmospheric particles leading to light extinction. Thus, water vapor does not affect visibility unless pollutants are present. To gain more insight into the relationship between RH and visibility at the studied sites, we have categorized RH into seven bins [<40, 40-50, 50-60, 60-70, 70-80, 80-90,>90]. Likewise, observed visibilities have been classified into the following six specific ranges: visibility 1 km, 1 km < visibility 2 km, 2 km < visibility 3 km, 3 km visibility < 5 km, 5 km visibility < 10 km, and visibility 10 km or higher. In the stacked bars (Figure 4), we have shown the percentage occurrence of visibility categories (distinguished by different colors bar) that fall into a particular RH bin. These plots also display the respective frequency distribution of RH. Figure 4 shows that with growing RH, the percentage of low visibilities (V < 5 km) increases sharply.

As depicted in Figure 4, for RH exceeding 80% in BWA, more than 78% of visibility observations are below 10 km and over 40% of the observation are below 5 km. When RH >90%, about 67% of visibility observations are low visibility (V < 5 km) and 40% of the visibilities are below 2 km. Similarly, Figure 4(b) clearly shows that the percentage of low visibility increases with an increase in RH at SKH as well. For RH < 90% at SKH, more than 50% of visibility observations are above 10 km, indicating a lesser impact of RH on visibility. While comparing Figure 4 (a) and (b), we see that there are some percentage of low visibilities (v < 3 km) observations at RH as low as 50% at BWA, while this is pronounced only in the high RH regime (RH>80%) at SKH. The poor visibilities in the RH regime above 90% could have resulted from either the occurrence of meteorological phenomena like rain, fog, and mist, or the hygroscopic effect of RH on secondary aerosol pollutants present in the atmosphere as discussed earlier. Due to the limitation of our dataset, we could not rule out the rain observations from our dataset. Ruling out the mist and fog observation from the data set is beyond the scope of this research as well. Thus, increased low visibility conditions at higher RH (RH >90%) should be because of the combined effect of meteorological phenomena and hygroscopic growth of secondary aerosol pollutants, more prominent in BWA Focusing on the effect of RH alone on visibility, poor visibility observed even at the lower regime of RH, especially at BWA highlights the prominent effect of hygroscopic aerosols on the extinction of the light. This indicates the presence of a specific type of hygroscopic aerosols at BWA, which can manifest its light extinction behavior even at the low RH regime.

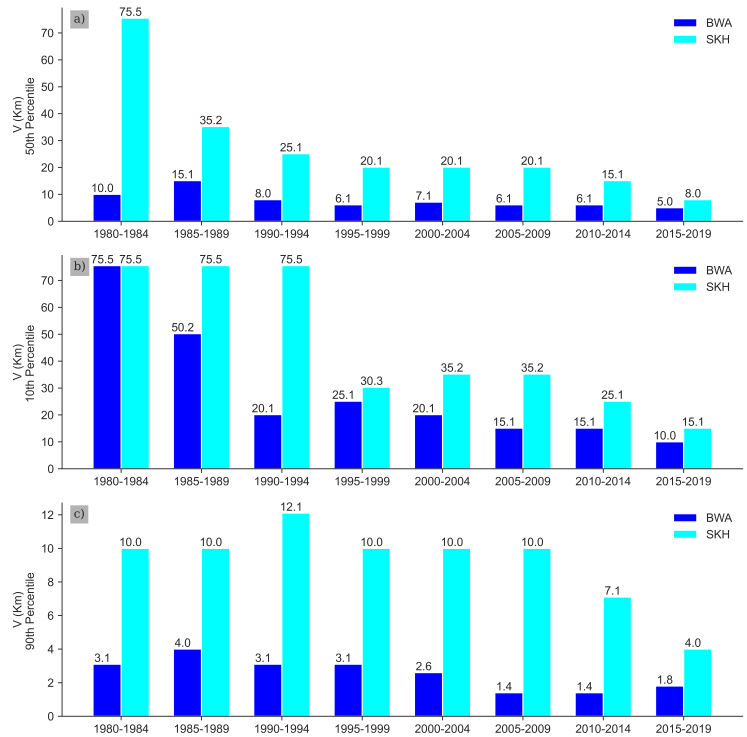

FIGURE 2. The 50th[a], 10th[b], and 90th [c] cumulative percentiles of visibility in Bhairahawa and Surkhet (1980-2020)

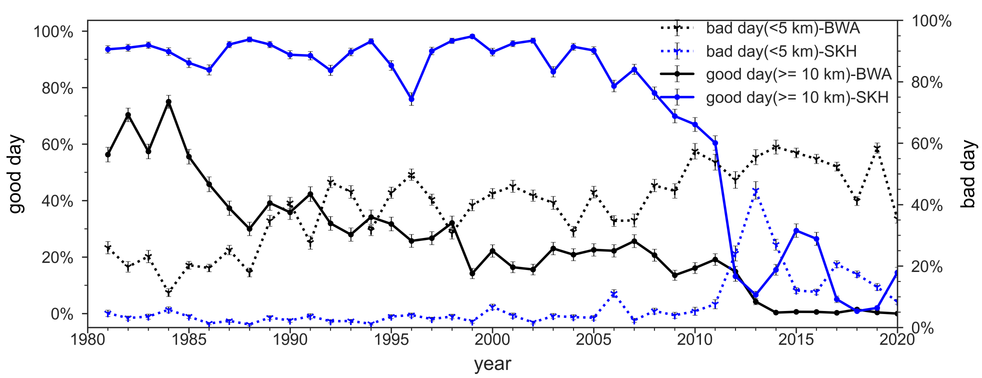

FIGURE 3. Long term variation of the annual good (visibility 10 km) and bad (<5km) day percentage based on visibilities of Bhairahawa (BWA) & Surkhet (SKH) for the period 1980-2020

[35] observed similar behavior of RH and visibility at Xiamen, China using high temporal resolution data during June 2011-May to 2012. They, too, found that percentage of low visibilities (V < 5 km) increases sharply with growing RH. We have also attempted to investigate the seasonal influence of RH on visibility. Seasonal variation of visibility with RH at both of our stations are shown in Figure 5 and their summary statistics have been presented in Table II. The two stations display quite contrasting seasonality concerning the occurrence of good and bad visibility conditions. At BWA the best visibility is observed (Figure. 5[a]) during the wet period of the summer Asian monsoon (June-September) and the poorest during the winter months (Dec-Feb). This might primarily be because of the scavenging of air pollutants by rainfall during the summer monsoon, irrespective of the extent of air pollution, and the occurrence of regionally widespread winter fog during winter (Dec-Feb). Many works of literature have pointed out that the presence of air pollutants enhances the severity of winter fog as well. Thus, RH might have played some role in worsening winter visibility through the hygroscopic growth of secondary

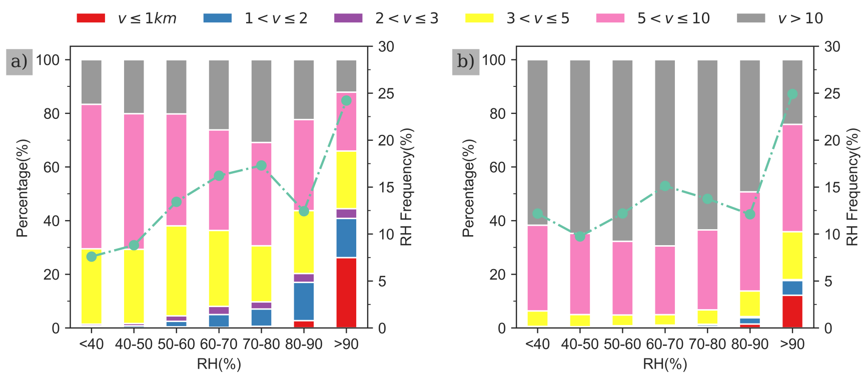

FIGURE 4. Percentage occurrence of different visibility classes (each denoted by a distinct color) at different RH categories represented by stacked bars and corresponding frequency distribution of RH represented by dotted lines and points at (a) Bhairahawa (BWA), and (b) Surkhet (SKH); 1977-2020

aerosols having their origin from local or transboundary emission sources. During dry pre-monsoon season, (Mar-May, RH 50%) and post-monsoon (Oct-Nov, RH70%) visibility generally shows reciprocal relation. Having not so different dispersion criteria during a season, this reciprocal behavior should be resulted from the extinction of light by a specific type of hygroscopic aerosols present in the atmosphere. This is because the RH at or above 50% can show its influence on visibility at BWA. While advancing towards the end of each season (e.g. from Jan-Feb, Apr-May), the relationship between visibility and RH seems more likely to follow the behavior of the upcoming season. This might be evident because of the weakening of the season towards its end and slowly gaining the characteristics of the season that follows. In contrast, the seasonal pattern of SKH exhibited (Figure 5[a]) almost opposite behavior to that of BWA in terms of the seasonal value of visibility. It witnesses a seasonal high value of visibility rather during post-monsoon months (Oct-Nov) and low during wet monsoon months (June-Sept.). In addition to having a cloudy sky during monsoon, a high RH value over 80% might have some influence on reduced visibility during the summer monsoon period, as only RH above 80% can manifest the adverse influence on visibility at SKH. The change in visibility during other seasons cannot be explained by the RH effect alone since typical seasonal RH values are lower than 80%.

CONCLUSION

After accomplishing a detailed study on the trend of visibility at two different locations,SKH and BWA, and exploring relationship between RH and visibility, we have reached to the following conclusions:

- Visibility displayed a significant declining trend at both of the locations during the study period (1980-2020), i.e. the air quality worsened over the period.
- The beginning of a decline in air quality occurred in the mid-1980s at SKH and another sharp decline occurred in 2011.
- The air quality at BWA was already poor since the beginning; this could be because of earlier urbanization and industrialization resulting in higher air pollution emissions. Trans-boundary air pollution also might have a greaterimpact on air quality. BWA airport is the gateway to the birthplace of Lord Buddha, Lumbini, a UNESCO heritage site, and the airport itself is being upgraded to an international airport, it is imminent to improve the air quality there to lessen the adverse effect of air pollution on tourism, health, aviation, etc. sectors. It requires enough attention from policymakers. The successful implementation of air quality control measure at BWA rely on regional coordinated effort.
- Although, the situation in SKH is not as alarming, the visibility condition is in a declining trend there too. Timely implementation of necessary measures to control the air quality is imminent.
- Only RH above 80% can affect reducing visibility by light extinction, meaning that there might be the presence of hygroscopic aerosols whose light extinction threshold for RH is higher than 80%. This effect is prominent during monsoon months. Whereas, the RH threshold for BWA is as low as 50%. The reciprocal relationship between RH and visibility shows its prominence during the dry seasons.

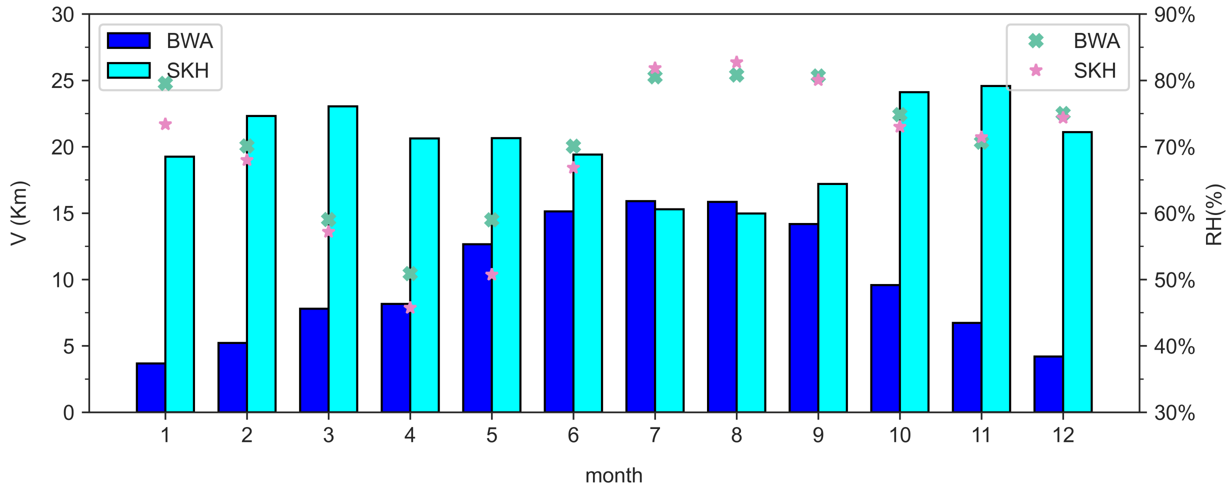

FIGURE 5. Seasonal variation of visibility (v, represented by bars) and relative humidity (RH, represented by points) at Bhairahawa (BWA) and Surkhet (SKH) for the period 1977-2020

TABLE II. Summary statistics of visibility and relative humidity at BWA and SKH

station	met.parameters	annual	pre-monsoon	monsoon	post-monsoon	winter
ine	v(km)	10.7[a]	10.5[a]	10.5[a]	17.0[a]	4.7[a]
BWA		6.1[b]	6.1[b]	6.1[b]	10.0[a]	3.1[a]
	RH(%)	71.7[a]	75.2[a]	57.4[a]	77.8[a]	74.0[a]
		71.0[b]	75.0[b]	53.0[b]	79.0[b]	73.0[b]
ine	v(km)	22.7[a]	24.7[a]	18.9[a]	24.8[a]	24.6[a]
SKH		20.1[b]	20.1[b]	15.1[b]	20.1[a]	20.1[a]
	RH(%)	62.3[a]	42.8[a]	72.1[a]	68.5[a]	65.0[a]
		65.0[b]	41.0[b]	74.0[b]	69.0[b]	63.0[b]

[a] mean
[b] median

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