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Fog and low stratus over the Swiss Plateau – a climatological study

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ABSTRACT: The occurrence of fog and low stratus (FLS) clouds is a common phenomenon over the Swiss plateau during the winter half years. Classical fog observations using horizontal visibility are of limited use for climatological analyses of persistent FLS situations. We present a simple method for determining long climatological series of days with FLS lasting at least a half or a full daylight day. The method relies solely on high quality relative sunshine duration measurements at two stations, a Plateau station below or within the FLS layer (e.g. Zürich/Fluntern) and a nearby peak station above the FLS layer (e.g. Säntis). The analysis for the period 1901–2012 shows that full day FLS are a typical phenomenon of the months November to January, whereas the half day FLS also often occur in October and February. There is substantial interannual and decadal variability. The total number of Zürich full FLS days varies between 4 and 31 d (mean: 17 d) and between 10 and 49 d (mean: 28 d) for at least a half FLS days in the September to March period. The foggiest decade in the 1901–2012 record was 1984–1993; the least foggy decade was 1999–2008 with roughly 40–45% less FLS occurrence than only 15 years before. In the most recent years a return towards the climatological mean can be observed. The long term data series does not show any significant long-term trends for the occurrence of full nor for half day FLS events. The reconstructed FLS occurrence is well correlated with the number of days with cold air pooling. They show very similar decadal variability and long term trends.

KEY WORDS fog; low stratus; cold air pools; Swiss Plateau; Switzerland; reconstruction; climatology; variability and trends; potential temperature; sunshine duration; lake freezing

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1. Introduction

Radiation fog (Roach *et al*., 1976; Sampurno Bruijnzeel *et al*. 2006) often develops in calm flow situations over the Swiss Plateau in the winter half years (Wanner, 1979; Troxler and Wanner, 1991). Often this fog is lifted up and forms a continuous layer of low stratus clouds, referred to as 'Hochnebel' (high fog) in German. Days with fog and low stratus (FLS) over the Swiss Plateau are abbreviated as FLS days in the following. During FLS periods direct radiation is blocked until afternoon or even for the entire day. This has significant impacts on the day to day life in Switzerland but also on the local environment. FLS days have an adverse effect on the moods of the people living below the fog cap, often causing tourists to travel to higher elevations in the Alps to get above the cloudy conditions. From the top, the FLS appears as 'Hochnebelmeer' (sea of fog, cf. Figure 1). Periods with FLS also have severe impact on traffic safety and air quality (Cermak *et al*., 2009). Further FLS substantially modifies the albedo and as such acts as a modifier in the local climate system and contributes to local temperature variations (van Oldenborgh *et al*., 2010). In essence FLS days are associated with significantly cooler temperatures compared to situations where no FLS is present. It was hypothesized that, like snow pack changes, changes in FLS frequency could have had measurable impacts on local temperature trends in the last decades (Ceppi *et al*., 2012; Scherrer *et al*., 2012).

There are a number of studies analysing the processes that lead to, sustain and destroy cold air pools in larger basins (Lareau *et al*., 2013; Zhong *et al*., 2001; Whiteman *et al*., 2001 among many other). However, literature on the climatology and the changes in FLS and cold air pool occurrence over several decades is sparse in Switzerland and worldwide. Apart from some newer publications which aim to identify FLS using recent satellite data (Bendix, 2002; Cermak *et al*., 2009) and the fog trend study using classical fog observations by von Dach (2008), the dissertation by H. Wanner dating back to 1979 is still a key reference on FLS aspects in Switzerland (Wanner, 1979). The satellite based data from Cermak *et al*. (2009) have high spatio-temporal resolution, but cover only a few years. Von Dach (2008) presents a trend analysis of long climatological series of classical ground-based fog observations, which include ground fog but no 'Hochnebel' (high fog) situations. Wanner (1979) is an excellent compendium for many FLS aspects but since

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Figure 1. Left panel: Typical 'Hochnebelmeer' (sea of fog) covering the Swiss Plateau as seen from Jungfraujoch (photo: Ruedi Wyss). Right panel: Switzerland as seen from the MODIS AQUA satellite on 11 December 2004 12:25 UTC showing an FLS day, i.e. a day with 'Hochnebel' (high fog) on the Swiss Plateau.

it is based on data from the 1960s and 1970s no current information on decadal variability or trends is available. More is known concerning changes in mist, haze and visibility in general. Visibility has increased and foggy and misty or hazy days have decreased substantially for most regions in Europe including Switzerland in the last two to three decades (Sachweh and Koepke, 1995; Vautard *et al*., 2009). These changes in the last three decades have been attributed mainly to air-quality improvements (i.e. decreasing aerosol emissions) and, to a smaller and uncertain degree, to large-scale circulation (van Oldenborgh *et al*., 2010).

In order to shed more light on the issues presented above, it is important to have a climatological FLS series at hand that can reliably describe FLS events and cover several decades. In the classical definition, fog is a suspension in the air of microscopic water droplets or wet hygroscopic particles, reducing horizontal visibility at the earth's surface to less than 1000 m (WMO, 1992; Glickman, 2000). In this article we are interested in longer lasting FLS events and the above definition is not very useful for our purpose since:

1. It does not include 'Hochnebel' (high fog) situations, where horizontal visibility is greater than 1000 m.
2. A classical fog day is defined as a day when fog has been observed anytime during the day, independent of fog duration (5 min or the whole day both make it a fog day).
3. The evening observation times of the ground-based fog observation changed around 1970 and it is almost impossible to construct more or less homogenous fog series for the times before and after 1970 (von Dach, 2008).
4. The observations are highly dependent on the reliability and continuity of the observer that took the observation (Schüepp, 1962).

One plausible way out would be deriving FLS series based on remotely sensed data from satellites (Bendix, 2002; Cermak *et al*., 2009). However, these series are rather short (a few years only). In short, neither satellite based climatologies of several decades nor long term climate series based on observations are available at the moment. All these reasons make it necessary to construct FLS proxy data in order to get more insight into the FLS changes over time.

In this article we present a simple but flexible method to construct long term proxy series of persistent FLS cases using relative sunshine duration data. After introducing the data and methodology used in Section 2, we present the reconstructed FLS climatology and its evolution over more than a century (1901–2012) for the Swiss Plateau in Section 3. We also compare the climatological FLS series with cold air pool series and finally explore a potential link between the occurrence of lake freezing and cold air pools. Conclusions are drawn in Section 4.

2. Data and methodology

2.1. Fog, sunshine and temperature data

Classical fog data is used in this article for comparison purposes only. A fog day is a day on which fog was observed at a given time during the day (also between the official observation times, WMO, 1992). Duration does not play any role, i.e. whether 5 min or 24 h of fog are observed, both days are classified as a fog day. Changes in the observational practices in 1970 make it very difficult to compare fog days before and after 1970 (von Dach, 2008). For the reconstruction of persistent FLS cases, we use daily relative sunshine duration values which are a fraction between 0 (no sunshine at all) and 1 (fully sunny). Unfortunately relative sunshine duration is not homogenized yet. This means that the series are not corrected for changes in observation location and changes or drifts of the instrumentation during the observation period 1901–2012. This can potentially lead to spurious results. An analysis of the relative sunshine data showed that in the early years the sunshine data of the Säntis peak station only reached relative sunshine duration values somewhat over 0.9 (instead of the expected 1) even on the sunniest days. Therefore a correction is applied (see below). The temperature series used have been carefully homogenized on a monthly basis (Begert *et al*., 2005), and daily values 1901–2012 have been computed by interpolating the monthly homogenisation values onto days using a spline interpolation technique (see Vincent *et al*., 2002 for details).

The Säntis station (2502 m asl) was considered the peak station, with Zürich/Fluntern (556 m asl), Luzern (454 m asl) and Schaffhausen (438 m asl) as Swiss Plateau stations. The Zürich and Säntis data are available from 1901 with only 181 missing days (0.4%) for Zürich and 382 missing days (0.9%) for Säntis. For Luzern and Schaffhausen, data are available since 1931 with only 14 d (0.04%) missing values in Luzern and 174 d (0.6%) missing values in Schaffhausen.

2.2. Fog reconstruction methodology

The FLS proxy is based on relative sunshine duration measurements only. Figure 2 shows two typical FLS situations, called type 'fog' and type 'low stratus'. Both situations block direct sunshine radiation completely but low stratus cases would not be classified as fog by the standard fog definition. The idea behind the method is as follows. A persistent FLS situation is characterized by the fact that it lasts several h, has a cloud top that lies above the mostly populated areas on the Swiss Plateau but below the higher peaks of the Alpine foothills. This situation results in almost maximum sunshine above the cloud top and little sunshine in or below the cloud. This leads to the following proxy for an FLS day on the Swiss Plateau:

$$FLS_i^{\mathrm{lim}^{\mathrm{basin}};\mathrm{lim}^{\mathrm{peak}}} = \begin{cases} 1 & \textit{if} \quad \left(s_{\mathrm{rel},i}^{\mathrm{peak}} > \mathrm{lim}^{\mathrm{peak}} \text{ and } s_{\mathrm{rel},i}^{\mathrm{basin}} < \mathrm{lim}^{\mathrm{basin}} \right) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where i stands for the day i in the series, $\mathrm{lim}^{\mathrm{basin}}$ is the maximum fraction of sunshine that is allowed at the station in or below the fog layer, $\mathrm{lim}^{\mathrm{peak}}$ is the fraction of sunshine that must be exceeded at the station above the fog layer and $s_{\mathrm{rel},i}$ is the relative sunshine duration on day i. To allow for some high clouds (e.g. cirrus type clouds) above the peak station, the $\mathrm{lim}^{\mathrm{peak}}$ value must be set smaller than 1. Testing several values for $\mathrm{lim}^{\mathrm{peak}}$, we found 0.8 to be a reasonable choice that allows for some high clouds be present. In the beginning of the 20th century the Säntis station never reaches the theoretical s_{rel} value of 1 even during the sunniest days. This indicates that either the theoretical value of the maximum sunshine duration used to compute relative sunshine duration was wrong or that the strip registering the sunshine was registering or evaluated incorrectly during these time periods. To remedy this problem, we constructed a $\mathrm{lim}^{\mathrm{peak}}$ value that varies with time y (the year in question) as follows:

$$\mathrm{lim}_y^{\mathrm{peak}} = 0.8 - \left(1 - \max \left(s_{\mathrm{rel},y}^{\mathrm{peak}} \right) \right) \quad (2)$$

The limit is reduced by the difference between 1 and the maximum observed s_{rel} in the corresponding year. We did not find similar problems for the stations used as 'basin' stations in or below the fog layer, hence no correction was applied for those stations.

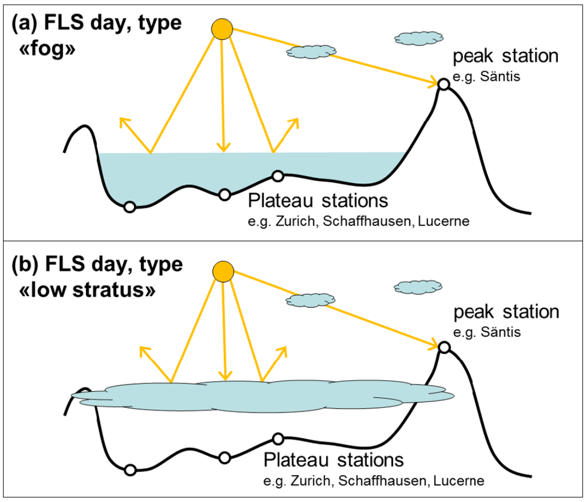

Figure 2. Schematic of possible FLS days with type 'fog' (a) and type 'low stratus' also known as 'Hochnebel' (high fog) (b) over the Swiss Plateau. Both fog types block the direct solar radiation (sunshine) at stations below or in the fog layer. Our method tries to identify days with both types of fog. Days with high (low) relative sunshine duration at high (low) altitude stations are used as fog indicator (see text for details).

Varying the value of $\mathrm{lim}^{\mathrm{basin}}$ allows for the detection of either FLS days with FLS disappearance during the day ($\mathrm{lim}^{\mathrm{basin}}$ much larger than 0) or all day long FLS events ($\mathrm{lim}^{\mathrm{basin}}$ close to 0). Table I shows the average annual sum of FLS days for different $\mathrm{lim}^{\mathrm{basin}}$ values using Säntis as peak station with $\mathrm{lim}^{\mathrm{peak}} = 0.8$ and Zürich/Fluntern as basin station for the period 1901–2012. As expected, the number of FLS days increases with the value of $\mathrm{lim}^{\mathrm{basin}}$. This increase is 2 days per 10% relative sunshine duration for $\mathrm{lim}^{\mathrm{basin}}$ values between 0.1 and 0.3 and increases to 3–4 days per 10% rel. sunshine duration for $\mathrm{lim}^{\mathrm{basin}}$ values between 0.4 and 0.5. Note that the $\mathrm{lim}^{\mathrm{basin}}$ should be considerably smaller than $\mathrm{lim}^{\mathrm{peak}}$. If $\mathrm{lim}^{\mathrm{basin}}$ and $\mathrm{lim}^{\mathrm{peak}}$ get too close, days with clouds other than FLS could be classified as FLS day. Note also that our approach can only be used to determine FLS cases which last several hours. To estimate appropriate $\mathrm{lim}^{\mathrm{basin}}$ values to classify FLS days, we can study the correlation structure of the FLS series constructed with different $\mathrm{lim}^{\mathrm{basin}}$ values. Table I shows that for $\mathrm{lim}^{\mathrm{basin}} \leq 0.5$, the correlation values are very high (between 0.90 and 0.98, $n = 111$), suggesting that similar cases are classified as FLS days. The correlation values decrease for $\mathrm{lim}^{\mathrm{basin}}$ values larger than 0.5 ($r = 0.86$ for $\mathrm{lim}^{\mathrm{basin}} = 0.6$ and $r = 0.81$ for $\mathrm{lim}^{\mathrm{basin}} = 0.7$) which indicates that in these cases sunny situations with a few cloudy hours might be classified as fog situations. In order to classify FLS days we recommend that $\mathrm{lim}^{\mathrm{basin}}$ should not be larger than 0.5, although the determination of this value remains somewhat subjective.

The most obvious shortcoming of the definition via relative sunshine duration is that the index only classifies

Table I. Sensitivity of the annual average sum of September to March fog and low stratus (FLS) days 1901–2012 at the station Zürich/Fluntern depending on the value of $\lim^{basin}$. Also shown is the correlation coefficient r between the fog days determined with $\lim^{basin} = 0.1$ as an arbitrary reference and all other $\lim^{basin}$ values considered.

$\lim^{basin}$	0.05	0.1	0.2	0.3	0.4	0.5
$\overline{FLS}^{\lim^{basin};0.8}$	15	17	19	21	24	28
$r\left(FLS_i^{\lim^{basin};0.8}; FLS_i^{0.1;0.8}\right)$	0.98	1.00	0.98	0.95	0.92	0.90

FLS during daylight hours. Night-time is not considered at all. It can be assumed that the effect on the FLS days is relatively small at least for the $\lim^{basin}$ values considered here where at least half of the day with daylight needs to be foggy or covered with low stratus. Another shortcoming is that since the index is binary (FLS day yes/no) and uses fixed empirically determined limits $\lim^{peak}$ and $\lim^{basin}$ some days just below/above the limits are classified differently.

In the following we will refer to three different FLS day proxies: (1) $FLS_i^{0.1;0.8}$ the ‘full day FLS’ index referred to as FLS_{FD} in the following, (2) $FLS_i^{0.5;0.8}$ the ‘at least half day FLS’ index referred to as FLS_{HD+} in the following and (3) the difference $FLS_i^{0.5;0.8} - FLS_i^{0.1;0.8}$ which represents the ‘partly FLS days’ where the FLS disappears during the day but was present at least half a day referred to as FLS_{HD} in the following. Note that the the FLS_{FD} cases are a subset of the FLS_{HD+} cases. It is thus plausible that the FLS_{HD+} and the FLS_{FD} index are well correlated.

A validation of the FLS proxies is not straight forward since there are no standard observations of FLS available. We use the manually edited MeteoSwiss ‘weather diary’ in order to validate the FLS classification. We compared whether the days identified as FLS_{FD} also were mentioned as FLS days in the MeteoSwiss ‘weather diary’ for the five winter seasons 2007/2008 to 2011/2012. Of the 72 days that were classified as FLS_{FD}, 71 were mentioned in the diary. One day shows low stratus clouds associated with frontal systems. This shows that in some cases our method may classify a non-classical FLS day as a FLS day, but the above numbers show that the vast majority of the classified days are ‘real’ FLS days and that the proxy index is a good approximation of the true FLS day series.

3. Results

3.1. Reconstruction of FLS days in Zürich

Figure 3 shows the number of reconstructed FLS days in Zürich/Fluntern for the September to March periods within the period 1901–2012. The number of FLS_{FD} are plotted in red, FLS_{HD+} in blue, FLS_{HD} days in black and the classical fog observations in green. For the FLS_{FD} a mean total of about 17 days per fog season is found. For the FLS_{HD+} the mean total is about 28 d and 11 d for the FLS_{HD} days. There is large interannual to decadal variability in all the series probably mainly caused by a different mix of governing weather types. The total number of FLS days lies between 4 (year 1999) and 31 d (year 1964) for FLS_{FD}, between 10 (year 1999) and 49 d (years 1964, 1969) for FLS_{HD+} and between 4 (year 2000) and 24 d (year 1996) for FLS_{HD}. The period between 1984 and 1993 with an average of about 21 FLS_{FD} days, 36 d of FLS_{HD+} and 15 FLS_{HD} days is the foggiest decade in the record. Strong decreases are observed just after this maximum. The decade from 1999 to 2008 is the least foggy period in the entire series with an average of about 12 FLS_{FD} days, 21 d of FLS_{HD+} and 9 d of FLS_{HD}. This is roughly 40–45% less than only 15 years before. A slight return towards more long term climatological values seems to be on the way in the most recent years. Similar results using classical fog observations are reported by von Dach (2008) which also found strong fog declines between 1920 and 1940 and since the 1990s. The classical fog observations (green) are shown for the period 1971–2012. Due to changes in the observations, the values before 1971 cannot be compared to the values after 1971. The mean number of classical fog days in this period (38 d) is about 2.4 times the FLS_{FD} mean of 16 d and roughly 1.4 times the FLS_{HD+} mean of 28 d. This strong discrepancy in absolute numbers was expected, since the classical observation also classifies very short fog events as foggy days. The decadal variations are quite similar though. Especially the strong decrease in the 1990s is also found in the classical observations. The FLS long term linear trends over the whole period 1901–2012 are small and insignificant (FLS_{FD}: −0.4 d/100 years, p-value = 0.82; FLS_{HD+}: +1.4 d/100 years, p-value = 0.58; FLS_{HD}: +1.8 d/100 years, p-value = 0.12). The weak trend in the FLS_{HD+} is caused by the slight increases in FLS_{HD} days.

So far we focused on simply counting the number of FLS days, but often FLS situations persist over several days and it is interesting to ask whether there is decadal variability in the number and length of the FLS events. An event is defined as a period of consecutive days with FLS, interruptions with non FLS days are not allowed. Figure 4(a) shows the time series of the number of FLS events, the average and maximum length of an FLS event for every September to March period between 1901 and 2012. The mean number of FLS_{HD+} events is 15.5 with an interannual range of 5–26 and 10.3 with a range of 3–19 for FLS_{FD}. The number of FLS events is relatively stable with rather small decadal variations over time. One exception is a drop in the number of events that can be seen after 1998, especially for FLS_{HD+}.

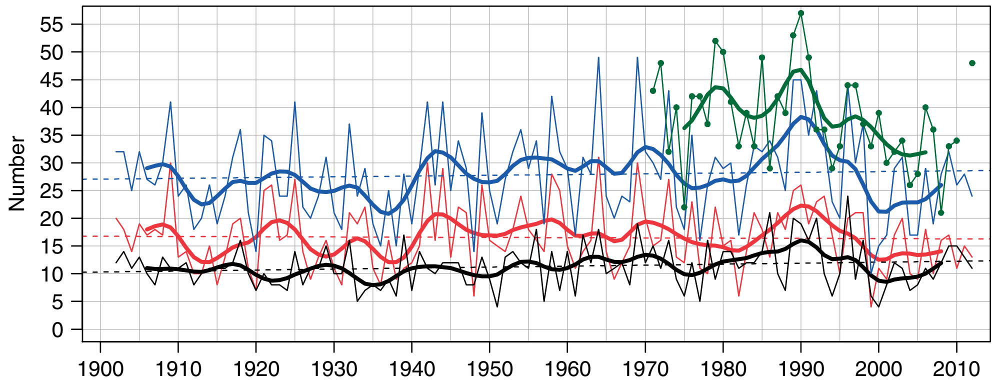

Figure 3. Number of FLS days in Zürich/Fluntern for the September to March periods 1901–2012 and classical fog observations (green), at least half day FLS (FLS_{HD+}, blue), full day FLS (FLS_{FD}, red) and partly FLS days (FLS_{HD}, black). The thin lines show the yearly values, the thick lines an 11 year Gaussian smoothed version and the dashed lines the least-square linear trend lines over the whole period.

How about decadal changes in the average length of an FLS event? Figure 4(b) shows that an average FLS event lasted about 1.8 d for FLS_{HD+} and 1.6 d for FLS_{FD}. There is not much decadal variability and a few years with larger average lengths on the order of 2.5–3.5 d. In the last 30 years, the FLS_{HD+} values seem to increase a bit, but the series shows no clear long term trend. Finally, Figure 4(c) shows the series of the maximum length of the FLS events. The FLS_{HD+} and FLS_{FD} series go in parallel until the 1970s, after that the longest FLS_{HD+} events seem to increase somewhat [last 30 year average (1983–2012) is 6.3 compared to 5.0 in 1901–1982] while the longest full day events stay almost constant (1983–2012 average is 3.8 compared to 3.9 for 1901–1982). Thus it seems that for FLS_{HD+}, the decline in the number of FLS events is compensated to a certain degree by somewhat longer events.

3.2. FLS climatology for Zurich

Figure 5(a) shows the average sum of days classified as FLS days by the classical fog observation, FLS_{HD+} and FLS_{FD} for all calendar months in the 1971–2012 period. The number of classically identified fog days is normally highest. It shows a very strong seasonal cycle with almost no foggy days in the summer months (Wanner, 1979; von Dach, 2008). The classical fog season (>1 fog day/month) starts in September and lasts until April. In contrast, the FLS season starts in September/October and lasts until February/March depending on the s_{rel} value considered. All fog indicators show that the main foggy months are October to February. This is in good agreement with the results of Wanner (1979). The difference between the fog indicators is largest at the beginning and the end of the fog season, while in the months December and January, the differences are lowest. In other words, in autumn and late winter/early spring, short-lived fog banks are dominating; while in winter long lasting 'Hochnebel' is abundant. Figure 5(b) shows the climatologies of FLS_{HD+} and FLS_{FD} for different time periods (whole series, foggiest and least foggy decade). For the foggiest decade (1984–1993, blue), compared to the whole series mean more fog was present in all months from October to March. For the least foggy decade (1999–2008, red), deficits are found in all months.

3.3. Reconstruction of FLS series at other stations

Figure 6 shows the time series for three different basin stations. It shows a comparison of the number of FLS_{HD+} in Zürich/Fluntern with those determined for Luzern and Schaffhausen. Note that because of a lack of other peak stations with long sunshine duration series, the Säntis station has been used as the peak station for all three fog day reconstructions. The most obvious feature is that the three stations are highly correlated and show very similar features. The correlation coefficients are 0.90 for Zürich/Fluntern and Luzern and 0.84 for Zürich/Fluntern and Schaffhausen. Also the decadal variability is very similar (cf. the smoothed lines). A detailed trend analysis or comparison with the past should not be made with these data since the sunshine data used are not carefully homogenized yet. The data suggest that Luzern and Schaffhausen have a similar number of FLS_{HD+} days per year, about 5–7 more days than Zürich/Fluntern which lies more than 100 m higher than the other two stations. An analysis of the monthly data also confirms the very good correspondence between the three stations analysed (not shown).

3.4. Comparison with cold pool days

During days with FLS, the direct radiation from the sun is blocked for the regions below the fog and the temperatures are considerably lower for these days compared to non-FLS days. Table II quantifies this effect for the station Zürich/Fluntern in detail. In summary, during FLS events, daily mean air temperatures measured 2 m above the surface are decreased by 1.5–2.5 °C in the autumn and 3–3.5 °C in the winter months including March. In contrast, temperatures in regions above the FLS are higher than normal. In other words, FLS situations are typical situations with cold air pooling over the

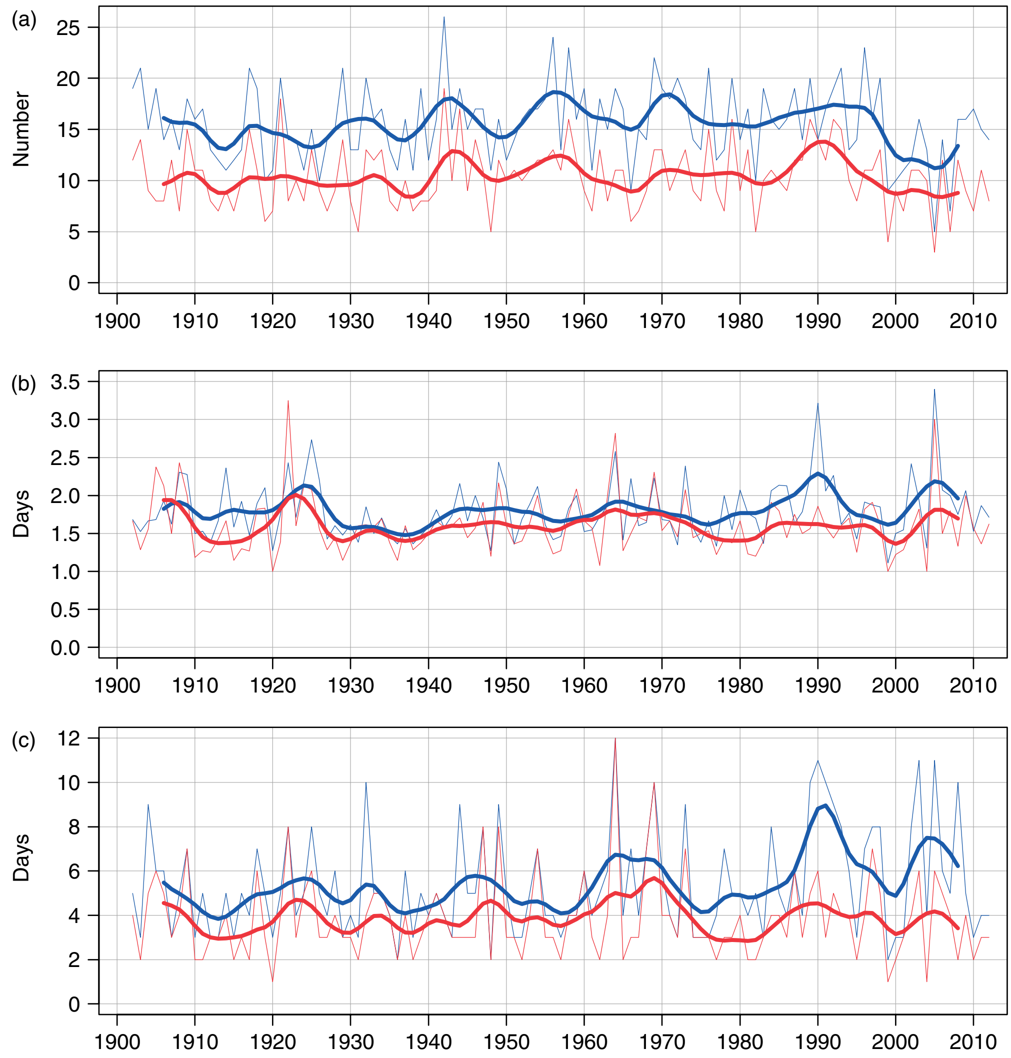

Figure 4. The number (a), the average length (b) and the maximum length (c) of the reconstructed FLS events in Zürich/Fluntern for the September to March season 1901–2012. At least half day FLS (FLS_{HD+}): blue curve, full day FLS (FLS_{FD}): red curve.

Swiss Plateau. In this section we investigate the relation between cold air pools and FLS situations and make a short comment about the relation to lake freezing.

There are several measures to characterize cold air pooling. Two of them are used here: the lapse rate and the potential temperature deficit (Lareau *et al*., 2013). We show a climatology of the lapse rate and the potential temperature deficit by using the daily mean temperature, pressure and altitude difference between Zürich/Fluntern and Säntis for the years 1901–2012. Figure 7(a) shows that the standard lapse rate of 0.65 °C/100 m (ISO, 1975) is not useful in the Alpine region during winter months as shown by previous authors (Rolland, 2003; Kunz *et al*., 2007). For example in the months October to February, the daily mean temperature lapse rate is smaller than 0.65 °C/100 m on 82–87% of the days. In 8–9% of the cases in December and January, the lapse rate is even negative, i.e. the daily mean temperature is higher on the Säntis (2502 m) asl than in Zürich/Fluntern (556 m asl). Figure 7(b) shows the potential temperature deficit of the Zürich/Fluntern compared to Säntis. The pattern is very similar to that of the lapse rate. Large potential temperature deficits (>15 K) are found only in the winter half year. We can now define a cold air pool index as days with a potential temperature deficit >15 K and compare the number of cold air pool days with the FLS reconstruction. Figure 8 shows the number of FLS_{HD+} days in Zürich/Fluntern and the number of days with a potential temperature deficit >15 K for the September to March period 1901–2012. As expected, the correspondence between the two series is high. The cold air pool index also shows no clear trends and very similar decadal variability with a clear maximum around 1990 and minimum around 2000. The correlation coefficient between the FLS reconstruction and the cold air pool index is 0.69 for 1901–2012 and 0.77 for 1973–2012. Very similar results are found with a cold air pool index defined as days with lapse rate <0.2 K/100 m (not shown). Figure 8 thus shows, that the decadal

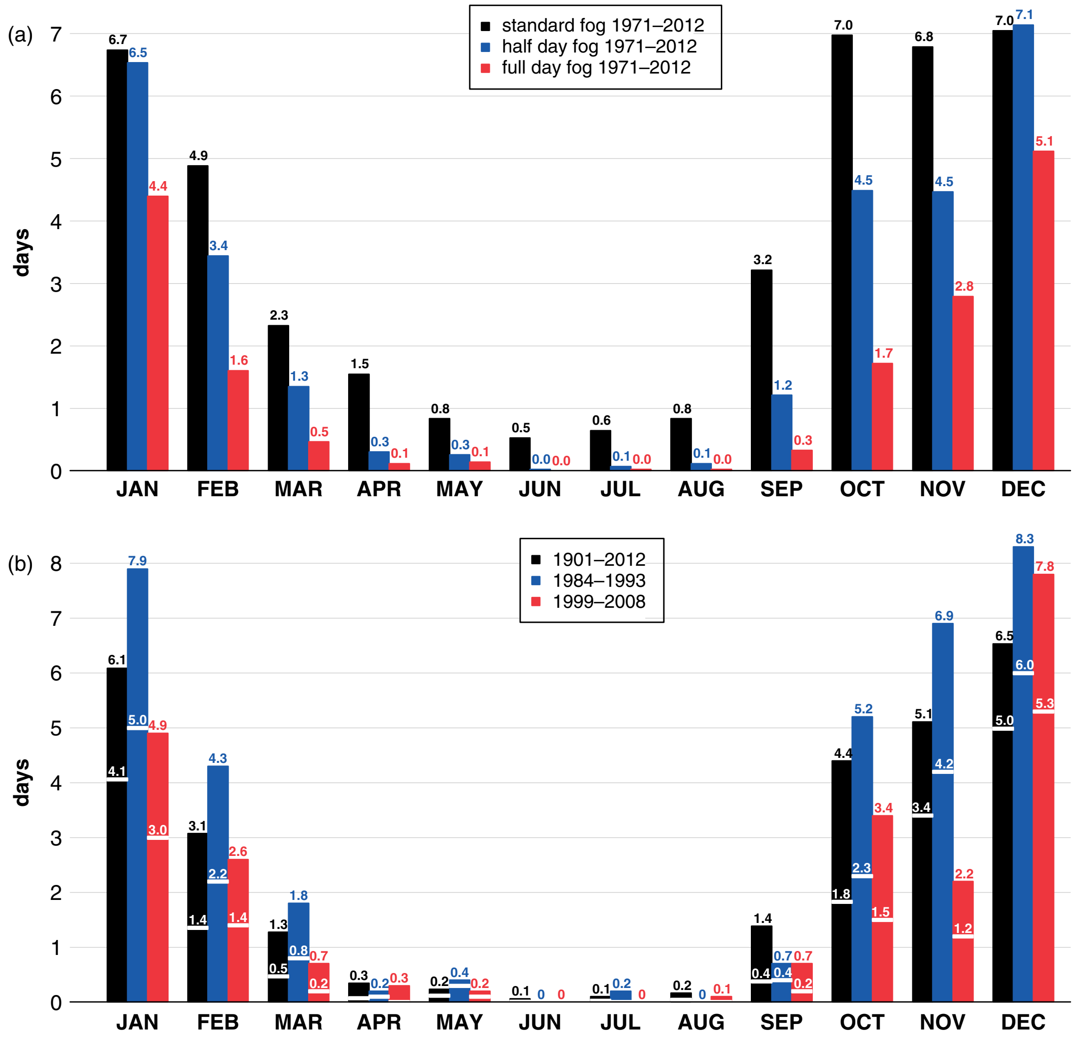

Figure 5. Monthly fog climatologies (in days per month). (a) Classical fog observations (black bars and numbers), at least half day FLS (FLS_{HD+}, blue bars and numbers), and full day FLS (FLS_{FD}, red bars line and numbers) for the period 1971–2012. (b) FLS_{HD+} (bars) and FLS_{FD} (horizontal white line and numbers) for three time periods: the full series 1901–2012 (black columns), the foggiest decade 1984–1993 (blue columns) and the decade with the least fog 1999–2008 (red columns).

Table II. Daily average temperature deviation from the monthly mean value in the period 1961–1990 (in °C) for days with at least half day (FLS_{HD+}) and full day (FLS_{FD}) FLS compared to days with no FLS for winter half year months and the period 1901–2012 at the station Zürich/Fluntern.

Fog type	October	November	December	January	February	March
FLS_{HD+}	−1.3	−2.4	−3.5	−3.6	−3.6	−3.3
FLS_{FD}	−1.5	−2.6	−3.4	−3.3	−3.4	−2.9

variability and trends in FLS days and cold air pooling have been very similar on the Swiss Plateau.

3.5. Further comment

Periods with persistent FLS have a severe impact on various aspects of daily life and on ecosystems. The details of these effects are beyond the scope of this article. One interesting question is whether the major lake freezing events in Switzerland can be related to the FLS frequency or the number of cold air pool days. We used the lake freezing data from Hendricks Franssen and Scherrer (2007) and find that neither the number, nor the average length, nor the maximum length of FLS days (cf. Figure 4) are well related to the major lake freezing events. The relation with cold pool days is a bit better. Most years with major freezing events show relatively high numbers of cold pool days (1929, 1963), but not all years with a high number of cold pool days (e.g. 1949 and 1973) are major lake freezing years. As was shown by Hendricks Franssen and Scherrer (2007), the negative degree days are a good proxy to determine when a lake freezes. These are large if very cold air masses are advected to Switzerland several times during winter and stay for a very long time on the Plateau. This is

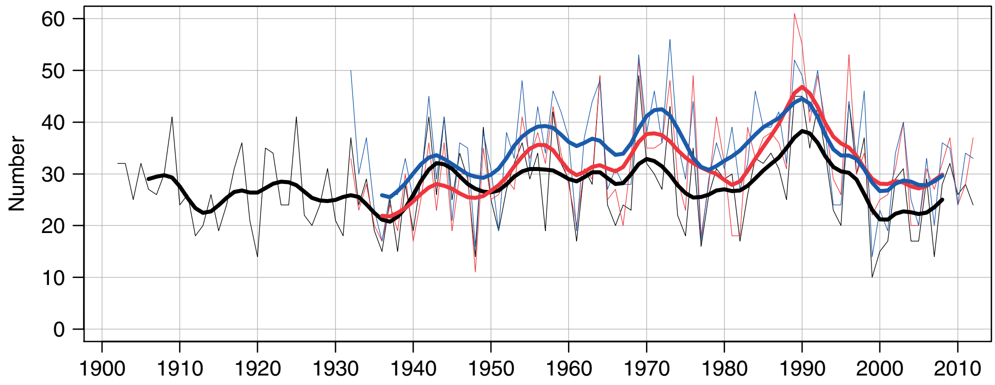

Figure 6. The number of at least half day FLS days (FLS_{HD+}) in Zürich/Fluntern 1901–2012 (black), Luzern 1931–2012 (blue) and Schaffhausen 1931–2012 (red) for the September to March periods. The thin lines show the yearly values, the thick lines an 11 year Gaussian smoothed version.

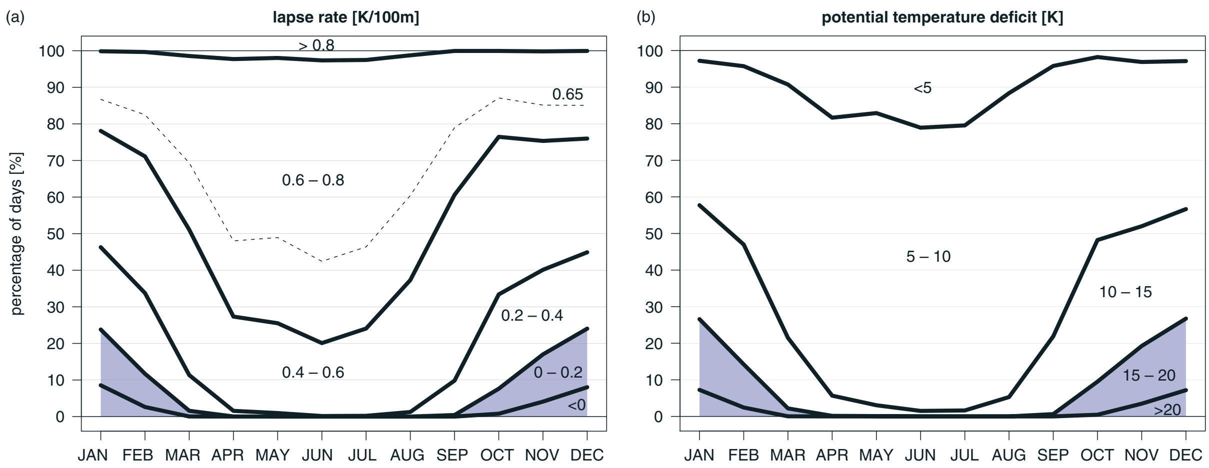

Figure 7. The percentage of days per month stratified according to (a) the lapse rate defined as the negative temperature difference with height between the station Zurich/Fluntern (556 m asl) and Säntis (2502 m asl) using daily mean temperature and (b) the Zurich/Fluntern—Säntis potential temperature deficit (K). The shaded regions (lapse rate <0.2 K/100 m and potential temperature deficit >15 K) represent the days classified as cold pool days. The dashed lines show the lapse rate of the international standard atmosphere (ISO, 1975). The data period analysed is 1901–2012.

not necessarily linked to cold air pools, since the cold air masses often affect the whole air column over the Plateau and not just the boundary layer.

4. Conclusions

Classical ground-based fog observations are of limited use for analysing the winter climatology of FLS situations in a basin such as the Swiss Plateau. We present a simple and flexible method for determining long climatological series of days with FLS lasting at least a half day (FLS_{HD+}) or a full day (FLS_{FD}). The method relies solely on high quality relative sunshine duration measurements at two stations, one within/below and one above the FLS layer. The data are restricted to daylight situations. We present three persistent FLS proxies for three locations on the Eastern Swiss Plateau for the periods 1901–2012 and 1931–2012. In contrast to classical ground-based fog defined via horizontal visibility, FLS_{FD} is a typical phenomenon of the months November, December and January (3.5–5 d per months). FLS lasting a half day or more also occurs often in October and February. There is large interannual to decadal variability. The Zürich/Fluntern September to March number of FLS_{FD} lies between 4 (year 1999) and 31 d (year 1964) with a mean of 17 d. The FLS_{HD+} vary between 10 (year 1999) and 49 d (years 1964 and 1969) with a mean of 28 d. FLS_{HD} vary between 4 (year 2000) and 24 d (year 1996) with a mean of 11 d. The period between 1984 and 1993 is the foggiest decade in the record. Strong decreases are observed just after the mid-1980s to early 1990s maximum. The decade from 1999 to 2008 is the least foggy period in the entire series with roughly 40–45% fewer FLS than only 15 years before. A slight return towards more long term mean values seems to be occurring in the most recent years. The long term trends over the whole 1901–2012 period are small and not statistically significant. Also the number of FLS events shows no clear trends over time and has small decadal variations. The average and maximum length

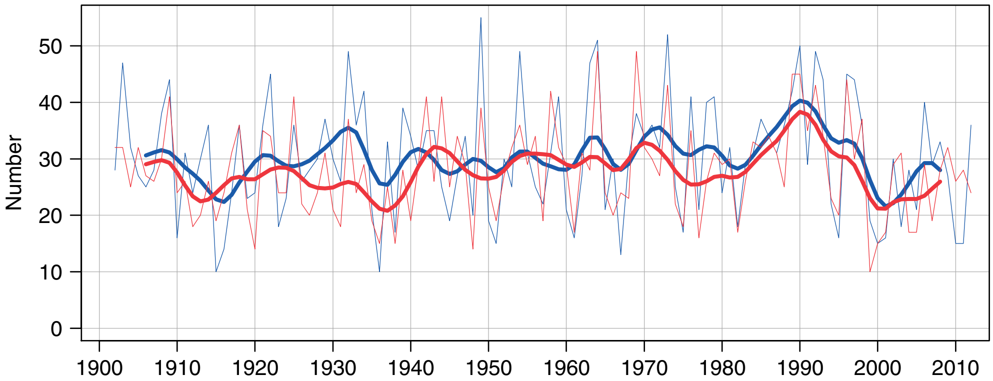

Figure 8. The 1901–2012 September to March sum of the number of days with at least half FLS days (FLS_{HD+}, red) and the number of cold air pool days (blue) in Zürich. The thin lines show the yearly values, the thick lines an 11 year Gaussian smoothed version.

of a FLS event seem to have increased somewhat in the last 30 years. The maximum length of continuous FLS events shows huge variations between 1 and 12 d. The reconstructed 1931–2012 series for Luzern and Schaffhausen are very highly correlated with the Zurich series ($r = 0.90$ and 0.84, respectively). There is a good correlation between the FLS series and the number of cold air pool days. They share very similar decadal variability and long term trend behaviour. We find that neither the number, nor the average length, nor the maximum length of FLS days are well related to the major lake freezing events.

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