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European climatology of fog and low stratus based on geostationary satellite observations

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ABSTRACT: The distribution of fog and low stratus (FLS) is of importance in nowcasting, aviation forecasting and climate applications. This paper presents satellite-derived FLS maps as a basis for building a European FLS climatology with high spatial and temporal resolution. Averaged maps covering several winter seasons of Meteosat Second Generation (MSG) data are analysed and compared to a cloud climatology based on a 26-year record of ground-based visual cloud observations. The general patterns seen in both products are found to be in good agreement and plausible. Copyright © 2009 Royal Meteorological Society

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1. Introduction

Fog and low stratus clouds are of importance for many aspects of life. They impact on traffic safety and air quality, act as a modifier in the global climate system, and they are of ecological importance as a water source in coastal deserts and tropical cloud forests. Better knowledge of fog and low stratus (FLS) distribution in time and space, i.e. a high-resolution climatology, would be of benefit for assessing regional FLS risks and potentials. For example, Vautard *et al.* (2009) recently highlighted the relevance of fog in the climate system.

Fog is commonly defined as a condition with a visibility of less than 1000 m at ground level, caused by a suspension of small water droplets in the air (e.g. Gultepe *et al.*, 2007). This approach loosely follows WMO (1992). Phenomenologically, fog is a stratiform cloud (Welch and Wielicki, 1986). The difference between fog and some (very low) stratus clouds is of little importance for some applications; e.g. aircraft are denied take-off and landing permission when the cloud base drops below a certain level (Ellrod, 2002). Also, the radiative effect of fog and low stratus in the climate system does not depend on ground-level visibility. Therefore, while a distinction between fog and low stratus is made in some places in this paper, both are mostly treated together as FLS.

Ideally, a FLS climatology needs to provide information at high temporal and spatial resolutions. However, in reality, ground-based assessments of visibility and cloud cover are discontinuous and dispersed, and therefore do not satisfy this requirement. Even where ground-based observations are available at a high spatial density, their interpolation is problematic, because visibility is a highly complex phenomenon and depends on a number of factors (cf. Schulze-Neuhoff, 1976). In comparison, weather satellite data have the advantage of continuous spatial coverage. To construct a satellite-based FLS climatology, compatible data need to be available continuously over a given period with constant coverage of the same area. Also, an operationally applicable FLS detection algorithm is required to ensure comparability.

Considering these requirements, it seems more appropriate to use data from a geostationary satellite (GEO) than from a low-earth orbiting satellite (LEO) system. While maps of relative FLS frequencies in a set of scenes can be derived from LEO systems (cf. Bendix, 2002), GEO data with more frequent coverage allow for a more representative characterization of FLS patterns over larger areas.

Based on recently developed algorithms, this paper presents maps of FLS distribution in Europe at high spatial and temporal resolution not available from other sources. The data used and techniques applied in the construction of these maps are discussed in the next section; the maps are shown and discussed in the third section. Long-term ground-based statistics of FLS occurrence are introduced as a reference and for the comparison of spatial patterns.

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2. Data and algorithms

2.1. The MSG SEVIRI system

In the past, GEOs often carried sensors with poor spatial and spectral resolutions. For instance, the series of Meteosat satellites up until Meteosat-7 provided measurements in only three spectral bands at a resolution of 5 km (Schmetz *et al.*, 2002). Improving upon this, the first of a planned four Meteosat Second Generation (MSG) systems (commonly called MSG 1, MSG 2, MSG 3 and MSG 4), MSG 1, became operational in early 2004, while MSG 2 followed in 2007. These satellites are known as Meteosat 8 and Meteosat 9 today. MSG 4, the last in the series, is planned to remain in operation until about 2015, so that continuity is ensured for some time (Munro *et al.*, 2002; Schmetz *et al.*, 2002; Schumann *et al.*, 2002). Continuity after 2015 is also provided for with the Meteosat Third Generation satellites, which will succeed the MSG series (Stuhlmann *et al.*, 2005; Aminou *et al.*, 2007).

The Spinning-Enhanced Visible and InfraRed Imager (SEVIRI) aboard the MSG satellites is designed for the continuous monitoring of the Earth–atmosphere system. At a repeat rate of 15 min, data are collected in 11 infrared and visible spectral bands from 0.6 to 13.4 μm and one broadband visible band. (cf. Schmetz *et al.*, 2002). The satellite view is centred over the Equator at 0° longitude; one scan cycle covers the hemisphere seen from this point. Channel 12, the High Resolution Visible (HRV) broadband channel, has a spatial resolution of 1 km at the sub-satellite point. The FLS scheme applied here uses the other 11 bands, with 3 km resolution (cf. Pili, 2000, for more information on SEVIRI).

2.2. Detection of fog and low stratus

A definition of fog has already been given above. From the satellite perspective, FLS can be addressed as a phenomenon with the following characteristics:

1. A cloud
2. Liquid phase
3. Small droplets
4. Low above the ground
5. Stratiform upper surface
6. Cloud base at the ground (in the case of fog)

FLS detection is implemented as a chain of processes in accordance with the above sequence of items in the Satellite-based Operational Fog Observation Scheme (SOFOS; Cermak, 2006). The method makes use of a combination of spectral and spatial tests to assess the properties of individual pixels as well as environments of pixels. A detailed description is found in Cermak and Bendix (2008) (daytime technique) and Cermak and Bendix (2007) (night-time technique). Since testing mostly relies on thresholds determined dynamically (e.g. from histogram analysis), slight calibration differences between MSG satellites are easily accommodated.

To reach a discrimination between fog and low stratus, cloud-base height is computed and then compared to surface elevation. Cloud–ground contact and thus fog presence is detected on this basis as follows:

$$z_{\mathrm{b}} \leq z_{\mathrm{s}} \longrightarrow \text{fog} \qquad (1)$$

with z_{b} cloud-base height and z_{s} surface elevation. While the latter is taken from the GTOPO30 digital elevation model (USGS, 1993), the former is computed by fitting a model of cloud water distribution to cloud liquid water path retrieved from satellite data using the technique proposed by Kawamoto *et al.* (2001) as described in Cermak (2006). Cloud liquid water path and hence fog detection is available during daytime only.

Quantitative validation studies for all algorithms introduced above are presented in the various publications referenced above; a brief summary is given in the following sentences. In these studies, performance of the methods was evaluated statistically. As an overall measure of performance, threat scores (also called 'critical success index') were computed; they express the total fraction of the correctly identified occurrences of fog and/or low stratus in all predictions and observations of the situation to be detected (Marzban, 1998; Wilks, 2006). Threat scores found in the evaluation were around 0.7. Two main technical issues account for the difference to the ideal threat score value of 1.0 encountered in the validation studies: (1) FLS is not detected when there is another opaque cloud layer above. (2) Fog patches of very small spatial extent in the sub-pixel region will not be detected reliably. Both limitations lie within the nature of the satellite-based approach and cannot be remedied. However, these cases are relatively small in number and become less important when considering multi-temporal series. A detailed treatment of the issues to be considered in the interpretation of the validation results is given in Cermak and Bendix (2008).

2.3. Aggregation

The products described in the previous section are computed operationally on all MSG SEVIRI scenes received at the Laboratory for Climatology and Remote Sensing (LCRS), Marburg, Germany (Cermak *et al.*, 2008). All scenes from early 2004 to February 2008 have now been reprocessed using the newest versions of the FLS algorithms described above, except for the fog algorithm, which is more computationally expensive. For a number of reasons, the regional focus is on Europe: (1) Due to data availability, the validation of the algorithms (see above) took place in this region. (2) A great range of FLS types and situations occur here. (3) Focussing on one limited area saves computation time.

Since validation data are available mostly for land areas and algorithm testing was performed there accordingly, sea areas are not considered in this study. On the basis of the products described above, an averaging of all FLS products for 2004 to 2008 was performed. In the averaging ('aggregation'), all available scenes were considered without prior selection.

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2.4. Ground-based climatology

The satellite-derived averages are compared to cloud-cover maps produced on the basis of visual observations from European weather stations.

Stations where routine observations are made during both day and night were selected according to criteria given by Warren *et al.* (2007), giving a total of 1190 stations in Europe (excluding the former Soviet Union). Observations are usually made eight times per day, at universal time (UTC) hours 0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100. The observations are reported in the synoptic code of the World Meteorological Organisation (WMO), which requires the reporting of several cloud variables (WMO, 1956, 1974). The variables relevant to this work are total cloud cover (N), low cloud amount (Nh), low cloud-base height (h), low cloud type (CL), and present weather (ww). The cloud amount is given in oktas (eighths). The low cloud type is a code value from 0 to 9, of which the stratiform clouds are CL=4 (stratocumulus formed by spreading out of cumulus), CL=5 (stratocumulus not formed by spreading out of cumulus), CL=6 (stratus not of bad weather), CL=7 (bad-weather stratus or fractostratus), and CL=8 (cumulus under stratocumulus). Fog is not reported in the CL code; it is instead reported in the present weather, a code value (ww) from 00 to 99, of which several indicate fog (10–12, 40–49). For the climatology of Hahn and Warren (1999, 2003) the ww code was consulted for fog only if N=9 (sky obscured). The climatology thus gives the frequency of occurrence of 'sky obscured due to fog', and excludes fog at a distance and patchy fog through which cloud levels above the fog would be detectable. A climatology was developed for each weather station for the years 1971–1996, for each season, each month, and each of the eight reporting hours (Hahn and Warren, 2003). The station climatologies were averaged to form a gridded FLS climatology on a $5^\circ \times 5^\circ$ latitude–longitude grid (Hahn and Warren, 2007, http://www.atmos.washington.edu/CloudMap/). Some analyses of the observations for Europe were reported by Warren *et al.* (2007) at the finer resolution of $2.5^\circ \times 2.5^\circ$.

The amount of a cloud type is defined as the average fraction of the sky covered by that cloud type, and is obtained as the product of frequency of occurrence and amount-when-present (awp) (Warren *et al.*, 2007). For example, if stratocumulus is reported present in 50% of the observations in a month, and covers 60% of the sky when it is present, the monthly average stratocumulus amount at that station is 30%. In Europe in winter, the awp values of these cloud types are large, averaging about 70% for stratocumulus, 80% for stratus, and 100% for fog.

3. Distribution of FLS in Europe: Satellite maps

Averaging of satellite products as described in section 2 was performed for periods from months to seasons and years.

Figure 1 shows the frequency of FLS occurrence in the months December to February. Figure 1(a) displays the satellite-derived frequency of FLS days as averaged over the four seasons available at the time of writing: 2004–2005 to 2007–2008. A FLS day was counted whenever eight or more scenes indicated FLS presence. All available scenes were used (up to 96 scenes per day). In Figure 1(b), the average amount of FLS clouds in all December to February station observations for the years

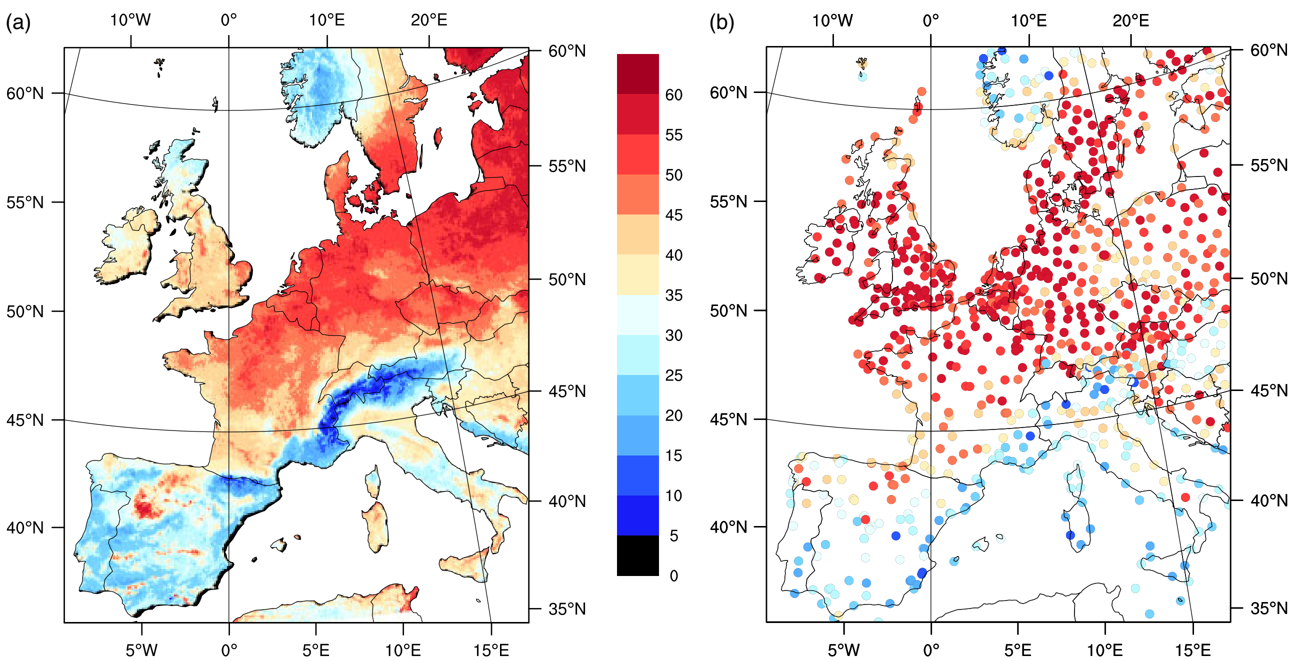

Figure 1. Relative frequency (%) of days with winter FLS (December–February). (a) MSG observations, 2004–2005 to 2007–2008 (16092 scenes). (b) Ground-based observations, 1971–1996. This figure is available in colour online at www.interscience.wiley.com/journal/qj

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1971–1996 is presented. Unfortunately, for unknown reasons, cloud types for stations in Switzerland were not available in the data source used by Hahn and Warren, so that part of Figure 1(b) is blank.

Apart from the obvious differences (i.e. more spatial detail in the satellite map, longer time series in the ground-based map, no temporal overlap between the two maps), the general patterns observed in both presentations agree well. There is a clear decreasing trend in FLS occurrence from North to South. In Scandinavia, more FLS is encountered in the East, in the Baltic Sea area. Some smaller-scale features, such as the higher frequency of FLS situations in north-central Spain or the reduced FLS amount along the Dalmatian coast (around 44°N, 16°E), are shown in both maps. Other small-scale patterns are only visible in the spatially continuous satellite map. One of these is the enhanced FLS occurrence on the Swiss Plateau and in the Danube valley (around 45°N, 8–15°E). In the Austrian Alps and in the northern Pyrenees, satellite-reported FLS frequency seems to be lower than that observed at ground stations. This apparent disagreement between the two methods can be partly explained by fog. The fog occurs in valleys below the mountaintops; most weather stations are in those valleys and therefore are not representative of the larger area. Representative station measurements at higher altitudes are missing. Also, features detected at station locations might not be spatially representative and thus be lost at sub-pixel scale. Another difference between the two maps is seen in the British Isles, where satellite-observed frequency is about 10–15% below ground-station averages. This could be due to differences in the two periods for which the data sets were compiled, possibly indicating reduced FLS frequency in the later years (in accordance with observations by Vautard *et al.*, 2009). Another explanation would be frequent high-cloud situations masking FLS from the satellite view.

In Figure 2 an anomaly map based on SOFOS satellite products is shown, highlighting the difference of days with FLS in January to March 2007 versus the mean of the same months in 2004–2006. Apparently, FLS occurrence was more frequent in southern Europe in the year 2007 than in the previous years. In particular, Spain and northern Italy (the Po valley; '1' on the map) display higher levels. The same applies to the Pannonian Plain ('2') centred on Slovakia. In the British Isles the trend is reversed. The deviation map underlines the climate-monitoring potential of the satellite-derived FLS maps.

Daytime ground fog occurrence can also be quantified. Although (due to limited computer processing capacities) data for only one month are considered here, some plausible patterns can be observed in Figure 3. In December, solar elevations in the north are low and the daytime fog detection algorithm (which requires a minimum solar elevation of 10°) is not applicable for prolonged periods of the day. Therefore, areas north of 57°N have been blanked out. To highlight the high temporal resolution of the satellite data, this figure is presented in total fog hours per month, a unit sometimes used in operational climatology. Since satellite data are

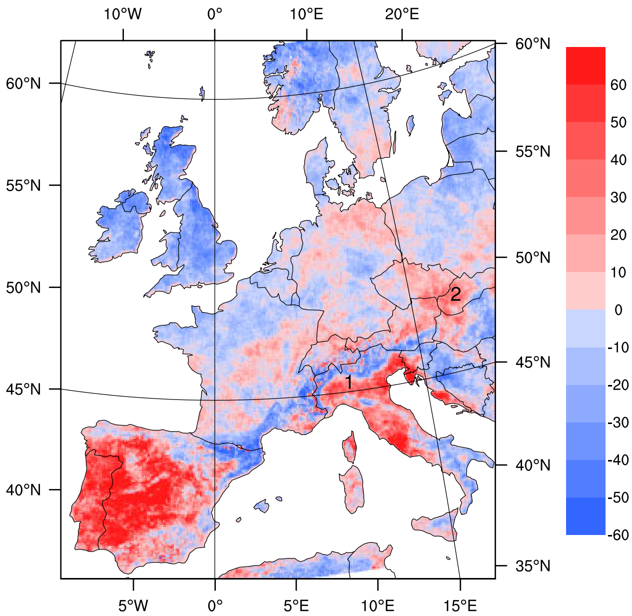

Figure 2. FLS anomaly (%) for JFM 2007 versus 2004–2006 (13185 scenes for 2004–2006, 3669 scenes for 2007. 1: Po valley, 2: Pannonian Plain. This figure is available in colour online at www.interscience.wiley.com/journal/qj

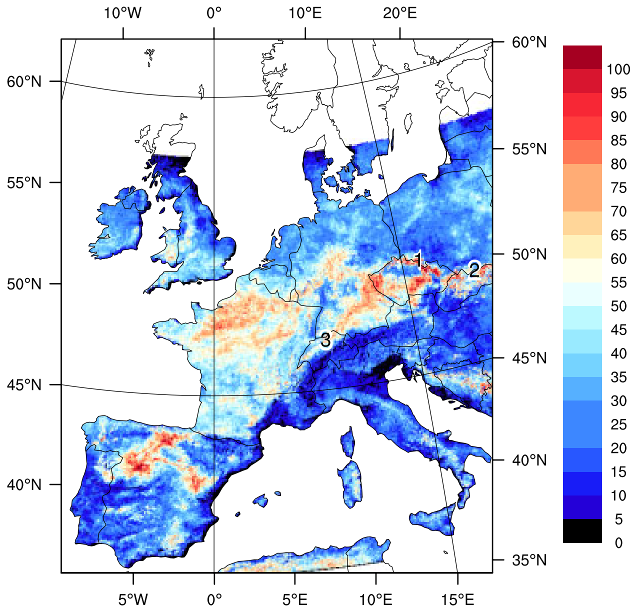

Figure 3. Total hours with ground fog, December 2004, daytime (1665 scenes; 31 days). 1: Sudetes, 2: Carpathians, 3: Swiss Plateau. This figure is available in colour online at www.interscience.wiley.com/journal/qj

available at 15 min intervals, a fog hour is counted for every four scenes reporting fog occurrence.

According to this map, in December 2004 ground fog occurrence was high in the fog-prone regions of northern France, the mountainous and elevated areas of Spain, Germany and the Czech Republic, along the Sudetes ('1' in the map), the Carpathians ('2'), and on the Swiss Plateau ('3'). Regions at lower elevations, such as the Netherlands, northern Germany and the Polish plains had a lower number of ground fog hours. The ability to produce maps of FLS hours is one of the greatest advantages of geostationary FLS detection; compatibility with routine weather observations at meteorological stations can be achieved in this way.

4. Conclusions and outlook

The FLS maps presented above provide information on FLS distribution in Europe with spatial detail not available before. Spatially continuous maps of FLS days based on multiple daily observations and maps of FLS hours per day introduce a new level of temporal precision. The general agreement with the patterns derived from ground-based observations is encouraging. Of course, a climatology is defined as the longer-term average state of a given parameter, the usual period being 30 years. Time series of this length are not available from MSG at this stage. However, the results presented here set the basis for a European climatology at high temporal and spatial resolutions that will have to be built in the coming years and decades.

In an analysis of station data for the last 30 years, Vautard *et al.* (2009) showed a relationship between the frequency of fog situations and surface temperature. However, their analysis only considered visibility observations at selected stations. Given the distribution of meteorological stations, large (mostly remote) areas are not included in their study, reducing the representativity of the findings. Also, they do not consider low stratus situations without ground contact. A satellite-based climatology as presented in this paper expands the database and will help gain a better understanding of FLS dynamics in a changing climate.

One of the main future challenges will be the merging of ground-based cloud climatologies reaching into the past with time series to be generated from satellite-based and ground-based observations. The availability of harmonious data series is vital for applications in climate research. This requires exploration of differences and commonalities in both types of product. Especially, the absolute frequencies of FLS occurrence will have to be explored in detail. As mentioned above, the satellite product does not detect FLS situations hidden under opaque cloud layers at higher levels. The development of a technique using multi-source information (e.g. blending ground-based and satellite data) may be necessary to resolve this problem.

The satellite product itself will be further developed in various ways and as satellite systems permit. Extending the current land-only product to include ocean coverage is an obvious priority. Also, the detection of fog presence at night is a component currently being worked on.

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