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Enhanced Nighttime Fog and Low Stratus Occurrence Over the Landes Forest, France

Eva Pauli[1,2], Jan Cermak[1,2], and Adriaan J. Teuling[3]

[1]Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, [2]Institute of Photogrammetry and Remote Sensing, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, [3]Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, The Netherlands

Key Points:
- Fog and low stratus (FLS) cloud cover is enhanced over the French Landes forest at night
- FLS cloud cover enhancement is most pronounced in summer and fall
- Low wind speed and low temperatures over the forest are potential drivers of FLS enhancement

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

E. Pauli,
eva.pauli@kit.edu

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Author Contributions:
Conceptualization: Eva Pauli, Jan Cermak, Adriaan J. Teuling
Formal analysis: Eva Pauli
Investigation: Eva Pauli
Methodology: Eva Pauli, Jan Cermak, Adriaan J. Teuling
Visualization: Eva Pauli
Writing – original draft: Eva Pauli
Writing – review & editing: Eva Pauli, Jan Cermak, Adriaan J. Teuling

Abstract

Understanding the drivers of fog and low stratus (FLS) cloud occurrence is important for traffic, ecosystems, and climate models, but it is challenging to analyze due to the complex interactions between meteorological factors and land cover. Here, we use active and passive satellite data, as well as reanalysis data to investigate nighttime FLS occurrence over the expansive Landes forest in France from 2006 to 2015. We find significant FLS enhancement over the forest compared to surrounding areas, especially in summer and fall. Lower wind speed and lower temperatures are found over the forest at night, which can enhance FLS development over the forest. Still, other drivers, such as biovolatile organic compounds acting as cloud condensation nuclei, are most likely important as well. The results show that the influence of forests on boundary layer clouds is not limited to convective daytime conditions.

Plain Language Summary

Fog and low stratus clouds (FLS) are influenced by various drivers. Their relationship to land cover, specifically forest, is thus difficult to investigate. In this study, we analyze nighttime FLS cover over a large forest area in south-western France using a mix of different types of satellite data. We find higher FLS occurrence over the forest area compared to its surroundings, especially in summer and fall. Lower temperatures and wind speed over the forest could contribute to this enhancement. These results can help when predicting FLS for traffic and underline the importance of different land cover types for weather and climate.

1. Introduction

Interactions between the land surface and clouds are manifold and highly dependent on cloud type as well as geographical region. The intensity and direction of these interactions are still uncertain. Considering the influence of surface characteristics on energy fluxes on the surface and the boundary layer (Pielke, 2001), specifically the effects of land cover on boundary layer clouds has been the subject of research in the past (Ray et al., 2003; Teuling et al., 2017; Theeuwes et al., 2019; Wang et al., 2009). An enhancement of convective cumulus cloud cover compared to the surroundings has been reported over forests, including the large Landes forest in southern France (Teuling et al., 2017), megacities (Theeuwes et al., 2019) and natural bushland (Ray et al., 2003). However, an increase in shallow cloud cover has also been found over deforested areas in eastern Amazonia (Wang et al., 2009). This is in line with findings from Xu et al. (2022), who found enhanced cloud cover over most temperate and boral forests but decreased cloud cover over forests in Amazonia, Central Africa, and the Southeast US. Possible reasons for shallow cumulus enhancement over forests are higher evaporation (Gentine et al., 2013) and higher sensible heat flux (Bosman et al., 2019; Gambill & Mecikalski, 2011) over forests, as well as higher aerodynamic roughness, leading to the development of a forest breeze (Mahrt & Ek, 1993). Besides the physical mechanisms for low cloud cover enhancement, biogeochemical processes can contribute to cloud development. Biovolatile organic compounds (BVOCs), emitted by forests can form secondary organic aerosols (SOA), which can act as cloud condensation nuclei (CCNs) and thereby favor cloud formation (Pöschl et al., 2010; Shrivastava et al., 2017). Enhanced emission of BVOCs has been found over the Landes forest (Kammer et al., 2018) while enhanced cloud cover due to the release of BVOCs has been found over boreal forests (Spracklen et al., 2008).

While the mechanisms for convective cloud enhancement over forests are understood relatively well, this is less in the case for fog and low stratus clouds (FLS). Topography is known to strongly influence FLS, leading to a higher FLS cover in valleys compared to mountainous areas (Bendix, 1994; Scherrer & Appenzeller, 2014). Higher temperatures, lower saturation of air with water vapor, and an increase in air quality lead to reduction of fog (Gray et al., 2019; Klemm & Lin, 2016; Yan et al., 2020), and have been observed to induce fog holes over urban areas (Gautam & Singh, 2018; Williams et al., 2015). An earlier onset of fog formation has been observed over fields compared to bare soil (Roach, 1995) and over a homogeneous grass surface compared to a surface with trees (Mazoyer et al., 2017). The influence of fog on vegetation has been well-studied for several specific ecosystems around the world, including tropical-montane cloud forests (TMCFs) (Weathers et al., 2019), in the Namib desert (Gottlieb et al., 2019) or in the Californian redwood forests (Dawson, 1998). Here, fog plays a major role for water and nutrient input. Still, temporally and spatially extensive studies looking at the influence of land cover on fog and low clouds are rare.

Satellite data can potentially provide information on fog and low stratus clouds over larger areas not covered by weather stations. Passive sensors, such as the geostationary Meteosat Spinning Enhanced Visible and Infrared Imager (SEVIRI), provide high temporal resolution and cover a large area, and have been used successfully for the detection of FLS in Europe (Cermak et al., 2009; Cermak & Bendix, 2011; Egli et al., 2017) and the Namib desert (Andersen & Cermak, 2018). Still, classification errors, small-scale FLS features and multiple cloud layers can lead to misclassifications (Cermak & Bendix, 2008; Cermak, 2018). These classification errors can be minimized when using active satellite data such as LiDAR data from Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations (CALIPSO) (Cermak, 2018; Vaughan et al., 2009). Despite its low temporal sampling rate, CALIPSO data is still highly valuable for the study of fog and low cloud patterns, especially when combined with passive satellite data.

To isolate potential local effects of forests on fog and low cloud occurrence, the strong influence of topography on FLS occurrence discussed above should be minimized. A forested area with low topographic variability (cf. Figure S1 in the Supporting Information S1) and large spatial extent is the Landes forest in southern France. Here, we analyze nighttime (0–6 UTC) fog and low stratus cloud cover over the Landes forest over a period of 10 years. We compare the FLS detection based on passive and active satellite data, and thus minimize the influence of potential misclassifications on the results. Furthermore, we investigate seasonal differences of FLS cover over the area and analyze the influence of wind and temperature on the observed patterns. With this long-term analysis, we can discuss potential interactions of FLS and forests, independent of satellite sensor and short-term fluctuations in FLS cover.

2. Data and Methods

2.1. Data

The Landes forest covers an area of about 12,000 km^2 in southern France directly at the Atlantic coast. The forest is mainly composed of maritime pine (*Pinus pinaster*) (Kammer et al., 2018) and shows a distinct contrast to its surrounding land cover types (compare Figure 2d). The study site has previously been used for the investigation of daytime cumulus clouds using satellite data, showing its potential for the investigation of land-atmosphere interactions (Teuling et al., 2017).

The primary fog and low cloud data set used in this study was created by Egli et al. (2017). It uses passive satellite data from Meteosat SEVIRI following the Satellite-based Operational Fog Observation Scheme (SOFOS) by Cermak (2006) using the approach presented in Cermak and Bendix (2007) for nighttime data. The resulting data set provides a binary FLS mask for every 15-min time step covering the entire central European land mass and the years 2006–2015. The data set has been validated against ground observations, showing that 80%–90% of FLS and no-FLS situations are classified correctly (Egli et al., 2017). The binary FLS mask is available for daytime and nighttime hours but not during, as well as shortly before and after twilight due to sensor and algorithm constraints. For the purpose of this study, nighttime observations (0–6 UTC) of FLS are used. This is in line with BVOC emissions observed during night over the Landes forest (Kammer et al., 2018), which can potentially serve as CCN. The time frame of 0–6 UTC was chosen to minimize the amount of missing observations during twilight and to select a time frame with nighttime observations across all seasons. As a plausibility check for the FLS data set by the passive satellite sensor, an additional FLS classification based on active satellite data from CALIPSO was created. For this, the CALIPSO level 2 1-km cloud-layer product (Version 4.20) (NASA Langley Atmospheric Science Data Center DAAC, 2018) was used. The cloud and aerosol discrimination (CAD) algorithm classifies 90% of layers correctly (Liu et al., 2009). Over the 10 years, 186 nighttime overpasses over the

Landes region were available. Due to missing data in both data sets, 179 of those overpasses could be used for comparison.

For the surface (10 m) winds, ERA5-land reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) was used (Muñoz Sabater, 2019). For temperature and wind data at different pressure levels ERA5 was used as well (Hersbach et al., 2018). The land cover data plotted in the results is taken from HILDA (Winkler et al., 2021). The Fraction of Vegetation Cover data serving as the background for the binary FLS maps are based on data from the EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF) (Trigo et al., 2011).

2.2. Methods

The CALIPSO overpasses usually took place between 02:15 and 02:30 in the night. The CALIPSO FLS mask was derived similarly to the approach presented in Cermak (2018). First, the cloud layer altitude was calculated by subtracting the terrain altitude from the observed feature altitude. Then all cloud layers with a cloud top height equal to or smaller than 2.5 km and a cloud base height equal to or smaller than 2 km were defined as FLS. The thresholds differ slightly to those used in Cermak (2018) to include not only fog but also low stratus clouds.

To compare the SEVIRI based data set with the FLS mask derived from CALIPSO, the FLS observations of both data sets at the location of the CALIPSO overpass were contrasted by creating a confusion matrix. The time step of the SEVIRI-based data set used for comparison was 02:15 UTC. To take into account the larger pixel size of SEVIRI and the small mismatch of observation time of both data sets, the comparison was done for the complete CALIPSO swath area across the forest area and not pixel-by-pixel. For example, an observation was marked as true positive, when any pixel along the CALIPSO swath for both data sets showed FLS. If there was no FLS pixel in both data sets, the observation was marked as true negative.

This comparison was followed by creating nighttime averages of FLS using the data from 0 to 6 UTC of the SEVIRI based data set. The respective days belonging to one of the categories of the confusion matrix were flagged accordingly.

3. Results

3.1. Cross-Validation of FLS Products

Out of the 179 used CALIPSO observations, 50 were identified as true positive and 83 as true negative. On 12 observations, no FLS was identified by CALIPSO but FLS was identified by the SEVIRI based data set (false positive). On 34 observations, FLS was identified by CALIPSO, but no FLS was present in the SEVIRI data set (false negative). Possible reasons for this could be multilayer cloud situations or classification errors in the FLS data set (cf. Cermak and Bendix (2008); Cermak (2018)). Further reasons are also described in the discussion. The confusion matrix can be found in Table S1 in the Supporting Information S1.

Two true positive cases are displayed in Figure 1. On 2008-07-14 (Figure 1a) most of the forest is covered by a large FLS patch, which is also visible in the CALIPSO profile, where the cloud top is situated at approximately 2.5 km and cloud base at or below 2 km. A slight mismatch of the two products is visible at the CALIPSO swath at 44°N, where no FLS is present in the SEVIRI-based product, but FLS is present in the CALIPSO based product. On 2015-09-20 (Figure 1b) both FLS patches over the forest and south of the forest are present in both data sets.

3.2. Climatological Means

To decrease and visualize the influence of potential misclassifications on the climatological mean of nighttime FLS cover, three types of climatological means were constructed using the FLS data set:

1. Climatological mean over all days of the SEVIRI based data set by Egli et al. (2017) (3,652 days)
2. Climatological mean over days with CALIPSO overpasses (179 days)
3. Climatological mean over days where the FLS observations of the SEVIRI and CALIPSO based data set match (true positives and true negatives) (133 days)

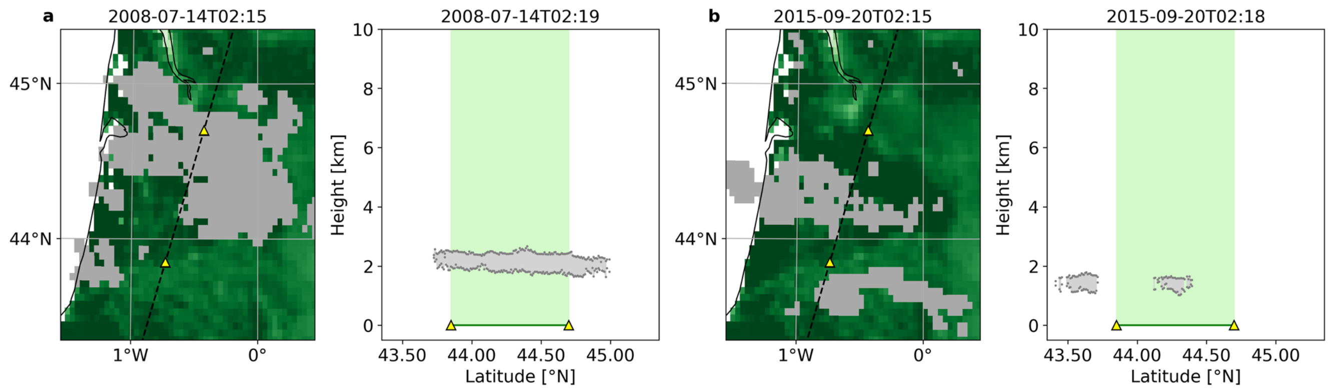

Figure 1. Example validation of Spinning Enhanced Visible and Infrared Imager (SEVIRI)-based fields with the corresponding Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations (CALIPSO) profiles. Shown are two days, 2008-07-14 (a) and 2015-09-20 (b), with the SEVIRI based Fog and low stratus (FLS) maps on the left and the corresponding CALIPSO profiles on the right. The gray pixels in the maps of the SEVIRI-based data set display FLS, the background is a map of mean fraction of vegetation cover of the study area. For orientation, the CALIPSO swath is plotted as a dashed line in the maps. In the CALIPSO profiles, the cloud layers are plotted as a gray area at their corresponding height and with their latitudinal extent. The green line, as well as the light green background in the profiles mark the forest area. The yellow triangles in both the maps and the profiles mark the beginning of the forest area.

The corresponding maps, together with a land cover map of the Landes region are shown in Figure 2. In all three climatology maps, mean FLS cover from 0 to 6 UTC is higher over the forest, with differences in mean FLS cover between forest and non-forest most distinct in the northern forest area. Nighttime FLS cover is up to 1 hr longer over the forest than over the surrounding areas and local patches of enhanced FLS cover over the forest are visible (e.g., south of 44°N). The difference in nighttime FLS cover over forest versus other land cover types is significant (two sample *t*-test, $P < 0.05$, Table S2 in the Supporting Information S1) for all three climatologies, and strongest for the true positive and negative days (Figure 2c). This significance independent of calculated climatology, shows the robustness of the results.

3.3. Seasonal Analysis

A seasonal analysis of FLS cover (only true positive and true negative observational days) shows that nighttime FLS enhancement over the forest is significant ($P < 0.05$) for all months except January, February, June, and October (see Table S3 in the Supporting Information S1 for all *t*-test results and Figures S1 and S2 in the Supporting Information S1 for all monthly maps). The difference in mean FLS cover between forest and non-forest areas is shown here for the months of May, July, August, and September (Figure 3a), when FLS is most likely the result of more localized processes, as opposed to the winter months. Nonetheless, differences in FLS cover between forest and non-forest areas can still be significant in winter but are most likely due to higher FLS cover over the study area but lower FLS cover in the Pyrenees (south of 43.5°N) (cf. Egli et al. (2017)). In May, especially the central Landes forest shows enhanced nighttime FLS compared to its surroundings. In July, enhanced FLS cover extends to the south of the forest, toward the Pyrenees. In August, the shape of the forest is quite well replicated by the pattern of enhanced FLS cover over the forest. In September, nighttime FLS cover is enhanced mostly in the central and western parts of the forest. Similar to the patterns depicted in the full-year means in Figure 2, local patches of enhanced FLS cover are apparent inside the forest area in all of those monthly plots.

To investigate the potential reasons for high FLS cover over the Landes region, maps of mean wind speed are created. They show lower wind speed over the forest compared to the surrounding area (around 0.5 m s^{-1}) (Figure 3b) and wind speed is highest directly at the coastline. The differences in mean wind speed above forest and non-forest pixels are significant (two sample *t*-test, $P < 0.05$, Table S3 in the Supporting Information S1) in March, April, June, July, and August. The main wind direction is west, with variations over the different months and over the study area. Patterns of wind direction also seem to be split into two subpatterns, with westerly winds prevailing near the Pyrenees (south of 44°N) and changing wind directions north of 44°N, for example, with northerly winds in July and August.

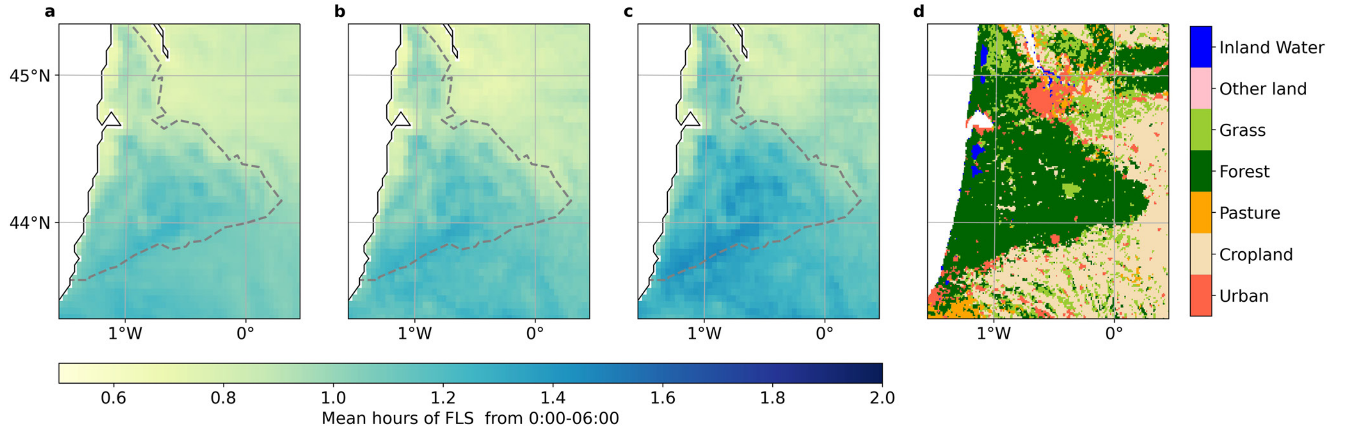

Figure 2. Spatial distribution of climatological mean Fog and low stratus (FLS) cover over the study region. In (a) all observations from 2006 to 2015 are used to calculate mean FLS cover (3,652 days), in (b) only days with Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations overpasses (179 days), in (c) only true positive and true negative observations (133 days), and (d) shows HILDA land cover for the year 2006. The gray dashed line approximately marks the forest border.

3.4. Vertical Temperature Profiles

To better understand boundary layer effects on enhanced FLS cover over the Landes region, vertical profiles of temperature gradient in combination with wind vectors on the different pressure levels are analyzed. For this study, the temperature gradient is calculated by subtracting the temperature of a pressure level from the temperature of its overlying layer, that is, positive values indicate a temperature inversion. In Figure 4, hourly means over the respective true positive and true negative days in August (Figures 4a and 4b) and September (Figures 4c and 4d) are presented. Both longitudinal (Figure 4a) and latitudinal (Figure 4b) vertical profiles show a temperature inversion (positive temperature gradient) over the forest compared to the surrounding areas, especially at

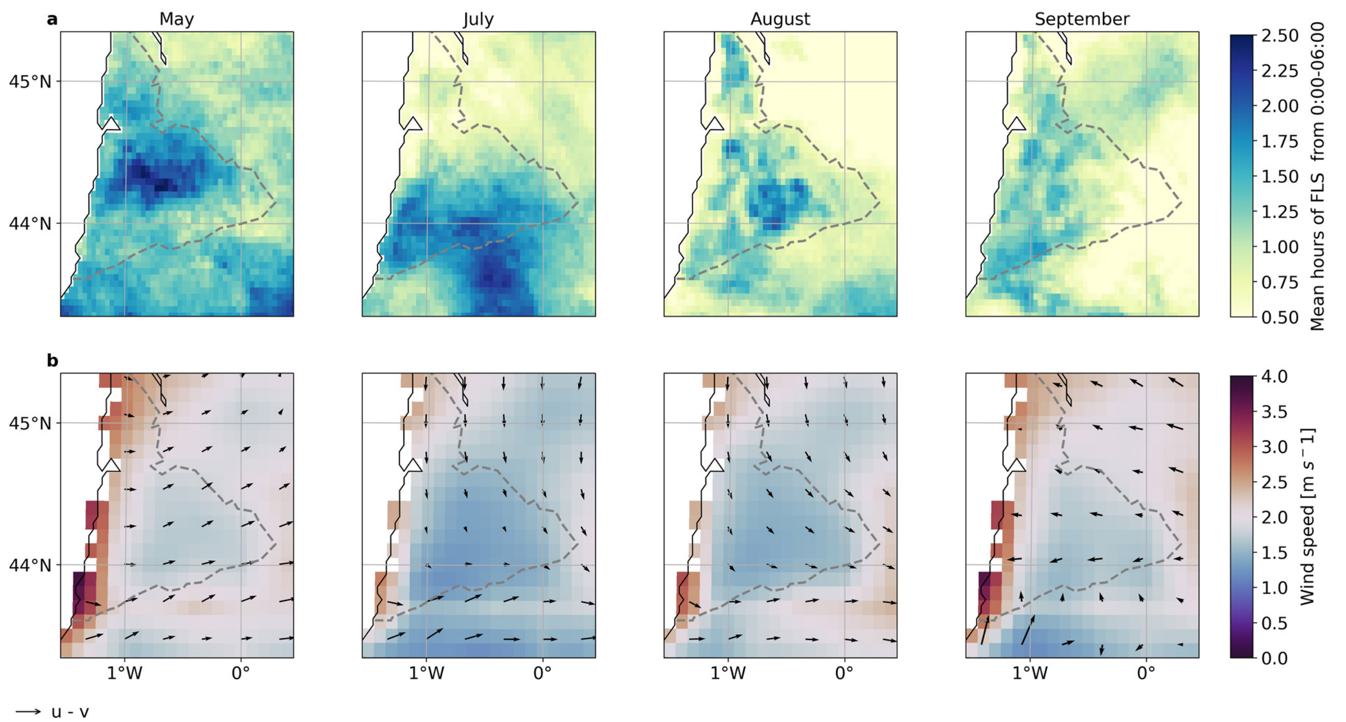

Figure 3. Climatological mean fog and low stratus hours by month based on true positive and true negative observations (a), and the corresponding ERA-5 land wind speed and wind direction (u and v wind components) on the respective days (mean from 0–6UTC) (b). The number of true negative and true positive days available to calculate the climatologies is as follows: 9 (May), 11 (July), 12 (August), and 13 (September). The gray dashed line approximately marks the forest border.

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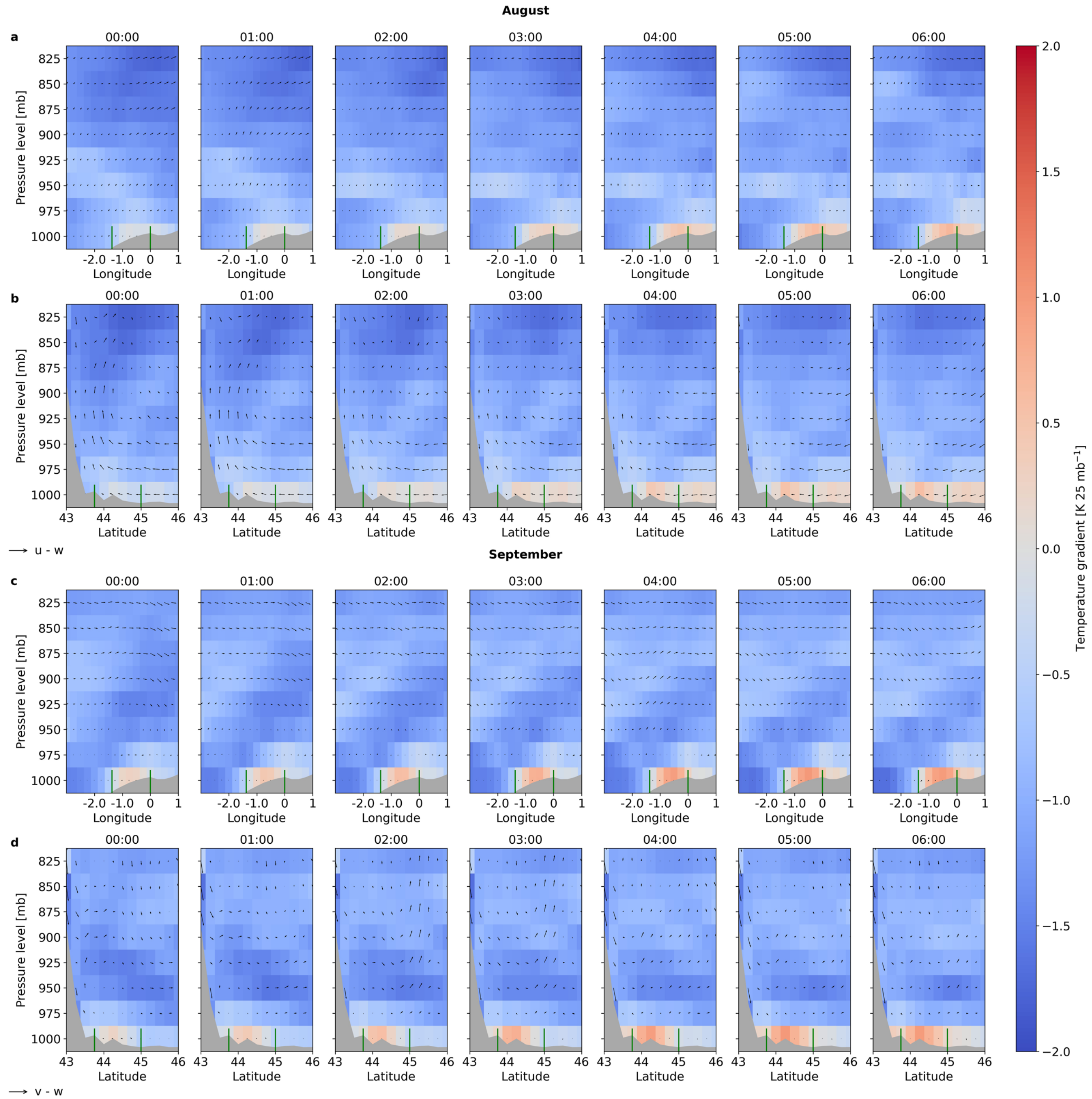

Figure 4. Profiles of mean hourly temperature gradient in K 25 mb^{-1} for the true positive and true negative days in August (a and b) and September (c and d), from 825 to 1000 mb along 44.25°N (a and c) and −0.25°W (b and d). In the longitudinal profile (a and c) u-w wind vectors are plotted, in the latitudinal profile (b and d) v-w wind vectors are plotted. For visibility reasons, the w vector is enhanced by a factor of 20. The location of the Landes forest is marked in both plots as green vertical lines. The topography is plotted in gray.

05:00 and 06:00 UTC. In August, the temperature gradient reaches values up to +0.67 K 25 mb^{-1} at −0.25°W in the longitudinal profile and +0.57 K 25 mb^{-1} at 44.25°N in the latitudinal profile. In September, the temperature gradient reaches values up to +1 K 25 mb^{-1} at 44.25°N and −0.5°W (both in the latitudinal and longitudinal profile). The u-w component vectors plotted in the longitudinal plots are very weak, whereas the v-w component vectors (latitudinal plot) show wind from the north in the pressure levels up to 850mb during the night. Especially at 00:00 and 01:00 UTC air rises at around 44°N, just before the Pyrenees. Over the night the v-w wind component weakens.

4. Discussion

The passive and active satellite data used in this study reveal enhanced FLS cover over the Landes forest compared to the surroundings. Both data sets agree well in most cases (74%), disagreement is potentially due to misclassifications in the FLS data set (cf. Cermak (2018)) or due to difficult FLS detection in the transitional zone ("twilight zone") between aerosols and clouds (Koren et al., 2007). Local patterns of higher FLS cover over the forest area are visible, especially in the southern part of the Landes forest. This is similar to the findings by Teuling et al. (2017), who found enhanced daytime cumulus cover over the Landes forest with local maxima in the southern part of the forest. FLS enhancement over the forest compared to the surrounding areas is primarily visible in summer and fall, when local processes are potentially more important than in winter.

Various drivers are important for the development of FLS (Pauli et al., 2020). Here, the roles of wind speed and temperature are investigated. Based on the results of the *t*-test we identify lower wind speeds over the forest as a potential driver of higher FLS occurrence, especially in the summer months. While some turbulence is required for the formation of a stable fog layer (Haeffelin et al., 2010), lower wind speeds are generally beneficial for FLS development (Bergot, 2016; Bergot & Lestringant, 2019; Gradstein et al., 2011; Pauli et al., 2020; Roach, 1995). Similar to the processes described in Gradstein et al. (2011) for lowland cloud forests, low wind speeds combined with nighttime cooling and saturation of air are a potential pathway leading to the enhanced FLS cover described in this study.

The vertical profiles of temperature gradient show lower temperatures and a positive temperature gradient in the forest area at night, which is unusual for temperate forests since they usually have higher nighttime temperatures than their surroundings due to turbulence and the storage of heat (Li et al., 2015; Schultz et al., 2017). Still, in both of these studies, the Landes region seems to be an exception, showing lower temperatures over the forest compared to unforested areas. A potential explanation is a strong nighttime cooling through evapotranspiration, similar to nighttime cooling over forests in tropical regions (Li et al., 2015). In combination with the observed temperature inversion, nighttime cooling increases the relative humidity over the area, supporting the development of fog and low stratus.

Further likely reasons for enhanced FLS cover over the Landes forest are the interplay between BVOC emissions and high evapotranspiration over the forest area. High loadings of natural aerosols from late spring to early fall have been found for boreal forests (Tunved et al., 2006). It has been shown that secondary organic aerosol emissions together with evapotranspiration over forests can lead to an increase of liquid water path and cloud droplet number concentration in low-level liquid clouds (Petäjä et al., 2022). This could also be a potential pathway in the Landes forest, where BVOC emissions have been measured in summer (Kammer et al., 2018). A higher number of CCN and therefore potentially a higher number of small cloud droplets could lead to more FLS identified by both FLS detection algorithms. Measurements of BVOC emissions and fog and low cloud occurrences in the Landes forest could test the interactions between BVOCs and FLS in the future.

The patterns and drivers of higher FLS occurrence over the forest area is further modified by the general synoptic situation and geographic position of the Landes forest, with the Atlantic Ocean to the west and the Pyrenees to the south. While the former is a source of moisture, the latter might enhance stationarity of air masses in the region, preventing high wind speeds and supporting the build-up of atmospheric moisture.

5. Conclusion

In this study, we have analyzed nighttime fog and low stratus cloud cover over the Landes forest in southwestern France using active and passive remote sensing products. We have found significantly higher FLS cover over the forest compared to non-forest areas and identified lower wind speed and a temperature inversion over the forest as potential drivers. As these parameters only partially explain the enhanced FLS cover over the forest, further atmospheric and biophysical drivers should be included into the analysis in the future, such as soil moisture, evapotranspiration, and BVOC emissions. For future work we propose a systematic approach combining modeling and sensitivity studies to further quantify the role of forests for fog and low stratus cloud formation over varying geographic and synoptic backgrounds.

Data Availability Statement

The fog and low stratus cloud data set can be downloaded from http://vhrz669.hrz.uni-marburg.de/lcrs/data_pre.do?citid=291. The CALIPSO level 2 1-km cloud-layer product (Version 4.20) is distributed by the Atmospheric Science Data Center (ASDC) at https://doi.org/10.5067/CALIOP/CALIPSO/LID_L2_01KMCLAY-STANDARD-V4-20. The era5-land data is available at https://doi.org/10.24381/cds.e2161bac. The era5 data on different pressure levels can be downloaded from https://doi.org/10.24381/cds.bd0915c6. FVC data is provided by the EUMETSAT Satellite Application Facility on Land Surface Analysis (Trigo et al., 2011) and can be downloaded from https://landsaf.ipma.pt/en/products/vegetation/fvc/.

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