1	Role of thermodynamic and turbulence processes on the fog life cycle during
2	SOFOG3D experiment
3	Cheikh DIONE <sup>1*</sup> , Martial HAEFFELIN <sup>1</sup> , Frederic BURNET <sup>2</sup> , Christine LAC <sup>2</sup> , Guylaine CANUT <sup>2</sup> , Julien
4	DELANOË <sup>3</sup> , Jean-Charles DUPONT <sup>4</sup> , Susana JORQUERA <sup>3</sup> , Pauline MARTINET <sup>2</sup> , Jean-Francois
5	RIBAUD <sup>5</sup> , and Felipe TOLEDO <sup>3</sup>

6 1) Institut Pierre Simon Laplace, CNRS, École Polytechnique, Institut Polytechnique de Paris, Paris, France

7 2) CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France

8 3) Laboratoire Atmosphères, Milieux, Observations Spatiales/UVSQ/CNRS/UPMC, 78280 Guyancourt, France

9 4) Institut Pierre-Simon Laplace, École Polytechnique, UVSQ, Université Paris-Saclay, 91128 Palaiseau, France

10 5) Laboratoire de Météorologie Dynamique, École Polytechnique, Institut Polytechnique de Paris, 91128 Palaiseau, France.

11 \* corresponding author: Cheikh DIONE, <u>cdione@ipsl.fr</u>

### 12 Abstract:

13 In this study, we use a synergy of in-situ and remote sensing measurements collected during the SOuthwest FOGs 3D experiment for processes study (SOFOG3D) field campaign in autumn and winter 2019-2020, to 14 15 analyze the thermodynamic and turbulent processes related to fog formation, evolution, and dissipation across southwestern France. Based on a unique measurement dataset (synergy of cloud radar, microwave 16 radiometer, wind lidar, and weather station) combined with a fog conceptual model, an analysis of the four 17 deepest fog episodes (two radiation fogs and two advection-radiation fogs) is conducted. The results show 18 that radiation and advection-radiation fogs form under deep and thin temperature inversions, respectively. 19 20 For both fog categories, the transition period from stable to adiabatic fog and the fog adiabatic phase are driven by vertical mixing associated with an increase in turbulence in the fog layer due to mechanical 21 production (turbulence kinetic energy (TKE) up to 0.4 m<sup>2</sup> s<sup>-2</sup> and vertical velocity variance ( $\sigma_w^2$ ) up to 0.04 22 m<sup>2</sup> s<sup>-2</sup>) generated by increasing wind and wind shear. Our study reveals that fog liquid water path, fog top 23 height, temperature and radar reflectivity profiles and fog adiabaticity derived from the conceptual model 24 25 evolve in a consistent manner to clearly characterize this transition. The dissipation time is observed at night for the advection-radiation fog case studies and after sunrise for the radiation fog case studies. Night-time 26 dissipation is driven by horizontal advection generating mechanical turbulence (TKE at least 0.3 m<sup>2</sup> s<sup>-2</sup> and 27  $\sigma_w^2$  larger than 0.04 m<sup>2</sup> s<sup>-2</sup>). Daytime dissipation is linked to the combination of thermal and mechanical 28 turbulence related respectively to solar heating (near surface sensible heat flux larger than 10 W m<sup>-2</sup>) and 29 wind shear. This study demonstrates the added value of monitoring fog liquid water content and depth, 30 31 combined with wind, turbulence and temperature profiles, and diagnostics such as fog liquid water reservoir and adiabaticity to better explain the drivers of the fog life cycle. 32

*Key words:* Fog conceptual model, radiation/advection fog, fog life cycle, turbulence, Southwestern France,
 SOFOG3D

## 35 1. Introduction

Fog is an extreme meteorological phenomenon forming in several regions of earth under 36 different atmospheric conditions depending on the season and location (Gultepe et al., 2007). It is 37 defined by the suspension of water droplets in the lowest troposphere which reduces the horizontal 38 visibility to lower or at least 1000 m. Fog has significant negative impacts on air, road and marine 39 traffic causing large economical and human losses (Bartok et al., 2012, Bartoková et al., 2015, 40 Huang and Chen, 2016). It also has a high impact on solar energy, particularly in the mid-latitudes 41 during autumn and winter. Based on in-situ measurements, several studies have focused on fog 42 formation at different regions and highlighted the main processes leading to its initiation allowing to 43 define five categories of fog: radiation fog (Price 2019), advection-radiation fog (Gultepe et al., 44 2007, 2009; Niu et al., 2010a, b, Dupont et al., 2012), advection fog (Koračin et al., 2014; Liu et al., 45 2016, Fernando et al., 2021), fog by stratus lowering (Koračin et al., 2011; Fathalli et al., 2022) and 46 precipitation fog (Tardif and Rasmussen, 2007; Liu et al., 2012). According to the literature, several 47 processes are identified to drive fog evolution and dissipation depending on each category. Fog 48 formation requires low intensity of turbulence (Nakanishi 2000; Bergot 2013; Price 2019). 49

Dhangar et al., 2021 found that optically thin fog develops under low-turbulence kinetic 50 energy and the transition to dense fog is observed when the turbulence increases and reaches 51 enough values to allow the vertical mixing of the fog layer. The dissipation of radiation fog is 52 usually observed after sunrise and linked with the increase in solar heating leading to the 53 evaporation of water drops and a vertical mixing of water vapor (Roach, 1995; Haeffelin et al., 54 2010; Maalick et al., 2016). Bergot et al., 2015 relied on large eddy simulations (LES) to 55 characterize the role of dry downdrafts in allowing solar radiation to reach the ground and increase 56 the turbulence, leading to the dissipation. Additionally, Pauli et al., 2022 studied the climatology of 57 fog and low stratus cloud formation and dissipation times in Central Europe using satellite data and 58 showed that fog dissipation is also often related to topography. The dissipation processes are more 59 difficult to study then the fog formation processes, due to the complexity of fog's scale. At the state 60 of the art, based on case studies, numerical weather prediction models (Philip et al., 2016, Bell et 61 al., 2022) and high resolution models (Price et al., 2018, Ducongé et al., 2020, Fathalli et al., 2022) 62 63 up to LES (Bergot et al., 2015, Mazoyer et al., 2017) have the ability to simulate fog formation in several complex areas. However, they have difficulties in simulating the processes driving fog 64 evolution over land in real time (Steeneveld et al., 2015, Price et al., 2015, Román-Cascón et al., 65 2016; Wærsted et al., 2019; Pithani et al., 2020, Boutle et al., 2022). 66

67 Toledo et al., 2021 developed a one-column conceptual model of adiabatic continental fog allowing to define key fog metrics as the equivalent fog adiabaticity by closure and the reservoir of 68 liquid water path (RLWP) that can be estimated in real-time and allowing a diagnostic of fog 69 evolution. Based on seven years of measurements collected at SIRTA (Site Instrumental de 70 Recherche par Télédétection Atmosphérique), a French observatory located at Palaiseau/France, 71 Toledo et al., 2021 have validated their model on the timing of fog dissipation using the RLWP. 72 The limitation of this model is that the estimation of the reservoir depends on fog specific 73 parameters and does not take into account local (turbulence) or large scale (advection) processes . 74 75 Indeed, to further understand uncertainties associated with the estimation of the RLWP, the validation of the model using data from other measurement sites having a large occurrence of fog is 76 another step before using it as a nowcasting tool. 77

Finding the right instruments allowing nowcasting fog is also another challenge that can be partly resolved by field campaigns combining both in-situ and remote sensing measurements and numerical simulations. At the state of the art, nowcasting fog requires more efforts in in-situ measurements and modelling. In this context, the SOuth westFOGs 3D (SOFOG3D) project, led by Météo-France, was designed to document local processes involved in fog formation, evolution and dissipation to better improve its predictability in numerical weather prediction models.

84 In order to improve our understanding of the processes driving the fog life cycle and to validate the fog conceptual model from Toledo et al., 2021 on another region than the one on which 85 it has been developed, the current study aims at identifying the main dynamical and thermodynamic 86 processes driving fog's formation, evolution, and dissipation in the framework of SOFOG3D 87 project. In particular, the role of horizontal advection, atmospheric stability and turbulence is further 88 analyzed to better identify the drivers of radiation and radiation-advection fog phases. Using an 89 instrumental synergy of in-situ and remote sensing measurements and the fog conceptual model, the 90 phenomenology of fog and the different phases driving its evolution are deeply analyzed 91 92 considering four heavy fog case studies observed over Southwestern France during Winter 2019-2020. 93

This paper is structured into five sections. The datasets and methodological approach are described in the following section. Section 3 gives an analysis of the processes involved in fog evolution based on two different categories of fog formation phenomenology. Section 4 includes a discussion on the thermodynamical and turbulent processes driving the fog phases and Section 5 presents the conclusion.

# 99 2. Data and methodology

In a mesoscale context, the SOFOG3D field experiment is located in Southwestern France, 100 in the Nouvelle Aquitaine region (Fig. 1a). The field campaign was carried out during the autumn 101 and winter 2019-2020 period leading to 15 intensive observation periods (IOPs). A unique dataset 102 has been collected across a complex region with a very contrasted topography. This region is 103 bordered in the east by the "Massif Central", in the west by the Atlantic Ocean, in the north by 104 Bordeaux and in the south by the "Pyrenees". In the region, several dynamical effects can be 105 observed such as sea breeze, land breeze, and mesoscale foehn circulations influencing the fog life 106 cycle. At the local scale, the supersite under focused here is bordered by two rivers: "La Garonne" 107 to the East and "L'Eyre" to the west (Fig. 1a). These two rivers and the surrounding surface 108 heterogeneities can modulate the fog formation and dissipation times. During the campaign, several 109 in-situ and remote sensing measurements were jointly deployed in the studied area of SOFOG3D. 110 In this paper, our analysis focuses on the data collected in the surroundings of the supersite at 111 112 Charbonnière, the most instrumented site (Fig. 1b). Below, the descriptions of the in-situ and remote sensing measurements and then the fog conceptual model are presented with emphasis on 113 114 the main meteorological variables used in this study.

### 115 **2.1 Dataset**

## 116 **2.1.1 Surface measurement data**

117 A network of surface weather stations was installed in the study domain of SOFOG3D at the vicinity of Charbonnière, to document the spatial variability of fog and surface heterogeneities at 118 the local scale (Fig. 1b). Four weather stations were also deployed around the supersite in a 119 120 northeast-southwest transect (Fig. 1b). These stations were installed at Moustey, Cape Sud, Tuzan and Noaillan, almost at the same altitude, and operated continuously with very high temporal 121 resolution (0.1 s time interval) during the period from 18 October 2019 to 31 December 2020. In 122 addition to temperature, pressure, relative humidity sensors and anemometer, a scatterometer 123 provided the visibility used to estimate fog formation and dissipation times at each station. 124 Temperature data are used to characterize the spatial variability of the radiative cooling, and wind 125 speed and direction the local circulations. 126

In this study, fog occurrence is defined using the visibility at the supersite based on an algorithm developed by Tardif and Rasmussen, 2007. This algorithm consists of dividing visibility time series into 10 min blocks. A fog block means that half of the visibility measurements during a 10 min period are below 1000 m. Blocks are characterized by a positive or negative construct. A positive construct indicates that five consecutive blocks of which the central block is fog and at least two other blocks are also fog blocks. The opposite means a negative construct. Thus, the fog formation time corresponds to the first fog block in the first positive construct encountered. The fog dissipation time corresponds to the last fog block in the last positive construct before either a negative construct or three consecutive non-fog blocks are encountered. This algorithm discards fog events shorter than 1 hour.

Meteo-France installed in a fallow field near the supersite, several sensors as Licor analyzers 137 and sonic anemometers to continuously measure the near-surface (3 m a.g.l) meteorological 138 conditions (air temperature and relative humidity), the three components of the wind, and pressure 139 at 0.3 m a.g.l). These instruments provided high frequency data at 20 Hz. In this study, to document 140 141 turbulence and thermodynamical processes driving fog phases, we use the sensible heat flux (SHF), turbulence kinetic energy (TKE), and vertical velocity variance  $(\sigma_w^2)$ . These variables are estimated 142 using the Eddy-covariance methods (Foken et al., 2004, Mauder et al., 2013) calculated every 30 143 minutes after a high quality control of the data. More details on the data can be found in Canut, 144 145 2020.

## 146 **2.1.2 Observation of cloud characteristics**

For the monitoring of cloud layers, a BASTA cloud radar (Delanoë et al., 2016) was
deployed at Charbonnière and a CL51 Ceilometer at Tuzan (7.4 km northwest of Charbonnière)
(Fig. 1b).

150 BASTA is a 95-GHz cloud radar manufactured by the Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS) with an absolute calibration method for frequency-modulated 151 continuous wave (FMCW) cloud radars based on corner reflectors (Toledo et al., 2020). From 7 152 November 2019 to 12 March 2020, the radar was operated continuously with a vertical pointing 153 mode having three vertical resolutions (12.5 m, 25 m, and 100 m). It provided radar reflectivity and 154 Doppler velocity. The lowest mode, having its first available gate at 37.5 m a.g.l and 12.5 m of 155 vertical resolution, is used to estimate the cloud top height (CTH) which gives the fog thickness at a 156 time resolution of 30 seconds. It also provides the level of highest concentration of droplets in the 157 fog layer. The CTH is estimated using a radar reflectivity threshold of -34 dBZ. 158

The CL51 is manufactured by Vaisala and automatically provided three estimates of cloud base height (CBH) allowing the detection of cloud decks every 30 seconds with a vertical resolution of 15 m from 10 October 2019 to 2 April 2020. In this study, we use the lowest CBH, which corresponds to the base height of stratus cloud lowering or lifting when fog forms or dissipates, respectively. More information on the data provided by the CL51 can be found in Burnet, 2021.

A microwave radiometer Hatpro (MWR) manufactured by Radiometer Physics GmbH 165 (RPG) was installed at the supersite to characterize thermodynamic atmospheric conditions during 166 the field campaign. From 4 December 2019 to 9 May 2020, the MWR operated continuously at the 167 supersite using two spectral-bands: the K-band which 22.24-31 GHz used for the retrieval of 168 humidity profiles, integrated water vapor (IWV) content and liquid water path (LWP), and the V-169 band which 51-58 GHz to retrieve temperature profiles. In order to improve the vertical resolution 170 in the boundary layer, the MWR was set up to scan in 10 elevation angles (5° above ground level) 171 every 10 minutes with a zenith pointing each 1 second. Using neural networks, brightness 172 173 temperatures measured by the MWR at all elevation angles (the lower elevations angles added to measurements at zenith) are inverted to temperature and humidity variables. More details on this 174 method can be found in Martinet et al., 2022. Comparing temperature and humidity profiles 175 retrieved by the MWR with radiosonde data, Martinet et al., 2022 found that air temperature has 176 177 cold biases below 0.5 K in absolute value below 2 km but increases up to 1.5 K above 4 km altitude. The low biases in the lowest atmosphere allow a good estimation of the lowest temperature 178 179 inversion under focus in this study. For each case study, the transition from stable to adiabatic fog is 180 estimated using the static atmospheric stability in the lowest atmosphere computed using the 181 temperature profile. The air temperature profiles are also used to characterize the atmospheric conditions linked to the development of fog at Charbonnière. For the absolute humidity, the 182 maximum dry bias of the MWR is around 1.4 g m<sup>-3</sup> in the lowest troposphere up to 1.7 km and 183 becomes wet above (0.3 g m<sup>-3</sup>). Martinet et al., 2022 showed that the LWP accuracy has been 184 validated in clear-sky conditions and has shown errors between 1 and 14 g m<sup>-2</sup>. These error range is 185 186 in the scope of those defined in the literature (Crewell and Löhnert, 2003; Marke et al., 2016). The LWP is a key parameter to consider for the microphysical characteristics of fog and is used in the 187 conceptual model. More information regarding the data can be found in Martinet, 2021. 188

The WindCube lidar has become a common instrument used in documenting very low 189 190 atmospheric phenomena such as turbulence (Liao et al., 2020; Kumer et al., 2016). Dias Neto et al., 2023 demonstrated the usefulness of the wind speed and direction estimated using the WindCube 191 V2. Comparing wind from WindCube V2 with GPS radiosonde, they found low biases of 0.52 m s<sup>-1</sup> 192 and 0.37° for the wind speed and direction, respectively. To investigate the dynamics of the 193 atmosphere at the supersite, a WindCube V2 lidar manufactured by Leosphere was deployed by 194 Meteo-France during the field campaign to provide from 1 October 2019 to 10 April 2020, the wind 195 measurements at 10 levels ranging from 40 m to 220 m above ground level (a.g.l). The 196 measurements made at a 1 Hz frequency and a 20 m vertical resolution provided the estimation of 197 turbulence parameters such as the turbulent kinetic energy (TKE). The wind component are 198

estimated every 10 minutes using a Carrier-to-Noise Ratio (CNR) at least -23 dB and a total data 199 availability of at least 50 %. Note that the CNR depends on atmospheric turbulence characteristics 200 and relative humidity (Aitken et al., 2012). In the presence of fog or low stratus, the Lidar vertical 201 202 range becomes low. The TKE is computed as the sum of the horizontal variances as in Kumer et al., 2016. Velocity variances are estimated every 30 minutes using the wind components at the high 203 resolution. It is used in this study to analyze the role of turbulence within the foggy-layer to further 204 characterize fog formation, evolution, and dissipation. More details on the WindCube lidar data can 205 be found in Canut et al., 2022. 206

# 207 2.1.4 Fog adiabaticity and reservoir

To further understand fog characteristics, it is essential to focus our analysis on several 208 variables related to the formation, evolution and dissipation of fog. Fog adiabaticity and reservoir 209 210 are key metrics driving the life cycle of fog. They are estimated using the fog conceptual model (Toledo et al., 2021) developed at SIRTA. This model is a uni-dimensional model inspired by 211 212 previous numerical models for stratus clouds (Betts, 1982, Albrecht et al., 1990; and Cermak and 213 Bendix, 2011). The basic hypothesis is to consider a well-mixed fog layer and to express the increase in height of the fog liquid water content as a function of the local adiabaticity and the 214 negative of the change in the saturation mixing ratio with height  $(\Gamma_{ad}(T,P))$  (equation A1). Fog 215 liquid water path is parameterized as a function depending on the equivalent fog adiabaticity ( $\alpha_{eq}$ ) 216 and the CTH (equation A3). The equivalent fog adiabaticity is used to characterize the buoyancy in 217 low clouds.  $\alpha_{eq}$  varies depending on the in-cloud mixing parameter  $\beta$  and is expressed as  $\alpha_{eq} = (1-\beta)$ 218 219 (Betts, 1982 and Cermak and Bendix, 2011). For low-level clouds, as stratus and stratocumulus,  $\alpha_{eq}$ is between 0.6 and 0.9 (Braun et al., 2018) indicating sufficient buoyancy in the cloud layer with an 220 adiabatic profile. To parameterize this parameter in the fog conceptual model, Toledo et al., 2021 221 used an inversion of Eq. (A3) to define a fog adiabaticity from closure ( $\alpha_{eq}^{closure}$ ) given as: 222

223 
$$\alpha_{eq}^{closure} = \frac{2(LWP - LWC_0CTH)}{\Gamma_{ad}(T, P)CTH^2}$$
(1)

 $\alpha_{eq}^{closure}$  depends on the accumulated liquid water content (LWC) at the fog base (LWC<sub>o</sub>), fog thickness (e.g. CTH), the LWP and the adiabaticity. The adiabaticity lapse rate is a function of air temperature and pressure. Toledo et al., 2021 found that the equivalent fog adiabaticity from closure is negative when the LWP is below 30 g m<sup>-2</sup>. They defined the transition phase from stable to adiabatic conditions when the equivalent fog adiabaticity from closure is around 0.5. In the conceptual model, this parameter is estimated only for a CTH below 462.5 m with free cloud above.

230

The model considers that the fog dissipates when its liquid water path is below a certain threshold depending on the local thermodynamic atmospheric conditions. In case of dissipation by lifting the base height of the fog, Wærsted, 2018 found a deficit in LWP in the fog layer. This assertion allows defining a minimum amount of LWP necessary to maintain the horizontal visibility at surface lower or equal to 1000 m, defined as the critical liquid water path (CLWP). Thus, based on equation A3, the CLWP can be expressed in equation (2) considering a critical liquid water content at surface (LWCc).

238 
$$CLWP = \frac{1}{2} \alpha_{eq} \Gamma_{ad} (T, P) CTH^2 + LWC_c CTH$$
 (2)

Theoretically, the LWCc corresponds to the LWC that would cause a 1000 m visibility. It is estimated from the parameterization of Gultepe et al., 2006 based on the horizontal visibility at surface.

Considering that adiabatic fog exists because the liquid water path in its thickness is strictly greater or equal to its CLWP (Toledo et al., 2021), it is possible to define an associated quantity named the fog reservoir of liquid water path (RLWP). The RLWP is defined as the difference between fog current liquid water path and the critical value, as:

246 
$$RLWP = LWP - CLWP = LWP - \frac{1}{2}\alpha_{eq}\Gamma_{ad}(T, P)CTH^{2} - LWC_{c}CTH$$
(3)

The RLWP depends on the LWCc (A4), the adiabaticity and fog thickness. The calculation of RLWP can be used to anticipate the dissipation or thickening of the fog in the coming minutes or hours. Based on 20 fog cases at SIRTA, Toledo, 2021 found that for a RLWP > 30 g m<sup>-2</sup> in a given time instant, fog does not dissipate within the following 30 minutes. He also showed that the RLWP trend decreases before fog dissipation time and increases when fog is persisting. This behaviour motivates the analysis of the RLWP trend in this study to improve the characterization of the different fog phases.

The number of fog events observed during the SOFOG3D field campaign is not sufficient to 254 calibrate the fog conceptual model in southeastern France as in SIRTA (Toledo et al., 2021). In this 255 study, we use the model with its parametrization at SIRTA to further characterize the different 256 phases observed in the lifetime of fog based on identified case studies. The model is performed 257 when the visibility is lower than 1000 m.  $\alpha_{eq}^{closure}$  is used to characterize the fog transition from 258 stable phase to adiabatic phase. The RLWP gives an estimation of the excess/deficit of liquid water 259 of the fog that enables the fog layer to remain at surface or dissipate. It can be used as a diagnostic 260 261 of how likely the fog will persist in the coming minutes, hours (nowcasting tool for fog dissipation time). More details on the fog conceptual model is given in appendices and can be found in Toledo,2021.

## 264 2.2 Case studies and methodological approach

For the whole SOFOG3D campaign, based on the fog defined criteria described in section 265 2.2.1, 31 fog events are identified during 31 October 2019 - 26 March 2020 period. For each one, a 267 visual inspection of the time-height cross-section of the radar reflectivity from BASTA cloud radar 268 and the cloud base height from the Ceilometer was carried out. We selected the four most 269 developed fog episodes, namely case studies 1 (IOP 5), 2 (IOP 6), 3 (IOP 11) and 4 (IOP 14).

As in Toledo et al., 2021 (their Fig. 3), Figure 2 shows the equivalent adiabaticity by closure 270 versus LWP and CTH for the 4 fog case studied. It indicates that  $\alpha_{eq}^{closure}$  reaches 0.5 when LWP > 271 20 g m<sup>-2</sup> and the CTH > 150 m which should be the conditions favorable for the fog to become 272 273 optically opaque to the infrared radiation. At the supersite, the LWP observed during that transition is lower than the threshold at SIRTA (LWP > 30 g m<sup>-2</sup>) (Wærsted et al., 2017 and Toledo et al., 274 275 2021). However, there is a consistency between both sites on the computation of the equivalent 276 adiabaticity by closure. This legitimises the choice of the four days, and motivates the use of the  $\alpha_{eq}^{closure}$  in this study to define the transition phase between stable and adiabatic fog. 277

For the selected case studies, Table 1 contains the fog formation and dissipation times, fog formation types, and fog duration at the supersite. For all selected fog events, the formation time of fog is observed between 20:40 and 22:40 UTC and the dissipation time varies from night to daytime. These selected fogs are triggered by radiation (2 cases) or advection-radiation (2 cases) processes.

For each selected case study, temperature profiles from the MWR, radar reflectivity profiles from the BASTA cloud radar and the equivalent fog adiabaticity derived from the conceptual model are used to define the four fog phases characterizing the fog evolution: fog pre-onset, stable fog, adiabatic fog, and fog dissipation. Note that an important time of the fog life cycle is the transition time between stable and adiabatic fog. Each fog phase is defined as following:

1/ Fog pre-onset corresponds to the two hours preceding fog onset associated with cloud freeconditions.

290 2/ In the four cases studies, the stable phase starts at fog onset. It is characterized by a stable
 291 temperature profile in the lowest 100 m of the atmosphere.

292 3/ The transition time separating the stable and adiabatic phases can be defined differently 293 depending on the meteorological variables considered. Price et al., 2011 defined this transition time 294 as the time when the air temperature becomes constant in the fog lowest layer (1.5 - 50 m a.g.l).

Toledo et al., 2021 found that the transition is observed when the equivalent fog adiabaticity by 295 closure is increasing between 0 and 0.5. In this study, for a better definition of this period, we take 296 into account the static stability given by the hourly profiles of mean air temperature from the MWR, 297 the fog geometry (CTH) from the cloud radar, and the  $\alpha_{eq}^{closure}$  from the conceptual model. Indeed, 298 the transition period is defined as the time when the temperature profile becomes unstable or neutral 299 in the 0-75 m a.g.l layer, while the fog CTH increases with time, and  $\alpha_{eq}^{closure}$  increases from 0 to 300 about 0.5. Note that the thickening of the fog is associated with the elevation of the level of the 301 maximum radar reflectivity. The transition phase starts when  $\alpha_{eq}^{closure} < 0.5$ , the CTH suddenly 302 increases more than 25 m in 5 minutes under a stable or neutral layer. This phase ends when  $\alpha_{eq}^{closure}$ 303 reaches 0.5 and the fog layer becomes neutral or unstable. 304

4/ Fog adiabatic phase is characterized by  $\alpha_{eq}^{closure}$  around 0.5, a neutral or unstable temperature profile, and a radar reflectivity that increases with increasing altitude and peaks a few tenths of meters below cloud top.

5/ Fog dissipation phase is defined as being the period between 30 minutes before and after dissipation time (when horizontal visibility becomes greater than 1 km). Since the fog dissipation time does not appear abruptly, as it is also driven by thermodynamical processes, we consider this time range to further document them.

Based on these fog phase definitions, in the following, we describe the four case studies. For each fog event, we document the processes involved in the evolution of fog in each of these phases, using the fog conceptual model and the instrumental synergy, in order to identify the main processes driving the fog life cycle.

**Table 1 :** Case study number, fog onsets, type of fog formation, fog dissipation times, fog duration and type of fog dissipation for the four documented case studies. Time is in UTC. Dates are in the format "dd/mm/yyyy". "dd" indicates the day, "mm" the month and "yyyy" the year.

Case	Formation	time	Fog types	Dissipation	Fog	
study						duration
number	Date	Hours		Date	Hours	(hh:min)
	dd/mm/yyyy	(UTC)		dd/mm/yyyy	(UTC)	
1	28/12/2019	22:40	Radiation	29/12/2019	11:00	12:20
2	05/01/2020	20:40	Radiation	06/01/2020	08:40	12:00
3	08/02/2020	20:40	Advection-radiation	09/02/2020	03:40	7:00
4	07/03/2020	21:20	Advection-radiation	08/03/2020	04:00	6:40

### 319 **3. Fog formation, evolution, and dissipation processes**

## 320 **3.1 Radiation fog case studies**

## 321 3.1.1 Case study 1 (IOP 5) analysis

322 Figures 3a and 3b indicate the time-cross sections of the radar reflectivity estimated from BASTA cloud radar during case study 1, on the 28-29 December 2019, respectively up to 600 m 323 and 12000 m. They show a clear sky before fog formation time at 22:40 UTC on 28 December 324 2019. During fog evolution, cloud free conditions are observed above the fog top height until 09:00 325 UTC when sparse thin high-altitude clouds occur above the cloud radar. Figure 3c presents a quasi-326 327 homogeneous fog formation time between the three sites and heterogeneous dissipation time. At Charbonnière, fog dissipated at 11:00 UTC, on 29 December 2019 and two hours earlier at 328 Noaillan. At all sites, low temperatures below 4 °C (Fig. 3e) are observed during the fog period. 329 Near the surface, light winds ( $< 1 \text{ m s}^{-1}$ ) are recorded at all sites from fog pre-onset to fog 330 331 stable/adiabatic transition times (Fig. 3d and 3f).

The fog pre-onset is marked by a double stratification of the atmospheric boundary layer 332 333 with a thin inversion from surface up to 100 m and deep and strong inversion (around 8 °C km<sup>-1</sup>) 334 above (Fig. 4a). Atmospheric conditions are dominated by an easterly wind that reaches 5 m s<sup>-1</sup> above 100 m a.g.l which could be considered as a nocturnal low-level jet (Fig. 4d). The mean 335 cooling rate near the surface is -0.9 °C h<sup>-1</sup>. The strong decrease in temperature is associated with a 336 negative SHF (-0.23 W m<sup>-2</sup>) (Fig. 4h), near surface low wind (0.61 m s<sup>-1</sup>) (Fig. 3d and 3f) and low 337 turbulence (TKE = 0.11 m<sup>2</sup> s<sup>-2</sup> and  $\sigma_w^2$  = 0.002 m<sup>2</sup> s<sup>-2</sup>). These conditions lead to thermally-stable 338 atmospheric conditions which are favourable for radiation fog formation (Table 1). 339

The fog stable phase lasts around 6 h (22:50 - 05:00 UTC) and is characterized on average by a very low negative near surface cooling rate (-0.18 °C h<sup>-1</sup>), an almost zero SHF, an easterly light wind (0.78 m s<sup>-1</sup>), low turbulence (TKE = 0.07 m<sup>2</sup> s<sup>-2</sup>,  $\sigma_w^2$  = 0.01 m<sup>2</sup> s<sup>-2</sup>), negative  $\alpha_{eq}^{closure}$  (-1.3) (Fig. 4e), low LWP (2.18 g m<sup>-2</sup>) (Fig. 4g), slight increase in time of the fog thickness up to 50 m, and relatively stable temperature inversion height. These characteristics maintain the fog thermally stable with an horizontal visibility of 736 m on average.

The transition time from stable to adiabatic fog is observed between 05:00 and 07:00 UTC (02:00 duration) and associated with a lowest visibility (198 m), a transition in the vertical profiles of air temperature (Fig. 4a) from stable at 05:00 to unstable at 06:00 UTC in the fog layer, a deepening of the cold layer, an increase of the mean SHF reaching 4.4 W m<sup>-2</sup> and around 10 W m<sup>-2</sup> at the phase end (Fig. 4h), an increase of the turbulence (TKE up to 0.15 m<sup>2</sup> s<sup>-2</sup> and  $\sigma_w^2$  up to 0.04 m<sup>2</sup> s<sup>-2</sup>) generated by the strengthening of the wind speed (1.14 m s<sup>-1</sup>) and its shift in direction from East to Southeast. From 05:00 to 06:00 UTC, the coldest temperature shifts from the surface up to 50 m a.g.l, the vertical profile of radar reflectivity increases with height, indicating a vertical development of fog (Fig. 4b) generated by turbulence processes. At the end of this phase,  $\alpha_{eq}^{closure}$  reaches 0.5 which is consistent with the threshold obtained at the SIRTA site by Toledo et al., 2021.  $\sigma_w^2$  values observed are higher than the threshold fixed by Price et al., 2019 for a thermally-stable surface layer. The LWP (28 g m<sup>-2</sup>) and RLWP (+15 g m<sup>-2</sup>) peak at the end of the transition phase consistently with a decrease in visibility. Due to the simultaneous increase in SHF, TKE and  $\sigma_w^2$ , the transition phase is driven by both thermal and mechanical turbulence.

The fog adiabatic phase is observed between 07:00 and 11:00 UTC (04:00 duration) at the 360 supersite and characterized by a vertical development of fog up to 187.5 m (Fig. 4b) and the arrival 361 of sparse high clouds (Fig. 3a and 3b) associated with the lowering of the temperature inversion top 362 height above the fog top (Fig. 4c). Note that these clouds have no effect on the radiative cooling at 363 the top height of the fog. The fog layer becomes warmer (+0.77 °C h<sup>-1</sup> on average) and its LWP and 364 RLWP reach 26.16 g m<sup>-2</sup> and +6.38 g m<sup>-2</sup>, respectively. The turbulence gradually increases in the 365 fog layer (Fig. 4f) (TKE = 0.23 m<sup>2</sup> s<sup>-2</sup>) due to an increase of the horizontal wind speed (2.4 m s<sup>-1</sup>) 366 combined with an increase of the vertical shear and the wind shift from southeasterly to easterly 367 (Fig. 4d). In the same way,  $\sigma_w^2$  increases to 0.04 m<sup>2</sup> s<sup>-2</sup> and is driven both by the vertical wind shear 368 and the increase in SHF (12.9 W m<sup>-2</sup>) (Fig. 4h). For this case study, the moderate mechanical and 369 thermal turbulence causes the vertical mixing in the fog layer, which slightly increases the surface 370 371 horizontal visibility (370 m) and fog top height (185 m).

At the supersite, in the absence of any cloud above the fog layer, the fog dissipates after 372 sunrise. It is marked by a continue increase in SHF (Fig. 4h) due to solar radiation (daytime 373 atmospheric convection), negative RLWP (-11.39 g m<sup>-2</sup>), an increase in CTH (290 m), LWP 374 (maximum of 43.34 g m<sup>-2</sup>), stable  $\alpha_{eq}^{closure}$  around 0.63, and more thermal turbulence ( $\sigma_{w}^{2} = 0.06 \text{ m}^{2} \text{ s}^{-1}$ 375 <sup>2</sup>) allowing more vertical mixing. Based on the RLWP, the fog conceptual model would predict a 376 deficit of liquid water in the fog layer one hour before the lifting of its base height (Fig. 4g). The fog 377 dissipation phase is induced by the increase of the vertical mixing generated by the thermal (solar 378 heating) and mechanical turbulence associated with TKE values larger than 0.4 m<sup>2</sup> s<sup>-2</sup> (Fig. 4f). 379

In summary, for this radiative fog event, the fog conceptual model is consistent with the insitu measurements of turbulence on the timing of the different fog phases. It has provided additional elements for understanding the different phases of the fog life cycle.

383 3.1.2 Case study 2 (IOP 6) analysis

As in case study 1, case study 2 is a radiation fog that forms under clear skies a few hours after sunset (Fig. 5a and 5b), under a double stratification of the low atmosphere (Fig. 6a), southerly very low near-surface wind speed ( $0.2 \text{ m s}^{-1}$ ), low TKE ( $0.06 \text{ m}^2 \text{ s}^{-2}$ ) and negative surface SHF. The fog lasts 12 h and completely dissipates around 08:40 UTC, on 6 January 2020 at the supersite (see Table 1) and at 04:30 UTC at Noaillan revealing more spatial variability than in case study 1.

The fog stable phase last 3 h 20 min (20:40 to 00:00 UTC), half the time of case study 1, 389 with fog characteristics similar to those of case study 1. A 2-hour fog transition phase is observed 390 from 00:00 to 02:00 UTC, (02:00 duration as for IOP 5) at the supersite (Fig. 6a and 6b) and 391 characterized by positive SHF (7.76 W m<sup>-2</sup>) and larger values of TKE (0.23 m<sup>2</sup>.s<sup>-1</sup>) allowing vertical 392 mixing and transition towards adiabatic fog. A significantly longer fog adiabatic phase is observed 393 from 02:00 to 08:40 UTC (twice longer than in IOP 5). The first period from 02:00 to 05:00 UTC is 394 characterized by continued positive SHF (10 W m<sup>-2</sup>) (Fig. 6h) and significant turbulence (TKE > 0.2 395  $m^2 s^{-2}$  and  $\sigma_w^2 > 0.02 m^2 s^{-2}$ ) (Fig. 6f) leading to a deeper fog with relatively high LWP (42 g m<sup>-2</sup>), and 396 a positive RLWP until 04:30 UTC (Fig. 6g). The second period from 05:00 to 08:40 UTC is 397 characterized by continued positive SHF, significant  $\sigma_w^2$  (> 0.02 m<sup>2</sup> s<sup>-2</sup>), while the TKE decreases (< 398 0.2 m<sup>2</sup>.s<sup>-2</sup>) associated with the decrease in wind speed in the fog layer. A sharp decrease in LWP, 399 with a reduction of fog top height leads to RLWP oscillating around 0 g m<sup>-2</sup>, while the horizontal 400 visibility increases and then decreases again. During this period, the sharp decrease in LWP (< 20 g 401 m<sup>-2</sup>) results in a fog layer that is not very resilient to the significant turbulence, as shown by the very 402 low RLWP values and rapidly changing horizontal visibility (Fig. 5c). The decrease in LWP could 403 be driven by production of drizzle, as scientist reported droplet freezing on the tethered balloon. Fog 404 dissipation occurred after sunrise (08:40 UTC), under positive SHF (14 W m<sup>-2</sup>), driven by the 405 turbulence associated with mechanical and thermal processes (mean TKE ~ 0.28 m<sup>2</sup> s<sup>-2</sup> and  $\sigma_w^2$ 406  $\sim 0.048 \text{ m}^2 \text{ s}^{-2}$ ). 407

## 408 **3.2 Radiation-advection fog case studies**

Case study 3 and 4 correspond to two fog cases that form after sunset (near 21 UTC) in a moist westerly flow, with an initial condensation about 100 m a.g.l (ultra-low stratus or elevated fog) followed by a rapid subsidence of the cloud layer to the ground (see Figures 7 and 9, respectively). West-east gradients are observed in terms of temperature and fog formation time, combined with a weak temperature inversion at the time of fog formation, justifying the classification of fog formation by advection-radiation processes (Ryznar, 1977).

In spite of different formation conditions for case study 3, compared to case 1 and 2, the stable fog 416 phase of this case is characterized by fog conditions that are similar to those of case 1 and 2 (Figure 417 8): slightly negative SHF, low turbulence (TKE =  $0.03 \text{ m}^2 \text{ s}^{-2}$ ) and low LWP (<10 g m<sup>-2</sup>). Case study 418 3 differs from the previous case studies with a longer duration for the stable-to-adiabatic fog 419 transition (03:30 duration) during which SHF remains slightly negative, TKE remains mostly below 420 0.03 m<sup>2</sup> s<sup>-2</sup>, and CTH, LWP and  $\alpha_{eq}^{closure}$  increase progressively, while RLWP remains relatively 421 stable (5-10 g m<sup>-2</sup>). In case study 3, the very short fog adiabatic phase (1 hour) is characterized by 422 increasing vertical wind shear near fog top height (Fig. 8d) that generates dynamical instability 423 driving the vertical mixing, reducing the temperature inversion above fog top (Fig. 8c), and 424 promoting vertical development of the fog layer. The rapid increase in CTH is not sufficiently 425 compensated by the increase in LWP, leading to a decrease in RLWP (Fig. 8g) and subsequent 426 increase in near-surface visibility and dissipation of the fog. Increasing wind aloft brings warm drier 427 air over the top of the fog that then mixing into it (TKE = 0.33 m<sup>2</sup> s<sup>-2</sup> and  $\sigma_w^2$  = 0.07 m<sup>2</sup> s<sup>-2</sup>), 428 evaporating fog droplets, reducing the RLWP to negative values and causing the fog to lift into low 429 430 stratus. The fog dissipation phase is thus driven by the advection of warm air at the supersite (Fig. 431 7e).

432 **3.2.2 Case study 4 (IOP 14) analysis** 

As in case study 3, fog case study 4 starts with a very low stratus fog, subsidence of the cloud layer resulting in a fog. The fog layer is perturbed by the advection from the northwest (captured in Meteosat Second image, not shown) around 00:30 UTC of another stratus with a base height above the fog top height. From 04:00 UTC, the fog becomes intermittent with a first dissipation observed at that time and a definitive dissipation around 07:00 UTC.

The 2-hour long fog stable phase is also characterized by a cooling rate near  $-1^{\circ}$ C h<sup>-1</sup>, slightly negative SHF and low turbulence (TKE < 0.1 m<sup>2</sup> s<sup>-2</sup>). The relatively short transition from stable to adiabatic fog (< 1 h 30 min) is characterized by an increase in mechanically-driven turbulence (wind shear, Figure 10d) with a southerly wind that likely brings additional moisture, leading to a rapid increase in both CTH and LWP (near 40 g m<sup>-2</sup>).

Fog adiabatic phase is observed from 00:20 to 04:00 UTC (03:40 duration) followed by a temporary dissipation of the fog from 04:00 to 05:30 UTC and a definitive fog dissipation at 07:00 UTC. This adiabatic phase is characterized by a 250-300 m deep fog with 40-50 g m<sup>-2</sup> LWP. The mechanically driven TKE ranges between 0.2-0.4 m<sup>-2</sup> s<sup>-2</sup> (Figure 10f) which confirms the turbulence that a relatively deep fog layer can withstand. The evolution of RLWP to negative values after 04:00 UTC (Figure 10g) shows that the conceptual model captures the transition from an adiabatic fog with low near-surface visibility (< 300 m) to one with horizontal visibility at or above 1000 m (Figure 9c). The definitive dissipation is not associated with increasing turbulence, but rather with the presence of middle-altitude clouds that likely reduce significantly the fog top radiative cooling, as precisely characterized by Waersted et al. (2017), and hence liquid water content production. Indeed, Figure 10g reveals a significant LWP reduction after 6:30 UTC, that explains the definitive dissipation of the fog before sunrise.

## 455 4. Discussion

Figure 11 shows the mean vertical profiles of air temperature derived from the MWR and radar reflectivity measured by the cloud radar for each fog phase and each case study. It highlights the thermal and microphysical characteristics of fog phases and differences in atmospheric conditions between fog categories: radiation and radiation-advection fogs.

For radiation fog case studies (1 and 2), fog develops below the dry, warm and cloud free 460 stable atmospheric boundary layer (Fig. 4c and 6c). Atmospheric conditions preceding (two hours 461 before) fog formation are dominated by a strong and thick temperature inversion (more than 14 °C 462 and 1000 m) which is associated with anticyclonic conditions over Europe favouring easterly wind 463 and clear sky across the studied area. These atmospheric conditions allow a strong surface radiative 464 cooling, negative heat fluxes and cooling of near surface air at a rate of -0.9 and -0.7 °C h<sup>-1</sup> for case 465 study 1 and 2, respectively. This cooling is associated with low turbulence indicated by low values 466 of TKE (0.18 m<sup>2</sup> s<sup>-2</sup> in case 1, and 0.06 in case 2) and near surface vertical velocity variance ( $\sigma_w^2 \leq$ 467 0.003 m<sup>2</sup> s<sup>-2</sup>) which reinforce the surface thermally stable boundary layer (Fig. 11a and 11b) 468 favoring the triggering of radiation fog. These results are consistent with the definition of radiation 469 fog proposed by Price, 2019. 470

471 In advection-radiation fog case studies (3 and 4), two hours before fog formation, a westerly sea breeze is present, transporting mild wet air from the ocean. Surface heat fluxes are negative, 472 favoring cooling of the near-surface air (-1 °C h<sup>-1</sup> in case study 3 and -0.5 °C h<sup>-1</sup> in case study 4) and 473 turbulent mixing is low (TKE  $< 0.06 \text{ m}^2 \text{ s}^{-2}$ ). An East-West gradient of formation and dissipation is 474 observed in line with the westerly synoptic advection of Atlantic inflow. Fog forms earlier in the 475 West and dissipates later in the East. The combination of advection and radiative cooling favours 476 stratus fog formation at about 150 m a.g.l followed by a rapid (less than 30 min) lowering of it base 477 height to the surface triggering the onset of the fog in an unstable (case 3) and neutral (case 4) 478 surface atmospheric boundary layer (Fig. 11c and 11d). 479

480 The stable fog phase is characterized by a stable temperature profile and radar reflectivity 481 which is maximum near the surface and decreases with height (see Fig. 11). The fog remains

shallow (less than 100 m) with a low LWP ranging less than 12 g m<sup>-2</sup> proportional to fog depth 482 (Table 2). The equivalent fog adiabaticity by closure parameter ( $\alpha_{eq}^{closure}$ ) is typically negative during 483 the stable phase indicating that the fog is not in an adiabatic phase. The near-surface temperature 484 decreases very moderately (-0.2 °C h<sup>-1</sup>) in cases 1 and 2, while the air keeps cooling at about -1 °C 485 h<sup>-1</sup> in cases 3 and 4. For the four cases, surface heat fluxes are slightly negative (-3 to 0 W m<sup>-2</sup>) and 486 turbulence remains low (TKE at about 0.1 m<sup>2</sup> s<sup>-2</sup> and  $\sigma_w^2$  at 0.01 m<sup>2</sup> s<sup>-2</sup>). This phase is characterized 487 by very low LWPs (1-2 g m<sup>-2</sup> for radiation fogs and 6-11 g m<sup>-2</sup> for advection-radiation fog). For 488 radiation fog cases, the stable phase lasts around 6 and 4 hours, respectively, while for advection-489 radiation cases, it lasts around 2 hours. This is consistent with the strength of the surface inversion 490 of each category of fog, as shown in Figure 11. These macrophysical characteristics of the fog 491 stable phase are consistent with those found by Toledo et al., 2021. 492

The transition from stable to adiabatic phases is a key period in the fog life cycle. This 493 494 period is well characterized using the macrophysical parameters of the conceptual model, namely the equivalent fog adiabaticity by closure ( $\alpha_{eq}^{closure}$ ) parameter of the fog, the fog geometry (CTH) 495 496 and fog LWP. During the transition from stable to adiabatic phases, these three parameters increase significantly (see Table 2). In particular,  $\alpha_{eq}^{closure}$  evolves progressively from negative values towards 497 +0.5 (Toledo et al., 2021). The transition phase lasts from 1 h 30 min to 3 h 30 min, however its 498 timing of occurrence is quite variable (case 1 at (05:00 - 07:00 UTC), case 2 (00:00 - 02:00 UTC), 499 case 3 (23:00 - 02:30 UTC), and case 4 (23:30 - 01:00 UTC). During this phase, a change is 500 observed in static stability from stable profiles to neutral adiabatic profiles (Fig. 11), while the radar 501 reflectivity profile presents maximum values near the ground that decrease with height (Fig. 11). In 502 503 cases 1, 2 and 4, the transition phase is characterized by an increase in turbulence that can explain the decrease in thermal stability of the fog layer, either shown in the vertical velocity variance  $(\sigma_w^2)$ 504  $\geq 0.02 \text{ m}^2 \text{ s}^{-2}$ ) associated with positive surface heat fluxes (cases 1 and 2), or TKE exceeding 0.3 505 m<sup>2</sup> s<sup>-2</sup> (cases 2 and 4). In all the cases, the fog LWP increases significantly which allows a more 506 efficient radiative cooling of the fog layer, hence contributing to the destabilization of the fog layer. 507 In case 3, the transition phase is not marked by a significant increase in turbulence. The transition is 508 more progressive than in the other case studies, with gradual increases of CTH, LWP and  $\alpha_{eq}^{closure}$ 509 during this long phase (03:30 duration). 510

According to temperature vertical profiles from the MWR, at the end of the transition time from stable to adiabatic fog, the temperature profile becomes neutral or slightly unstable. This is consistent with the definition of the transition given by Price et al., 2011. We also find that it is during this period that the fog reaches its maximum value of RLWP, showing that the LWP increases beyond the critical liquid water path value, which gives information on the persistence offog.

For radiation fog case studies, the adiabatic phase lasts 04:00 and 06:40 hours for case 1 and 517 2 respectively, maintaining the fog life cycle during the night until after sunrise. In cases 3 and 4, 518 the adiabatic phase is shorter and lasts 01:00 and 03:40 hours, respectively, with a night-time 519 dissipation at 03:40 and 04:00 UTC, respectively. In this fog phase, for radiation fog, the LWP 520 ranges from 22-26 g m<sup>-2</sup> with CTH near 187.5 m a.g.l. The fog is deeper for advection-radiation fog 521 cases with LWP / CTH at 30 g m<sup>-2</sup> / 200 m a.g.l and 43 g m<sup>-2</sup> / 287.5 m a.g.l, respectively (Table 2). 522 523 The adiabatic phase is characterized by an equivalent fog adiabatic closure parameter near or above 0.5, and a positive yet low RLWP. For all the cases except case 3, the adiabatic phase is associated 524 with moderate turbulence in the fog layer (0.2 < TKE < 0.4 m<sup>2</sup> s<sup>-2</sup> and 0.03 <  $\sigma_w^2$  < 0.04 m<sup>2</sup> s<sup>-2</sup>) which 525 indicates significant vertical mixing generating an unstable surface atmospheric boundary layer 526 527 (Fig. 11). This finding is consistent with the result of Ju et al., 2020 who based their analysis on one case study and Ghude et al., 2023, Dhangar et al., 2021 and Zhou and Ferrier, 2008 for more case 528 529 studies analysis. In addition, this phase can also be driven by horizontal advection (mesoscale and synoptic systems) as in the case study 3. 530

This study shows two distinct fog dissipation periods, at night and after sunrise. Daytime 531 dissipation is observed for radiative fog cases and night-time dissipation for advection-radiation 532 ones. All of them are observed when  $\alpha_{eq}^{closure} > 0.5$ , TKE > 0.3 m<sup>2</sup> s<sup>-2</sup>,  $\sigma_{w}^{2} > 0.04$  m<sup>2</sup> s<sup>-2</sup>, and the LWP 533 > 40 g m<sup>-2</sup> (except case study 2). For cases 1 and 2, turbulence is thermally driven by positive SHF, 534 while for cases 3 and 4, the night-time turbulence increase is mechanically driven by increased wind 535 speed. For all case studies, the RLWP decreases significantly from the stable phase to the 536 dissipation phase, confirming that dissipation through fog-base lifting is linked to insufficient liquid 537 water content in the fog layer, as suggested by the conceptual model. For case 3, the RLWP 538 becomes negative 20 min after dissipation. This delay is likely due to very rapid changes in LWP 539 540 and CTH at the fog dissipation time.

## 541 **5. Summary and Conclusions**

The SOFOG3D field campaign provides a unique dataset documenting thermodynamic and dynamical atmospheric circulations to further understand the processes driving fog formation and dissipation over Southeastern France. Based on an innovative instrumental synergy combining insitu and remote sensing measurements, combined with an adiabatic fog conceptual model, this study documented key processes and conditions such as advection, turbulent mixing, radiative cooling, atmospheric stability, fog water content and depth, presence of clouds above. We analysed the role of these processes and impacts of these conditions on fog formation, evolution and dissipation, focusing on four fog case studies: two radiation and two advection-radiation fogs. For each case study, we defined the different phases characterizing the fog life cycle, namely (i) its formation, (ii) an initial phase where the fog develops under thermally stable conditions, (iii) a transition phase towards an adiabatic fog, (iv) an adiabatic phase during which the fog vertical profile is adiabatic, and (v) a dissipation phase where the fog base lifts.

The results showed that for both radiation fog cases, the conditions are marked by very cold 554 atmospheric conditions associated with a continental easterly nocturnal low-level jet. For these 555 cases, the stable fog phase develops under strong surface radiative cooling and weak turbulence, in 556 a deep temperature inversion layer. The stable phase lasts as long as the wind speed and turbulence 557 remain very low (typically 1 m s<sup>-1</sup> and 0.1 m<sup>2</sup> s<sup>-2</sup>). The transition phase is driven by an increase of 558 wind speed and turbulence in the fog layer, reaching 2 m s<sup>-1</sup> and 0.2 m<sup>2</sup> s<sup>-2</sup>, respectively. This 559 560 increased turbulence is of mechanical origin (increased wind shear associated with an evolution of the airmass) hence its time of occurrence varies widely from one case to the other (05 and 00 UTC, 561 562 respectively). The adiabatic phase is characterized by sustained turbulence  $(0.2 < TKE < 0.4 \text{ m}^2 \text{ s}^2)$ 563 sufficient to ensure vertical mixing in the fog layer. The fog layer is then typically deeper than 100 m, and the LWP exceeds 20 g m<sup>-2</sup>. For these fog events, dissipation time is observed after sunrise, 564 when both thermal and dynamic production of the turbulence are high (TKE > 0.4 m<sup>2</sup> s<sup>-1</sup> and  $\sigma_w^2$  > 565 0.04 m<sup>2</sup> s<sup>-2</sup>). For both fog cases, we observe simultaneous increase of near-surface visibility and 566 decrease of the fog LWP reservoir (RLWP) derived from the fog conceptual model, about one hour 567 before dissipation time. 568

The analysis on the advection-radiation case studies shows that they have the shortest life 569 cycle linked to the low surface boundary layer stability, because they occur under westerly air 570 masses that evolved during the night (change in wind direction, increased wind shear). In this 571 category of fog, the processes driving the stable, stable/adiabatic transition and adiabatic phases are 572 573 similar to those of the radiation fog category. However, in one case, we observe a transition phase that occurs with a more subtle increase in turbulence than in the other three cases. As a result, the 574 increase in LWP and CTH is very slow; it takes more than 3 hours to reach adiabatic conditions. 575 Dissipation occurs before sunrise in both cases. In one case it is due to a sudden increase in wind 576 speed and wind shear leading to TKE values exceeding 0.4 m<sup>2</sup> s<sup>-1</sup>. In the other case, we have a deep 577 adiabatic fog (CTH > 200 m) with sustained turbulence ( $0.2 < TKE < 0.4 m^2 s^{-2}$ ) where the LWC 578 production is barely sufficient to maintain the fog all the way down to the surface. The conceptual 579 model shows negative RLWP values, while the visibility oscillates around 1 km. The full 580

dissipation of the fog is here associated with the presence of a cloud above the fog that furtherreduces the LWC production.

In summary, this paper provides quantitative analyses of key parameters and conditions that 583 drive the fog life cycle. The level of turbulent mixing in the fog, of both thermal and mechanical 584 origin is key to understand important transitions (from stable to adiabatic, and from adiabatic to 585 dissipation). This level of turbulence should be analysed considering the depth of the fog and its 586 liquid water path. Our study confirms that the RLWP, combined with visibility is an interesting 587 parameter to study the state of the fog, even though LWP and RLWP measured during SOFOG3D 588 present lower values than at the SIRTA site, close to the uncertainty of the measurement. Fog 589 formation, evolution and dissipation across southern France require an analysis of the synoptic 590 atmospheric circulation in terms of wind, cloud cover, and thermodynamical processes. Indeed, this 591 paper highlights that fog nowcasting tools in this region needs in addition to the numerical weather 592 593 prediction models, a cloud radar, a microwave radiometer, a wind lidar, a surface energy balance, and meteorological stations. Operationalizing these instruments would allow to improve fog 594 nowcasting, which will reduce its socio-economic impacts in this region. 595

## 596 Appendix A: Fog conceptual model parametrization

#### 597 A.1 Liquid water content

The conceptual model for adiabatic fog has been developed at SIRTA by Toledo et al., 2021. This model is a unidimensional model inspired by previous numerical models for stratus clouds (Betts, 1982, Albrecht et al., 1990; and Cermak and Bendix, 2011) (see equation 1). The basic hypothesis is to consider a well-mixed fog layer and express the increase with height of the fog liquid water content as a function of the local adiabaticity (a(z)) and the negative of the change in the saturation mixing ratio with height ( $\Gamma_{ad}(T,P)$ ), given in equation A1.

604 
$$\frac{dLWC(z)}{dz} = \alpha(z)\Gamma_{ad}(T, P)$$
(A1)

605 Where T and P are air temperature and pressure, respectively. z is the height above the surface and varies between 0 and the cloud top height (CTH). By integrating equation 1, it is 606 important to take into account fog geometry which is different from that of the stratus cloud. For a 607 fog, the LWC at the base is non-zero due to the presence of liquid droplets down to the ground 608 609 level. This presence of droplets drives surface visibility reduction and water deposition on the soil. Thus, as indicated in equation A2, the vertical integral of the LWC(z) is a function of the variation 610 with height of the adiabaticity,  $\Gamma_{ad}(T,P)$  and the measurement of the LWC at surface (LWC<sub>0</sub>). This 611 equation shows that the LWC increases with the thickness of the fog up to the height where upward 612

motions of moisture from the surface are constrained by downward motions of dry air from the fog
top height (Walker, 2003; Cermak and Bendix, 2011). From this interface level, the LWC decreases
with height and becomes zero at the fog top height (Brown and Roach, 1976; Cermak and Bendix,
2011).

617 
$$LWC(z) = \int_{z'=0}^{z'=z} \alpha(z') \Gamma_{ad}(T, P) dz' + LWC_0$$
(A2)

#### 618 A.2 Liquid water path

1

619 The fog liquid water path (LWP) represents the total amount of liquid water present in the 620 fog layer. It can be estimated by integrating equation A2 in height considering that the fog thickness 621 is equivalent to the CTH (equation A3). An approximation assuming a constant adiabaticity is introduced by using the equivalent fog adiabaticity term  $\alpha_{eq}$ . This simplifies the calculation, since a 622 complete computation would require a knowledge of the vertical profile of adiabaticity which 623 depends on the thermodynamic properties of the fog layer. In this conceptual model, the LWC is 624 treated as if it increased linearly with height from the surface to the CTH. At the surface level the 625 LWC from the model and fog are the same, connecting a given LWP with surface LWC. This 626 quantity is converted to visibility values using Gultepe et al., 2006 parametrization. Hence, the 627 conceptual model connects fog LWP with its CTH and surface visibility values, it provides an 628 estimation of the equivalent fog adiabaticity. 629

630 
$$LWP = \frac{1}{2} \alpha_{eq} \Gamma_{ad} (T, P) CTH^2 + LWC_0 CTH$$
(A3)

*Data availability.* All the data used in this study are hosted by the French national center for
Atmospheric data and services AERIS in the link <u>https://sofog3d.aeris-data.fr/catalogue/#masthead</u>.
Data access can be free following the conditions fixed by the SOFOG3D project.

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*Author contributions.* Cheikh DIONE: Conceptualization, Methodology, Investigation,
Validation, Formal-analysis, Writing – original draft, Writing – review & editing, Visualization.
Martial HAEFFELIN: Supervision, Methodology, Investigation, Formal-analysis, Writingoriginal draft, Writing-review & Editing, , Funding acquisition. Jean-Charles DUPONT:
Supervision, Investigation, Editing. Felipe TOLEDO: Methodology, Investigation, Editing.
Frederic BURNET: Project administration, Resources, Investigation, Editing, Funding acquisition.

Christine LAC: Supervision, resources, Investigation, editing, Funding acquisition. Jean-Francois
RIBAUD: Visualization, Investigation, Editing. Pauline MARTINET: Editing, Investigation, Data
curation. Guylaine CANUT: Investigation, Editing, Data curation. Susana JORQUERA: Data
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# 828 List of tables

**Table 1 :** Case study number, fog onsets, type of fog formation, fog dissipation times, fog duration and type of fog dissipation for the four documented case studies. Time is in UTC. Dates are in the format "dd/mm/yyyy". "dd" indicates the day, "mm" the month, and "yyyy" the year.

832 **Table 2**: Summary of fog features at the supersite during the five defined phases during its 833 evolution for each case study. The formation, dissipation times are estimated using the visibility (m) from the Scatterometer. The transition from stable to adiabatic fog is defined using temperature 834 from the microwave radiometer. The cooling rate (dT/dt), wind speed (WS), and wind direction 835 (WD) are derived from the meteorological station. Sensible heat flux (SHF), turbulent kinetic 836 energy (TKE) and the vertical velocity variance ( $\sigma_w^2$ ) at 3 m a.g.l are derived from the flux station. 837 The liquid water path (LWP) is estimated from the MWR. The fog reservoir of liquid weather path 838 (RLWP) and the equivalent adiabaticity of closure  $\alpha_{eq}^{closure}$  parameter are computed by the 839 conceptual model. Cloud top height (CTH) and middle and high cloud base and top heights are 840 derived from the radar reflectivity from Basta cloud radar."-" indicates that the variables are not 841 842 measurable or calculable.

# 843 List of figures

Figure 1: In a), the geographical map of the study area of the SOFOG3D field campaign including
the five instrumented sites (Agen, Bergerac, Biscarrosse, Mont-de-Marsan, and Saint-Symphorien)
where a microwave radiometer was installed (adapted from
<a href="https://fr.wikipedia.org/wiki/Grand\_Sud-Ouest\_fran%C3%A7ais#/media/">https://fr.wikipedia.org/wiki/Grand\_Sud-Ouest\_fran%C3%A7ais#/media/</a>

Fichier: Topographic map of South-West France with main rivers and cities.svg). Blue lines indicate the rivers. The cities are indicated in black dots. The most instrumented domain around the supersite is indicated in a) by the red rectangle. In b), the orography of a 100 x 100 km<sup>2</sup> domain centered on Charbonnière which includes locations of four of the meteorological stations installed around the supersite used in this study. Orography data are from the National Aeronautics and Spatial Administration (NASA) shuttle radar topography mission (SRTM) (90 m of resolution).

**Figure 2:** (a) Scatter plot of the equivalent adiabaticity by closure versus the CTH and LWP at the supersite. b) Boxplot of the equivalent adiabaticity by closure versus the different LWP ranges from the MWR. In b), numbers at the figure top indicate total values included in each boxplot and computed between 2 hours before and after the fog. Horizontal dashed line indicates the threshold of the equivalent adiabaticity from closure defining the transition from stable to adiabatic fog.

Figure 3: In (a-b) time-height cross-section from surface up to 600 and 12000 m, respectively of 859 860 radar reflectivity from Basta (shaded) radar, time evolution of the cloud top height from Basta (red line), and the cloud base height from the Celiometer (CL51) (green line). Time evolution of (c) 861 surface visibility, (d) 10 m wind speed, (e) 2 m air temperature, and (f) 10 m wind direction 862 863 observed on the 28-29 December 2019 (case study 1, IOP 5) at the five meteorological stations (in red, black, blue, green, and pink lines for Moustey (1 m a.g.l), Charbonnière (3 m a.g.l), Cape Sud 864 (3 m a.g.l), Tuzan (3 m a.g.l), and Noaillan (1 m a.g.l), respectively) deployed around the supersite. 865 Note that wind was not collected at Tuzan. In (c), the visibility measured at Moustey was 866 interrupted by technical issues. Vertical black dashed lines indicate fog formation (left) and 867 dissipation (right) times. Green dashed lines show the transition time from stable fog to adiabatic 868 fog (fog mature phase). Red dashed line indicates the sunrise. 869

**Figure 4:** Evolution of fog macrophysical characteristics observed on the 28-29 December 2019 (case study 1, IOP 5) at Charbonnière. In (a-b) vertical profiles of air temperature from the Hatpro microwave radiometer (MWR) and radar reflectivity from Basta radar, respectively. In (c) timeheight cross-section of air temperature from the MWR (shaded), time evolution of inversion top

height (ITH) (open gray circles), inversion base height (IBH) (open gray squares), cloud top height 874 (CTH) from the cloud radar (open black squares), and the cloud base height (CBH) from the 875 Celiometer (open black circles). In (d) wind speed (shaded) and direction (arrows) from the 876 877 WindCube. Arrows in (d) indicate only the direction of the horizontal flow. Time evolution of (e) air temperature at 3 m a.g.l from the meteorological station (red line) and equivalent adiabaticity of 878 closure from the fog conceptual model (blue line), (f) the mean of the turbulent kinetic energy 879 (TKE) in the layer 40 – 220 m for the WindCube (black line) and the TKE (blue line) and vertical 880 velocity variance (red line) at 3 m a.g.l from the flux station at Charbonnière, (g) the LWP estimate 881 from the MWR (blue line), the RLWP from the fog conceptual model (red line), and (h) sensible 882 heat fluxes (SHF) (red and blue lines, respectively) from the flux station. Vertical black dashed lines 883 indicate fog formation and dissipation times. Green dashed lines indicate the transition period (fog 884 mature phase) from stable to adiabatic fog. The red dashed line indicates sunrise. 885

**Figure 5:** As in Figure 3 but for the 5-6 January 2020 (case study 2, IOP 6). In (c), only Charbonnière and Noaillan have valid data. In (c), the visibility measured at Moustey, Tuzan and Cape Sud were interrupted by technical issues.

**Figure 6:** As in Figure 4 but for the 5-6 January 2020 (case study 2, IOP6).

**Figure 7:** As in Figure 3 but for the 8-9 February 2020 (case study 3, IOP 11).

**Figure 8:** As in Figure 4 but for the 8-9 February 2020 (case study 3, IOP 11).

Figure 9: As in Figure 3 but for the 7-8 March 2020 (case study 4, IOP 14).

Figure 10: As in Figure 4 but for the 7-8 March 2020 (case study 4, IOP 14). The LWP, RLWP, and  $\alpha_{eq}^{closure}$  are disrupted between 00:30 and 02:30 UTC because the LWP estimated by the MWR take into account the liquid water in the advected stratus.

Figure 11: Vertical profiles of air temperature and radar reflectivity put together for each fog case study: (a) for case study 1, (b) case study 2, (c) case study 3 and (d) case study 4. Line and shaded area indicate the mean and standard deviation of air temperature and radar reflectivity during each fog phase. 900 *Table 2 : Summary of fog features at the supersite, during the five defined phases during it evolution for each case study.* 

901 The formation, dissipation times are estimated using the visibility (m) from Scatterometer. The cooling rate (dT/dt), wind

902 speed (WS) and wind direction (WD) are derived from the meteorological station. Sensible heat flux (SHF), turbulent

903 kinetic energy (TKE), and the vertical velocity variance ( $\sigma_w^2$ ) at 3 m a.g.l are derived from the flux station. The liquid

904 water path (LWP) is estimated from the MWR. The fog reservoir of liquid weather path (RLWP) and the equivalent

adiabaticity of closure  $a_{eq}^{closure}$  parameter are computed by the conceptual model. Cloud top height (CTH) and middle

and high cloud base and top heights are derived from the radar reflectivity from Basta cloud radar."-" indicates that the

907 *variables are not measurable or calculable.* 

Case study number	Phase names	Time range (UTC)	Duration (h:min)	Visi bility (m)	dT/dt (°C h-I)	α <sub>eq</sub> cosure (g m <sup>-3</sup> )	LWP (g m <sup>-2</sup> )	RLWP max (g m <sup>-2</sup> )	CTH (m a.g.l)	WS (m s-1)	WD (°)	TK E (m <sup>2</sup> s <sup>-2</sup> )	$\frac{\sigma_w^2}{(m^2 s^{-2})}$	SHF (W m <sup>-2</sup> )	Cloud above fog (m a.g.l)
1 (IOP5)	Pre-fog	[20:50 - 22:50]	2:00	9962	-0.9	-	0	-	-	0.61	61	0.11	0.002	-0.23	clear
	Stable	[22:50 - 05:00]	6:10	736	-0.18	-1.3	2	-	50	0.7	84	0.07	0.01	-1.16	clear
	Transition stable/a diabatic	[05:00 - 07:00]	2:00	173 - 262	0.08	-0.8 - 0.4	7 - 28	8 - 15	75 - 187.5	0.5 - 2.1	68 - 112	0.06 - 0.15	0.02 - 0.03	2.3 - 8.8	clear
	Adiabatic	[07:00 - 11:00]	4:00	370	0.77	0.5	26	6	187.5	2.4	116	0.23	0.04	12.9	[8000 - 10000]
	Dissipation	[10:30 - 11:30]	1:00	1549	1.1	0.63	43	-11	287.5	2.6	94	0.36	0.06	22.02	clear
2 (IOP6)	Pre-fog	[18:40 - 20:40]	2:00	15566	-0.7	-	0	-	-	0.2	195	0.03	0.003	-0.17	clear
	Stable	[20:40 - 00:00]	3:20	242	-0.13	-0.69	2	-	75	1	183	0.06	0.009	0.28	clear
	Transition stable/a diabatic	[00:00 - 02:00]	2:00	219 - 291	-0.007	-0.2 - 0.45	1 - 17	-1 - 4	75 - 162.5	1.6 - 2.6	149 - 147	0.15 - 0.23	0.02 - 0.04	3.7 - 11	clear
	Ad ia batic	[02:00 - 08:40]	6:40	450	0.17	0.51	22	1	187.5	2.2	110	0.21	0.04	6.62	clear
3	Dissipation	[08:10 - 09:10]	1:00	944	0.43	0.53	12	-8	187.5	2.5	136	0.28	0.048	14.02	[250 - 1000]
	Pre-fog	[18:40 - 20:40]	2:00	13239	-1.03	-	0	-	-	1.3	242	0.05	0.011	-5.5	rain
1.0000	Stable	[20:40 - 23:00]	2:20	243	-1.2	-0.69	6	-	75	1	220	0.03	0.002	-1.7	clear
3(10P11)	Transition stable/a diabatic	[23:00 - 02:30]	3:30	134 - 260	-0.08	-1.35 - 0.4	5 - 20	8-6	50 - 150	1.8 - 0.4	144 - 78	0.06 - 0.03	0.006 - 0.004	-1.9 0.2	clear
	Ad ia batic	[02:30 - 03:40]	1:10	271	0.81	0.54	31	3	200	1	120	0.04	0.008	-0.49	clear
	Dissipation	[03:10 - 04:10]	1:00	1445	1.34	0.6	42	2	237.5	3.6	143	0.33	0.07	-3.02	clear
4 (IOP14)	Pre-fog	[19:20 - 21:20]	2:00	14088	-0.47	-	0	-	-	1.1	233	0.02	0.002	-1.17	[5000 - 6000] [8000 - 10000]
	Stable	[21:20 - 23:30]	2:10	230	-0.88	-0.46	11	-	87.5	1.2	177	0.06	0.012	-3.26	clear
	Transition stable/a diabatic	[23:30 - 01:00]	1:30	240 - 253	0.12	-0.17 - 0.64	11 - 59	10	100-200	1.6 - 2.7	141 - 184	0.06 - 0.27	0.01 - 0.05	-1.6 - 2.7	clear
	Ad ia batic	[00:20 - 04:00]	3:40	372	0.47	0.59	43	8.10	287.5	2	179	0.17	0.03	1.2	[250 - 500]
	Dissipation	[03:30 - 04:30]	1:00	1160	-0.14	0.60	40	-2	237.5	2.7	174	0.23	0.04	0.82	clear



Figure 1: In a), the orography of the study area of the SOFOG3D field campaign including the five
instrumented sites (Agen, Bergerac, Biscarrosse, Mont-de-Marsan, and Saint-Symphorien) where a
microwave radiometer was installed (adapted from <a href="https://fr.wikipedia.org/wiki/Grand\_Sud-">https://fr.wikipedia.org/wiki/Grand\_Sud-</a>
Ouest\_fran%C3%A7ais#/media/Fichier:Topographic\_map\_of\_South-

912 West France with main rivers and cities.svg). Blue lines indicate the rivers. The cities are 913 indicated in black dots. The most instrumented domain around the supersite is indicated in a) by the 914 red rectangle. In b), the orography of a 100 x 100 km<sup>2</sup> domain centered on Charbonnière which 915 includes locations of four of the meteorological stations installed around the supersite and used in 916 this study. Orography data are from the National Aeronautics and Spatial Administration (NASA) 917 shuttle radar topography mission (SRTM) (90 m of resolution).



**Figure 2:** In (a) Scatter plot of the equivalent adiabaticity by closure versus the CTH and LWP (colored circles) at the supersite. b) Boxplot of the equivalent adiabaticity by closure versus the different LWP ranges from the MWR. In b), numbers at the figure top indicate total values included in each boxplot and computed between 2 hours before and after the fog. Horizontal dashed line indicates the threshold of the equivalent adiabaticity from closure defining the transition from stable to adiabatic fog.



Figure 3: In (a-b) time-height cross-section from surface up to 600 and 12000 m, respectively of radar 924 reflectivity from Basta (shaded) radar, time evolution of the cloud top height from Basta (red line), 925 926 and the cloud base height from the Celiometer (CL51) (green line). Time evolution of (c) surface visibility, (d) 10 m wind speed, (e) 2 m air temperature, and (f) 10 m wind direction observed on the 927 28-29 December 2019 (case study 1, IOP 5) at the five meteorological stations (in red, black, blue, 928 green, and pink lines for Moustey (1 m a.g.l), Charbonnière (3 m a.g.l), Cape Sud (3 m a.g.l), Tuzan 929 930 (3 m a.g.l), and Noaillan (1 m a.g.l), respectively) deployed around the supersite. Note that wind was not collected at Tuzan. In (c), the visibility measured at Moustey was interrupted by technical issues. 931 Vertical black dashed lines indicate fog formation (left) and dissipation (right) times. Green dashed 932 lines show the transition time from stable fog to adiabatic fog (fog mature phase). Red dashed line 933 934 indicates the sunrise.



935 Figure 4: Evolution of fog macrophysical characteristics observed on the 28-29 December 2019 (case study 1, IOP 5) at Charbonnière. In (a-b) vertical profiles of air temperature from the Hatpro microwave radiometer 936 (MWR) and radar reflectivity from Basta radar, respectively. In (c) time-height cross-section of air 937 temperature from the MWR (shaded), time evolution of inversion top height (ITH) (open gray squares), 938 939 inversion base height (IBH) (open gray squares), cloud top height (CTH) from the cloud radar (open black squares), and the cloud base height (CBH) from the Celiometer (open black circles). In (d) wind speed 940 (shaded) and direction (arrows) from the WindCube. Arrows in (d) indicate only the direction of the 941 horizontal flow. Time evolution of (e) air temperature at 3 m a.g.l from the meteorological station (red line) 942 and equivalent adiabaticity of closure from the fog conceptual model (blue line), (f) the mean of the turbulent 943 kinetic energy (TKE) in the layer 40 - 220 m for the WindCube (black line) and the TKE (blue line) and 944 vertical velocity variance (red line) at 3 m a.g.l from the flux station at Charbonnière, (g) the LWP estimate 945 946 from the MWR (blue line), the RLWP from the fog conceptual model (red line), and (h) sensible heat fluxes (SHF) (red and blue lines, respectively) from the flux station. Vertical black dashed lines indicate fog 947 948 formation and dissipation times. Green dashed lines indicate the transition period (fog mature phase) from 949 stable to adiabatic fog. The red dashed line indicates sunrise.



Figure 5: As in Figure 3 but for the 5-6 January 2020 (case study 2, IOP 6). In (c), only Charbonnière
and Noaillan have valid data. In (c), the visibility measured at Moustey, Tuzan and Cape Sud were

952 interrupted by technical issues.



**Figure 6:** As in Figure 4 but for the 5-6 January 2020 (case study 2, IOP6). The red vertical dashed

954 line indicates the sunrise.



**Figure 7 :** As in Figure 3 but for the 8-9 February 2020 (case study 3, IOP 11)



**Figure 8:** As in Figure 4 but for the 8-9 February 2020 (case study 3, IOP 11).



**Figure 9 :** As in Figure 3 but for the 7-8 March 2020 (case study 4, IOP 14).



**Figure 10 :** As in Figure 4 but for the 7-8 March 2020 (case study 4, IOP 14). The LWP, RLWP, and  $\alpha_{eq}^{closure}$  are disrupted between 00:30 and 02:30 UTC because the LWP estimated by the MWR take into account the liquid water in the advected stratus.



Figure 11: Vertical profiles of air temperature and radar reflectivity put together for each fog case study (a) for case 1,
(b) case 2, (c) case 3 and (d) case 4. Line and shaded area indicate the mean and standard deviation of air temperature
and radar reflectivity during each fog phase.