Towards a three-dimensional prediction of fog on airports with the Météo-France operational forecast model AROME.

Alain Dabas, Météo-France, CNRM/GMEI
alain.dabas@meteo.fr
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Thierry Bergot, Christine Lac, Frédéric Burnet, Pauline Martinet, Yves Bouteloup, François Bouyssel
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Speaker: Alain Dabas

Fog is a common weather phenomenon. Reducing the visibility to short distances, it has an adverse impact on human activities, in particular in aviation, marine or land transportation. Fog can be a source of fatal accidents as it was the case in 1977 when two commercial aircrafts collided on the Tenerife airport [1]. To avoid such accidents, the air traffic control (ATC) define a low visibility procedure (LVP) when the horizontal visibility or the cloud ceiling is too low. During LVP conditions, the capacity of the airport, that is, the number of take-offs or landings per unit time, is substantially reduced (50% at Paris Charles-de-Gaulle CDG airport). Many flights are cancelled or delayed. Flights already en route are stacked in waiting volumes that may saturate. Diversion to other airports are then necessary. Many passengers miss their connections. In December 2006, London Heathrow airport was drowned in a dense fog for 5 consecutive days. More than 1000 flights and 800000 passengers were affected, and the cost for British Airways was estimated at more than 40 million £ [2].

The provision of accurate prediction of fog formation or dissipation from 1 to 24 hours in advance would greatly help airport authorities mitigate the costly consequences of the phenomenon. Such accurate predictions are beyond the reach of current numerical weather prediction systems. The reasons are multiple. Fog has a very fine vertical extension (400m or 500m in worst cases) and involves many highly non-linear processes such as visible or infrared radiation, the formation and evolution of water drops, the turbulence, the deposition of water at the surface... Fine vertical resolution models are thus necessary, which until recently could not run in real time on high-power computers unless restricted to the single vertical coordinate. An example of such a 1D column model is COBEL which was run operationally at CDG airport for several years [3]. These models suffer some limitations by nature. They cannot for instance simulate properly the advection of humidity on a cold surface or the impact of surface heterogeneities. In addition, they must be initialized with vertical profiles of the various parameters that characterize the state of the atmospheric layer concerned by the fog. Some of them can be extracted from larger-scale operational models, although with a coarse vertical resolution that may not be sufficient. Others can be measured on site with specific instruments (surface temperature and humidity for instance), but adequate operational measurement systems lack for several parameters like the concentration and size distribution of aerosol particles before fog formation or water drops when the fog is formed.
The difficulty to fully characterize the state of the fog layer also explains why our knowledge of several key processes is limited and why their representation in the model needs to be improved. Scientific studies are needed to:

- assess the impact of surface heterogeneities (hills, vegetation types and water bodies) on the fog life cycle via their influence on local wind circulations, turbulent fluxes and liquid water deposition processes,
- quantify more precisely the impact of aerosol on radiative cooling and heating, and their effect on optical thickening pointed out by Boutle et al., 2017 [4],
- quantify the entrainment and turbulent mixing of clear air at the top of the fog layer and evaluate the impact of free troposphere properties on the fog life cycle,
- quantify the weak and sporadic turbulence in stable layers and its contribution to the energy budget.
- make progress in our understanding of processes and conditions leading to stratus cloud-to-fog transitions as stratus lowering cases are less well predicted (Philips et al., 2016) [5].

Research activities have been recently conducted in order to advance our understanding on these subjects. A common approach is to take advantage of the growing capacity of high-power computers and run large-eddy-simulation (LES) models. With a horizontal and vertical resolution of the order of a meter, these models can be used to assess the relative importance of the various processes at stake in the different stage of the fog life cycle and point out which processes shall be improved in order to reduce the major differences with observations made during real fog cases. A first example can be found in Bergot et al., 2015 [6]. There, the impact of the terminal buildings of the airport on the formation of fog on the platform is studied. The simulations show the buildings have a blocking effect and induce thickness heterogeneities during the fog formation phase (see Figure 1), but has no significant impact of the fog layer characteristics once the fog has reached a mature stage. Then, the fog evolution is mostly governed by the processors at its top. Another more recent example Mazoyer et al. 2017 [7], where an LES study on radiation fog is conducted for the time with microphysical parametrization scheme while considering the effect of heterogeneities such as forests on the fog dynamics. The article shows that the deposition of the water at the surface exerts the most significant impact on fog prediction as it not only erodes the fog near the surface but also modifies the fog life cycle and induces vertical heterogeneities.
On the observation side, several systems have been developed that significantly extend our capacity to characterize fog. Microwave radiometers provide fine temporal resolution profiles of the temperature [8]. W-band radars [9] are now available that are enough sensitive to detect the water drops that form the fog (see Figure 2). They open the possibility to measure the liquid water content in real time at fine spatial and temporal resolutions. Low-level Doppler lidars can characterize the level of turbulence in the first hundreds of meters just before the formation of the fog. Miniaturized sensors can be deployed with tethered balloons and characterize the concentration and size distribution of water drops throughout the fog life cycle. At last, Unattended Aerial Vehicles (UAV) equipped with miniaturized sensors (see Figure 3) can explore the three-dimensional structure of a fog layer and characterize its heterogeneity. Not only these systems provide useful information for scientific research, but most of them could become operational and feed numerical models for improved forecasts of fog through an assimilation process.
The possibility to simulate fog with an operational, limited-area, fine resolution model has recently been tested by Philip et al., 2017 [5]. The model is a specific version of the French forecast model AROME [10]. Operational forecasts of fogs with such a model now seem to be within reach. The capacity of the next generation of high-power computers should be able to run a 500m or better horizontal resolution of the model with a fine enough vertical resolution and improved parametrizations of surface exchanges and microphysics. Météo-France has launched a research program aimed at assessing its performance. During the winter of 2019-2020, the model will be run on a site located in the south-western part of France prone to fog formation (fogs were reported on more than 800 days at Mont-de-Marsan in the last 10 years) while a reach instrumental set-up will be deployed. The purpose is to evaluate the capacity of the model to simulate correctly the various fog processors, the impact of surface heterogeneities, and provide accurate forecasts.
Figure 3: AUV flying in fog.