Numerical Forecasting of Radiation Fog. Part II: A Comparison of Model Simulation with Several Observed Fog Events

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ABSTRACT

A 1D model adapted for forecasting the formation and development of fog, and forced with mesoscale parameters derived from a 3D limited-area model, was used to simulate three fog event observations made during the Lille 88 campaign. The model simulation correctly reproduced the time of fog formation and its vertical development when forcing terms derived from observations were used. It determined the influence of different physical processes and in particular that of dew deposition. The initial conditions deduced from the 3D model proved to be correct in two of the three events. On the other hand, the prediction of advection terms necessary for forecasting the vertical growth of fog was a more delicate matter.

1. Introduction

In a companion article (Bergot and Guedalia 1994, hereafter referred to as BG), we described the characteristics of a one-dimensional nocturnal boundary layer model COBEL (Couche Brouillard Eau Liquide) designed to simulate the formation and evolution of radiation fogs. We now intend to implement a method for forecasting dense fogs that affect the Nord-Pas de Calais region (located in the north of France, between Paris and the France–Belgium border). This region has a rather homogeneous and flat surface (consisting mainly of bare, ploughed soil under winter conditions), which is the site of numerous occurrences of dense fog.

The forecasting method consists of using the COBEL model forced by advection terms and the geostrophic wind deduced from the French limited-area forecasting model PERIDOT (horizontal grid of 35 km). This method was inspired by that proposed by Musson-Genon (1987), in which the forcing terms were deducted from a general circulation model with a much larger horizontal grid (approximately 150 km) and much cruder physical parameterizations.

In BG we described the results of a sensitivity study concerning the initial conditions and forcing terms. This study emphasized the importance of initial conditions (see also Musson-Genon 1987; Fitzjarrald and Lala 1989; Ballard et al. 1991) and advective terms (see also Turton and Brown 1987). The influence of these different parameters is even greater when the fog forms late in the night, when the atmospheric cooling rate is low. Advection is especially important for simulating the vertical growth of the fog. We also demonstrated the determining role of dew (or frost) deposition, which can delay and even prevent the formation of fog. The precision required for these different input parameters is such that fog forecasting remains a difficult question. Consequently, the method will have to be tested on real cases.

This paper aims at two main goals. The first one consists in testing the ability of the COBEL model to characterize the properties of a fog layer; in this case, COBEL is run using all the available observations (initial profiles, clouds, advection) thanks to Lille 88 data (Guedalia and Bergot 1992). The second goal relates to verifying the model skill in fog forecasting. To do so, COBEL is forced by the terms obtained from the PERIDOT meteorological model. The quality of this forecasting may be evaluated from three parameters: fog onset, vertical depth, and fog intensity.

This approach allows us to separate the errors produced by the COBEL model from those proceeding from the external parameters predicted by PERIDOT.

This study should be considered in relation to some previous work done on the simulation of real cases using numerical models. One might mention the work of Turton and Brown (1987), who simulated the fog that occurred during two nights at Cardington (United Kingdom); they reached the conclusion that the differences between simulations and observations might be due, in particular, to the fact that advection and vegetation presence had not been taken into account. More

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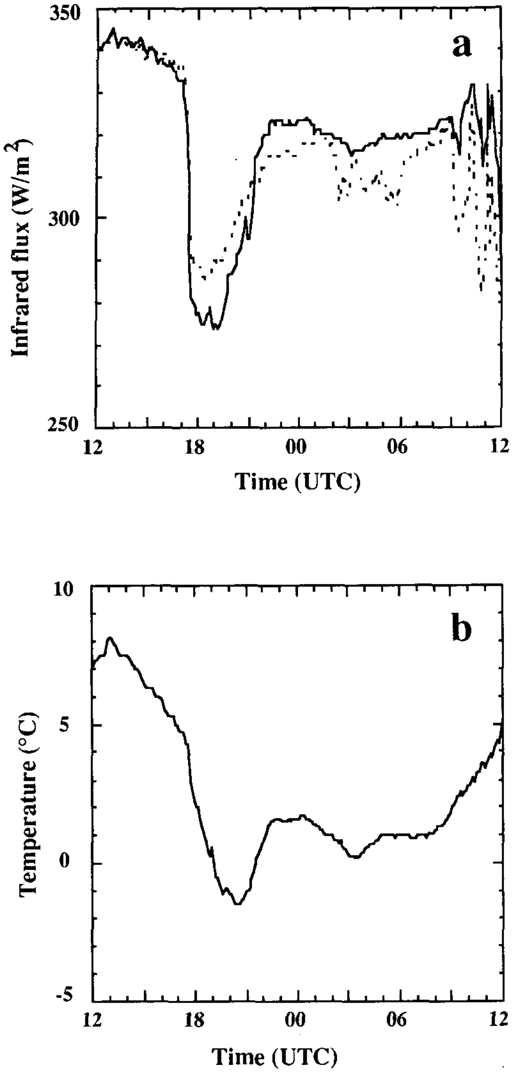

FIG. 1. Case study 6–7 November 1988: (a) Time variation of observed downward infrared flux at 1 m (solid) and at 80 m (dashed); (b) time variation of the observed temperature at 0.7 m.

recently, Duynkerke (1991) simulated a case observed at Cabauw (the Netherlands). His model included a detailed representation of soil–vegetation–atmosphere interactions, thus enabling a good reproduction of the time evolution of surface temperature. On the other hand, there were differences in the simulated and observed liquid water content, which causes more significant radiative cooling in simulations (and hence a greater mixing). In this case, advection terms were not taken into account.

2. Description of the model

The forecasting method was based on the use of a 1D nocturnal boundary layer (NBL) model forced by mesoscale terms (geostrophic wind and horizontal advections of temperature and humidity) resulting from a 3D, limited-area model PERIDOT used by Meteo-France.

The 1D model, called COBEL, has been described in detail in BG. It is an NBL model including a parameterization of soil–atmosphere exchanges (not including vegetation) (Estournel and Guedalia 1985). It includes six prognostic variables (temperature, mixing ratio, two components of horizontal wind, liquid water, and turbulent kinetic energy) that are calculated for 30 levels between the surface and 1400 m. The diffusion of heat in the soil is calculated on five levels between the surface and 1 m in depth; parameterization of the dew and frost fluxes makes it possible to calculate the hydric flux between the soil and the atmosphere. A radiative scheme is used to calculate longwave radiative fluxes for all levels of the model. The turbulent closure is at 1.5 order and takes into account the cases of strong vertical stability.

The simulations described in this article started at 1500 UTC, under close to neutral conditions. We used two different methods to determine the initial profiles. The first consisted of using observed data from the Lille 88 experiment (80-m tower and radiosonde observations), which meant that the initial conditions were very close to those observed. The second method consisted of using data predicted by the PERIDOT model, since one of the objectives of this study was to evaluate the quality of the 1D simulation, initialized and forced by the PERIDOT mesoscale model, to forecast dense fog formation.

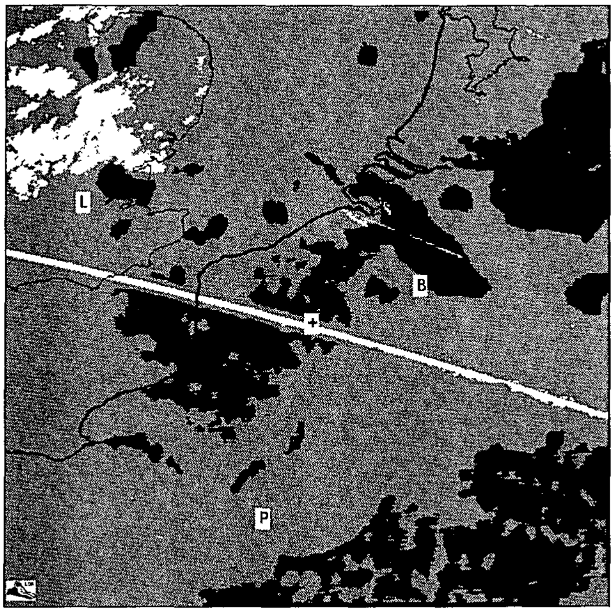

FIG. 2. Case study 6–7 November 1988. Spatial distribution of fog deduced from *NOAA-9* AVHRR data. Black: fog; white: clouds. Geographic points: Paris (P), Brussels (B), London (L), and Carnin site (+).

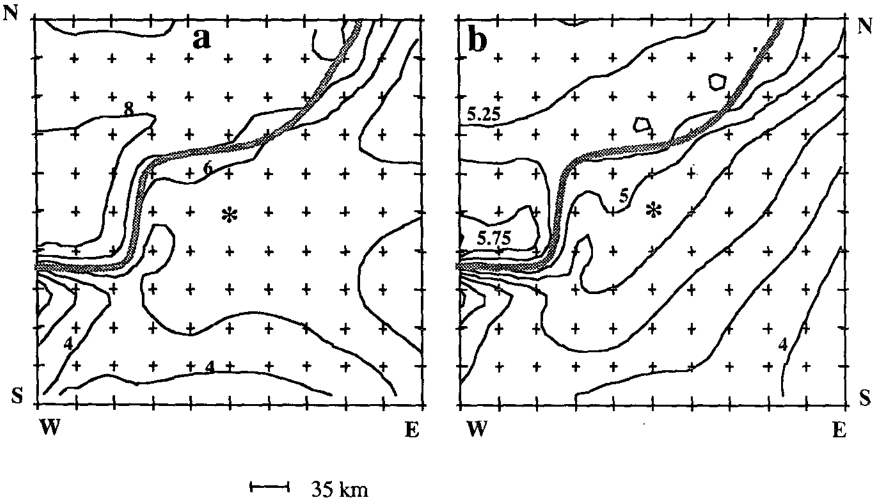

FIG. 3. Case study 6–7 November 1988. Regional fields predicted by PERIDOT at 0000 UTC: (a) temperature isolines, contour interval of 1°C; (b) humidity mixing ratio isolines, contour interval of 0.25 g kg^{-1}. The asterisk represents the Carnin site. The shaded line represents the coastline.

As has been shown in the sensitivity study (BG), it is necessary to know the precise value of the thermal conductivity K_s of the superficial soil layer (0–10 cm). In the simulations described here, the value of superficial K_s was determined using the budget of the measured fluxes at the surface. The K_s value of the deepest layers was taken to be 1.5 W K^{-1} m^{-1}, which is representative of a moist soil.

3. External forcing terms

Realistic situations rarely enable omission of the horizontal advection terms (Brown and Roach 1976; Turton and Brown 1987). In this study, the mesoscale parameters (geostrophic wind, horizontal temperature, and humidity advections) are computed from PERIDOT forecasting model data. Another input forcing term is the infrared "cloudy flux." The solar flux value at the beginning of the simulation and its time decrease corresponds to the climatological value.

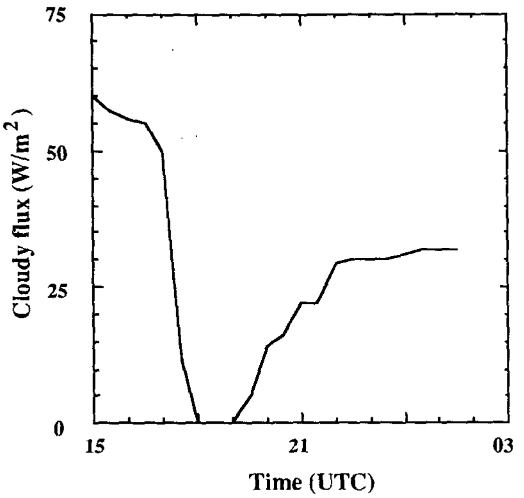

FIG. 4. Case study 6–7 November 1988. Cloudy flux used for the model simulation, deduced from observed downward infrared flux.

a. Brief description of the PERIDOT model

PERIDOT is one of the models used by the French Meteorological Office. It was developed to improve short-range forecasting (1–2 days). PERIDOT has been described by Imbard et al. (1986). Let us recall its general features. It is a limited-area hydrostatic model. Its horizontal grid size is 36 km on the region studied (north of France) and its vertical grid (vertical coordinate sigma) varies with altitude in such a way as to provide an accurate description of the low troposphere. The PERIDOT model is initialized every 12 h and the forecasts are stored every 6 h.

b. Computing of the forcing terms

1) ADVECTIVE TERMS

The advective terms are calculated in sigma coordinates in such a way as to avoid the very unreliable calculation of the vertical velocity in a vertical z coordinate. The isosigma advection for $\alpha = \theta, q$ is expressed as follows (Holton 1979):

$$\mathrm{Adv}_\sigma \alpha = \mathbf{u}\nabla_\sigma \alpha + \frac{\partial \alpha}{\partial \sigma}\frac{d\sigma}{dt}. \qquad (1)$$

At ground level, the term $d\sigma/dt$ is zero. (The isosigma plots follow the orographic features.) This term

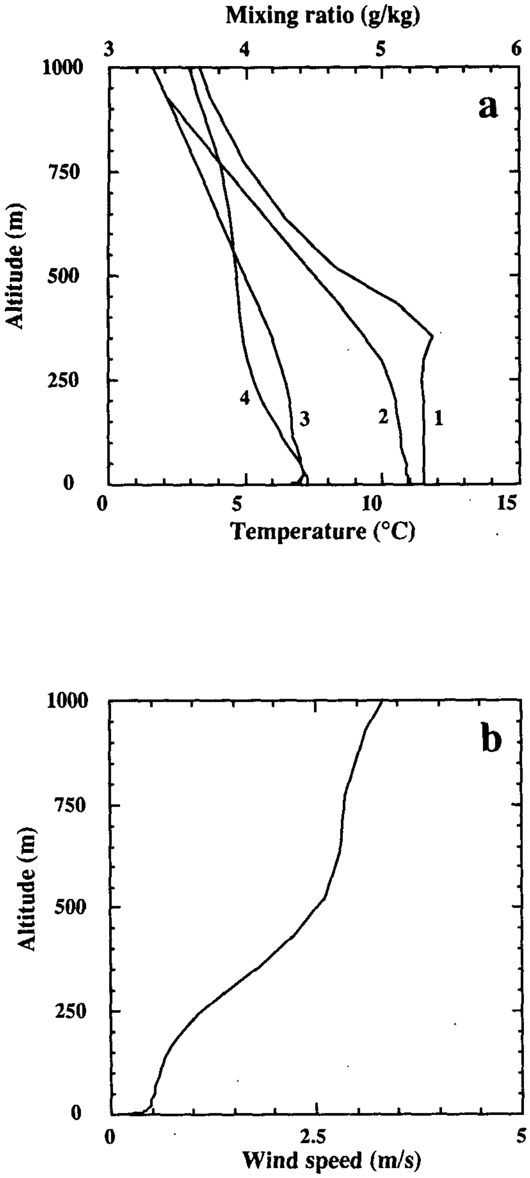

FIG. 5. Case study 6–7 November 1988. Initial profiles used for the model simulation: (a) temperature derived from observed data (curve 3) and from PERIDOT (curve 4) and mixing ratio derived from observed data (curve 1) and from PERIDOT (curve 2); (b) wind derived from PERIDOT.

is very low for anticyclonic conditions that are favorable to fog formation, especially at altitudes lower than 100 m. Hence, it will be neglected. This leads us to write

$$\mathrm{Adv}\alpha = \mathbf{u}_p \nabla_\sigma \alpha, \qquad (2)$$

where $\nabla_\sigma \alpha$ is the horizontal isosigma gradient, and $\mathbf{u}_p$ the wind predicted by PERIDOT. The horizontal gradients are calculated on a spatial interval twice the size of the PERIDOT grid, namely, 72 km.

Above the first PERIDOT model level (about 20 m) the interpolation onto the vertical grid of the COBEL model is based on the cubic-spline method. Under this level, the advection is extrapolated by using the wind profile calculated by the COBEL model:

$$\mathrm{Adv}\alpha(z) = u(z)\frac{\mathrm{Adv}_\alpha(z_1)}{u(z_1)}, \quad \text{for} \quad z < z_1, \qquad (3)$$

where $u(z_1)$ is the wind calculated by the COBEL model at an altitude corresponding to the first PERIDOT level, $u(z)$ is the wind calculated by the COBEL model at a z altitude, and $\mathrm{Adv}_\alpha(z_1)$ is the horizontal advection predicted by PERIDOT for the first level. The temporal interpolation is linear.

2) GEOSTROPHIC WIND

The geostrophic wind is calculated in vertical sigma coordinates (Holton 1979):

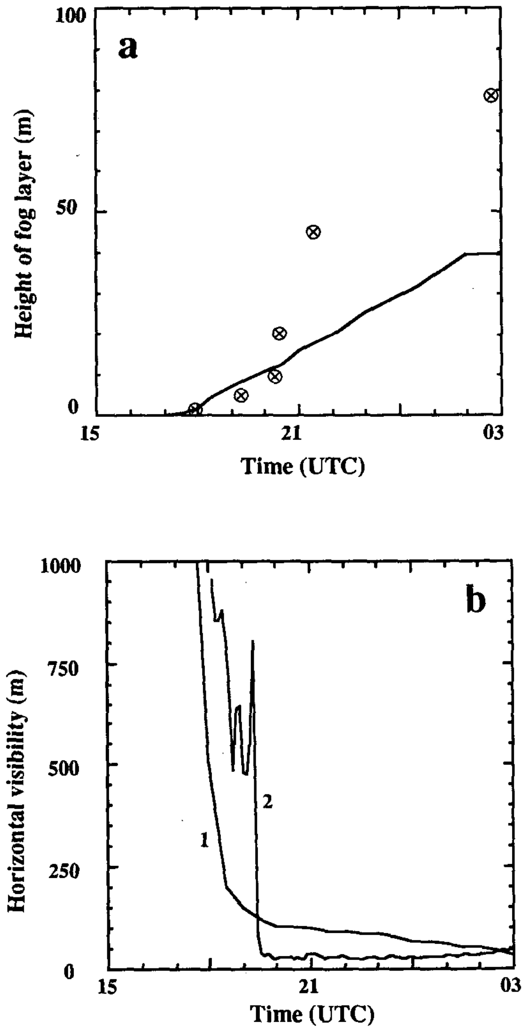

FIG. 6. Case study 6–7 November 1988: (a) simulated (line) and observed (×) fog height; (b) simulated (curve 1) and observed (curve 2) horizontal visibility at 1 m.

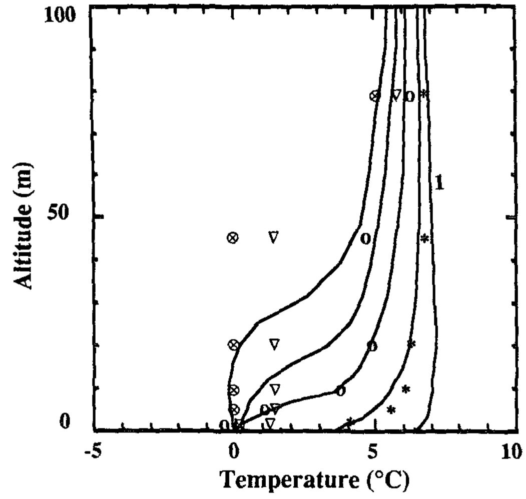

FIG. 7. Case study 6–7 November 1988. Temperature profiles. Model simulations (lines). Number 1 corresponds to initial profile at 1500 UTC; each profile corresponds to a 3-h interval. Observations: 1800 (*); 2100 (O); 0000 (∇); 0300 (⊗) UTC.

$$u_g = -\frac{1}{f}\left[\frac{\partial\Phi}{\partial y} + RT\frac{\partial \ln(p_0)}{\partial y}\right] \tag{4}$$

$$v_g = \frac{1}{f}\left[\frac{\partial\Phi}{\partial x} + RT\frac{\partial \ln(p_0)}{\partial x}\right], \tag{5}$$

where Φ is the geopotential obtained by integration of the hydrostatic equation starting from the surface, R is the gas constant, and p_0 is the pressure at ground level. The geostrophic wind is calculated on a spatial interval four times larger than the PERIDOT grid (144 km) in such a way as to minimize the errors. The interpolation of the geostrophic wind on the grid of the COBEL model is identical to that of the advective terms above the first level. Under this level, the geostrophic wind is considered to be constant and equal to its value at the first PERIDOT level. The temporal interpolation is linear.

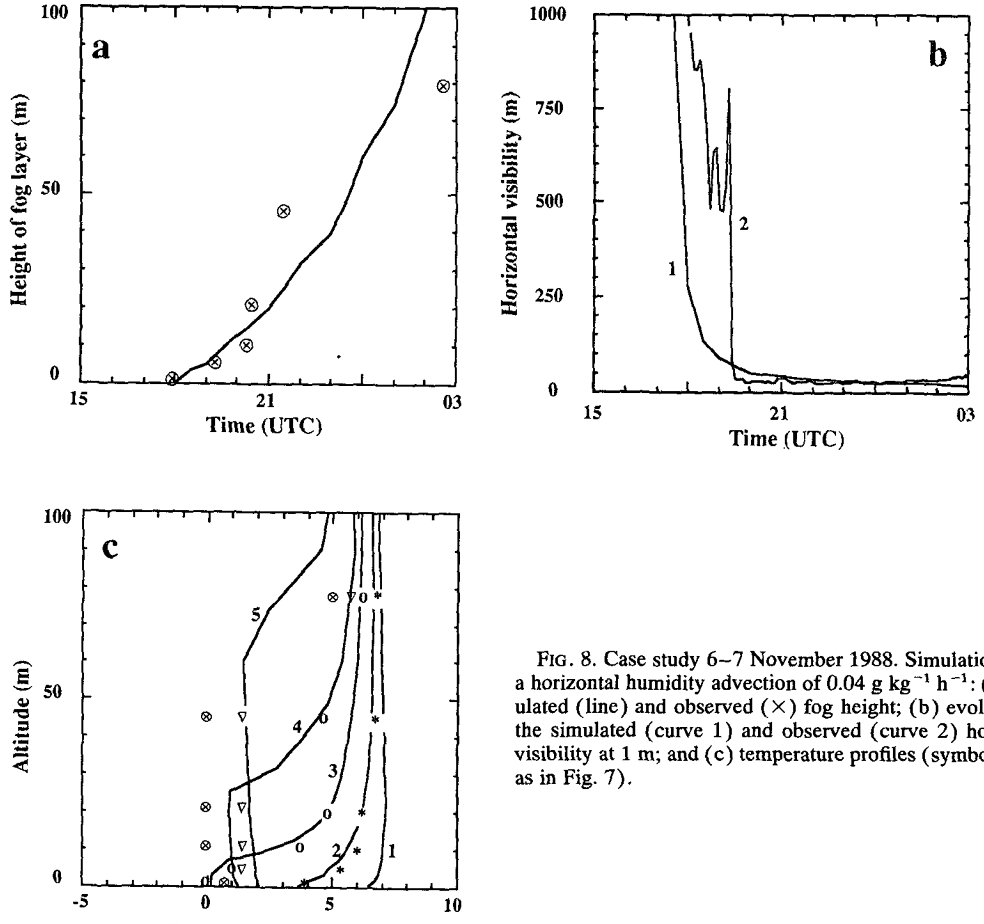

FIG. 8. Case study 6–7 November 1988. Simulation using a horizontal humidity advection of 0.04 g kg^{-1} h^{-1}: (a) simulated (line) and observed (×) fog height; (b) evolution of the simulated (curve 1) and observed (curve 2) horizontal visibility at 1 m; and (c) temperature profiles (symbols same as in Fig. 7).

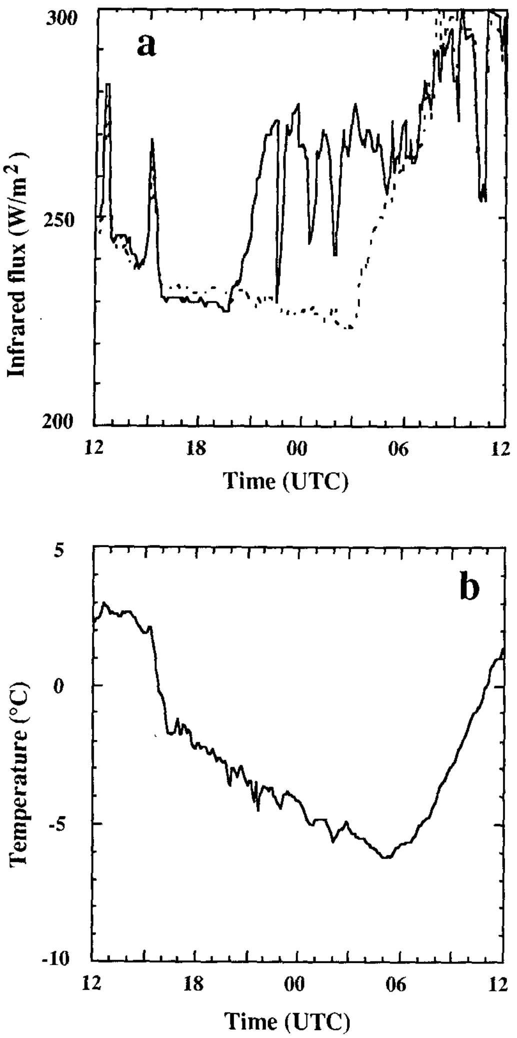

FIG. 9. Case study 21–22 November 1988: (a) observed downward infrared flux at 1 m (solid) and at 80 m (dashed); (b) evolution of the observed temperature at 0.7 m.

4. Observations

a. Lille 88 field experiment

A field experiment, called Lille 88 (Guedalia and Bergot 1992), was organized on the Carnin site (northern France, 50°31′N, 2°58′E) during October and November 1988. The objective was to observe and describe, as thoroughly as possible, several fog events. This site is located in a region with a relatively homogeneous and flat surface. During this season most of the ground surface consists of bare soil without vegetation cover.

The following parameters were continuously measured on the Carnin site:

- temperature, humidity, wind speed, and direction at eight levels: 80, 45, 20, 5, 2.5, 1.4, 0.7, and 0.3 m;
- horizontal visibility at six levels: 80, 45, 20, 10, 5, and 1 m;
- the upward and downward visible and infrared fluxes at 1 and 80 m;
- the liquid water content by means of a 10-μm laser absorption device at 1 m; and
- the soil temperature at 5, 10, 20, 50, and 100 cm in depth.

During the fog episodes, the droplet size distribution was measured at the 1.5-m level once an hour using a Knollemberg forward-scattering spectrometer probe. In addition to these measurements, vertical radio soundings were made at regular intervals in order to obtain vertical profiles for temperature, humidity, and wind up to 5000 m.

The data used for the simulations described here correspond to two dense fog events, 6–7 November 1988 and the 21–22 November 1988, and to a case in which the fog did not form in spite of favorable conditions (light wind, clear sky, and almost 100% relative humidity during the night) between 31 October and 1 November 1988.

b. The regional network of automatic meteorological stations

A regional network of automatic meteorological stations is operational in the north of France; the parameters measured are temperature and humidity at 1.5 m, and wind speed and direction at 10 m. These data have been used to determine the mesoscale surface fields for wind and temperature (the humidity measurements were of a very poor quality). These mesoscale fields enable us, as will be seen from the simulations of real cases, to validate the fields predicted by the PERIDOT model.

5. Simulation of dense fog events

a. 6–7 November 1988

1) SYNOPTIC BACKGROUND

During this period, the northern France region lay beneath a ridge of high pressure (1025 hPa). This resulted in a very light wind of less than 2 m s^{-1} in the 0–100-m layer, and a northwest direction.

The time variation of the downward IR flux measured at 1 and 80 m (Fig. 1a) shows presence of clouds during the afternoon between 1200 and 1700 UTC (value of the IR flux, approximately 340 W m^{-2}) and after 2200 UTC during the night (increase of IR flux at 80 m although the fog did not reach this level before 0300 UTC). The atmosphere cooled slowly (Fig. 1b) between 1400 and 1700 UTC (2°C during 3 h), and then more rapidly due to the disappearance of the clouds (6°C between 1700 and 2000 UTC).

The fog appeared on the site around 1800 UTC during the period of strong atmospheric cooling and became dense (horizontal visibility less than 50 m) from 1900 UTC on. The vertical growth of the fog was sig-

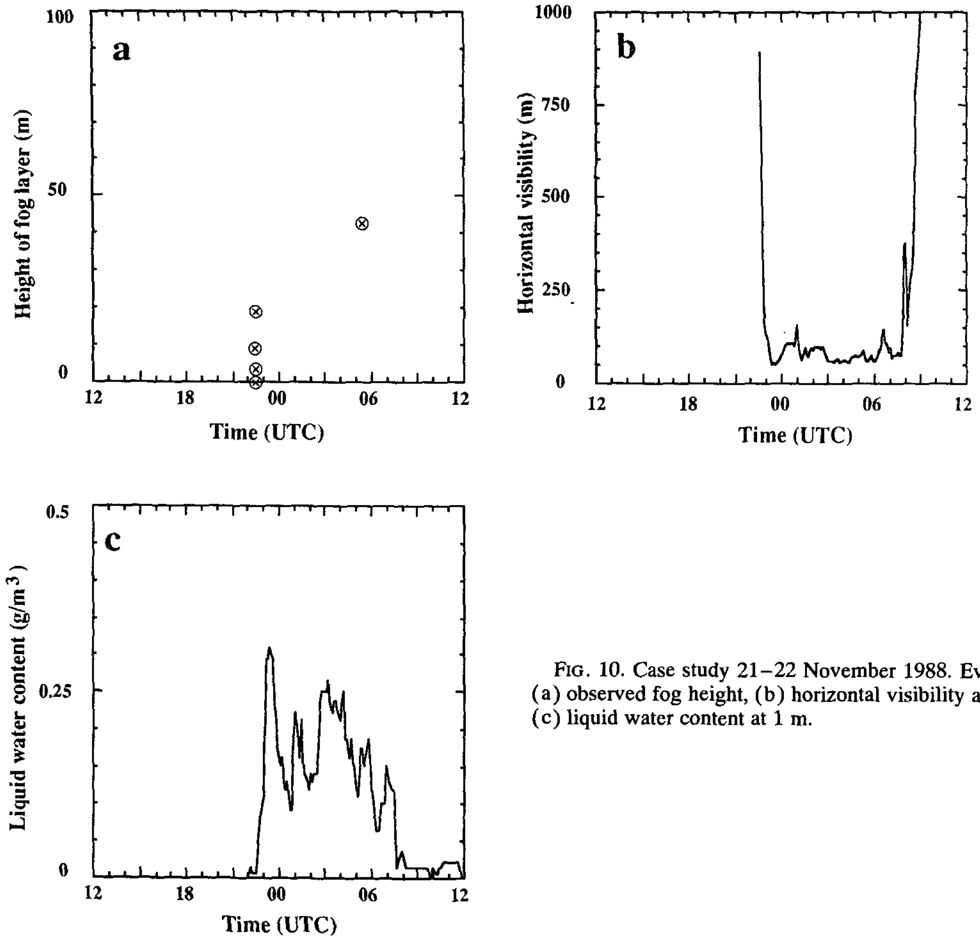

FIG. 10. Case study 21–22 November 1988. Evolution of (a) observed fog height, (b) horizontal visibility at 1 m, and (c) liquid water content at 1 m.

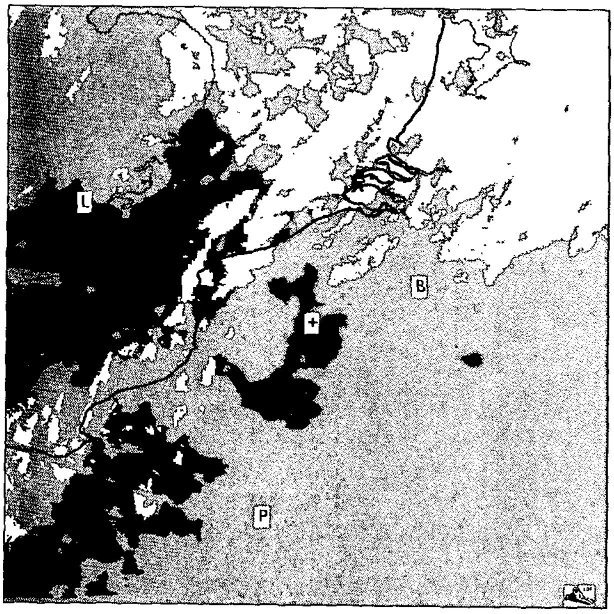

FIG. 11. Same as Fig. 2 except for case study 21–22 November 1988.

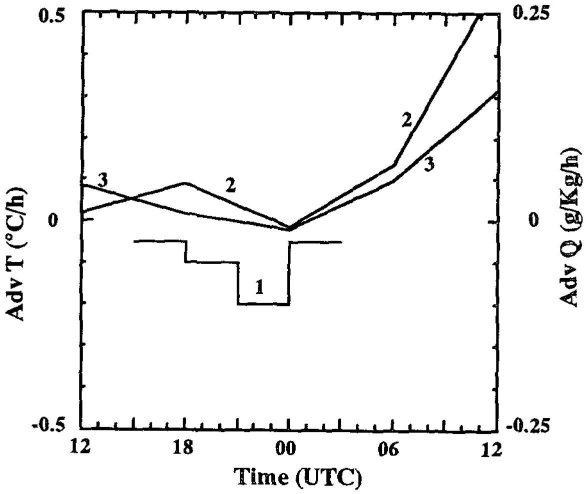

FIG. 12. Case study 21–22 November 1988. Horizontal advection temperature (curve 2) and humidity (curve 3) at the first PERIDOT level as a function of time. Curve 1 is the temperature advection deduced from the budget method using observed data.

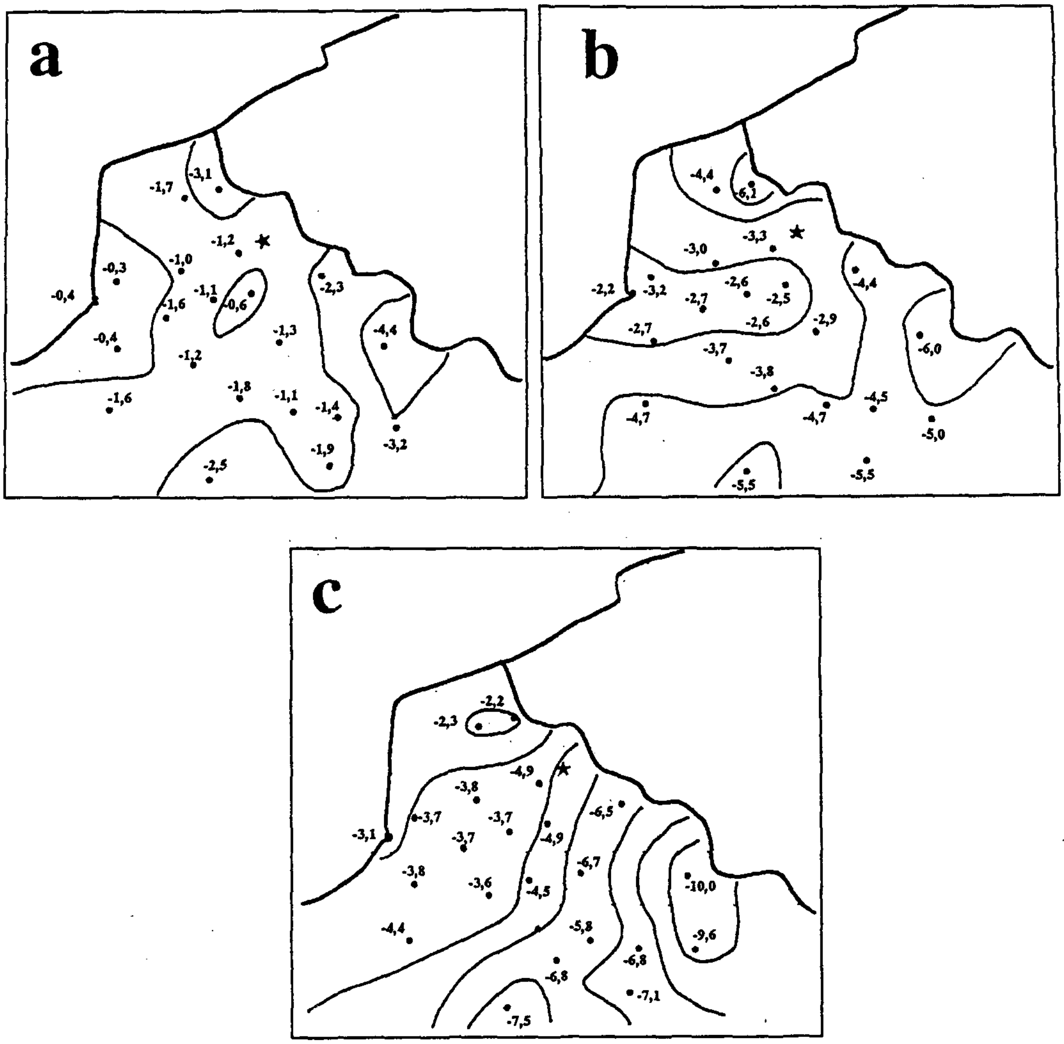

FIG. 13. Case study 21–22 November 1988. Horizontal field temperature at 2 m deduced from regional network stations: (a) 1800 UTC; (b) 0000 UTC; and (c) 0600 UTC. The asterisk represents the Carnin site.

nificant (it reached 45 m around 2100 UTC and exceeded 80 m after 0300 UTC).

The combination of the T3 (3.7 μm) and T4 (11 μm) channels of the *NOAA-9* Advanced Very High Resolution Radiometer (AVHRR) (Vanbauce 1992) was used to detect the spatial distribution of the fog. Figure 2 shows that at 0450 UTC 7 November the fog covered almost the whole of the region and even overlapped the sea in the west.

2) FORCING TERMS AND INITIAL CONDITIONS

The mesoscale temperature and humidity fields predicted by the PERIDOT model (Figs. 3a,b) show a weak horizontal gradient for the region; as the wind was light, the advective terms were very weak (less than 0.04°C h^{-1} and 0.02 g kg^{-1} h^{-1}). The geostrophic wind determined by PERIDOT was less than 3 m s^{-1} in the 0–1000-m layer.

We calculated the value of the IR downward flux at the surface corresponding to clear sky conditions, which enabled us to determine the cloudy flux value introduced into the model (Fig. 4). It should be noted that the PERIDOT model had not predicted any clouds for the night. The thermal conductivity coefficient value for superficial soil, deduced from experimental data, was $K_s = 1$ W K^{-1} m^{-1}.

Figure 5a shows the initial temperature and humidity profiles derived from the experimental data and those derived from PERIDOT. The differences are small—for instance, in the 0–100-m layer (where fog is likely to develop) the differences were less than a few tenths of a degree for temperature and approximately 0.1 g kg^{-1} for the mixing ratio. The initial wind derived from PERIDOT was very light in the 0–100-m layer (less than 1 m s^{-1}) and reached 3 m s^{-1} at 1000 m (Fig. 5b). The wind direction observed at the site was northwest instead of northeast as predicted by PERIDOT.

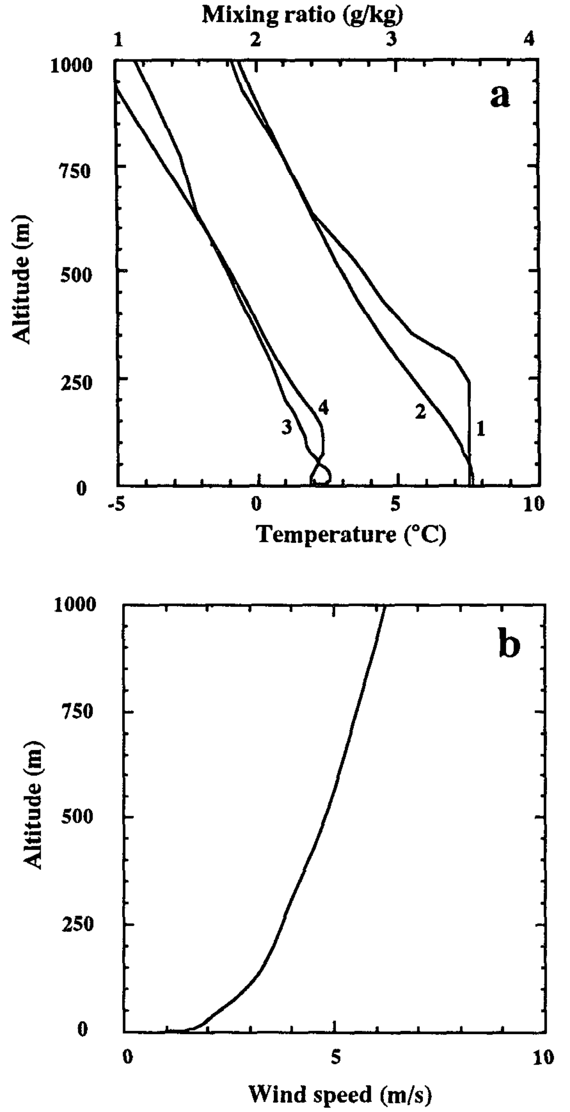

FIG. 14. Case study 21–22 November 1988. Initial profiles used for the model simulation: (a) temperature derived from observed data (curve 3) and from PERIDOT (curve 4) and humidity mixing ratio derived from observed data (curve 1) and from PERIDOT (curve 2); (b) wind derived from PERIDOT.

3) RESULTS

A first simulation was peformed in order to test the COBEL model. This simulation uses the observed initial conditions and cloudy flux and the advections predicted by PERIDOT. (The temperature advection calculated from the regional network of meteorological stations is very close to the PERIDOT advection; unfortunately, no observation is available to calculate the real humidity advection.)

This simulation shows a fog onset around 1745 UTC, at approximately the same time as in the observed situation; however, the fog had a less significant vertical thickness (Fig. 6a) and a slightly greater horizontal visibility at 1 m (Fig. 6b). The simulated temperature profiles were very close to the observed profiles up to 2100 UTC (Fig. 7), during the cooling phase that preceded the fog formation and 2 h after this formation, as long as simulated fog depth stays close to that observed. After 2100 UTC, the simulated fog was not as high as the real fog, and the differences appearing between observed and simulated temperature profiles are due to the differences between observed and simulated mixing layers.

We looked for the cause of the underestimation of fog depth. First, the cooling rate of the surface is correctly represented, as well as the vertical temperature profile, until 2100 UTC. Neither can we incriminate the value of settling velocity (1.6 cm s^{-1}), in agreement with that deduced from in situ measurements (1.7 ± 0.2 cm s^{-1}). The sensitivity study (BG) had shown that the vertical growth of fog is very sensitive to the nocturnal horizontal advection. In the case of 6–7 November, the thermal advection provided by PERIDOT is close to that deduced from the regional meteorological network. On the other hand, precisely measured values of the horizontal humidity field are not available. The PERIDOT forecast (Fig. 3a) displays a moist advection over the site. These considerations led us to test the effect of a slight increase of the advection (0.04 g kg^{-1} h^{-1} instead of 0.02 g kg^{-1} h^{-1} predicted by PERIDOT) on the vertical growth of fog. An extra justification of this new value of humidity advection proceeds from the fact that the observed wind was northwest instead of the northeast predicted by PERIDOT. As shown by Fig. 3b, a northwest wind produces a more important moist advection over the site than a northeast wind.

Therefore, a new simulation was performed with a humidity advection of 0.04 g kg^{-1} h^{-1}. The obtained results are closer to the observations of the fog depth (Fig. 8a) and of fog intensity (Fig. 8b) than for the previous simulation. The temperature profiles (Fig. 8c) are also closer to those observed, including the formation of a 60-m mixing fog layer. This simulation aims only at demonstrating the extreme sensitivity of fog depth to advection. This sensitivity is all the higher as the fog grows in a layer with a weak vertical temperature gradient (after 2100 UTC).

In a second stage, we carried out two new simulations forced by PERIDOT forecasts (initial conditions and cloudy flux). First, initializing with PERIDOT data does not change the simulation results in any way, because of the very slight difference between the initial profiles observed and those derived from PERIDOT. A second simulation was performed with a zero cloudy flux (no cloud was predicted by PERIDOT). This simulation led to fog onset 2 h earlier than for the real case with, however, a vertical development fairly similar to the previous simulations.

To conclude, in the case of 6–7 November, the COBEL model forced by the observations correctly reproduces the fog onset and fog intensity but underestimates the vertical growth (except if an arbitrary value

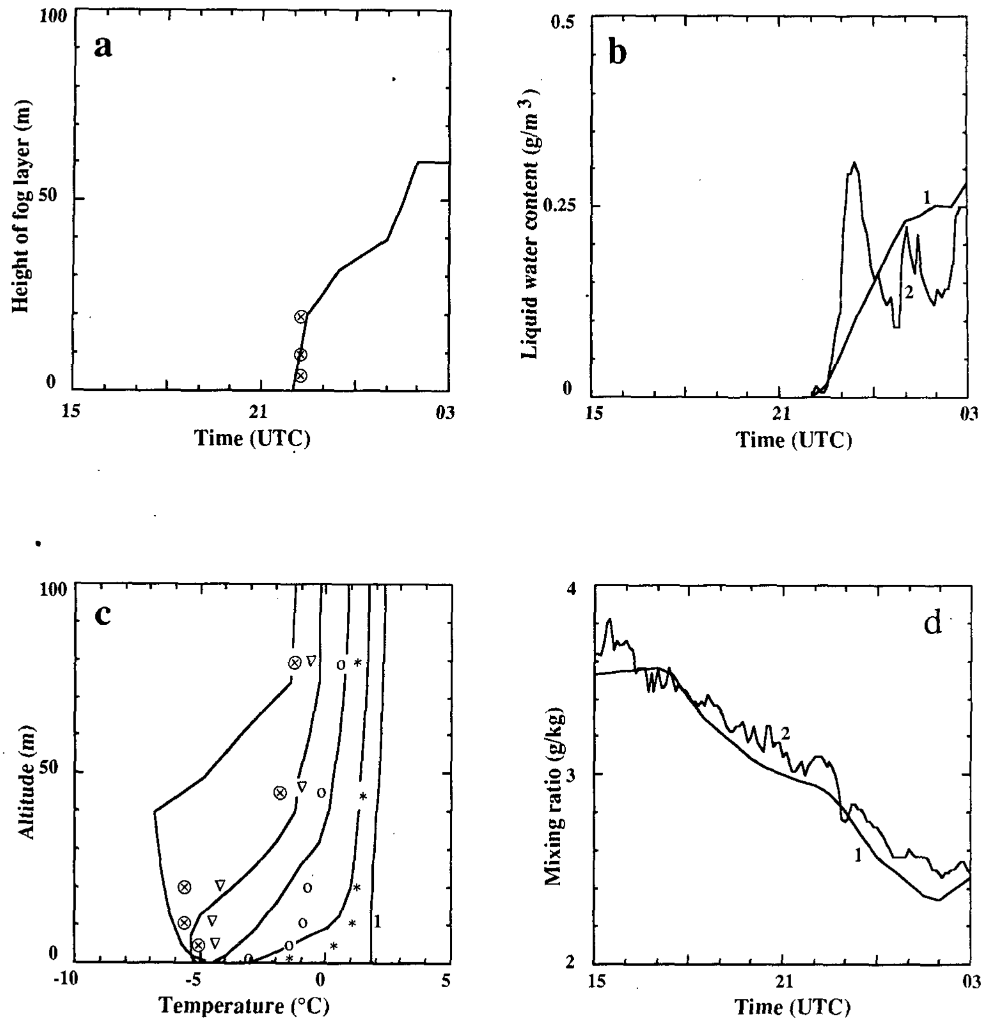

FIG. 15. Case study 21–22 November 1988. Simulation with forcing terms deduced from observed data: (a) simulated (line) and observed (×) fog height; (b) evolution of simulated (curve 1) and observed (curve 2) liquid water content at 1 m; (c) temperature profiles (identical symbols as Fig. 7); and (d) simulated (curve 1) and observed (curve 2) humidity mixing ratio at 0.7 m.

of the humidity advection is introduced). The COBEL model, when initialized and forced by PERIDOT data, predicts a fog onset 2 h early. This is due to a bad forecast of the cloud observed after 1900 UTC.

b. 21–22 November 1988

1) THE SYNOPTIC BACKGROUND

The synoptic situation was characterized by an anticyclone (1030 hPa) centered on Ireland and by a very low pressure gradient in the region. The wind speed was light throughout the night, with a northerly direction, and then grew stronger in the morning (4–5 m s^{-1}) before the arrival of a synoptic disturbance. The downward IR flux measured at the site showed that there were two short cloud passages during the afternoon, between 1200 and 1300 and between 1500 and 1600 UTC (Fig. 9a), before the start of nocturnal cooling. The atmosphere cooled rapidly (4°C) between 1600 and 1800 UTC (Fig. 9b). A significant frost deposition was observed in the measuring area during the night.

The fog formed on the site toward 2230 UTC throughout the 1–20-m layer and very quickly became dense (Fig. 10a). It was observed that there were significant fluctuations in several parameters (downward IR flux, Fig. 9a; liquid water content, Fig. 10c; and horizontal visibility, Fig. 10b) during the whole fog period. Unlike the case of 6–7 November, the temperature profile did not show a strong inversion as one might have expected on a clear night with light wind.

The spatial distribution of the fog obtained by means of the *NOAA-9* AVHRR satellite data (Fig. 11) shows that at 0530 UTC 22 November the fog had covered more than half of the region and it had a marked north–

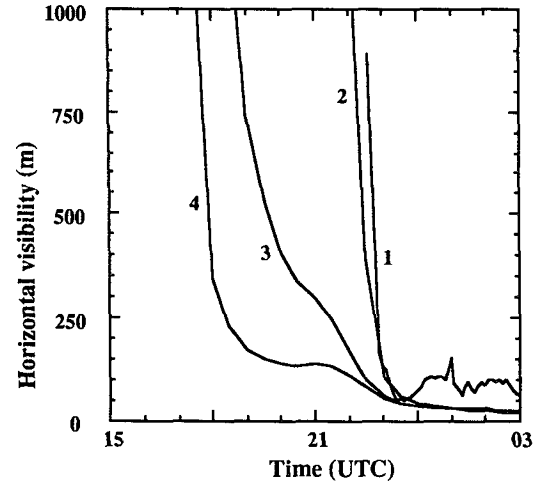

FIG. 16. Case study 21–22 November 1988. Influence of the dew and frost deposition on the fog formation. Horizontal visibility at 1 m; observed (curve 1); simulated with dew and frost deposition (curve 2); with dew deposition only (curve 3); without dew and frost deposition (curve 4).

south orientation. In addition, a large cloudy system was observed over northern Europe, associated with the synoptic disturbance. From 0500 UTC in the morning of 22 November, cloudy cover and increasing wind caused the fog to dissipate rapidly.

2) FORCING TERMS AND INITIAL CONDITIONS

The horizontal advections predicted by PERIDOT were relatively weak until 0000 UTC and increased only toward the end of the night (with the arrival of the synoptic disturbance) (Fig. 12). Thermal advection was also determined from observations, using two different methods. The first one is a budget method (Estournel 1988) using the site data:

$$\frac{\partial T}{\partial t} = R_{\rm tur} + R_{\rm rad} + {\rm Adv}T. \qquad (6)$$

The term $\partial T/\partial t$ was determined by means of measured temperature profiles; the radiative cooling term $R_{\rm rad}$ was calculated from the radiative model. If one neglects the turbulent cooling term $R_{\rm turb}$ by applying the method above the surface layer, then the advective term Adv$T$ is calculated. This budget method applied to the event shows a cold advection between 45 and 80 m and between 1800 and 0000 UTC of the order of 0.1–0.2°C h^{-1} (Fig. 12).

The second method uses the regional network data (Fig. 13). These data show that the experimental site undergoes a cold advection during north-northeasterly wind periods. This advection is 0.15°C h^{-1} at 1800 UTC and 0.2°C h^{-1} at 0000 UTC—that is, similar to that previously calculated using the budget method.

Therefore, the thermal advection predicted by PERIDOT is different from that deduced from experimental data by two methods. The geostrophic wind deduced from PERIDOT was 1–2 m s^{-1} in the 0–100-m layer and 5–6 m s^{-1} at 1000 m.

A weak cloudy flux (20 W m^{-2}) was introduced between 1500 and 1600 UTC at the start of the simulation. The cloud cover predicted by PERIDOT was zero throughout the night, and from 0600 UTC 22 November a low cloud layer associated with the synoptic disturbance was predicted. The value of the superficial K_s was 0.8 W K^{-1} m^{-1}.

Figure 14a shows the initial temperature and humidity profiles used in the simulation, derived from the experimental data or from PERIDOT. The differences are small; for instance, in the 0–100-m layer, they were less than 0.3°C and 0.05 g kg^{-1}, respectively. As was the case for 6–7 November, one may expect these differences to have very little effect on the simulation. The initial wind profile derived from PERIDOT prediction is shown in Fig. 14b; this profile, just like the geostrophic wind, has a significant vertical gradient.

3) THE RESULTS

A first simulation was performed in order to test the COBEL model, using the observed initial conditions, advections, and cloudy flux. The time of fog formation (Fig. 15a) and the liquid water content (Fig. 15b) have been satisfactorily reproduced.

The fog height is correctly reproduced during the first hours and beyond that slightly overestimated: this height reaches 50 m around 0200 UTC, whereas the observations show that this level is actually reached only around 0600 UTC. This discrepancy between simulated and observed fog height causes the differences between simulated and observed temperature profiles after 0300 UTC (Fig. 15c).

A comparison of the time evolution of the observed and simulated humidity (Fig. 15d) shows the realistic representation of the dew and frost deposition process in the model. As condensation occurs in the middle of the night and since the temperature is negative, it is important to know the influence of dew and frost deposition on the simulation of fog formation. We therefore did two new simulations: the first without frost deposition, and the second with neither dew nor frost deposition. With respect to the time of fog formation, the difference with the observed fog was 3.5 h for the simulation using only dew deposition and 4.5 h for simulation without dew and frost deposition (Fig. 16). The deposition flux at the surface, of the order of 5 g h^{-1} m^{-2}, delayed the moment when the fog appeared. This process in conjunction with a cold advection led to creation of an atmospheric layer without humidity gradient (about 50 m thick) and explains the extremely rapid vertical growth of the fog at around 2230 UTC.

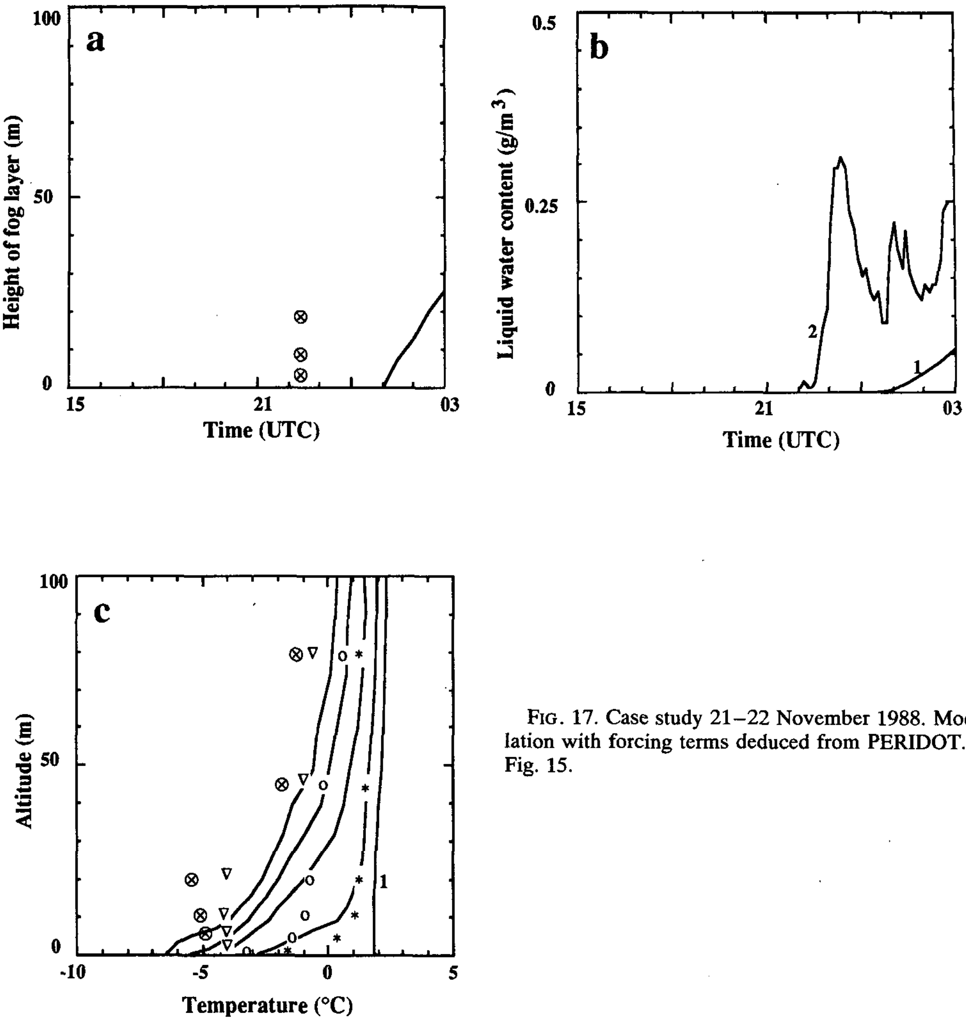

FIG. 17. Case study 21–22 November 1988. Model simulation with forcing terms deduced from PERIDOT. Same as Fig. 15.

We subsequently carried out a series of simulations using the COBEL model forced by PERIDOT, implying new initial conditions, zero cloudy flux, and new values of advection. A first simulation forced only by the new initial conditions and zero cloudy flux does not provide significant changes in the results. On the other hand, forcing with PERIDOT advection leads to a fog onset occurring 2.5 h later than in the observations (Fig. 17a). The simulated vertical thickness of the fog layer was lower than the observed thickness, and the liquid water content at the 1-m level was too weak (Fig. 17b). A comparison of the observed and simulated temperature profiles (Fig. 17c) revealed significant differences at 80 m, and these differences indicate an erroneous value of the advection.

Finally, the COBEL model forced by the observations correctly simulated the time of fog onset and slightly overestimated the fog height during the second half of the night. When forced by PERIDOT data, the model also leads to a fog onset but with a 2.5-h delay and a lower height.

6. Simulation of a case close to fog formation: 31 October–1 November 1988

During the Lille 88 field experiment, we observed some episodes for which many of the parameters were favorable to fog formation (light wind, clear sky, significant relative humidity) even though the fog was not able to form, in spite of humidity close to or equal to 100% in the first few meters of the atmosphere during the night. Simulation of these kinds of events is very interesting since it enables the model to be tested for extreme cases.

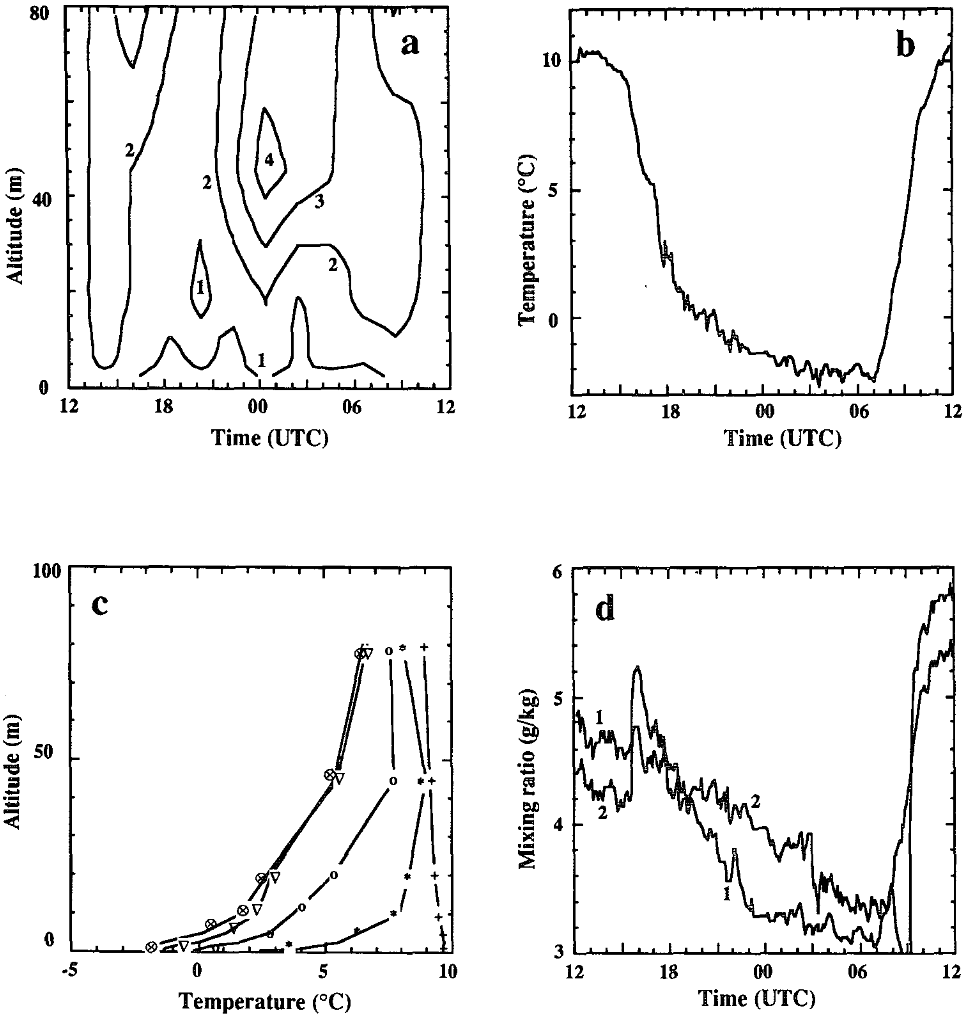

FIG. 18. Case study 31 October–1 November 1988. (a) Evolution of observed wind (m s^{-1}); (b) temperature at 0.7 m; (c) temperature profiles (symbols same as in Fig. 7); and (d) humidity mixing ratio at 0.7 m (curve 1) and 5 m (curve 2).

a. Synoptic background

The synoptic situation was marked by a weak high pressure area (1020 hPa) centered over England at 1800 UTC and coming during the night over central Europe. A depression (1005 hPa) was located in the southern part of the Scandinavian countries, and related to it, a synoptic disturbance started moving toward England. The wind was light (1–2 m s^{-1} in the 0–20-m layer), with a northwest direction at the beginning of the night and then coming regularly from the west. We observed the formation of a weak nocturnal jet (4 m s^{-1}) above 45 m from 2200 UTC on (Fig. 18a). The sky was clear throughout the night.

The atmosphere cooled very quickly (about 9°C between 1700 and 2000 UTC) (Fig. 18b) and then more slowly until morning (about 3°C in 12 h). The vertical temperature profiles showed that there had been a very strong nocturnal inversion (Fig. 18c). The relative humidity near to the surface was 100% from 2200 UTC on and this caused an important dew and then frost deposition after 0000 UTC. This deposition in turn caused a vertical water vapor gradient in the surface layer (Fig. 18d). To sum up, it was a nocturnal situation with a clear sky and a light wind, leading to strong cooling located close to the surface; the relative humidity remained close or equal to 100% near to the ground but the fog did not develop.

b. Forcing terms and initial conditions

The horizontal advections predicted by PERIDOT were very weak (less than 0.1°C h^{-1} and 0.02 g kg^{-1} h^{-1}). The data at the experimental site and those from the regional network also indicate an almost

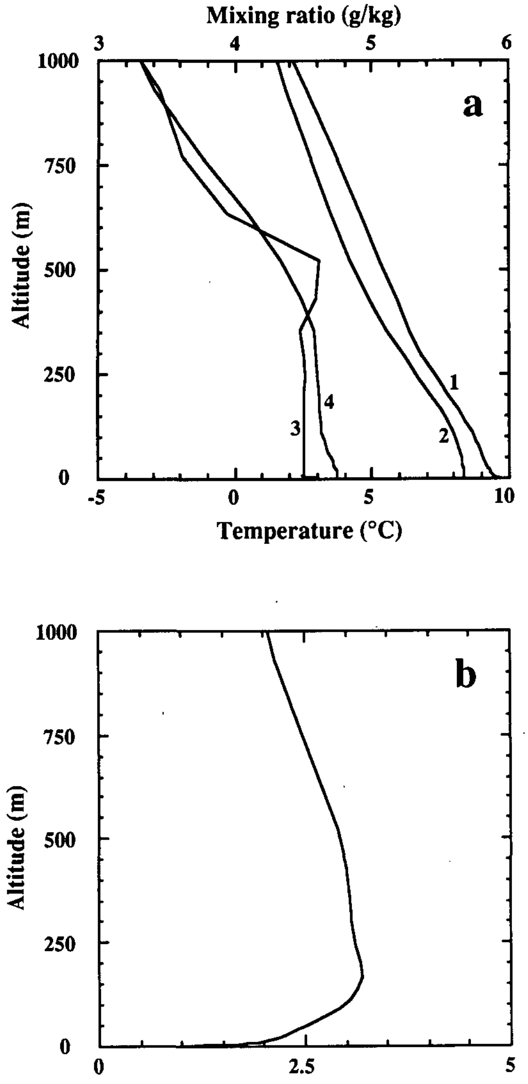

FIG. 19. Case study 31 October–1 November 1988. Initial profiles—the symbols are the same as in Fig. 14.

zero advection. In this case, there is good agreement between observed and PERIDOT-predicted advection.

The geostrophic wind was less than 3 m s^{-1} below 1000 m. PERIDOT did not predict any clouds. The value of the superficial K_s was 0.4 W K^{-1} m^{-1}. Figure 19a shows the initial temperature and humidity profiles used in the model derived from the experimental data or from PERIDOT. The PERIDOT data were colder by almost 1.5°C and more moist by about 0.2 g kg^{-1}. The initial wind profile obtained from the PERIDOT model is shown in Fig. 19b; it may be seen that the wind is light (less than 3 m s^{-1} in the 0–1000-m layer).

c. Results

Simulation using the initial conditions derived from the observations and with the forcing terms previously described did not lead to fog formation in spite of the fact that the air near to the ground was saturated around 2200 UTC. Comparison of the simulated and observed temperature profiles showed that they were very close (Fig. 20a) with creation of a strong nocturnal inversion. The time evolution of the mixing ratio in the 0–5-m layer was correctly reproduced (Fig. 20b); this enabled validation of the parameterization of the dew and frost deposition in a real case. The simulated relative humidity field revealed a layer close to saturation in the first few meters of the atmosphere and a strong vertical gradient above. The wind fields were correctly reproduced, with appearance of a nocturnal jet (Fig. 20c) that was slightly too strong (5 m s^{-1} instead of the 4 m s^{-1} measured on the site).

Dew and frost deposition is an important element in the prediction of fog formation. To test them we did a new simulation without dew deposition. This new simulation resulted in formation of a not very dense fog layer from 1800 UTC on that was close to the ground (thickness less than 0.5 m). The fog reached a height of 5 m and the horizontal visibility was less than 200 m at 0300 UTC (Fig. 21). It may therefore be observed that it is the dew and frost deposition that prevent fog formation in spite of the strong cooling of the atmosphere.

Simulation initialized using PERIDOT data resulted in a dense fog forming at 0000 UTC and reaching 10 m in height at 0300 UTC (Fig. 21). This result confirmed the results obtained in the sensitivity study (BG): the initial values need to be very precise (error less than 0.5°C and 0.1 g kg^{-1}) in order to correctly simulate the extreme cases of episodes close to fog formation.

7. Conclusions and future work

The results presented in this paper must be considered as first tests of a method of dense fog forecasting. This method is based on a 1D model forced by the mesoscale parameters provided by the limited-area forecast model PERIDOT. A previous study of the sensitivity of the method (BG) had shown the need for precise knowledge of the initial conditions and advections in order to be able to successfully simulate the formation and development of a fog layer. The subsequent stage involved the simulation of three real events: two cases of formation of dense fog, and one event in which the fog did not form in spite of favorable conditions. The observations were made during the Lille 88 campaign, on the Carnin site located in a flat region with a fairly homogeneous surface with a predominance of bare soil.

These real case simulations allow us to reach two different goals. First, using all the available observations as forcing terms, the ability of the COBEL model to correctly simulate the fog properties has been tested. Second, the quality of fog forecasting has been examined using the COBEL model forced by PERIDOT outputs.

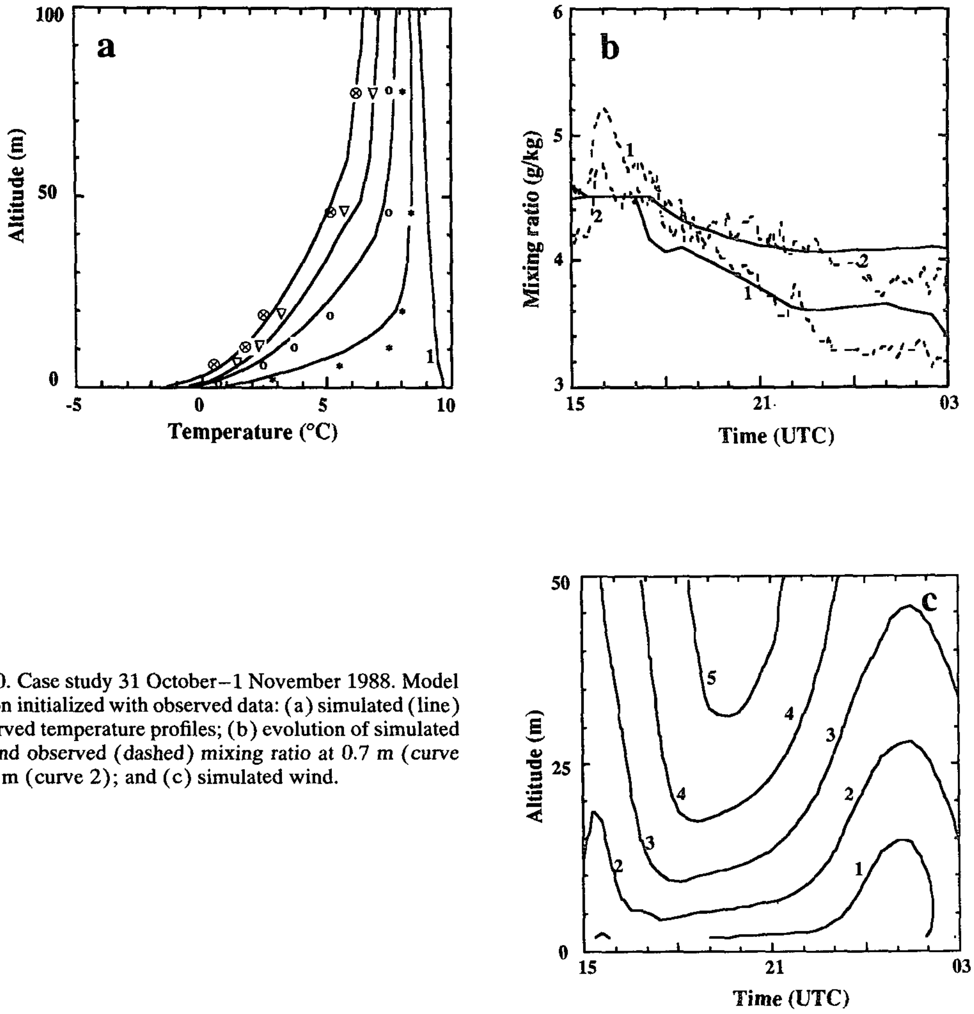

FIG. 20. Case study 31 October–1 November 1988. Model simulation initialized with observed data: (a) simulated (line) and observed temperature profiles; (b) evolution of simulated (solid) and observed (dashed) mixing ratio at 0.7 m (curve 1) and 5 m (curve 2); and (c) simulated wind.

Concerning the first goal, it has been shown that the COBEL model forced by observations correctly reproduces the case of 31 October (no formation of fog) as well as both cases of fog, even if the height is underestimated on 6 November. These different simulations demonstrated that the COBEL model was capable of correctly reproducing the main physical processes involved in the nocturnal boundary layer and in fog (turbulent exchanges, radiative cooling at the top of the fog layer, dew, and frost deposition, etc.). The importance of dew and frost deposition has also been shown. A comparison of the simulations and observations confirmed that this deposition had been correctly parameterized in the model. We observed that the dew deposition caused a delay in the appearance of the fog due to the loss of water vapor in the layers close to the surface.

The results obtained by forcing COBEL by PERIDOT require a more complex analysis; the quality of fog forecast directly depends upon that of the mesoscale parameters provided by PERIDOT. It must be noted that the three cases simulated here are not statistically significant to definitely test the forecasting method. But the analysis of the results provides useful information.

(a) The predicted fog onset time is very sensitive to the initial conditions; in the two fog simulated cases, the initial conditions provided by PERIDOT are close to those observed. On the other hand, in the 31 October case, the error on the initial conditions derived from PERIDOT leads to the prediction of fog onset at late night, located near the surface.

(b) The presence of clouds during the night may delay the fog onset. Among the three simulated cases, only that of 6 November was accompanied by unpredicted cloud, which caused an error on the time of fog onset.

(c) Fog height forecast is a difficult question. As a matter of fact, this height strongly depends upon ad-

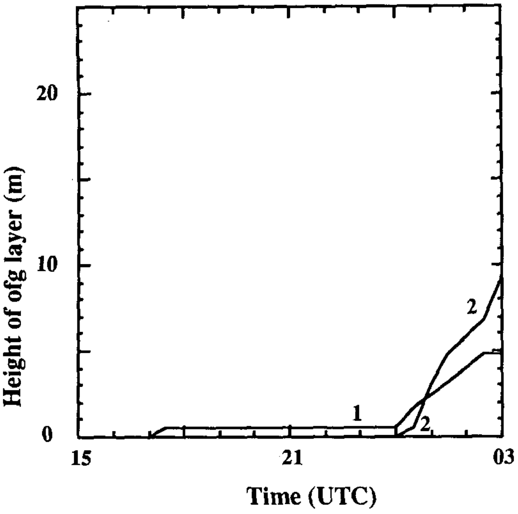

FIG. 21. Case study 31 October–1 November 1988. Evolution of the simulated fog height: without dew deposition (curve 1); using initial profiles deduced from PERIDOT data (curve 2).

vection; the 6 and 21 November simulations are good examples of such a difficulty.

The definition of a correct fog forecast is a good question to be raised. It is first necessary to know the present quality of fog forecast. A recent study (Eiselt et al. 1993) was carried out on this topic concerning northern France between 1989 and 1992. It shows that the performance is close to a persistence forecast and that the time of fog onset forecast is currently not realistic. In these conditions, our present results sound encouraging and show that in a certain number of cases the prediction of fog onset time is possible with an accuracy of a few hours.

In a next stage we intend to force the COBEL model by PERIDOT in a large number of real situations. This work will start at the end of 1993 on a sample of more than 50 cases at the Carnin site documented between 1990 and 1992 (routine data obtained from the 80-m instrumented tower). It will therefore be possible to compare the present forecast to that carried out by the COBEL model. We will be able to evaluate the possible forecast improvement on a large number of cases. If the method has been validated, Meteo-France will start operational forecasting of dense fogs in the north of France at the end of 1994.

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