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Application of the Transmission Line Matrix method for outdoor sound propagation modelling – Part 2: Experimental validation using meteorological data derived from the meso-scale model Meso-NH

Pierre Aumond [a], Gwenaël Guillaume [a,*], Benoit Gauvreau [a], Christine Lac [b], Valery Masson [b], Michel Bérengier [a]

[a] *Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux, Département Infrastructures et Mobilité, Route de Bouaye, B.P. CS4, 44344 Bouguenais Cedex, France*

[b] *Météo-France, 42 Avenue Gaspard Coriolis, 31100 Toulouse, France*

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ABSTRACT

Outdoor sound prediction is both a societal concern and a scientific issue. This paper deals with numerical simulations of micrometeorological (temperature and wind) fields for environmental acoustics. These simulations are carried out using the reference meso-scale meteorological model at the Meteo-France weather agency (Meso-NH). Meso-NH predictions at very fine scales (up to 3 m), including new developments (drag force approach), are validated both numerically and experimentally under stable, unstable and neutral conditions. Then, this information can be used as input data for the acoustic propagation model. The time-domain acoustic model is based on the Transmission Line Matrix method. Its development has also been promoted for application to outdoor sound propagation, i.e. to take into account topography, ground impedance, meteorological conditions, etc. In part 1, the presentation and evaluation of the Transmission Line Matrix method showed the relevance of this method's use in the context of environmental acoustics. Finally, simulated noise levels under different propagation conditions were compared to *in situ* measurements. Satisfactory results were obtained regarding the variability of the observed phenomena.

1. Introduction

Regarding environmental acoustics, outdoor sound prediction is both a societal concern and a scientific issue. It is now considered that as of 50 m from the sound source, the meteorological effects on sound propagation must be taken into account [1]. In order to qualify and quantify this influence, many acoustical propagation models have been developed. The meteorological information is introduced through an atmospheric model of differing complexity (from the simple linear vertical profile of wind and temperature to a complex representation of the atmospheric boundary layer). In order to obtain such a complex representation of the boundary layer, the purpose of this paper is to use simulation results of the meso-scale meteorological model Meso-NH in Large-Eddy Simulation (LES) configurations. Then, this information can be used as input data for the time-domain sound propagation model: The Transmission Line Matrix (TLM) method. The associated paper (part 1) deals with the presentation and evaluation of the Transmission Line Matrix method in the context of environmental acoustics. In this paper (part 2), the two different models (acoustical and meteorological) are compared with experimental data derived from the Lannemezan-2005 campaign.

In Section 2, the experimental campaign of Lannemezan-2005 is first presented. An overview of the meso-scale meteorological model Meso-NH and its configuration is given in Section 3. The results obtained by this model over the Lannemezan site are next compared with the meteorological measurements during the experimental campaign. In Section 4, the numerical results of the TLM simulations using Meso-NH simulated meteorological fields as input data are shown and discussed.

2. Experimental campaign: Lannemezan 2005

Lannemezan-2005 was an experiment conducted near the city of Lannemezan (France) by the Laboratoire Central des Ponts et Chaussées (ex-LCPC, now Ifsttar), Electricité De France (EDF), Société Nationale des Chemins de Fer (SNCF) and École Centrale de Lyon (ECL) [1]. It was designed to be a three-month experiment (from June until August 2005) in order to study meteorological and

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* Corresponding author.
E-mail address: gwenael.guillaume@ifsttar.fr (G. Guillaume).

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ground effects on outdoor acoustic propagation. Fig. 1 shows the Lannemezan-2005 site, its topography and the location of a selected set of sensors. The Lannemezan-2005 site is flat and covered with prairie grass. There are tree barriers around 10 m high on each side of the domain studied. The sound level of a broad-band omnidirectional sound source had been measured throughout the duration of the campaign by a cluster of microphones following 3 propagation directions: PD1, PD2, PD3 (and PD4, not considered in this paper because of the non flat ground). In addition to microphones, a large number of meteorological sensors were deployed in this area. For the meteorological part of the study, a 3D ultrasonic anemometer and two 10 m high fully-equipped meteorological towers (wind speed, wind direction and temperature at heights of 1 m, 3 m and 10 m) were placed respectively at 75, 125 and 175 m from the source in each direction. Moreover, a 60 m high meteorological tower with three 3D ultrasonic anemometers, 3 temperature sensors and 3 humidity sensors was located 200 m north of the source. Information about turbulence kinetic energy was given by the 3D ultrasonic anemometers and one 60 m mast with a sampling rate of 10 Hz averaged over 10 min. The meteorological towers provided temperature and wind measurements every 10 s, averaged over 15 min samples. Regarding noise measurements integrated on 1 s duration (Leq_{1s} for each 1/3 octave bands on [100 Hz; 5 kHz]), the different microphones were located 50, 100 and 150 m from the sound source in the different propagation directions. More details are given in Ref. [1].

In order to validate the meteorological model, 3 typical clear-sky conditions were chosen in the Lannemezan-2005 experimental database. As presented by Foken [2], the dimensionless stability parameter ζ ($\zeta = z/L_{MO}$, where z is the height above ground and L_{MO} stands for the Monin–Obukhov length [2]) has been used to define the degree of stratification of the surface layer (unstable, neutral and stable atmospheres correspond respectively to $-1 < \zeta, -1 < \zeta < 0$ and $0 < \zeta$). These parameter values have been calculated from averaged measurements (15 min) of the 3D ultrasonic anemometers.

The 3 days chosen were:

- 17th June 2005 during day-time, corresponding to unstable conditions ($\zeta = -0.3$), unfavourable propagation conditions along the PD1 direction and homogeneous conditions along PD3;
- 3rd July 2005 during night-time, corresponding to very stable conditions ($\zeta = 0.3$) and favourable propagation conditions along PD3;
- 16th June 2005 during night-time, presenting neutral-stable atmospheric characteristics ($\zeta = 0.1$) and favourable propagation conditions along the PD1 and PD3 directions.

3. Meso-NH

3.1. Presentation

Meso-NH is the non-hydrostatic meso-scale atmospheric model produced by the French research community [3]. It is intended to be applicable at all atmospheric scales, ranging from large (synoptic) scales to small scales (Large-Eddy Simulation). The model can use a 3D 1.5 order turbulence scheme, with two different mixing

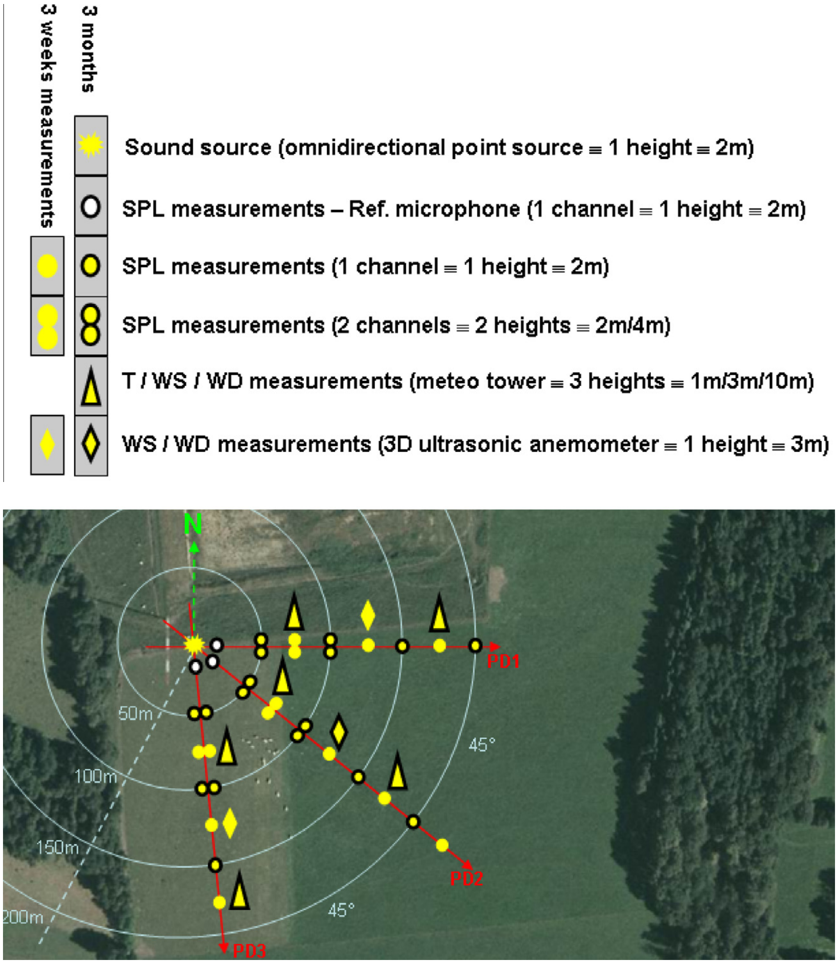

Fig. 1. Lannemezan-2005 experiment, acoustical and meteorological sensor locations.

Table 1
Configuration of the nested models – DEAR: Deardorff mixing length, BL89: Bougeault Lacarrere mixing length [2].

Horizontal resolution Mixing length	1st Grid	2nd Grid	3rd Grid
03-07-2005 04h30 Stable	50 m ($10 \times 10\ \mathrm{km}^2$) BL89	10 m ($2 \times 2\ \mathrm{km}^2$) BL89	3.3 m ($500 \times 400\ \mathrm{m}^2$) DEAR
16-06-2005 04h30 Neutral	50 m ($10 \times 10\ \mathrm{km}^2$) BL89	10 m ($2 \times 2\ \mathrm{km}^2$) BL89	3.3 m ($500 \times 400\ \mathrm{m}^2$) DEAR
17-06-2005 16h00 Unstable	50 m ($10 \times 10\ \mathrm{km}^2$) DEAR	10 m ($2 \times 2\ \mathrm{km}^2$) DEAR	X X

length parameterizations [4–6]. Its performance for several boundary layer regimes has been tested successfully [7–9]. The model allows for all types of boundary layers (stable, neutral, unstable) to be investigated over different types of surface cover and provides a resolution on the order of 1 m. However, for such high resolutions, a description of the effects of the canopy on flow using a roughness approach (as is usually done in large-scale atmospheric models) was not sufficient. Thus, a new development has been introduced in order to take into account the drag force of the high vegetation [10]. A detailed description of the basic equations of the Meso-NH model is available into the Meso-NH scientific manual [11].

3.2. Configuration

Simulations were conducted using 3 grid-nested domains centred on the main domain of the Lannemezan-2005 site. The domain size was chosen large enough to resolve the large-scale eddies. Large-eddy simulations (LES) are performed with horizontal resolutions of 50 m, 10 m and down to 2 m in order to resolve the smallest eddies. A vertical terrain-following stretched grid is used with 50 levels in the first 100 m above ground, for a total of 80 levels up to 6000 m. Table 1 summarizes the model configurations. It can be noticed that for the unstable case (17-06-2005), the vortices are large enough to make the third model unnecessary. Surface fluxes were output by the surface model ISBA [12]. The cover positioning was derived from interpolation of the Corine database [13] (horizontal resolution of 250 m) except for the field experiment of Lannemezan-2005 where the data have been completed manually in order to better describe the position of trees. As an initialization for the Meso-NH simulations, vertical wind and temperature profiles have been assumed using ARPEGE analysis [14] above 60 m and observations of the 60 m tower below. Then, this profile is interpolated vertically and horizontally over the whole domain, taking into account the orography.

3.3. Results

Figs. 2–4 show the comparison between simulation and experimental results for the profiles of wind speed, temperature and turbulent kinetic energy (TKE) at the three selected times (local time). The mean vertical profile is calculated from a space and time averaging over the different masts (on PD1, PD2 and PD3), and over 15 min time periods. In this particular case of the 16th of June 2005 at 04h30 (Fig. 2), we observe good agreement between experimental results and Meso-NH simulations. Let us note in particular the good reproduction of the inflection point in the wind speed and the very good representation of the TKE mean vertical profile. For the neutral and unstable cases (06-17-2005, Fig. 2 and 06-16-2005, Fig. 3), there is a good agreement between Meso-NH simulations and experimental results. For the stable case (07-03-2005, Fig. 4), Meso-NH simulations produce an excessive wind speed value. Regarding temperature and TKE values, a more detailed review

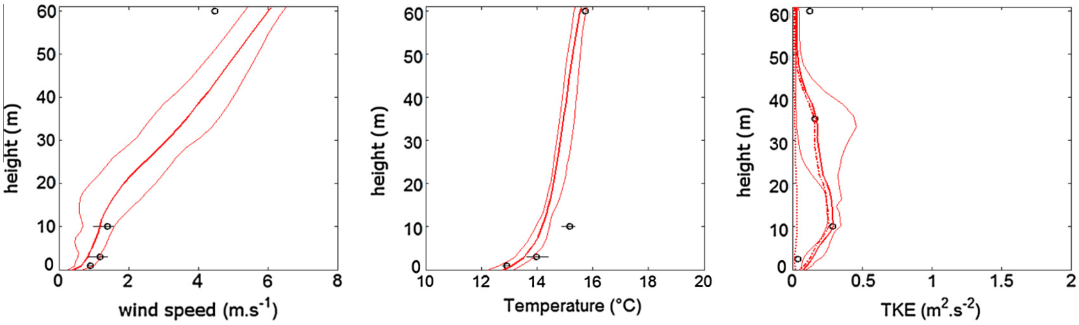

Fig. 2. Mean vertical profiles (thick line) and dispersion (thin lines) of the wind speed, temperature and turbulent kinetic energy (total TKE in continuous line with dispersion, subgrid TKE in dashed line and resolved TKE in dotted line), both measured (black) and simulated (red) on 16-06-2005 at 04h30 (neutral case). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

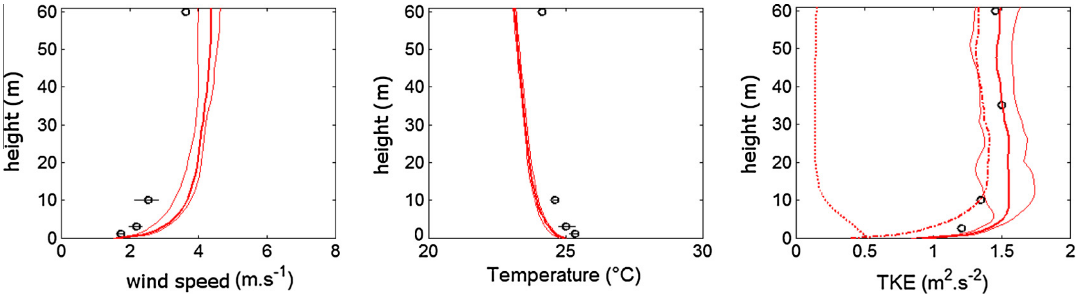

Fig. 3. Mean vertical profiles (thick line) and dispersion (thin lines) of the wind speed, temperature and turbulent kinetic energy (total TKE in continuous line with dispersion, subgrid TKE in dashed line and resolved TKE in dotted line), both measured (black) and simulated (red) on 17-06-2005 at 16h30 (unstable case). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

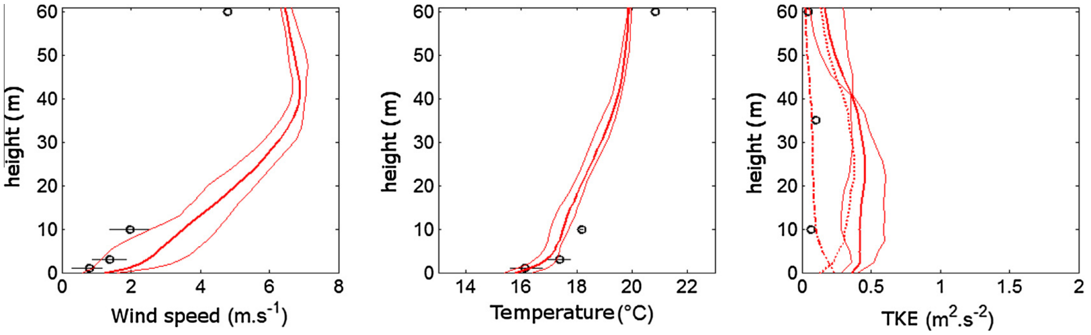

Fig. 4. Mean vertical profiles (thick line) and dispersion (thin lines) of the wind speed, temperature and turbulent kinetic energy (total TKE in continuous line with dispersion, subgrid TKE in dashed line and resolved TKE in dotted line), both measured (black) and simulated (red) on 03-07-2005 at 04h30 (stable case). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

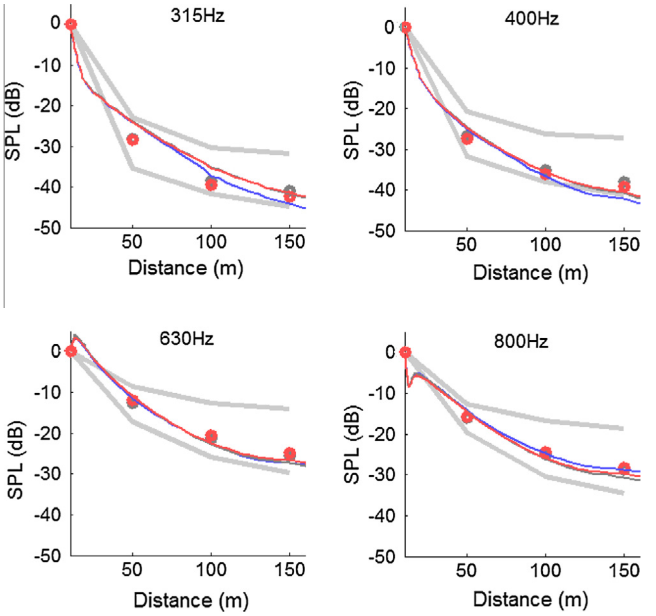

Fig. 5. Sound attenuation (normalised by the free field and by a reference microphone located 10 m from the sound source) as a function of the distance from the source, for 315 Hz, 400 Hz, 630 Hz and 800 Hz third octave bands. The bold grey lines traduce the experimental dispersion over the three-month measurements. Comparison between experimental data during the campaign of Lannemezan 2005 (points) and TLM predictions (full line) using (blue) measured meteorological conditions on 17-06-2005 at 16h30 following PD3, (grey) nearly-homogeneous conditions and (red) rough (linear) vertical profiles of sound speed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

has been presented in [15]. Finally, Meso-NH is considered as a relevant model to provide input data for propagation simulations with the TLM method.

4. TLM

As described in the associated paper (part 1), recent developments of the TLM method have been carried out and validated in order to take into account different ground impedance characteristics [16], fully-absorbing boundary layers [17] and meteorology [18]. Thus, the TLM can now be considered as a reference method for the simulation of outdoor sound propagation.

4.1. Configuration

For the following simulations, the spatial resolution of the TLM method is 0.04 m and performed in 2D during 0.65 s. The central frequency of the sound source (gaussian pulse) is 500 Hz. Perfectly absorbing boundary layers are set around the computational domain, except on the bottom side where ground impedance conditions are assumed to be absorbing. In the Miki impedance model [16], air flow resistivity is set at 150 k N s m^{-4}, which is the measured mean value during the Lannemezan-2005 experiment [19]. The meteorological fields (temperature and wind) are extracted on each propagation direction and integrated into the acoustic model. Because of the major difference in time scales between acoustical and meteorological fluctuations (e.g. sound speed $\sim$340 m s^{-1} vs air flow speed $\sim$10 m s^{-1}), it has been decided to use fixed meteorological variables during the time duration of the simulation (0.65 s).

4.2. Results

In this paper, only 315 Hz, 400 Hz, 630 Hz and 800 Hz third octave band results are presented for the different cases in the PD3

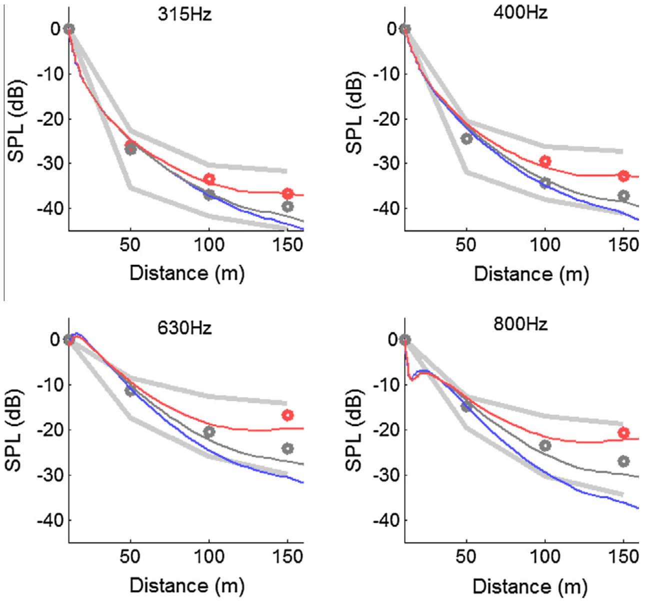

Fig. 6. Sound attenuation (normalised by the free field and by a reference microphone located 10 m from the sound source) as a function of the distance from the source, for 315 Hz, 400 Hz, 630 Hz and 800 Hz third octave bands. The bold grey lines traduce the experimental dispersion over the three-month measurements. Comparison between experimental data during the campaign of Lannemezan 2005 (points) and TLM predictions (full line) using (blue) measured meteorological conditions on 03-07-2005 at 04h30 following PD3, (grey) nearly-homogeneous conditions and (red) rough (linear) vertical profiles of sound speed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

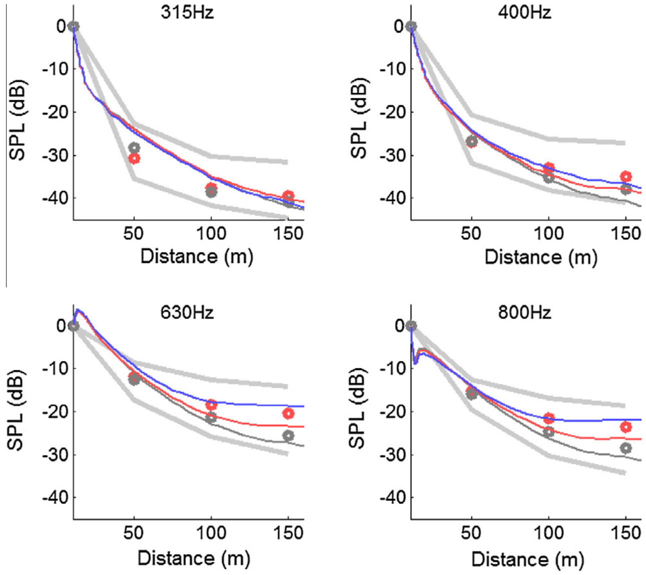

Fig. 7. Sound attenuation (normalised by the free field and by a reference microphone located 10 m from the sound source) as a function of the distance from the source, for 315 Hz, 400 Hz, 630 Hz and 800 Hz third octave bands. The bold grey lines traduce the experimental dispersion over the three-month measurements. Comparison between experimental data during the campaign of Lannemezan 2005 (points) and TLM predictions (full line) using (blue) measured meteorological conditions on 16-06-2005 at 04h30 following PD3, (grey) nearly-homogeneous conditions and (red) rough (linear) vertical profiles of sound speed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

propagation direction. It is possible to find exhaustive results in [15]. In order to compare TLM simulations with measurements under very weak meteorological effects, near perfect homogeneous conditions (vertical speed sound gradient <0.015 s^{-1}) have first been extracted from the Lannemezan-2005 database. This comparison is reported in grey on the Figs. 5–7, which shows a very good agreement between simulated and measured values at any distances and for all frequency bands. This confirms that the choice of ground impedance parameters is sufficiently accurate and relevant [14,20,21]. TLM simulations using vertical linear profiles are also proposed, in red on the figures. The gradient is calculated at a height of 3 m from the measurements, which allows validating the accuracy of the TLM method and better evaluating the impact of the input meteorological data.

Then, the meteorological variables (wind and temperature) of the TLM model are derived from Meso-NH simulation results on the same site and for the same dates. These comparisons between TLM simulations and experimental data are presented in red in Fig. 5 (blue line for "exact" profiles directly generated from Meso-NH). These comparison results generally show very good agreement and especially underscore the benefit in taking into account meteorological effects during acoustic propagation, even with only roughly fitted (linear) meteorological profiles. The different case studies have shown that:

- For unstable case (Fig. 5), a good accuracy of the TLM method under relatively homogeneous conditions. This confirms that the choice of ground impedance parameters is sufficiently accurate and relevant and moreover that TLM is suitable for the purpose of outdoor sound propagation.
- In stable conditions (Fig. 6), because the sound pressure levels are very sensitive to the meteorological fields and, in the case of low quality Meso-NH simulations, the TLM simulations can be sometimes quite far from experiments. When using vertical profiles calculated from measurements, the TLM simulations show significantly better results.
- For neutral case (Fig. 7), if the atmospheric boundary layer simulated by Meso-NH is in sufficient agreement with the meteorological observations, then the TLM sound predictions are also in good agreement with the corresponding experimental acoustic data.

Finally, these comparative results generally show a good agreement, even with only roughly fitted (linear) meteorological profiles.

5. Conclusion

This paper deals with the use of the meso-scale meteorological model (Meso-NH) in order to enhance the time-domain sound propagation model (TLM) with temperature and wind speed profiles. Thanks to the comparison between simulation results and experimental data derived from the Lannemezan-2005 campaign, this study has shown the strong sensitivity of the acoustical model to the vertical profiles of temperature and wind speed, and has thus demonstrated the need to make use of accurate meteorological simulations as input data. The associated paper (part 1) having shown the relevance of the TLM method for outdoor acoustic propagation modelling, the present part 2 has raised the interest of this prospective work from the perspective of coupling acoustical and meteorological models.

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