Paper II

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Simulation of a morning air temperature inversion break-up in complex terrain and the influence on sound propagation on a local scale

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Abstract

A mesoscale atmospheric model is used to model the break up of a morning air-temperature inversion during a clear weather situation with low wind speeds at ground. Modified slope-radiation parameterization in the model results in more realistic predicted air temperature profiles when compared to profiles measured with a tethered balloon. A wave number integration code is used to demonstrate how the modelled atmospheric profiles can be used to predict the reduction of sound level along ground during inversion break-up.
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1. Introduction

It is widely accepted that vertical gradients of air temperature and wind have strong influence on the temporal variation of out-door sound pressure levels at distances beyond approximately 100 m [1–3]. Wilson and Noble [2] provide an overview of the most common methods to include meteorological profiles in sound propagation calculations, such as similarity theory, in situ measurements, ground based measurement techniques and mesoscale modelling. The different methods all have limitations. Similarity theory based on measurements from surface towers breaks down in very stable conditions when there is little or no coupling between the

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ground and the air further up [4,5]. The main problem with in situ measurements in the boundary layer based on tethered balloons is that the typical time scale for a balloon ascent/descent cycle is 30–60 min, while changes in meteorological conditions in the boundary layer (wind speed and direction in particular) often have time scales of seconds or a few minutes. Another important limitation with tethered balloons is that they can not be operated in wind speeds above approximately 10 m/s. Wind direction measurements are also inaccurate at wind speeds below 1–2 m/s. Ground based methods such as the application of radars and sonars have significant range-limitations as well as uncertainties regarding accuracy and representativity of the measurements.

One meteorological condition with relatively slow temporal change is surface air temperature inversion (hereafter referred to as inversions), i.e. the absolute air temperature increases with height above ground. Such conditions are also normally associated with little or no wind and with cloud-free conditions, since they usually appear in high-pressure (anti-cyclonic) situations [6,7]. Inversions can result in sound pressure levels along the ground that are 20–30 dB higher than those typically observed during neutral atmospheric conditions [8–12]. Inversions normally persist for several hours at night and in the morning, and can even persist for days and weeks at high latitudes in winter [5].

Because of the obvious limitations and costs involved in field measurements, it is likely that the use of fine-scale numerical models to predict meteorological profiles for sound propagation calculations will become increasingly popular in the future. Due to the accelerating capacity and speed of computers in recent years, it has become feasible to run such mesoscale meteorological models with successively smaller grid cells. The typical horizontal grid spacing at present is 1000 m, but this limit is expected to decrease rapidly. Mesoscale models can now be used to extrapolate and supplement measurements in time and space and even make real forecasts of sound propagation conditions. Assimilation of measurement data into the models is also becoming increasingly popular.

As far as we know, few authors have combined mesoscale meteorological models and numerical sound propagation models. Heimann and Gross [13] used the FITNAH non-hydrostatic mesoscale model to simulate sound levels in slope wind circulation conditions in an ideal narrow valley during a 24 h period. They showed how changing drainage flows and temperature patterns will influence sound propagation, but no comparisons with measured data were made. Hole and Mohr [14] used the MIUU hydrostatic model to provide profiles in a situation with high wind speeds (10 m/s), but relatively stationary conditions. By comparison with measured meteorological and acoustical data, they showed that this approach can give a relatively accurate ''sound-forecast'' in flat terrain. A US army meteorological group at Aberdeen Test Center (http://www.atc.army.mil) performs daily operational noise forecasts by application of the mesoscale model MM5 [15].

The shape and temporal evolution of inversions are generally hard to describe theoretically [6], and few comparisons with measured soundings have been presented earlier. In the study presented earlier, MM5 has been used to reproduce a surface temperature inversion break-up which was also observed by a tethered balloon. A

new approach to include slope irradiance in MM5 has been introduced to cope with the complex terrain. This has resulted in more accurate inversion reproductions [16]. Further, the profiles form the basis for wave number integration to show how the altered meteorological conditions will influence sound propagation in the morning hours.

2. Environment and experiment

A case of morning inversion break-up from 06 to 16 UTC on 21 September 1994 was chosen for comparison. As part of a large field campaign [17], continuous measurements with a Tethersonde climbing to altitudes of 500–1000 m above ground, were carried out at Finnskogen in Hedmark County, NE of Oslo, Norway [18]. In this area, the ground is undulating and mostly covered with conifer forest, rising gradually from the river Glomma to the Swedish border. The area in a 2 km radius around the observation point is relatively flat, with a southwest-pointing slope in the order of 2–3°.

A high-pressure system was situated over southern parts of Norway during the period studied (Fig. 1), and synoptic wind speeds were low or moderate most of the time. As will be shown further down, a strong inversion formed during the night in the lowest 300 m of the atmosphere. According to classical theory [e.g. 6,7,19], the strongest inversions normally appear just after sunrise, as was also the case here.

3. Model configuration

MM5 was set up with an outer mesh with 13.5 km horizontal grid spacing and an inner mesh with 500 m spacing. The data were nested from ECMWF (European Centre for Medium-Range Weather Forecasts) data in four steps down to a 500 m grid distance (Fig. 2). The number of grid points were 40×40 for all domains and 31 vertical levels (6 below 100 m). The options for parameterization of sub-grid and physical processes were in addition to the first order turbulence closure [20], an advanced 5 layer surface model (LSM) [21, 22] with prognostic equations for soil moisture and temperature. Explicit moist "physics" including ice phase was used. Cumulus parameterisation has been used for the outer mesh (= 13.5 km) [23]. The radiation scheme based on Dudhia [32] has been modified to take into account the effect of sloping surfaces. For further details, see Ref. [16] and Section 4.

4. Mesoscale model modifications

The energy balance at the surface is given by:

$$(1 - \alpha)S^{\downarrow} + L^{\downarrow} - L^{\uparrow} = H + \lambda \cdot E_{tot} + G_0 \tag{2}$$

where α is the surface albedo, $S^{\downarrow}$ is short wave radiation, L is downward and upward long wave radiation, H is sensible heat-flux, λE_{tot} is latent heat-flux, G_0 is heat-flux down into the ground.
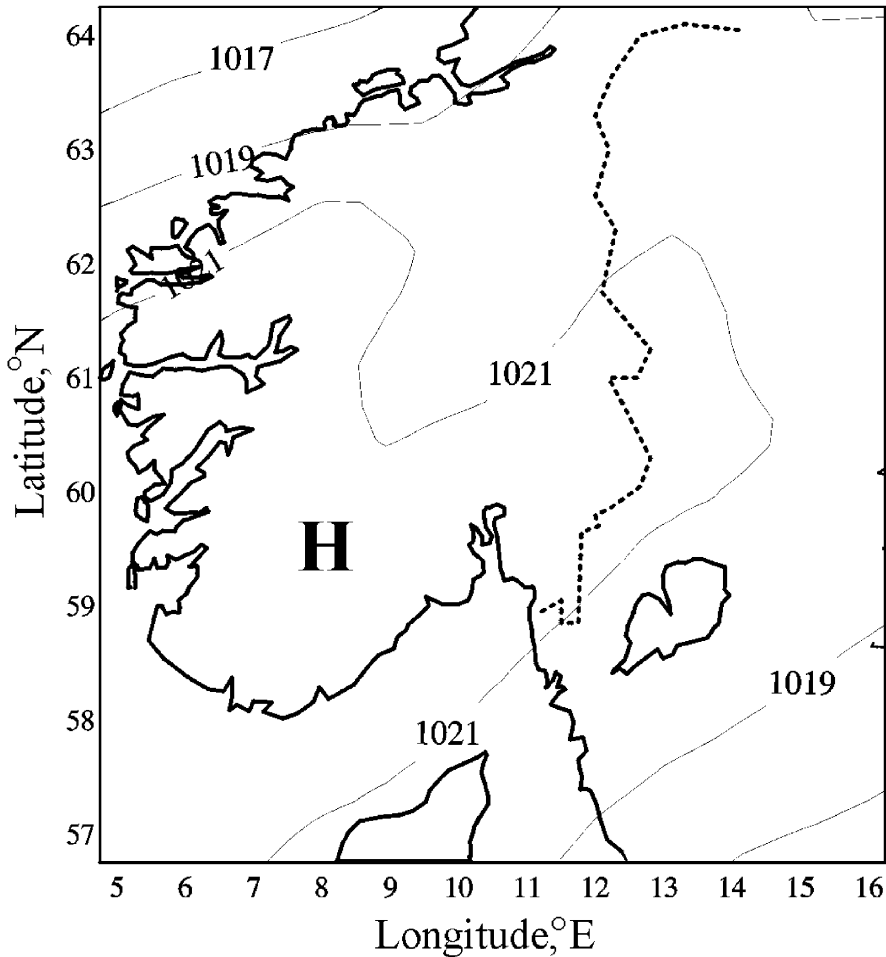
Fig. 1. Mean sea level air pressure (MSLP) at 12 UTC on 21 September 1994. Numbers on axes are latitude and longitude.

MM5 was first designed as a regional weather forecast model with rather coarse spatial resolution. For a grid spacing below 1 km, it was advisable to introduce an additional algorithm in MM5 to take into account the slope and orientation of the terrain in the calculation of short wave incoming radiation [$S^{\downarrow}$ in Eq. (2)] [16].

Consideration of this effect was introduced by Mahrer and Pielke [24] in a 3D atmospheric model. In contrast to Ref. [24], our approach requires the splitting of short wave radiation into its direct and diffuse components. This reduces the topographic influence in more cloudy conditions.

The approach chosen to describe the effect of a slant surface in our simulation is based on Refs. [25] and [26]. Following Skartveit and Olseth [26], knowing the hourly diffuse and beam irradiances, S_d and S_b, on a horizontal surface, the total
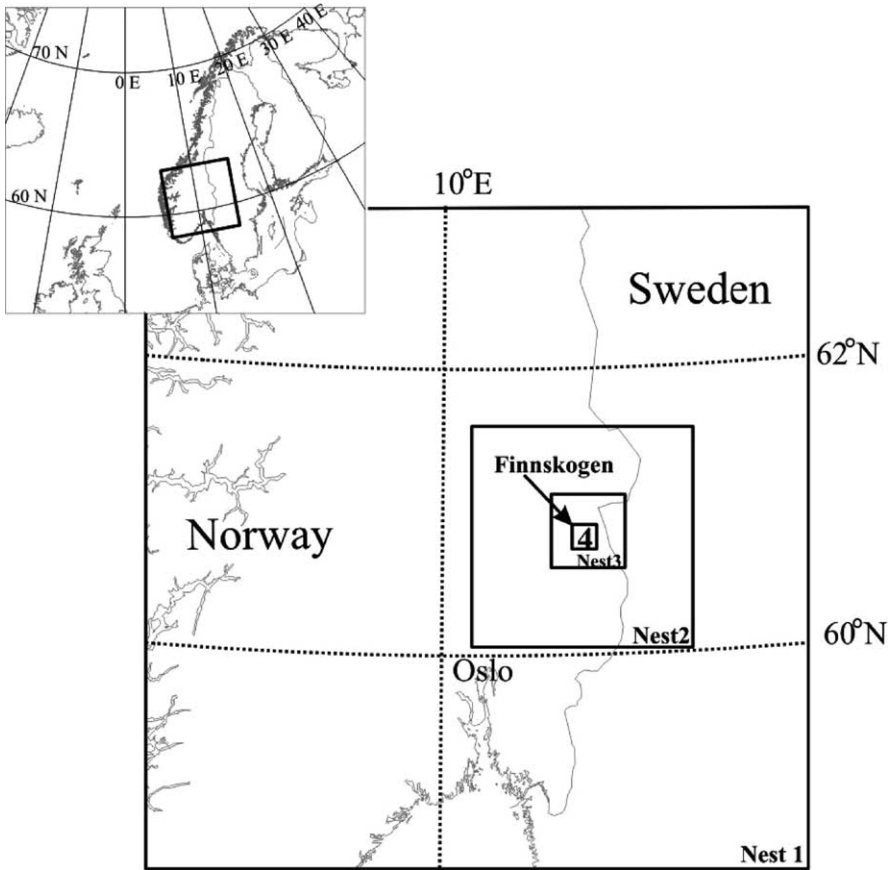
Fig. 2. Illustration of how the MM5 model is nested from synoptic scale to local scale.

irradiance on a surface inclined by an angle β towards an azimuth angle γ can be written:

$$S(\beta, \gamma) = S_b \frac{\cos(\theta)}{\sin(h)} + \sin^2 \frac{\beta}{2} \alpha(S_d + S_b) + S_d(\beta, \gamma), \tag{3}$$

where h is solar elevation θ is the solar beam's angle of incidence. Negative $\cos(\theta)$ is replaced by zero. It should be noted that the algorithm introduced only takes into account the slope's orientation and not shadow effects due to mountains. This is surely an important effect at low solar angles and steep mountains, but this is yet not implemented into MM5. However, it seems reasonable to assume that shading effects are small in the situation described here.

It has been shown that this new approach can result in significant improvement in wind and temperature profile predictions [16], e.g. the RMS error for the wind speed profiles compared to measured data is reduced with 35% for the case studied here.

5. Acoustical predictions

Sound propagation in the atmosphere is influenced by topography, ground conditions (nature of the ground type, e.g. snow, vegetation or asphalt) and weather conditions (refraction, diffraction and turbulent scattering in the atmosphere) [1]. Here we concentrate on the effect of atmospheric refraction, which has most influence on the diurnal variation of sound pressure levels at some distance.

Results from MM5 are used as input to a wave number integration code (also called a Fast Field Program (FFP)) [27], to demonstrate the meteorological influence on the sound propagation. The programme has earlier provided accurate predictions of airborne low-frequency pulses propagating in the same type of environment [3, 28]. The *Directional Sound Velocity* (thermal sound speed + wind component in the direction studied), *DSV*, was calculated for each model layer. The acoustically relevant vertical gradients of *DSV* are normally governed by vertical gradients of wind velocity vector. However, in the case studied here with low wind speeds, effects of temperature gradients are most important.

The *DSV* values were interpolated to 2, 10, 20, 50, 100, 200 and 500 m above ground and used as input to the FFP. Previous experience has shown that only profiles below 100 m or so will have a significant influence on the sound levels along the ground [2,3,14]. It is normally assumed that *DSV* profiles are range-independent, i.e. that wind velocities and air temperatures are horizontally homogeneous over the area considered, and thus only dependent on height above ground [29]. The purpose of the acoustical simulations presented here is to demonstrate how much the inversion break up will influence sound propagation, and thus this relatively simple approach was chosen. Also we are not aware of 3D acoustic models that can handle sound propagation at the distance studied here with realistic terrain and meteorology included. Ground conditions typical for the relatively soft forest floor in the area were taken from Ref. [28]. A porosity of 0.44, a poroelastic layer thickness of 0.5 m, an effective flow resisitvity of 17.4 kPa s m^{-2} were included. The flow resistivity is very low, but realistic for the soft forest floor in the area [28]. An infinite viscoelastic layer was placed below the poroelastic top layer in the ground.

1D calculations in 8 directions were interpolated horizontally to achieve a quasi-2D result (depending on distance from source and angle). *DSV* profiles were calculated from MM5 atmospheric profiles in each case and used as input in the FFP [27]. The sound source was a point source of 100 Hz at 2 m above ground. The receivers were also placed at 2 m above ground and the maximum prediction distance was 1000 m.

6. Results

Fig. 3 shows the time-evolution of the air temperature profiles in the lowest 500 m of the atmosphere at Finnskogen from 6 UTC to 16 UTC 21 September 1994. The figure reveals a classical example of morning inversion break-up. It can be seen how the ground is heated by solar radiation and how statically unstable air close to
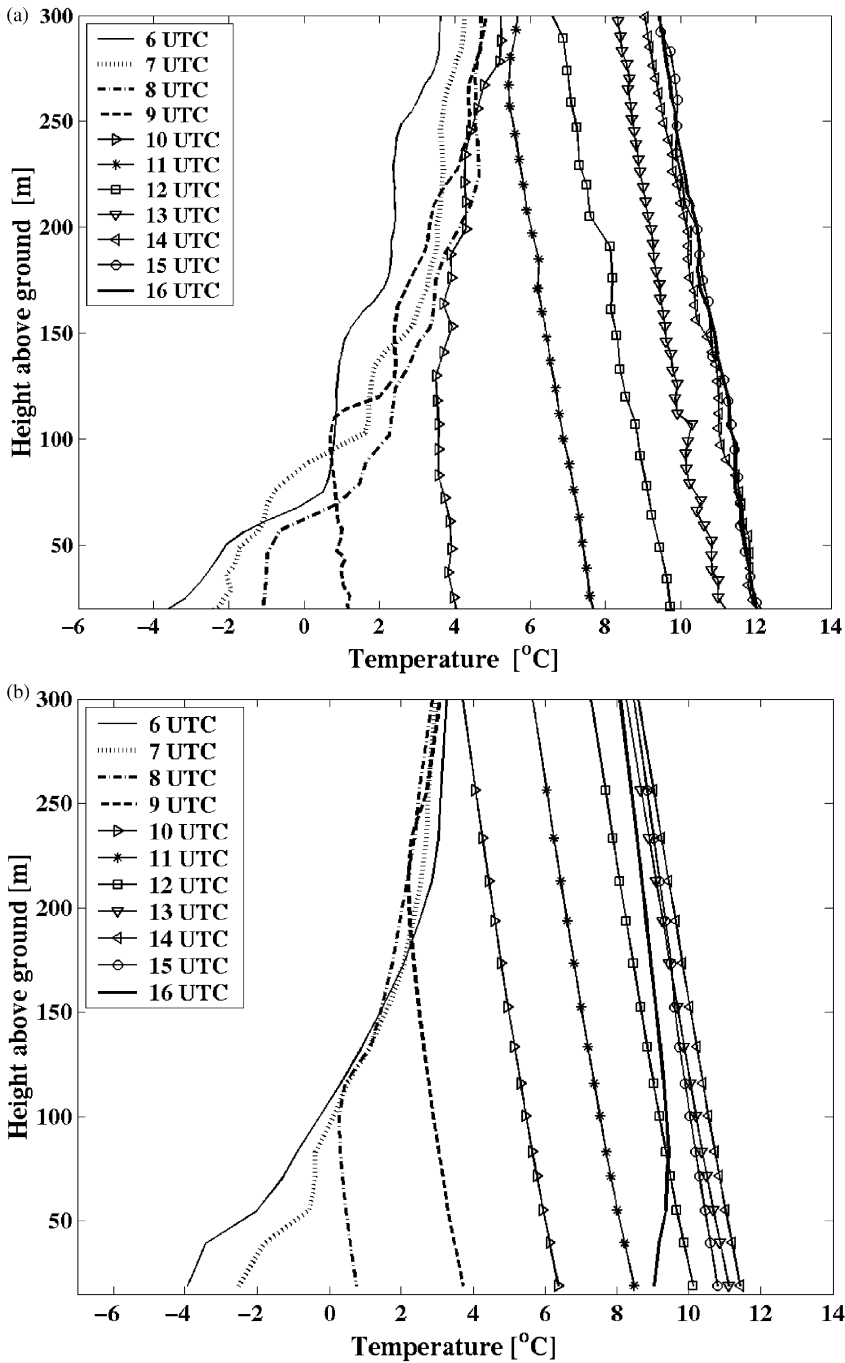
Fig. 3. Air temperature profiles from 06 to 16 UTC on 21 September 1994. (A) Measured by Tethersonde. (B) Predicted by MM5.
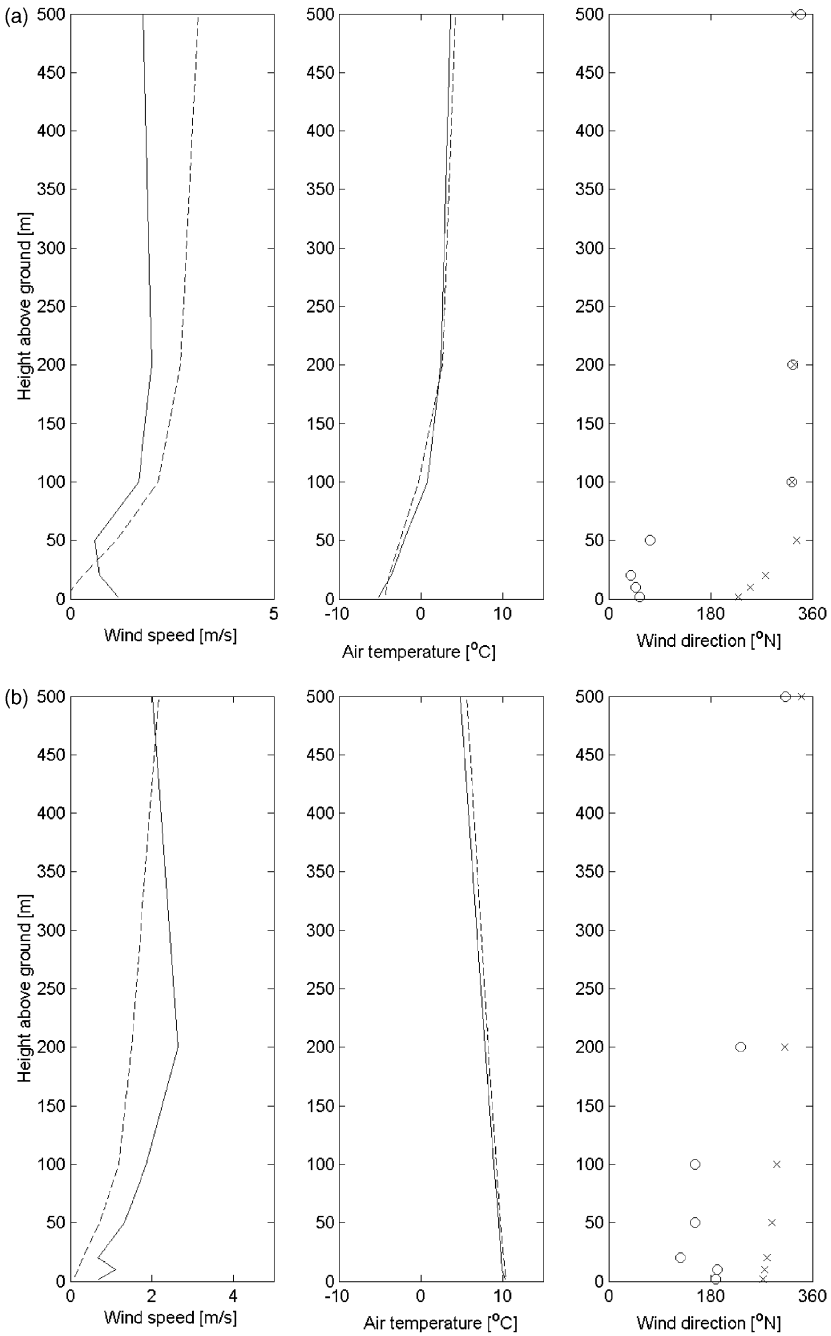
Fig. 4. (A) Comparison of measured and predicted atmospheric profiles 21 September 06 UTC. Solid lines are measured data and dashed lines are MM5 results. For wind directions the circles represent measured data and crosses are representing MM5 results. (B) same as (A), but at 12 UTC.

ground penetrates deeper and deeper into the inversion and destroys it from below. The air close to the ground was subject to a steady temperature increase from −4 to + 10 °C in 6 h from 06 to 12 UTC, i.e. more than 2°/hour. At 500 m, the increase in air temperature is only about 1° in the same period.

The inversion seems to be fairly well simulated at 6 and 7 UTC and after 11 UTC. On the other hand, the destruction rate of the inversion from 8 and 10 UTC was not satisfactorily simulated, where the inversion in the model is breaking up too fast. There are some possible explanations for this misfit that need to be investigated further. Between 7 and 8 UTC the surface temperature crosses the ''heat-capacity barrier'' [30]. Lack of soil water freezing in MM5 could be some of the explanation of this misfit in temperature at 8 UTC. However, the most probable cause of the heating between 8 and 10 UTC in the model, is that a too big part of the incoming solar energy is converted into sensible heat. This could happen if too little evaporation and thawing occurs. This error could be caused by the initialisation of soil moisture from the ECMWF, which has a rough horizontal resolution (40 km) compared to the finest nest in the MM5 simulation.

Modelled and observed wind and air temperature profiles are compared in Fig. 4. The error in simulated wind speed and directions in Fig. 4 can be a further explanation for the discrepancies seen in the break up of the temperature inversion.

At 16 UTC the observed profile is neutral or close to neutral. In the model, however, the formation of a new surface inversion has already started. The formation of a new inversion in the afternoon can be due to the parameterisation of the soil properties and soil heat flux [G_0 in Eq. (2)] in MM5, leading to a fast surface cooling. As the short wave radiation becomes small, there is a rapid response to the surface skin temperature. The drop in temperature leads to a large heat flux into the soil since this flux is dependent on the difference between the soil temperature and the skin temperature [Refs. 21 and 22]. This result suggests that the energy-diffusion from the surface into the soil is too fast in MM5. Unfortunately, no balloon measurements were made in the afternoon.

Other effects could be connected to the turbulence parameterisations. In this simulation, the formulations used are based on Ref. [20], a first order turbulence closure. Previous studies have shown that the strength of the inversion is sensitive to the formulation of the fluxes of momentum and heat profiles [30]. During strong stable stratification, the turbulent diffusion coefficients in the boundary layer used in the turbulence scheme [20] becomes too low. This could be improved by using other formulations, e.g. those applied in the operational ECMWF-model [29]. These heat-flux formulations are based on the dependency on Richardson number rather than the height above ground and the boundary layer height.

Fig. 5 demonstrates the effect of the temperature inversion on sound propagation conditions. The sound level at most distances beyond 100 m is reduced by more than 30 dB from 0600 UTC to 1200 UTC. Fig. 5A and B presents transmission loss relative to source level for wave number integration predictions based on Tether-sonde measurements (5A) and MM5 predictions (5B). The main difference between the two cases is the large transmission loss to the NE of the source in Fig. 5B). This is probably due to the logarithmic wind profile produced by MM5, with direction
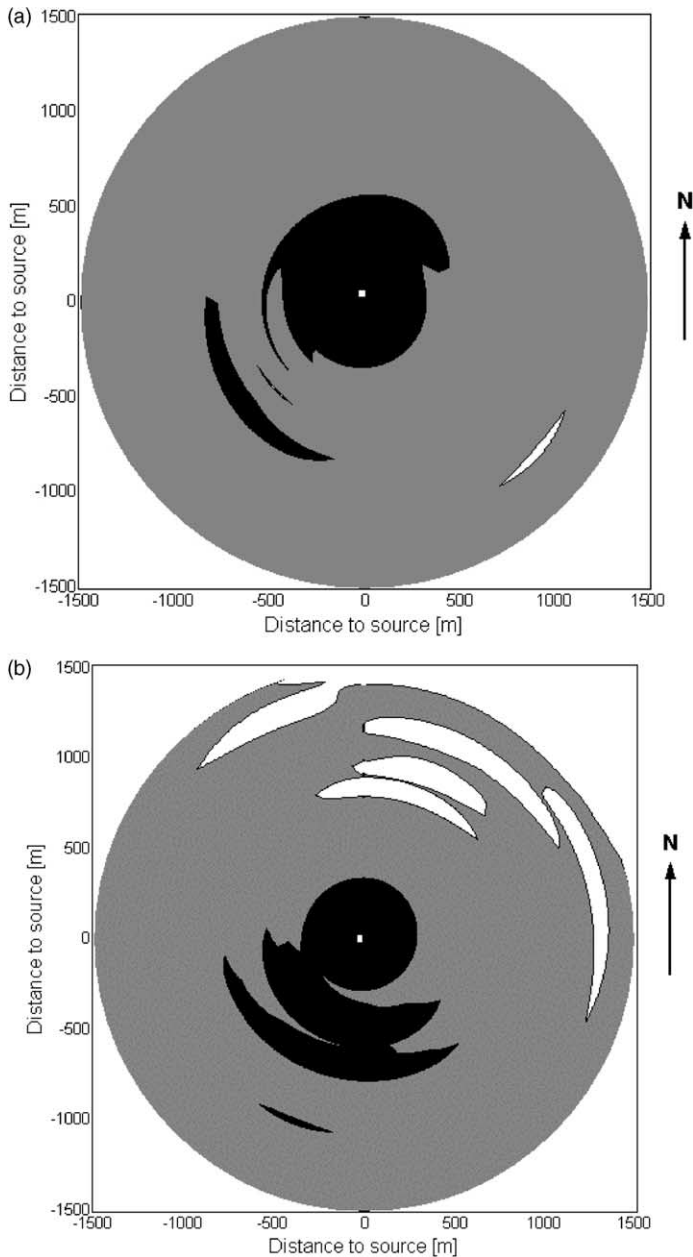
Fig. 5. (A) Plane view transmission loss [dB] 2 m above ground relative to source level at 100 Hz. FFP predictions based on Based on Tethersonde measurements at 06 UTC. Contours at 40 dB (black zones), 60 dB (grey zones) and 80 dB (white zones). (B) Same as (A), but FFP predictions are based on MM5 predictions at 06 UTC. (C) Change in sound level in dB/h from 06 to 12 UTC. Contours at −5 dB/h (black zones), −2.5 dB/h (grey zones) and 0 dB/h (white zones). Predictions based in Tethersonde measurements at 06 and 12 UTC. (D) Same as (C), but FFP predictions are based on MM5 predictions at 06 and 12 UTC.
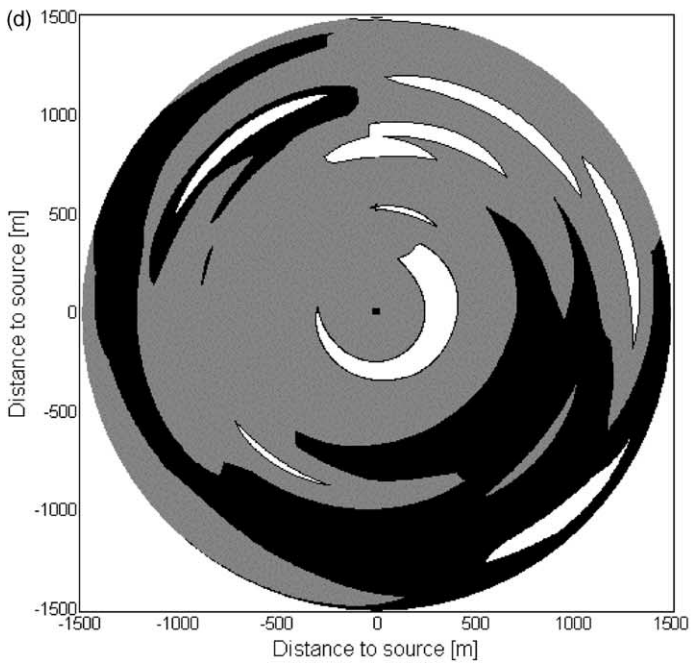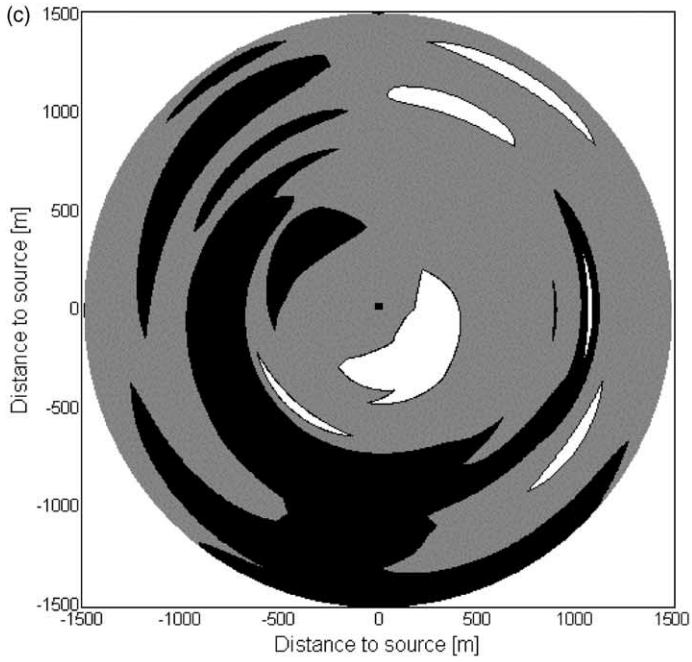
Fig. 5. (*continued*)

from SW close to the ground (Fig. 4B). This wind profile will cause stronger refraction downwards close to the source resulting in greater loss at some distance. The measured wind profile at 06 UTC (Fig. 4A) has a shape more similar to a lifted duct. However, the negative wind profile in the lower 50 m is not strong enough to cancel the effect of the inversion.

Fig. 5C and D shows the change in sound level from 0600 to 1200 UTC. The predictions are based on Tethersonde and MM5 profiles respectively. The pattern is complex. Some areas, in particular at some distance (600 m or more) S and SE of the source, show a reduction in sound level of more than 5 dB/h in this period, while areas of increased sound levels are observed NE of the source and in a zone 200–300 m SE because of the shift in wind direction. Differences between the two predictions is again due to differences between measured and modelled wind profiles since the modelled air temperature profiles corresponds well to those observed. The Tethersonde measurements show a shift in surface wind direction from NNE to S in this period, while the modelled profiles just show a slight shift from WSW to W (Fig. 4). The steady state wind direction in MM5 explains why Fig. 5D shows a slightly more directional pattern than Fig. 5C. This result demonstrates how sensitive acoustical conditions are to small changes in the local weather pattern.

7. Concluding remarks

The mesoscale atmospheric model MM5 has been used to predict the break up of a surface air temperature inversion in a typical autumn situation above a forest in eastern Norway. Slope irradiance has been implemented into MM5. The model now provides more realistic predictions of wind and temperature profiles in the atmospheric boundary layer. Predicted profiles are compared to profiles measured with a tethered balloon. To demonstrate the change in sound propagation conditions during the break-up, measured and predicted profiles are used as input in a Fast Field Program. Propagation of sound at 100 Hz is predicted out to 1500 m from the source. The two sets of predictions reveal similar patterns with a reduction in sound level of more than 5 dB/h during the morning air temperature inversion break up. There are some differences in the patterns of sound level change with time in the two cases. This due to differences between measured and modelled wind velocity profiles. At the low wind speeds in the case studied here, wind direction measurements by tethered balloon are not reliable since this parameter is measured by the orientation of the balloon. Unfortunately, no acoustic measurements are available to confirm the predictions made.

Atmospheric mesoscale models are developing fast and with considerable human and economical resources devoted to the task due to the obvious necessity of improved local weather forecasts for many applications (e.g., city and industrial pollution and wind energy estimates). We can expect that noise forecasts will be demanded in the near future as this pollution problem comes more in the focus of the public and politicians. The prospects are that the resolution and accuracy will improve in the coming years. We can expect that turbulence effects [31] on sound

propagation can also be included. However, with finer resolution, it is to be expected that additional effects will have to be taken into account, such as the slope irradiance effect described here.

Predictions of atmospheric air temperature profiles accurate enough for sound propagation forecasts seem feasible. Effort should be put into more comparisons of model predictions with measured acoustical and meteorological data. A major challenge is to obtain sources of high quality meteorological and associated acoustical data for interesting situations such as ground inversions, lifted inversions and ducts.

Another issue that must be elaborated further is the coupling of scales and resolution in meteorological mesoscale models and acoustical models. The horizontal resolution of a model like MM5 is typically 1 km or more, while the vertical resolution close to ground is typically 10 m. An acoustical model has a resolution at least one order of magnitude less. The same is the case for temporal resolution. On the other hand no 3D acoustical models available at the moment can handle sound propagation at ranges of practical interest with realistic terrain and meteorology included.

Acknowledgements

References

[1] Embleton T. Tutorial on sound propagation in the atmosphere. Journal of the Acoustical Society of America 1996;100:31–48.
[2] Wilson K, Noble J. Putting meteorology into sound propagation calculations. In: Proc. Inter-Noise, Nice, France; 2000.
[3] Hole LR. An experimental and theoretical study of propagation of acoustic pulses in a strongly refracting atmosphere. Applied Acoustics 1997;53(1-3):77–94.
[4] Mahrt L. Stratified atmospheric boundary layers. Boundary-Layer Met 1999;90:375–96.
[5] Holtslag AAM. Estimates of diabatic wind speed profiles from near-surface weather observations. Boundary Layer Meteorology 1984;29:225–50.
[6] Whiteman C. Breakup of temperature inversion in deep mountain valleys: part 1. Observations. Journal of Applied Meteorology 1982;21:270–89.
[7] Garratt J. The atmospheric boundary layer. Cambridge Univ Press, ISBN 0-521-46745-4, 1999.
[8] Larsson C. Atmospheric absorption conditions for horizontal sound propagation. Applied Acoustics 1997;50(3):231–45.
[9] Bronsdon RL, Forschner H. A propagation model based on Gaussian beams that accounts for wind and temperature inversions. Noise Control Engineering Journal 1999;47(5):173–8.
[10] Larom D, Garstang M, Lindeque M, Raspet R, Zunckel M, Hong Y, et al. Meteorology and elephant infrasound at Etosha National Park, Namibia. Journal of the Acoustical Society of America 1997;101(3):1710–7.

[11] Konishi K, Maekawa Z. Interpretation of long term data measured continuously on long range sound propagation over sea surfaces. Applied Acoustics 2001;62(10):1183–210.

[12] Hygen HO. An experimental study of sound propagation in a very stable atmospheric boundary layer. Masters thesis, Geophysical Institute, University of Bergen, 1997 [in Norwegian].

[13] Heimann D, Gross G. Coupled simulation of meteorological parameters and sound level in a narrow valley. Applied Acoustics 1999;56:72–100.

[14] Hole LR, Mohr HM. Modeling of sound propagation in the atmospheric boundary layer: application of the MIUU mesoscale model. Journal of Geophysical Research 1999;104(D10):11891–901.

[15] Grell G, Dudia J, Stauffer D. A description of the fifth-generation Penn-State/NCAR mesoscale model. NCAR technical report note TN-398, National Center for Atmospheric Research, Boulder Colorado, US; 1994.

[16] Hauge G, Hole LR. Implementation of slope irradiance in MM5 and its effect on the break-up of temperature inversions in complex terrain. Journal of Geophysical Research [accepted].

[17] Guice RL, Hole LR, Jenssen A, Kerry G. Impulse noise measurements during summer and winter conditions. Noise Control Engineering Journal 1998;46(5):185–9 (Spec issue).

[18] Hole LR, Gjessing Y, de Lange T. Meteorological measurements and conditions during ''Norwegian Trials''. Measurements During Summer and Winter Conditions. Noise 1998;46(5):199–207 (Spec issue).

[19] Stull RB. An introduction to boundary layer meteorology. Boston, USA: Kluwer Academic Publishers; 1988 379–381.

[20] Hong S, Pan H. Nonlocal boundary layer vertical diffusion in a medium range forecast model. Monthly Weather Review 1996;124:2322–39.

[21] Chen F, Dudia J. Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part 1: model implementation, and sensitivity. Monthly Weather Review 2001a;129:569–85.

[22] Chen F, Dudia J. Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part 2: preliminary model validation. Monthly Weather Review 2001b;129: 587–604.

[23] Grell G, Kuo Y, Pasch RJ. Semi-prognostic tests of cumulus parameterization schemes in the middle latitudes. Monthly Weather Review 1991;119:5–31.

[24] Mahrer Y, Pielke RA. A numerical study of airflow over irregular terrain. Beitr Phys Atm 1977;50: 98–113.

[25] Skartveit A, Olseth J. Modeling slope irradiance at high latitudes. Solar Energy 1986;36(4):333–44.

[26] Skartveit A, Olseth J. A model for the diffuse fraction of hourly global radiation. Solar Energy 1987; 38(4):271–4.

[27] Schmidt H. OASES version 2.2; Application and upgrade notes. Available: http://acoustics.mit.edu/arctic0/henrik/www/oases/oases.html, 1999.

[28] Hole LR, Kaynia A, Madshus C. Measurement and simulation of low frequency impulse noise and ground vibration from airblasts. Journal of Sound Vib 1998B;214(2):309–24.

[29] Attenborough K, Taherzadeh S, Bass HE, Raspet R, Becker GR, et al. Benchmark cases for outdoor sound propagation models. Journal of the Acoustical Society of America 1995;97(1):173–91.

[30] Viterbo P, Beljaars A, Mahfouf JF, Teixeira J. The representation of soil moisture freezing and its impact on the stable boundary layer. Quart J R Met Society 1999;125:2401–26.

[31] Waddington DC, Lam YW. A study on range-dependent meteorological conditions and their influences on outdoor sound propagation. In: Proc. International Congress on Acoustics 2001, Rome, Italy.

[32] Dudhia F. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. J Atmos Sci 1989;46(20):3077–107.