Simulation of surface temperature inversions in complex terrain and implementation of slope irradiance

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1 Introduction

It has been widely accepted that modelling of land surface processes plays an important role in mesoscale numerical models of the atmosphere (e.g. Avissar & Pielke [1989] or Mahfouf et al. [1987]). Solar radiation is obviously an important factor in many aspects of the surface forcing. To improve the solar shortwave radiation parameterization, slope irradiance has been implemented into the non-hydrostatic mesoscale model MM5.

General radiation processes on sloping surfaces has been thoroughly investigated by several authors (see e.g. Skartveit & Olseth [1986], Oliver [1992], Varley et al. [1996]). These authors investigated radiative processes in general, but did not include this effect into numerical weather prediction models (NWP's). Slope irradiance can, however, normally be neglected in numerical models when the horizontal model resolution is low ($O(10)km$ or more) and the slopes are moderate. On the other hand, when the resolution is higher ($O(1)km$), the effect of slopes might be considerable, especially at low solar zenith-angles and at high latitudes. Slope irradiance should therefore be included when the resolution becomes high and the terrain steep and undulating.

2 Implementation of slope irradiance

SW radiation [Dudhia 1989] at the surface is originally calculated under the assumption of horizontal surfaces [Dudhia 1989], i.e. SW radiation at the surface is a function of solar height [Iqbal 1983] and a function, F, depending on transmissivity, water vapour, clouds and scattering, given as:

$$S = S_0 \sin h \cdot F. \qquad (1)$$

S_0 is the solar constant, depending on the mean distance and the actual distance to the sun. The solar elevation is given as:

$$\sin h = \sin\delta \sin\phi - \cos\delta \cos\phi \cos\Omega, \qquad (2)$$

where δ is Earth's declination, ϕ is geographic latitude in degrees (north positive) and Ω is the hour angle. This method of estimating the SW radiation can lead to considerable errors when the model resolution becomes high and the model terrain steep. Since our interest is sloping terrain, we have to split the global irradiance into its direct and diffuse components in order to describe the slope irradiance. This splitting is done according to a method developed by Skartveit & Olseth [1987], valid at high latitudes ($> 30^o$) and implemented into MM5.

When slope and orientation of the surface (the topography-azimuth angle), and the hourly diffuse and beam irradiances are known, the total irradiance on a surface inclined by an angle β towards an azimuth angle γ (orientation) can be written:

$$\begin{aligned} S(\beta,\gamma) &= S_B \frac{\cos\theta}{sinh} + (1-\cos^2\frac{\beta}{2})\ \alpha\ (S_D + S_B) \\ &+ S_D(\beta,\gamma), \end{aligned} \qquad (3)$$

where h is solar elevation, β is ground slope (calculated using forward differences), and θ is the solar beam angle of incidence. $S_D(\beta,\gamma)$ is the diffuse sky irradiance, S_B is the direct radiation (beam) and $(1-\cos^2\frac{\beta}{2})\alpha\ (S_D+S_B)$ is ground reflected irradiance. Negative $cos\theta$ is replaced by zero in (3).

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The solar beam angle of incidence can be written as [Iqbal 1983]:

$$\cos\theta = \cos h \sin\beta \cos(\psi - \gamma) + \sin h \cos\beta, \quad (4)$$

which explains the correspondence between solar radiation and the orientation and slope of the underlying terrain. ψ is the solar azimuth where south is zero and east is positive. As in the original formulations [Dudhia 1989], the effects of clouds and scattering are still taken into account in the calculations of S_D and S_B. It is clearly seen that for $\beta = 0$ (flat surface), $cos\theta = sinh$ (Eq. 4).

3 Model Simulations

In order to evaluate and compare model results with measured data, a situation from 21 September 1994 was chosen. As part of a large field campaign, extensive measurements with tethersonde were carried out during this day from 06 UTC to 16 UTC (07-17 local time) (see Hole et al. [1998] for details). The geographical area of interest has been Finnskogen in Hedmark County, NE of Oslo In this area the ground is undulating and mostly covered with conifer forest. The choice of situation was also based on the fact that little or no clouds were present this period (not shown). Effects of the changes in the radiation formulations can therefore be seen more directly.

To test the effect of the changes made in the radiation scheme, two model runs are conducted. The first, called the *reference-run*, used the original SW parameterizations based on Dudhia [1989], and the second, called the *modified-run*, which had slope irradiance implemented. Results from the reference run are not presented directly here, but the difference between the simulations are shown.

3.1 Model setup

The initial and boundary conditions for the simulations are generated using the standard static initialization procedure for MM5, and first-guess fields are produced by interpolating data from ECMWF (European Centre for Medium Range Weather Forecast) to the outer computational grid. The meteorological fields are further interpolated from the outer grid to the inner next domain until the finest nest at 500 meters horizontal grid distance. The number of grid-points were 40×40 for all domains and 31 vertical layers. The 31 vertical sigma levels are spaced so as to provide much higher vertical resolution in the planetary boundary layer than at upper levels (13 layers below 1000 meters).

In the present simulations, the turbulence scheme based on Hong & Pan [1996] is used, coupled to an advanced land-surface model (LSM) described by Chen and Dudhia [2001a, 2001b]. For moisture, an explicit moisture scheme, including the ice phase, was used [Dudhia 1989]. The radiation scheme applied, based on Dudhia [1989], has been modified to take into account the effect of sloping surfaces (See Section 2 for more details). For the outer domain (grid distance 13.5 km) a cumulus parameterization based on Grell, Dudhia & Stauffer [1994] has been used. Topography and land-use were derived from the 1 km USGS (United States Geological Survey) dataset [Eidenshink & Faundeen 1998]. Further information on the model system can be found in Grell et al. [1994].

3.2 Results

The observed soundings between 06 and 16 UTC (07-17 local time) 21 September 1994 are illustrated on Fig. 1, revealing a classical example of a morning temperature inversion break-up (see e.g. Stull [1988]). The figure clearly demonstrates how the ground was heated by solar radiation and how statically unstable air close to ground penetrates deeper into the inversion layer and destroys it from below. At 11 UTC, the atmospheric boundary layer stratification was close to neutral (constant potential temperature), indicating that the break-up of the inversion was completed. The changes in the modified temperature soundings compared to the reference run (Fig. 2), are mostly seen in the morning and in the afternoon. The soundings are slightly to warm in both simulations in the middle of the day and too cold in the afternoon, compared to observations. The modified run seems to give a more accurate break-up of the temperature inversion. In the afternoon the observation area is oriented to south-west, giving less cooling than in the reference-run. This effect gives a slower formation of a new inversion and is more according to the observations.

In areas with large slopes the resulting temperature differences are influenced by the slope irradiance. The effect in the obseravation point of slope irradiance is not large and the reason for

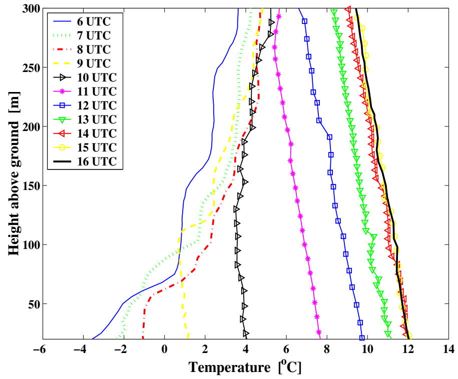

Figure 1: Observed temperature soundings 21 September 1994 in the observation

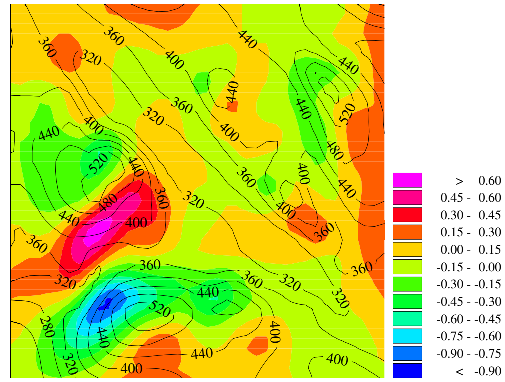

Figure 3: Difference in temperature in lowest model layer (20 meter) between the modified run and the reference run at 09 UTC 21.09

this is small terrain gradients (2-3 ^{o}) in this area. The temperature differences between the modified and the reference run in the lowest model layer (20 m) at 09 UTC 21 September are shown in Fig. 3. The solar height is low, and the largest cross-valley temperature difference ranges up to 1.5 degrees. Results were changed the circulation patterns and rising motion at the sun side and descending air at the shadow side of the valley (not shown).

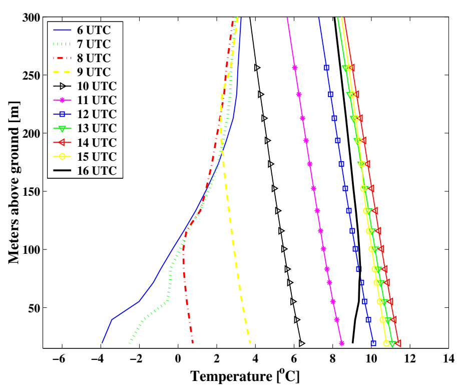

Figure 2: Modelled sounding in the modified run

4 Conclusive remarks

To evaluate the model results of wind speed and temperature, the root mean square errors (RMSE) have been computed. The RMSE shown on Fig. 4 is based on a the interpolated temperatures and windspeeds from 10 to 300 meters from 06 UTC to 16 UTC. The statistical analysis is done in discrete levels from 10 to 300 meters, and the RMSE at each level is calculated on the based on the observations from 06 UTC to 16 UTC (11 values at each level).

Results presented show improvements both in the modelled temperature and windspeeds compared to observed soundings. After the modification, the daily temperature variation has better correspondence to observations, especially in the morning and in the afternoon. The RMSE in temperature was reduced after the modification, but there are still some problems concerning the shape and strength in the break-up of the temperature inversion. The implementation of slope irradiances reduced the mean RMSE in temperature by 13 %. The largest improvements are seen in the wind fields, where the mean RMSE are reduced with 35 %. The large improvements in wind speed are seen because slope irradiance has greater influence in other areas of the domain. This forces circulation patters which has a non-local effect and influence in the observation point. This results suggests that the influence of slope irradiance is greater on the wind fields than on the temperature fields. The temperature near the surface has close dependency on the local physical grid-point properties such as albedo and emissivity, while the effects on the wind fields easier can be advected to other areas. Circulation set up in steeper areas can therefore have larger influence in other areas of the domain.

Errors in the simulations could be caused by many factors such as PBL parameterizations, horizontal diffusion, model setup and boundary conditions. However, this has not been a subject in

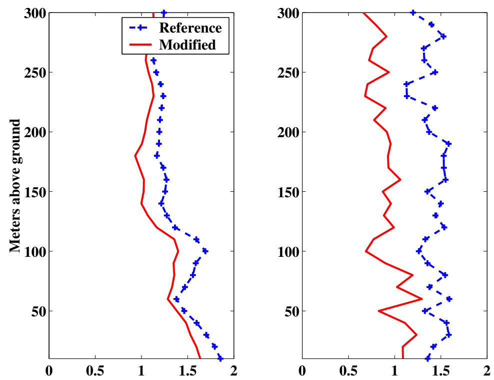

Figure 4: left: RMSE in temperature between 06 UTC and 16 UTC 21 September. Right: RMSE in wind speed

this study. To evaluate the usefulness of the modifications in the radiations scheme, more tests with other surface conditions should be performed. In addition, studies of how the modifications will influence the results in more cloudy conditions remain to be investigated.

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