

# Orography-related parametrizations in HIRLAM

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## 1 Scales of orography and model

### 1.1 Scales and processes

Fig. 1 shows one-dimensional spectral analysis of high-resolution surface elevation data (Satellite Radar Transfer Mission, Rodriguez et al. (2005)) along the northern latitude 45 N, i.e. variance of surface height as a function of horizontal scale. There is variance in all scales from one hundred metres to about 15 thousand kilometres and the largest variance is connected with the largest scales. In the orography spectrum, it may be possible to find power laws, showing dependency of the height variance on horizontal wave-number ( $k$ ). However, there are no theoretical reasons to expect a specific dependency on e.g.  $k^{-5/3}$  or  $k^{-3}$ , in contrary to the atmospheric kinetic energy spectrum, where this is predicted by the theory of three- or two-dimensional turbulence. However, the empirical dependencies found in the elevation spectra have been used for development of parametrizations of subgrid-scale orographic effects e.g. in the ECMWF model (Beljaars et al., 2004).

It is commonly assumed that different scales of orography can be connected with atmospheric processes of different physical origin. Table 1 summarises some orography-related atmospheric processes and corresponding scales. Some of the processes are discussed in the following sections.

### 1.2 Parametrized and resolved processes

The upper horizontal scale of Fig. 1 shows the estimated horizontal resolution of the model, needed to resolve orography scales shown in the lower scale. A model with horizontal resolution  $\Delta x < 1$  km will be able to see orography features of the scale  $> 3 - 4$  km. A model with a resolution of 2 - 4 km, which we expect to be operational within a few years from now, will not see orography features smaller than ca. 6 - 15 km. Saying that the “model sees” something means here that the model’s terrain-following vertical coordinate, which is based on the grid-scale mean surface elevation, follows the surface contours of the corresponding scale. Surface forcing of these scales can in principle influence the dynamics of the model. However, implicit and explicit smoothing within the model makes the effective resolution even coarser, maybe  $(7-8)\Delta x$  (Skamarock, 2004).

Also, all relevant orography-related processes are not necessarily correctly described (directly or through parametrizations) by the model equations. Known orography-related problems of the fine-scale models include the formulation of the vertical coordinate, handling of the pressure-gradient term of momentum equations, application of horizontal diffusion for smoothing, performing transformations between spectral and gridpoint representation in the terrain-following coordinates etc. Formulation of all physical parametrizations in independent vertical columns may cause problems in handling non-local subgrid-scale orography effects. Most physical parametrization schemes, for example HIRLAM radiation, surface and turbulence schemes, assume that the model surfaces are truly horizontal. The grid-square mean elevation is often different from the observation station heights, which causes complications for near-surface data assimilation and verification over complex terrain.

Fig. 2 shows a cross-section along northern latitude 46.5 N between longitudes 22 E - 27 E over Carpathian mountains, based on the 3” SRTM data. The blue curve depicts a Fourier-filtered profile, where only features representing orography features larger than 3.3 km have been retained. This is the elevation the finest-resolution (horizontal resolution higher than one kilometre) nonhydrostatic model would base its vertical coordinate on. The difference between the full-resolution data and the blue curve is given in black, and represents the smallest orography scales, whose effects would not be resolved even by the one-kilometre-resolution model. The differences between 10 km and 32 km resolution profiles and the basic 3.3 km curve are shown by the red and green curve, respectively.

Spectrum of surface elevation along 45N

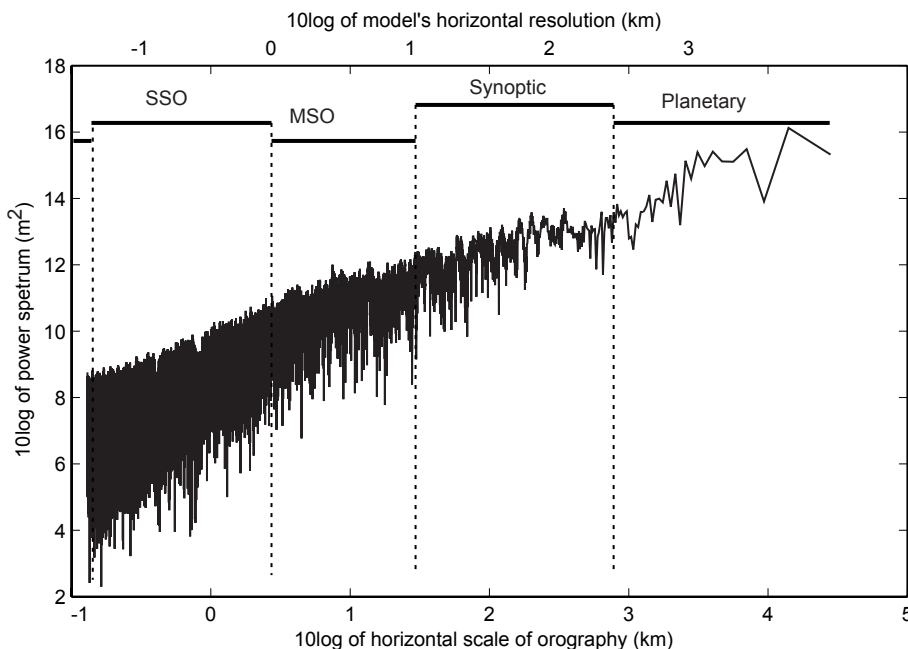


Figure 1: One-dimensional power spectrum of global orography cross-section along the latitude 45 N, based on SRTM data. See text for the details.

Table 1: Some mountain-related atmospheric processes

Scale	Orographic phenomena	Time scale	Horizontal scale	Essential dynamics
Planetary	Planetary waves	Weeks	1000 - 10000 km	barotropic, hydrostatic conservation of absolute vorticity
Synoptic	Cyclo- and frontogenesis Large-scale precipitation Orographic lift	Days	100 - 1000 km	baroclinic quasi-geostrophic, hydrostatic conservation of potential vorticity
Meso	Buoyancy waves and blocking <sup>1</sup> Local (thermal) circulations Orographic convection Fog and low clouds	Hours - Day	1 - 100 km	<sup>1</sup> stable stratification hydrostatic → nonhydrostatic rotating → nonrotating directional effects
Small Micro	Turbulent eddies	Minutes - Hours	100 m - 1 km 10 m	non-hydrostatic non-rotating isotropic

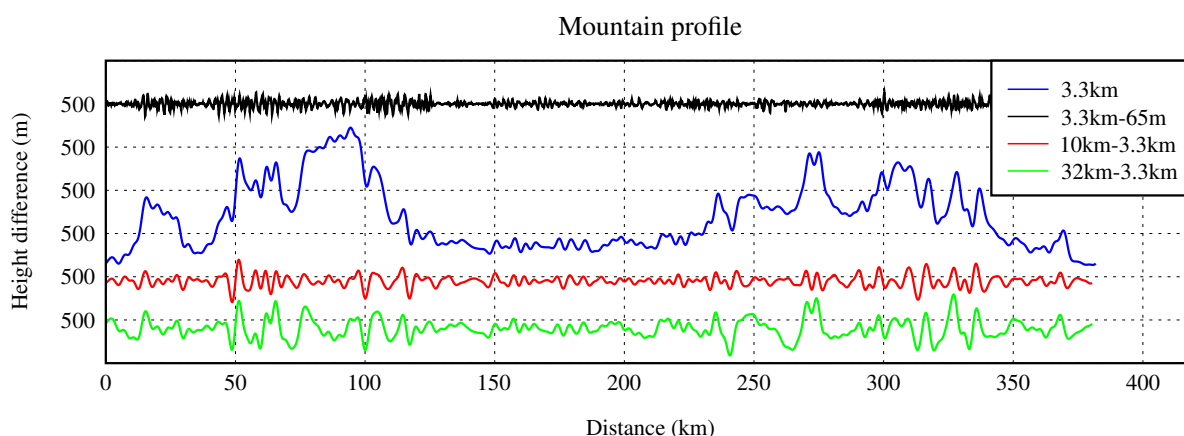


Figure 2: Cross-section along latitude 46.5 N over Carpathian mountains. Blue line: profile with the basic 3.3 km resolution; black, red and green lines: differences between profiles of different resolution. Vertical axis: 500 m between each pair of dashed lines. Curves are located at arbitrary levels. See legend and text for the details.

From the point of view of the atmospheric momentum budget, the effects related to the black curve are suggested to be taken care by the small-scale orography (SSO) parametrizations. These treat the effects as small-scale form drag due to the “orographic turbulence”. No (vertically propagating) buoyancy waves are assumed to exist in these scales. Evidently, the SSO effects remain to be parametrized in NWP models of any resolution. It would not be physically correct to formulate the model’s lower boundary condition so as to force the air to flow along the surface of every small-scale obstacle. However, the upper scale limit of 3 km should be understood as approximate limit of the (turbulent) SSO scale.

The effects related to the scales shown by the red or green lines fall to the category of mesoscale orography (MSO) effects. In the present MSO parametrization schemes, momentum fluxes related to the the mountain-waves (also known as buoyancy waves, gravity waves, lee waves) are considered. Parametrized are (1) the formation, reflection and dissipation of the vertically and horizontally propagating hydrostatic and nonhydrostatic buoyancy waves and (2) blocking of the stable air at the upwind side of mountain ridges and in the valleys. The phenomena of the first group generate orographic gravity-wave drag, the second cause meso-scale form drag on the air flow. The finest-scale nonhydrostatic models will be able to handle explicitly the generation of mountain waves and blocking. The MSO parametrizations are built in a way that their contribution will automatically decrease towards zero when the model resolution grows sufficiently high to resolve generation of the mountain waves. However, dissipation of the resolved waves may not be automatically handled by the turbulence parametrizations of the model.

## 2 MSO and SSO effects on momentum budget

A scale-dependent approach for parametrization of orographic momentum fluxes has been developed and validated during several years, see Rontu et al. (2002); Rontu (2006) and several earlier Newsletter reports (Sigg, Rontu, Sattler in NL37, NL38, NL41, NL44, NL45). It consists of a parametrization of the effects of mesoscale orography (MSO), developed for the Meteo France ARPEGE system (Geleyn et al., 1994); and those of small-scale orography (SSO), based on ideas by Wood et al. (2001). Latest updates and validation of the suggested parametrizations are descibed in detail in NL50 (Rontu et al., 2006).

### 2.1 Parametrizations and parametres

Both the MSO and the SSO parametrization schemes need information about the underlying orography beyond the resolved grid scale of the model. The sub-grid orography properties are represented by a number of parameters supposed to describe the impact of orography from the smallest scales, where the SSO scheme applies, and from the meso-scales, where the MSO scheme is employed. Table 2 lists these parameters.

Table 2: Orography parameters for the MSO/SSO parametrization

parameter	description	unit	usage	orography filter
$s_t$	mean maximum small scale slope	rad	SSO	high-pass
$\sigma_t$	mean small scale standard deviation	J/kg	SSO	high-pass
$\sigma_m$	mean meso scale standard deviation	J/kg	MSO	band-pass
$\alpha$	coefficient of anisotropy	-	MSO	band-pass
$\Theta$	x-angle of orography gradient	rad	MSO	band-pass

Derivation of these parameters in the climate generation system of HIRLAM, the filtering methods and analysis of the spectral properties of the filtered orography were discussed in (Rontu et al., 2006). Fig. 3 shows an example of 2D-orography spectra calculated for different climate generation sub-areas. There are several curves plotted in the same color, each representing one of those HDF-tiles that cover the given continent. The curves over different continents (with the exception of oceanic sub-areas and some of the island tiles) behave remarkably similarly as the spectrum of RCR area shown in Fig. 2 of (Rontu et al., 2006). Differences between the continents show mainly up in absolute power. Over some of the islands (green) and most ocean areas (cyan), the major fraction of the area consists of water. This affects also the shape of the power spectrum.

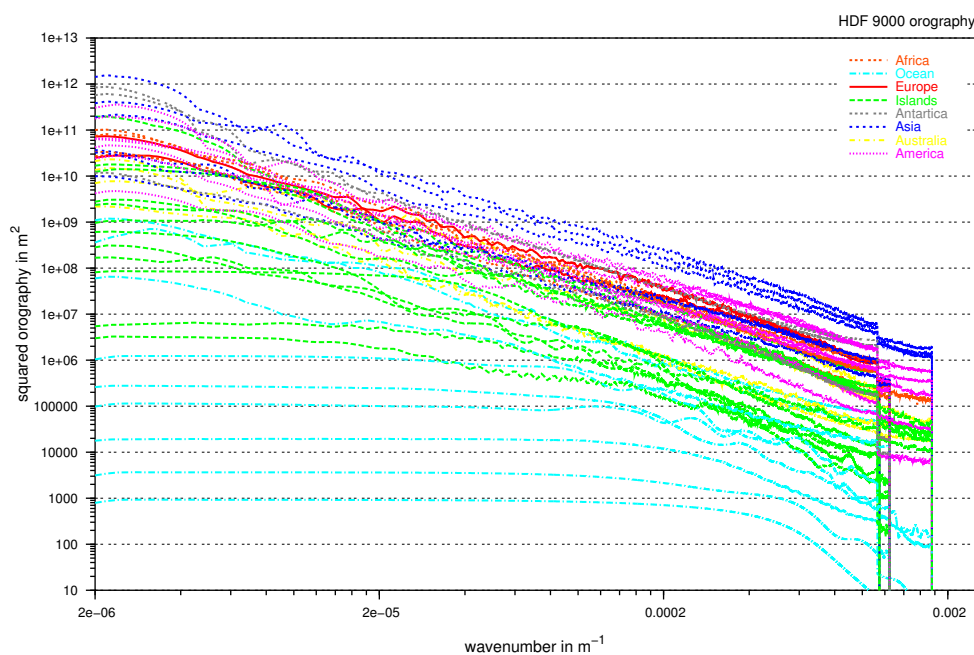


Figure 3: Unsmoothed absolute power spectral density estimations (PSDE) of the height fields processed for the HDF-tiles over different continents in the HIRLAM climate generation system.

The differences in the upper wave number limit in the curves of Fig. 3 are related to differences in metric resolution of the grid, on which the orography data is represented. The grid here is a rotated geographic grid with South Pole position at  $90^\circ$  longitude and  $0^\circ$  latitude, and the mesh sizes in x- and y-direction are not equal.

## 2.2 Norwegian validations

The suggested parametrizations were tested in one-month (11 km resolution) and two-week (4 km resolution) model experiments over Scandinavian mountains. In addition to the standard verification, the ten-metre wind values were compared with the Norwegian observations. A detailed analysis of the results is given in (Rontu et al., 2006), here only an example of the validation results is shown in Fig. 4<sup>1</sup>. Table 3 lists the values of the tunable coefficients of the suboro parametrizations used in these experiments (see Rontu et al. (2002) and Rontu et al. (2006) for details).

Table 3: Coefficients of the MSO-SSO parametrizations

parameter	related to	value
$K_g$	generation of MSO drag	$2.5 \cdot 10^{-6} m^{-1}$
$K_h$	obstacle height for MSO	3
$K_a$	wave resonance	0.6
$K_c$	nondimensional mountain height	3
$K_b$	blocked-flow drag	6.0
$C_o$	generation of SSO drag	100

The experiments NOF (orographic roughness replaced with MSO-SSO parametrizations, 11 km resolution) and SM4 (orographic roughness replaced with MSO-SSO parametrizations, 4 km resolution) are both based on HIRLAM v.6.4.3. They were run over the met.no operational areas. The station Finsevatn is situated at 1222 m elevation in the middle of Southern Norwegian mountains. There (and at other mountain stations), the new MSO-SSO parametrizations are able to produce stronger winds, which are closer to the observations than those of the reference experiment (not shown). The 4 km resolution experiment SM4 tends to be slightly closer to the observations - both in weak and strong wind cases - than the coarser resolution NOF. In the monthly mean statistics of NOF over Norwegian area, a positive wind bias is still prevailing. It has even increased compared to the reference HIRLAM. This systematic error is mainly due to the (increased) overestimation of the weak winds. This feature is possibly related more to the formulation of turbulence parametrizations in and above the surface layer than to the orography-related schemes.

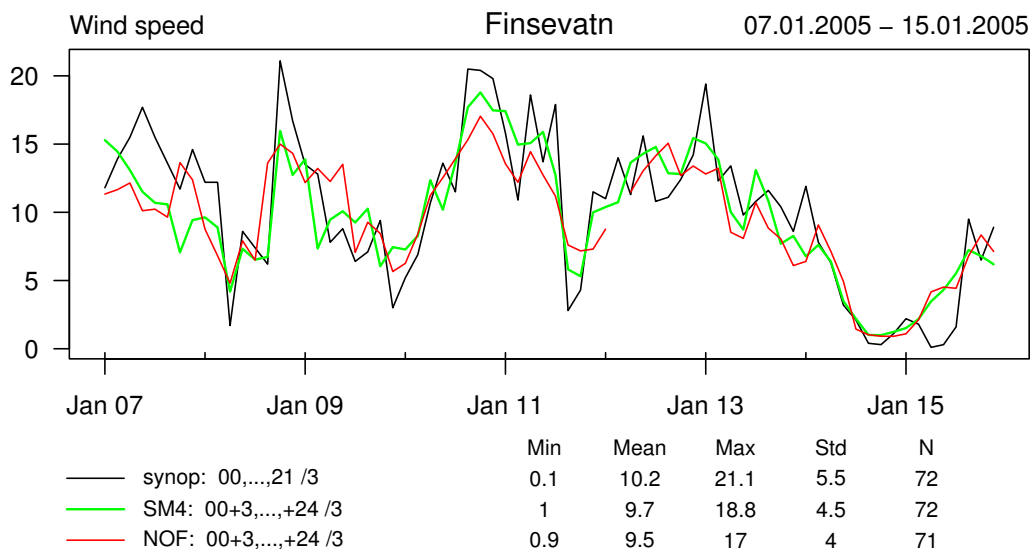


Figure 4: Time series of NOR and NOF experiments compared with wind speed observed at mountain station Finsevatn (01350). See legend for details.

<sup>1</sup>Maps and more time-series of Norwegian comparisons for January 2005 are available at the HIRLAM-ALADIN verification page via the link <http://www.knmi.nl/tijm/Verif/cases/20050108/case20050108.html>

### 3 Orographic effects on radiation

Thermal effects related to orography are due to differential heating of (sloping) surfaces at different elevations. They are mainly driven by differences in solar radiation. Modelling of the orographic effects on surface radiation become more important with increasing resolution. The surface radiation balance in a location at or in the vicinity of mountains is influenced by the local surface elevation, local horizon and by steepness and direction of surrounding slopes. Different heating of the slopes, mountain tops and valleys creates local temperature differences and may influence the local circulations, formation of fog, clouds and precipitation.

#### 3.1 Modified radiation calculations

The aim of a radiation parametrization in a NWP model is to calculate grid-scale air temperature change due to the solar and terrestrial radiation. In addition, it provides components of the surface radiation balance, i.e. the upwelling and downwelling radiation fluxes at the surface. These are used as input for the surface scheme, which calculates the surface energy balance over the different surface subtypes. It returns the grid-averaged albedo, emissivity and surface temperature, which are used as boundary values for calculation of the atmospheric radiation. The atmospheric radiation parametrizations do not directly deal with the subgrid-scale surface properties. In addition to albedo and emissivity, only the grid-scale mean surface elevation is known to the HIRLAM radiation scheme. From the point of view of the radiation parametrization, each grid-square is therefore assumed flat and effectively homogeneous.

The HIRLAM radiation scheme has been enhanced to take into account slope, shadow and sky view effects on surface radiation fluxes (Senkova et al., 2006). Directional fraction of slopes and slope angle in each direction, directional coefficients and the average sky view factor are calculated from one-kilometre-resolution digital elevation data (USGS, 2003) and aggregated to the model grid. At the moment this is done outside of the HIRLAM climate generation system. Time-dependencies of some of the parameters have been converted to direction-dependencies by using the idea of directional fractions.

After introduction of the orographic radiation parametrizations, the radiation calculations at each time step at each HIRLAM grid point will be organized as follows:

1. Use the astronomic formulae to calculate the time-dependent solar height and azimuth angle, based on time, date and position (latitude, longitude). Apply a new subroutine `hlsolar`, where formulation of some astronomic calculations is borrowed from ALADIN (to correct some inaccurate formulations of corresponding the original HIRLAM calculations).
2. Call the main radiation parametrization scheme to calculate the radiative temperature tendencies and fluxes, assuming the surface is flat and homogeneous. To calculate the surface fluxes, grid-square averaged surface elevation, albedo, emissivity and skin temperature from the previous time step are used. Use the subroutine `RADIA` rewritten as `hlradia`, coding and interfaces by Sami Niemelä, 2005.
3. Use the precalculated orography parameters to update the downwelling shortwave and longwave fluxes over the uneven terrain. The updated surface fluxes are not directly used as boundary values for atmospheric radiation calculations (2). Apply a new subroutine `hlororad`, using new orographic parameters, which are transmitted from the climate files.
4. Calculate, before entering the surface scheme, shortwave and longwave net fluxes for each surface subtype, using results of (3) together with the subtype-specific albedo and emissivity values. The net radiation fluxes are transmitted to the surface scheme for calculation of the surface energy balance. Use the old subroutine `RAD2SURF`.
5. After the surface parametrizations, calculate the grid-square averaged albedo, emissivity and skin temperature for the radiation calculations of the next time step. Use the old subroutine `SURF2RAD`.

All updated radiation routines are written in IFS-compatible form in Fortran-90. Only the interface routines between radiation and surface (`RAD2SURF` and `SURF2RAD`) have not been updated and remain in Fortran-77 format.

### 3.2 Effects and problems

Fig. 5 shows a problem. HIRLAM v. 6.4.3 experiments of 3.3 km horizontal resolution were run over Carpathian mountains during the five first days of June, 2000. The experiment RR03 represents the reference HIRLAM and RO03 contains parametrization of orographic effects on radiation. Both experiments used the same modified mean orography, derived from the Hydro1k data set. The two-metre temperatures given by the experiments are compared with observed temperatures at a Romanian high-mountain synoptic station Omu (25.45 E, 45.45 N, WMO number 15280, station elevation 2504 m). In almost all cases there is a systematic difference of 6-10 degrees between the observed and predicted temperatures both during day and night. Introduction of the sloping surface radiation parametrizations does not essentially change the picture: the maximum differences between the experiments are quite small (of the order of one degree).

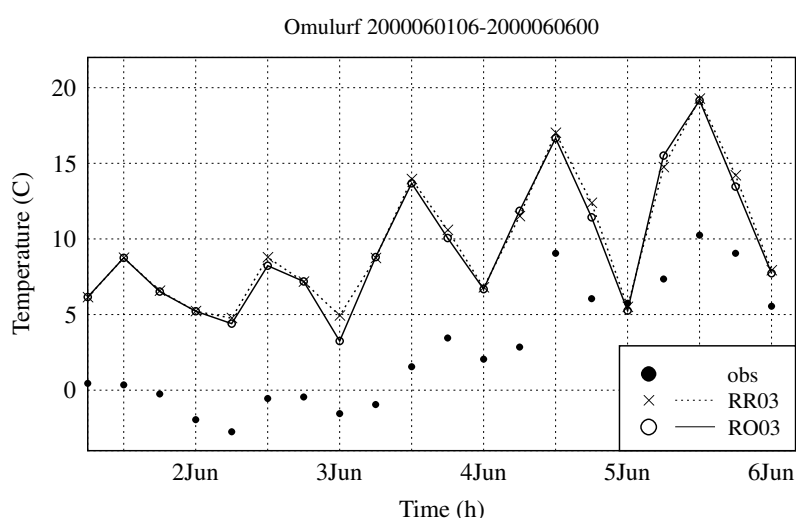


Figure 5: Time-series of observed and predicted by RR03 and RO03 two-metre temperatures at station Omu.

The clue to understanding this discrepancy seems to lie in the fact that the real height of the station is 2504 m above sea level, while the mean height over the corresponding grid-square of the 3.3 km experiments is 1405 m, 1257 m in 11 km experiments. The surface data assimilation system is not able to use the temperature observation of this (and another Carpathian high-mountain station), evidently because of the too large difference between the model's first guess and the observed value, maybe also because the temperature differs too much from those observed at neighbouring (low level) stations. The initial surface temperature of each forecast is already as incorrect as the forecasted values later. In the model there is no mechanism to correct it during the forecast cycle. Thus the observation and gridbox mean value represent totally different environment, even within this high-resolution model setup. This example shows that in the NWP system over the mountains there may be sources of uncertainty which are one order of magnitude larger than possible improvements due to improved parametrization schemes. It also points out the problems of verification over complex orography.

## 4 Outlook

Several practical tasks could be added into the todo-list in development and application of the orography-related parametrizations in HIRLAM, further in the common IFS-AROME system:

### **MSO-SSO-parametrizations and related issues**

Make a switch to choose between the present orographic roughness parametrization and MSO-SSO schemes. Implement the MSO-SSO to a beta-version of HIRLAM. *Ongoing*

Continue testing and comparisons, also in climate mode over Northern America together with the climate version of WRF, where similar MSO-SSO parametrizations are being implemented (Liang et al., 2006).

Combine MSO-SSO with possible improvements in the CBR scheme in stable cases, e.g. using the suggested stability functions by Veniamin Perov et al.

After removal of orographic roughness from HIRLAM, the use and values of the (vegetation) roughness all over in the model and in output should be carefully checked.

### **Orographic radiation parametrizations and related issues**

Implement the Fortran-90 IFS compatible radiation to a beta-HIRLAM, without orographic enhancements but including the updated astronomic calculations and output of diffuse radiation. *Ongoing*

Develop and validate the new orographic radiation parametrizations: simplify and improve the calculation of shadow and sky view factors; try higher resolution source data of orography; run systematic verifications over mountainous areas; report the results.

Calculate the needed orographic parameters within the HIRLAM climate generation system, run final comparisons in the reference system, implement the orographic radiation parametrizations to a beta-HIRLAM.

Combine the renewed radiation parametrizations with the new snow-forest-surface scheme, test the combination.

Plan and perform a common model comparison experiment over mountainous area (Carpathian mountains), with validation against surface temperature and radiation measurements. Models and radiation schemes to be included: HIRLAM, ALADIN, AROME (using ECMWF radiation scheme).

### **Orography-related parametrizations in the IFS framework**

Study methods for climate generation and calculation of the new scale-dependent orographic variables in the IFS framework. Define the relations of the orography-parametrizations to the externalized surface scheme.

Implement the SSO parametrizations to the common framework, to be used instead of the orographic roughness and together with the new version of ALADIN-ARPEGE MSO scheme.

Implement the renewed HIRLAM radiation parametrizations to the common system.

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