

# Derivation of orography-related climate variables for a fine resolution HIRLAM

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*Please note that Figs. 2-6 are available in original coloured format at the web-page version of this report at <http://hirlam.knmi.nl>*

## 1 Introduction

A problem in HIRLAM climate generation system has been the lack of data and methods to derive the finest scale (below the horizontal resolution of ca. 5 km) description of surface properties for experiments and operational use. A simple method to derive orography-related variables and fractions of surface subtypes, based on the data sets GTOPO30" and GLCC, is outlined below.

In HIRLAM, variables derived from the terrain elevation of a digital map, are used

1. for definition of the mean surface height (geopotential) at every grid point, which is used for the definition of the surface pressure for the terrain-following hybrid sigma coordinate of HIRLAM
2. for parametrization of the mesoscale orography effects, i.e. buoyancy waves and low level flow blocking
3. for parametrization of the pressure differences due to the smallest-scale orography, or orographic turbulence
4. in future, e.g. for parametrization of the effects of sloping terrain on the short-wave radiation fluxes at the surface

The source of the renewed calculation of the orography-related parameters is the 1 km  $\times$  1 km resolution Hydro1K elevation derivative database (<http://edcdaac.usgs.gov/gtopo30/hydro/>). These data are derived from the 30 arc second resolution GTOPO30" data. Hydro1K data are represented in an equal area azimuthal Lambert projection. Because of the area-conserving properties of this projection, the data set is well suited for further use in the rotated latitude-longitude coordinate system of HIRLAM. The Hydro1K data, prepared specially for the hydrological use, cover the whole globe excluding Greenland and Antarktis.

The reference HIRLAM system also uses the GTOPO30" data (The, 2002; Undén et al., 2002) but in its original latitude-longitude representation (<http://edcdaac.usgs.gov/gtopo30/gtopo30.html>). In the reference system basic data are interpolated to an intermediate rotated latitude-longitude grid with a maximum resolution of 0.05 x

0.05 deg in Europe and 0.1 x 0.1 deg elsewhere. From these, the climate variables in a HIRLAM experiment grid are derived according the user's definitions. In the present study, no intermediate grid nor any interpolations are applied. Instead, for every (rotated) grid configuration the orography-related parameters are derived directly from the basic one-kilometre resolution data.

Different averaging procedures are applied to the basic data in order to ensure that only the relevant for a particular process orography scales are contributing. It is assumed that only the smallest scales of below ca. 3 km x 3 km horizontal scale contribute to the orographic turbulence. Scales between 3 km and  $2\Delta x$ , where  $\Delta x$  is the model's horizontal resolution, are handled by the parametrization of mesoscale orography effects. Orography scales larger than that are included into the grid-square mean height. The choice of 3 km for the limit between small-scale (turbulent) and mesoscale (wave-related) processes is somewhat arbitrary - in reality flow features such as stability and flow velocity should influence the definition.

## 2 Parameters derived from the digital elevation data

From the basic Hydro1K data, only the terrain elevation  $h$  is used. From it, the following derived variables are calculated at each Hydro1K data point:

$h_9$	average of elevation over the point and its 8 neighbours (metres)
$s_{max}$	maximum small-scale slope based on $h-h_9$ (tangent, unit 0.001)
$p$	flag of peaks (integer code)

The basic Hydro1K data is first averaged so that at every Hydro1K data point an average  $h_9$  over 9 points representing  $h$  of a 3 km x 3 km area is calculated. This calculation includes smoothing due to the overlapping data as the same elevation values are accounted for in several adjacent points which lay 1 km apart from each other. The small-scale maximum slope  $s_{max}$  is the maximum difference of original and smoothed elevation  $h - h_9$  between the point and its 8 neighbours, divided by the distance. The flag of peaks tells if a point has a relative maximum value among 8 neighbouring points (the difference of the elevations  $h$  is larger than 50 m).

These parameters together with the basic elevation  $h$  are written to temporary files in the (unformatted integer) format of the original Hydro1K data. From the preprocessed data, the following variables are calculated for each HIRLAM grid-square of a given resolution. Averages are taken over the area indicated in the right-hand-side column.

### For resolved dynamics

$$H_{2\Delta x} = \frac{1}{N} \sum_{i=1}^N h_{9i}, \quad \text{mean height (metres)} \quad 2\Delta x$$

where  $N$  is the number of Hydro1K data points within a HIRLAM grid square  $2\Delta x \times 2\Delta y$  (see below).

### For orographic turbulence

$z_{0,oro}$	orographic roughness (metres)	$\Delta x$
$s_t$	averaged maximum slope $s_{max}$ (tangent)	$\Delta x$
$\sigma_t$	smallest scale standard deviation (metres)	$\Delta x$

### For mesoscale orography parametrization

$\sigma_m$	standard deviation of mesoscale orography (metres)	$2\Delta x$
$\alpha$	anisotropy of the mesoscale orography (0...1)	$2\Delta x$
$\theta$	angle between mesoscale ridges and model's x-axis (rad)	$2\Delta x$

The data handling procedures are illustrated in Fig. 1. Averaged variables are calculated at a HIRLAM grid point centered at  $(\lambda_{HI}, \phi_{HI})$  and represent the area of  $\Delta x \times \Delta y$ , except the mean height and the MSO parameters, which are averaged over an area  $2\Delta x \times 2\Delta y$ . The original and preprocessed Hydro1K data lay at points regular in the Lambert coordinate system.

The Hydro1K data points inside a square, defined in the rotated latitude-longitude coordinates of HIRLAM, are sought using the conversion from Lambert to regular and regular to rotated coordinates and vice versa. Standard HIRLAM tools are used for conversion between regular and rotated latitude-longitude coordinates. Conversion formulae between the Lambert and regular coordinates can be found in literature (e.g. Snyder (1987)). They are, from geographical  $(\lambda, \phi)$  to Lambert  $(x, y)$  coordinates,

$$x = k' \cos\phi \sin(\lambda - \lambda_0) \quad (1)$$

$$y = k' (\cos\phi_1 \sin\phi - \sin\phi_1 \cos\phi \cos(\lambda - \lambda_0)), \quad (2)$$

where  $\lambda_0$  and  $\phi_1$  are the latitude and longitude of the origin and

$$k' = a \sqrt{\frac{2}{1 + \sin\phi_1 \sin\phi + \cos\phi_1 \cos\phi \cos(\lambda - \lambda_0)}}, \quad (3)$$

where  $a$  is the radius of the sphere of influence (Earth), and the inverse transformation from Lambert to geographical coordinates,

$$\phi = \arcsin(\cos\gamma \sin\phi_1 + \frac{y \sin\gamma \cos\phi_1}{\rho}) \quad (4)$$

$$\lambda = \lambda_0 + \arctan\left(\frac{x \sin\gamma}{\rho \cos\phi_1 \cos\gamma - y \sin\phi_1 \sin\gamma}\right), \quad (5)$$

where  $\rho = \frac{\sqrt{x^2 + y^2}}{a}$  and  $\gamma = 2 \arcsin \frac{\rho}{2}$ .

Note that no interpolations are needed. The conversions are done in order to find and collect all Hydro1K data points inside the needed area in HIRLAM coordinates. In the following, calculation of the variables listed above is described in more detail.

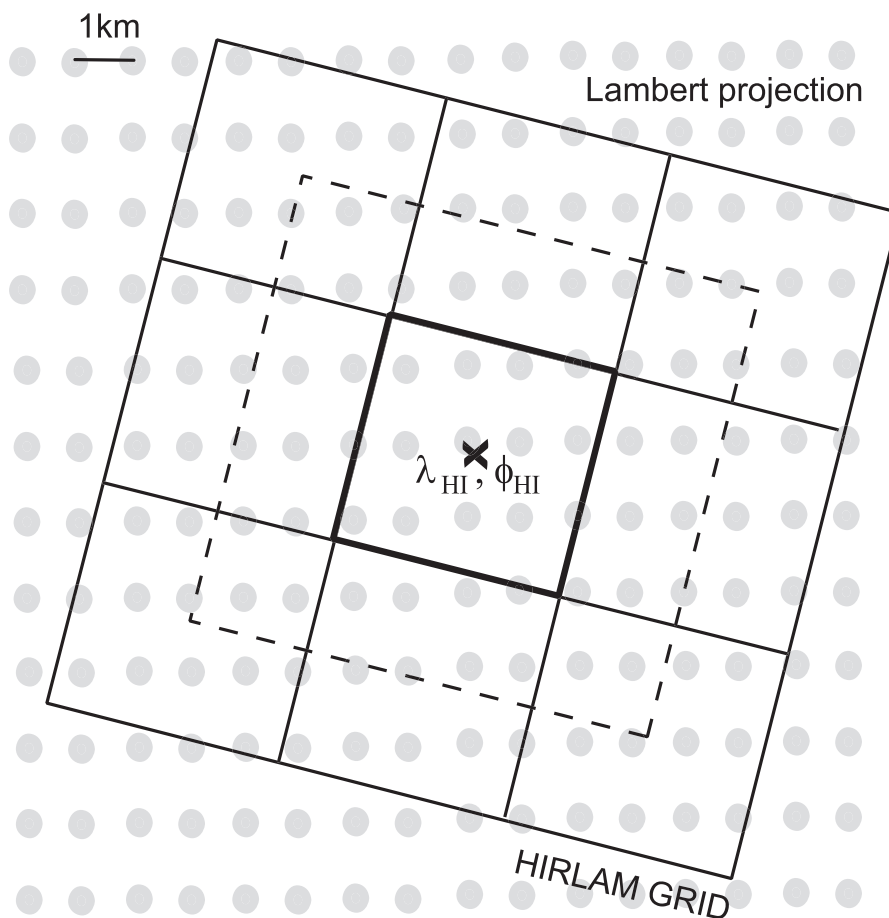


Figure 1: Derivation of variables from Hydro1K digital elevation data to HIRLAM grid. The grey balls represent a Hydro1K data square of  $1 \text{ km} \times 1 \text{ km}$ , containing the original and derived elevation data. The innermost square represents a HIRLAM grid-square centered at  $\lambda_{HI}, \phi_{HI}$ . Its center is marked with a cross and the length of its sides is  $\Delta x = \Delta y$ . The square with dashed sides represents an area  $2\Delta x \times 2\Delta y$ . The HIRLAM coordinates may be rotated with respect to the Lambert equal area azimuthal grid of Hydro1K.

### 3 Mean elevation

The **mean elevation**  $\mathbf{H}_{2\Delta x}$  is calculated for every HIRLAM grid-square based on values of  $h_9$  at all Hydro1K data points whose center falls inside the square of  $2\Delta x \times 2\Delta y$  (see Fig. 1). Thus the smallest scale features are already smoothed and should not be visible in the mean values. Averaging over  $2\Delta x$  excludes also the mesoscale variations. These would not be explicitly represented by the model and could cause problems for the semi-Lagrangian integration scheme of HIRLAM.

The mean elevation maps over Iceland given by the reference HIRLAM and the present method are compared in Fig. 2. Only the maps with horizontal resolution of 0.025 deg (2.8 km) are shown. The reference HIRLAM system applies a Raymond filter, while in the present calculations no additional filtering is used. The data of the reference HIRLAM is interpolated

from the 0.05 deg (5.6 km) resolution. In this case the present method reveals somewhat more organized fine scale patterns. The averaged over the whole area height is almost identical.

The mean elevation profiles and related wave components over a transection in Northern Iceland are depicted in Fig. 3 (Fig. 2 shows the line of the transection). The profiles are related to different model resolutions, as given by the reference HIRLAM climate generation system and the present method. It is seen that in both cases there are wave components also at and beyond the  $2\Delta x$  limit but their contribution to the total variance is small. Two-dimensional spectral decomposition might give more information about the possible small-scale noise than this illustration using one (arbitrary) mountain profile.

The role of the small-scale wave components is smaller in the present calculations than in the reference system in all but the highest resolution (with  $\Delta x$  of 0.025 deg) cases. One could argue that taking averages over, say  $3\Delta x$  (and not  $2\Delta x$  as here), might produce smoother and more reasonable highest resolution mean elevation field when applied to the Hydro1K data. With the present method, any desired approximation could easily be chosen, based on further model experiments.

## 4 Variables for orographic turbulence parametrization

The classical parameter for orographic turbulence calculation is the **orographic roughness length**  $z_{0,oro}$ . In the reference HIRLAM, this parameter is calculated as proposed by (Sattler, 1999). The description below is borrowed from Undén et al. (2002):

First an unscaled isotropic sub-grid orographic roughness length  $z_{0,oro,unsc}$  is determined on basis of the grid-dependent variance  $\sigma_{so,A}^2$ . It refers to the area  $A$  of the respective model grid square, and uses a modified formulation, which goes back to Tibaldi and Geleyn (1981):

$$z_{0,oro,unsc} = \frac{1}{2} \sqrt{\frac{n_p + 0.001}{A}} \sigma_{so,A}^2, \quad (6)$$

where  $n_p$  is the number of relative height maxima (peaks) within the grid square. The final sub-grid orographic roughness is then scaled as

$$z_{0,oro} = a (z_{0,oro,unsc})^B, \quad (7)$$

where the empirical parameters are  $a = 0.4038$  and  $B = 0.715$ . The final roughness field is filtered with a 4<sup>th</sup>-order Gaussian filter in order to avoid possible sources for  $2\Delta x$ -noise. With this approach, all obstacles with a scale smaller than the size of the model's grid-square contribute to the orographic roughness.

In the present study,  $z_{0,oro}$  is calculated according to these formulae but using the Hydro1K elevation  $h$  and peaks  $p$  when calculating the subgrid-scale variance and number of relative height maxima. The final roughness field is not filtered.

An example of the calculated  $z_{0,oro}$  with the the horizontal resolutions of  $\Delta x=0.025$  and 0.1 deg is shown in Fig. 4. Here, the difference between the reference HIRLAM and the present calculation is also shown. In this case, the values of orographic roughness given by the reference HIRLAM are quite independent of the model's resolution. This is because the basic orography resolution is about 5 km  $\times$  5 km. Based on this roughness represents obstacles of relative large scale. Use of the fine resolution elevation data leads to significantly smaller values which decrease with increasing resolution.

The scale dependence of the newly calculated orographic roughness is due to two reasons: 1) with decreasing resolution more scales become unresolved and included into the subgrid-scale variance, 2) with increasing grid-square size there may be more subareas with different elevations leading to different variance. As we expect only the smallest scales of orography to contribute to the orographic turbulence, only the second reason, presumably of minor importance, is physically relevant here.

It could be concluded, that the orographic roughness  $z_{0,oro}$ , at least as defined here, is not a useful parameter in the framework of fine-resolution modelling. However, its newly calculated values are included to facilitate comparison with the other approaches developed for parametrization of the orographic stress.

The difference between the original ( $h$ ) and mean ( $h_g$ ) elevation values is used when calculating slope and standard deviation of orography height for the renewed orographic turbulence parametrizations. The deviation at the point  $i$ ,

$$h'_i = h_i - h_{g_i} \quad (8)$$

contains only the smallest-scale features. The maximum slope  $s_{max}$  is calculated using the difference of  $h'_i$  between the point  $i$  and its 8 neighbours. The maximum slope values are averaged over a HIRLAM grid-square to get the **averaged maximum slope**  $s_t$  to be used in a parametrization of orographic turbulence based on Wood et al. (2001). Another possible parameter for calculation of orographic turbulence, the **smallest-scale orography variance**  $\sigma_t$  over a HIRLAM grid-square was also determined based on  $h'_i$  values.

The values of  $s_t$  and  $\sigma_t$  are illustrated in Fig. 5. General features of these parameters are similar to each other but the field of standard deviation looks out somewhat smoother. There is also a resemblance between these variables and  $z_{0,oro}$  shown in Fig. 4. However, the (minor) scale-dependence of  $s_t$  and  $\sigma_t$  is only due to the different areas included into averages, as only the smallest-scale orography features are contributing independently of the model resolution.

In principle, definition of the direction of slopes and ridges would be possible based on the Hydro1K data. Here, when calculating the variables describing the smallest-scale orography variations, no effects of obstacle shape or direction were taken into account. This is because the smallest-scale features are considered to be isotropic enough for the model calculations.

## 5 Mesoscale orography variables

Mesoscale orography variables should represent the orography scales between those resolved by the model dynamics and those included in the parametrization of the smallest-scale orography. Thus, their values are derived from the difference of the averaged values  $h_g - H_{2\Delta x}$  (see Fig. 1). For each grid-point they are calculated over the area  $2\Delta x \times 2\Delta y$ . After these averaging operations, no further filtering of the MSO variables is applied.

The basic variable for the Arpege-HIRLAM mesoscale orography (MSO) parametrization scheme (Rontu et al., 2002) is the **standard deviation of mesoscale orography**  $\sigma_m$ . The two other MSO parameters are the **anisotropy**  $\alpha$  and the **angle**  $\theta$  between model's x-axis and the principal axis (direction of maximum gradient) of the mesoscale orography. All three variables are calculated using the formulae explained in Rontu et al. (2002) but using the differences  $h_g - H_{2\Delta x}$  instead of the filtered source elevation. If the model's resolution is fine enough (horizontal scale less than ca.  $5 \text{ km} \times 5 \text{ km}$ ), the anisotropy and angle are given constant values

because the shape and direction are believed to play a minor role in the smallest scales close to those of orographic turbulence. In practice, the calculation of these parameters would become complicated when the amount of source data decreases.

An example of the calculated MSO parameters is shown in Fig. 6. Over Iceland a typical maximum value of the  $\sigma_m$  is about 600 m. This can be compared to the values of  $\sigma_t$  (Fig. 5) that are typically almost one order of magnitude smaller. Thus the mesoscale mountains influence the momentum fluxes at several levels in the lower troposphere whereas the effects of the smallest scale obstacles are restricted to a few lowermost model levels. The parameters  $\theta$  and  $\alpha$  describing direction and shape of the mesoscale mountains vary quite a lot in this resolution. Evidently, these parameters would contain more systematic features and be more important in the scales of climate models, where whole mountain systems are treated as subgrid-scale obstacles.

A **mesoscale slope parameter** (Lott and Miller, 1997) could also be derived from the present data. However, at the moment slope is not used by the HIRLAM MSO scheme and is thus not included into the present set of mesoscale orography parameters. (Its calculation from intermediate source data is already possible using the tools of the reference HIRLAM climate generation system, see The (2002)).

## 6 Land cover characteristics

The methods used when processing the Hydro1K data were also applied for definition of the surface subtype fractions for the HIRLAM ISBA surface parametrization scheme. The fractions were derived from the Global Land Cover Characteristics database (GLCC version 2, <http://edcdaac.usgs.gov/glcc/glcc.html>), that is also available in the Lambert azimuthal equal area projection. In the present (preliminary) study the 96 classes of Global Ecosystems table were directly combined into the five surface types of HIRLAM (water, ice, bare land, low vegetation, forest). Fractions inside every HIRLAM grid-square were then calculated. In addition, fractions of lake and urban areas were determined. The definitions used are first approximations that still need refinement and rethinking.

## 7 Open questions

More studies and careful analysis are needed to develop further the methods outlined here. Possible improvements depend on the source data available and methods applied but also on the requirements of the parametrization schemes. To answer the questions both analysis of the data and model experiments are needed. Among others, the following topics would require attention:

- How to improve the simple filtering methods suggested in this study? A more systematic study of the spectral properties of the source orography and the resulting HIRLAM fields for different model resolutions should be performed. Would a final smoothing with a Raymond-type filter improve the fields produced using the simple approximations?
- Where in the model goes the boundary between turbulence and wave processes and how does this influence in the derivation of the parameters from digital elevation data?

- What is the role of shape and direction of the obstacles in the parametrizations of orographic turbulence and mesoscale orography effects in the model with different resolutions, and how important is the definition of these parameters?

## 8 Technical notes

In practice, the following data and software were used for preparation of the fine-scale-updated climate files for a HIRLAM experiment:

1. Hydro1K data from <http://edcdaac.usgs.gov/gtopo30/hydro/>. Note that these data are not being developed for Greenland and Antarktis.
2. GLCC data in a Lambert projection from <http://edcdaac.usgs.gov/glcc/glcc.html>
3. FORTRAN-77 programmes hydroplus.f and glccplus.f to preprocess Hydro1K and GLCC data and write the derived parameters to files in the format of the original data
4. A HIRLAM reference system climate GRIB file cl00nn0000 prepared for the experiment area
5. FORTRAN-77 programme hydro2hir.f to calculate the needed variables in HIRLAM grid and write them, together with the unmodified climate files read from the input climate file, to an output climate file cl00nn0000.o
6. A script Run\_h2h to launch the programme (5) and to link the reference HIRLAM sub-routines for handling GRIB files.

Note that

- HIRLAM climate variables originating in other sources than GTOPO30” and GLCC (soil type, soil temperature and moisture, sea ice cover, albedo, snow cover etc.) were not modified during this study.
- GTOPO30” and GLCC data are divided into geographical blocks with optimal Lambert coordinate parameters. In the present study, data over Europe only was used. Combination of data from several data blocks would require some additional coding.
- The amounts of data used in this study are not difficult to handle in any modern home, office or computing centre environment. For example, the European Hydro1K elevation data in compressed format uses about 22 MB of disk space. The present computations were made interactively at the Finnish IBM supercomputing environment.
- The programmes and scripts have not yet been made universal or user-friendly, nor are they a part of the climate generating system of HIRLAM - rather some experimental tools for further discussion and development towards the reference system have been prepared.

## Acknowledgements

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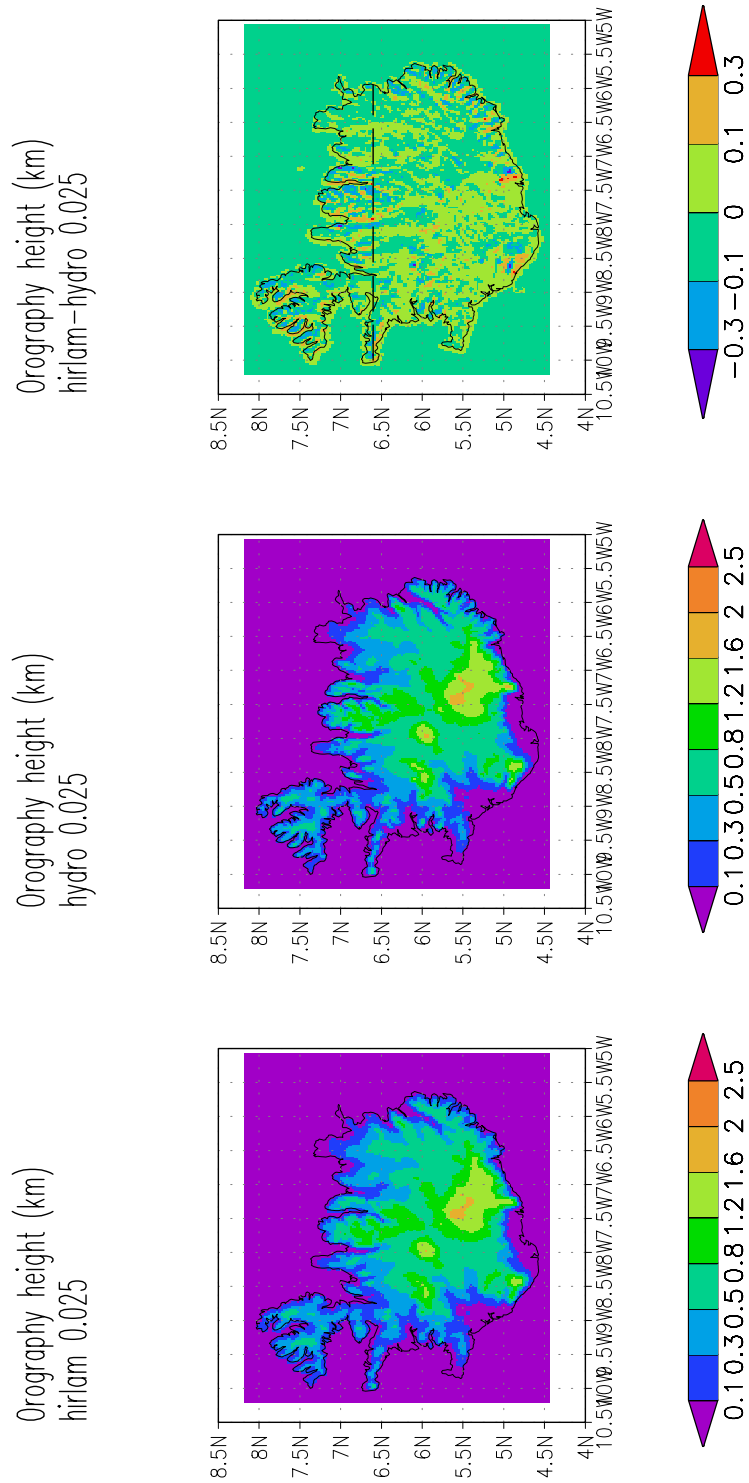


Figure 2: Mean elevation (km) over Iceland: HIRLAM reference (left), Hydro1K-based (middle) and their difference (right). The dashed line (left) shows the transection along rotated latitude 6.6N, used in Fig. 3

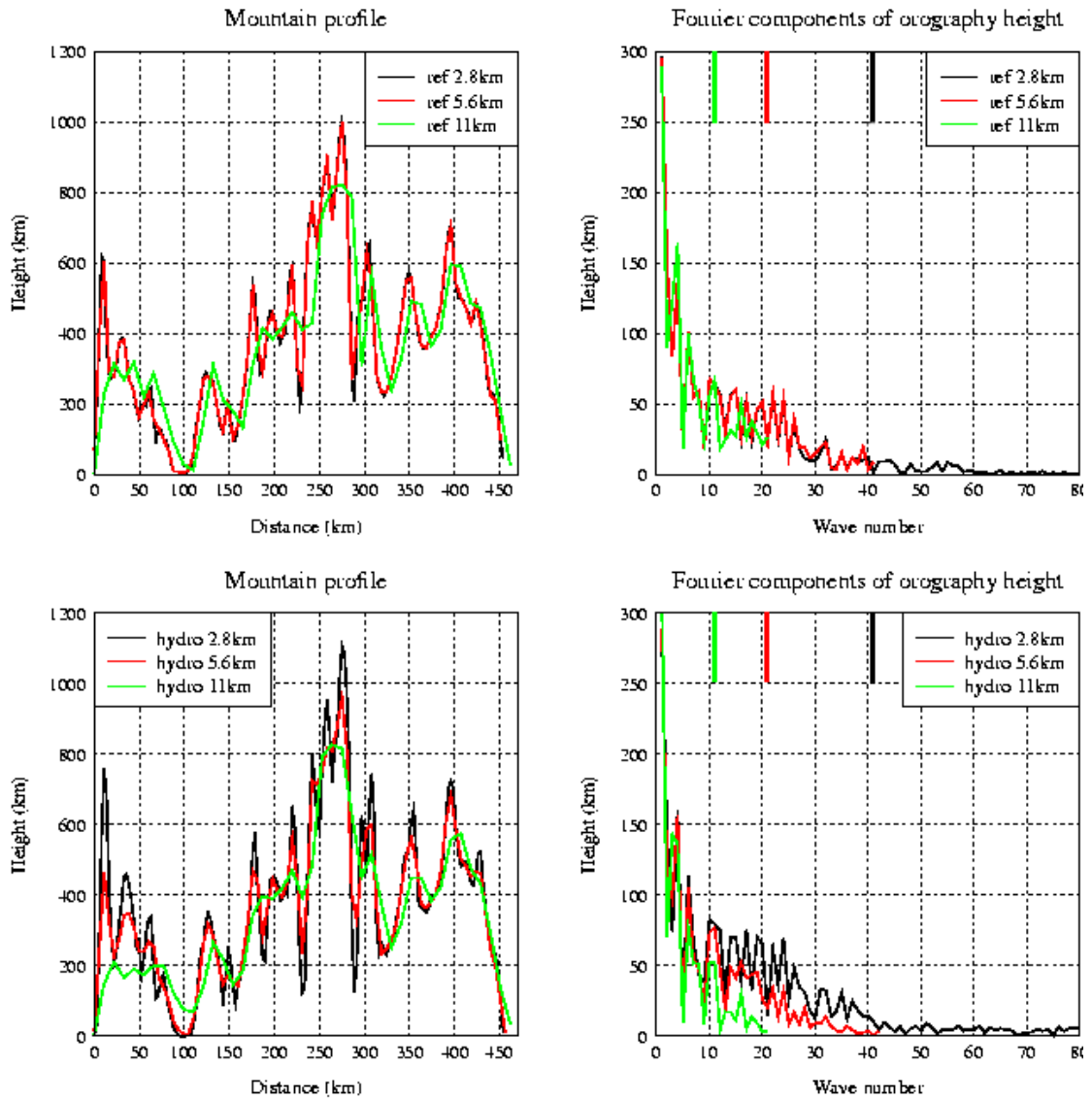


Figure 3: Mountain profile along the rotated latitude  $6.6N$  (metres, left; see map in Fig. 2) and wave components given by a Fourier-decomposition (metres, right). Upper panel: HIRLAM reference, lower panel: Hydro1K-based data. Three different lines in each figure refer to different model resolutions, see inserted legends. Three coloured ticks at the upper x-axis of the Fourier-decomposition figures show the wave numbers of the  $2\Delta x$  scale for each resolution.

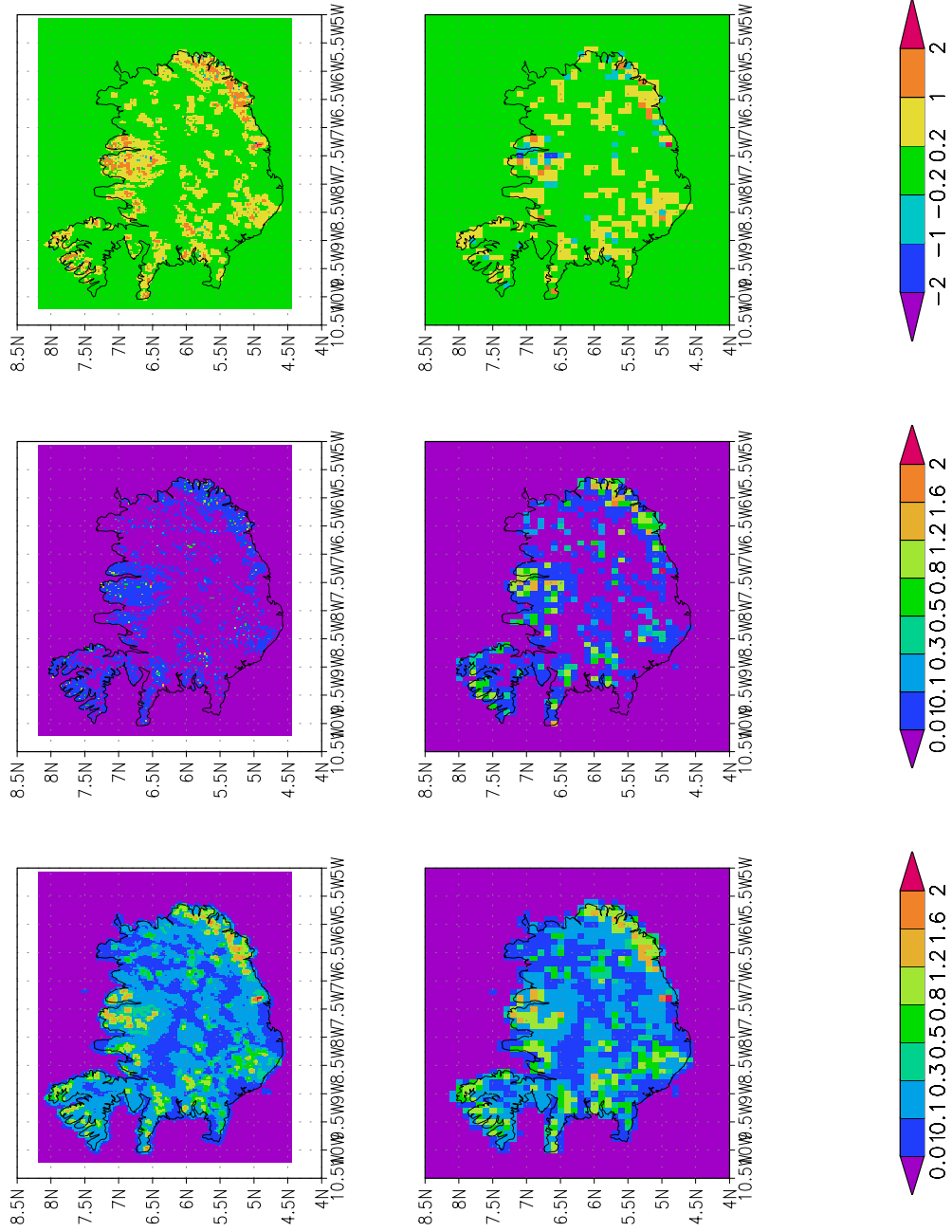


Figure 4: Orographic roughness (m): *HIRLAM* reference (left), *Hydro1K*-based (middle) and their difference (right) for horizontal resolutions of 0.025 deg (upper panel) and 0.1 deg (lower panel).

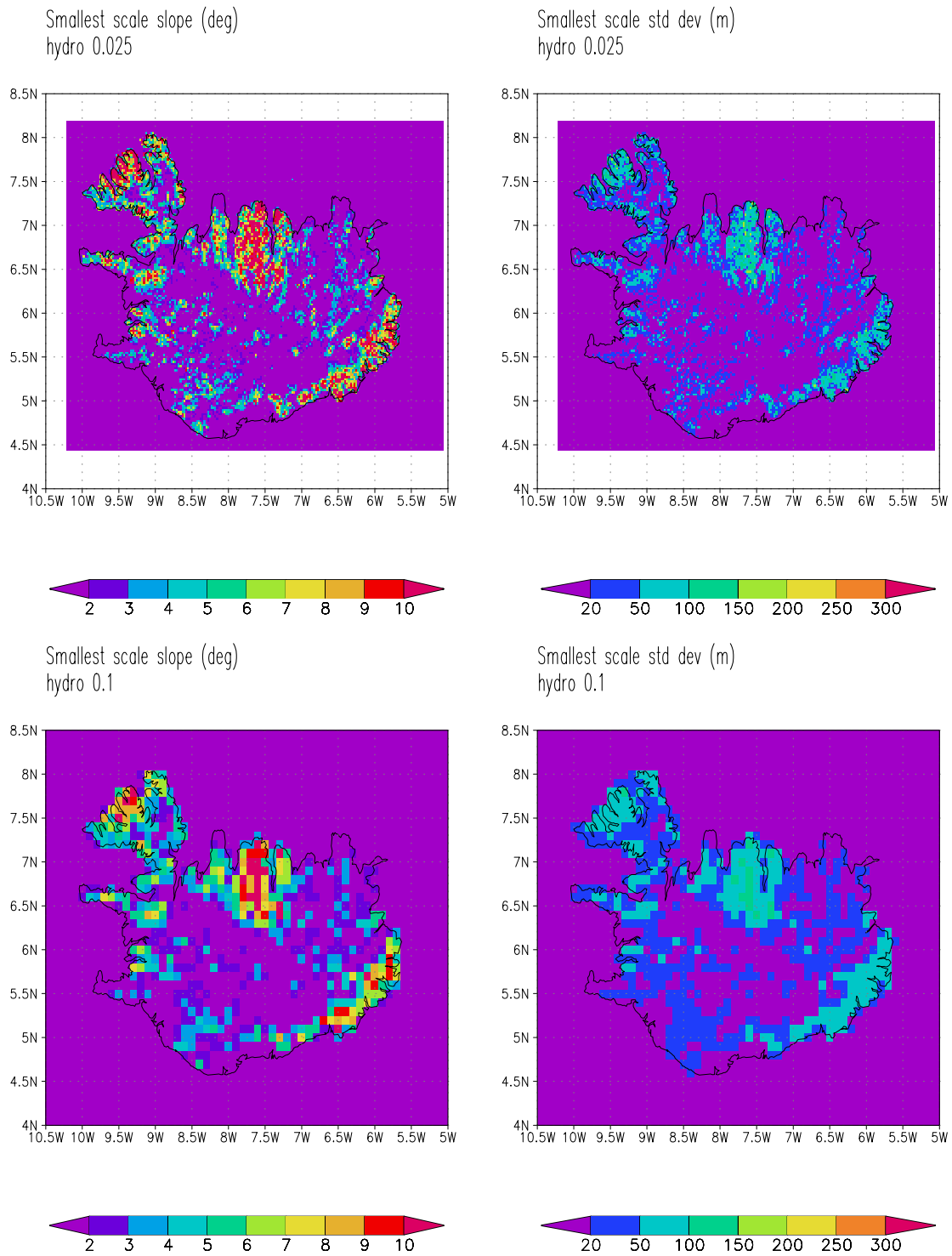


Figure 5: Variables for parametrization of orographic turbulence: averaged maximum slope  $s_{max}$  (degrees, left) and smallest scale standard deviation  $\sigma_t$  (metres, right) for horizontal resolutions of 2.8 km (upper panel) and 11 km (lower panel).

Mesoscale orography std dev (km)  
hydro 0.1

Mesoscale orography x-angle (deg)  
hydro 0.1

Mesoscale orography anisotropy  
hydro 0.1

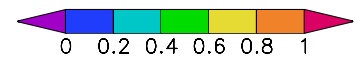
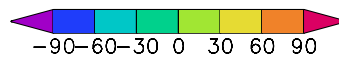
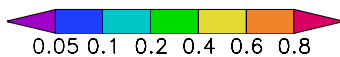
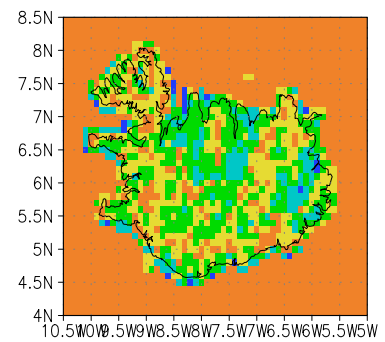
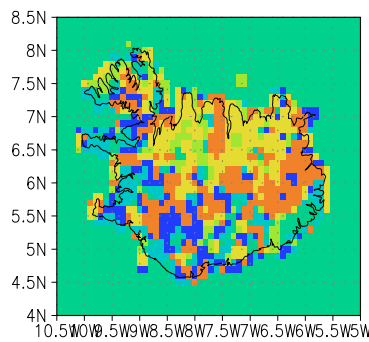
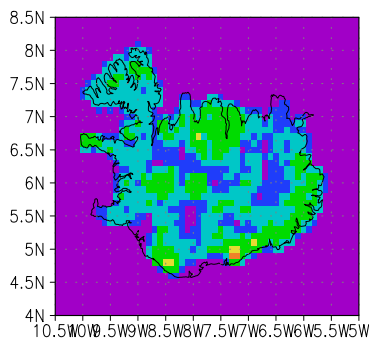


Figure 6: Variables for mesoscale orography parametrization: standard deviation of mesoscale orography  $\sigma_m$  (km), angle  $\theta$  (degrees) and anisotropy  $\alpha$  ( $0 \dots 1$ , where 0 denotes a circular mountain and 1 a two-dimensional ridge). In this example the horizontal resolution of the model grid is 11 km.