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STUDIES ON OROGRAPHIC EFFECTS IN A NUMERICAL WEATHER PREDICTION MODEL

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Abstract

Numerical models, used for atmospheric research, weather prediction and climate simulation, describe the state of the atmosphere over the heterogeneous surface of the Earth. Several fundamental properties of atmospheric models depend on orography, i.e. on the average elevation of land over a model area. The higher is the models' resolution, the more the details of orography directly influence the simulated atmospheric processes. This sets new requirements for the accuracy of the model formulations with respect to the spatially varying orography.

Orography is always averaged, representing the surface elevation within the horizontal resolution of the model. In order to remove the smallest scales and steepest slopes, the continuous spectrum of orography is normally filtered (truncated) even more, typically beyond a few gridlengths of the model. This means, that in the numerical weather prediction (NWP) models, there will always be subgrid-scale orography effects, which cannot be explicitly resolved by numerical integration of the basic equations, but require parametrization. In the subgrid-scale, different physical processes contribute in different scales. The parametrized processes interact with the resolved-scale processes and with each other.

This study contributes to building of a consistent, scale-dependent system of orography-related parametrizations for the High Resolution Limited Area Model (HIRLAM). The system comprises schemes for handling the effects of mesoscale (MSO) and small-scale (SSO) orographic effects on the simulated flow and a scheme of orographic effects on the surface-level radiation fluxes. Representation of orography, scale-dependencies of the simulated processes and interactions between the parametrized and resolved processes are discussed. From the high-resolution digital elevation data, orographic parameters are derived for both momentum and radiation flux parametrizations. Tools for diagnostics and validation are developed and presented.

The parametrization schemes applied, developed and validated in this study, are currently being implemented into the reference version of HIRLAM.

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Tutkimuksia vuoristojen vaikutuksesta numeerisissa säämalleissa

Tiivistelmä

Ilmakehätutkimukseen sekä sään ja ilmaston ennustamiseen käytettävät numeeriset mallit kuvaavat ilmakehän tilaa maapallon vaihtelevien pinnanmuotojen yllä. Monet mallin perusominaisuuksista riippuvat orografiasta eli maanpinnan korkeuden kuvauksesta. Mitä tarkempi on mallin erotuskyky, sitä pienemmät orografian yksityiskohdat vaikuttavat mallinnettuihin ilmakehän ominaisuuksiin. Tämä asettaa uusia vaatimuksia sille, miten malli käsittelee orografiatietoa.

Orografia on aina keskiarvo, joka kuvaa pinnan korkeutta mallin erotuskyvyn puitteissa. Mallin perusyhtälöt eivät pysty suoraan käsittelemään kaikkia orografian yksityiskohtia. Siksi muutamaa mallin hilaväliä pienemmät piirteet tavallisesti suodatetaan pois. Numeeriseen säänennustusmalliin jää aina alihilaisen orografian aiheuttamia ilmiöitä, jotka pitää kuvata parametrisoimalla, t.s. perusyhtälöiden lähde- ja nielutermien avulla. Alihilaiset piirteet ovat erikokoisia ja niiden fysikaaliset ominaisuudet erilaisia. Parametrisoidut ilmiöt vuorovaikuttavat toistensa ja mallissa suoraan kuvattujen ilmiöiden kanssa.

Tässä tutkimuksessa on kehitetty mallin erotuskyvyn ja orografian koon huomioonottavaa pinnanmuotovaikutusten parametrisointijärjestelmää pohjoismaista HIRLAM-säänennustusmallia (High Resolution Limited Area Model) varten. Järjestelmä koostuu meso- ja pienimittaisen orogafian vaikutusten parametrisoinnista mallin liikeyhtälöissä sekä maanpinnan tason lyhyt- ja pitkäaaltosäteilyvoiden parametrisoinnista lämpötilayhtälössä. Työssä käsitellään orografian kuvausta, mallinnuksen skaalariippuvuuksia sekä prosessien vuorovaikutuksia. Mallin orografiasuureet johdetaan tarkasta digitaalisesta karttatiedosta sekä liikemäärän että säteilyvoiden laskentaa varten Työssä kehitellään myös menetelmiä mallitulosten todentamista ja analysointia varten.

Työssä kehiteltyjä, sovellettuja ja arvioituja menetelmiä otetaan parhaillaan päivittäiseen ennustuskäyttöön HIRLAM-mallissa.

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Lisätietoja

Studies on orographic effects in a numerical weather prediction model

Laura Rontu

This work is dedicated to the memory of my parents

Sirkku and Helge Rontu

PREFACE

I have been working with mountain-related effects in atmosphere for years, without writing too many journal papers or finishing my dissertation. This is not because of the lack of support, advice and friendly pushing by colleagues, supervisors and friends. On the opposite: now, when this dissertation is composed, at last, I am deeply indebted to all of you for the invaluable support and cooperation that has made its appearance possible.

My first supervisor, Prof. Eero Holopainen from University of Helsinki (UH) educated the whole generation of 1980'ies meteorologists with the art of atmospheric diagnostics, that has been extremely useful during all these years. My second supervisor, Dr. Valentin Kozhevnikov from Moscow University, introduced me to the world of mountains and mesoscale modelling. In the early 1990'ies, my colleagues Kalle Eerola, Simo Järvenoja and Peter Lönnberg guided my first steps in modelling with HIRLAM (High Resolution Limited Area Model) at the Finnish Meteorological Institute (FMI). Somewhat later, our HIRLAM colleague Bent Hansen Sass (Danish Meteorological Institute, DMI) suggested application of the mountain knowledge from Moscow in HIRLAM. With the implementation of Mèteo France gravity-wave parametrization scheme in 2000'ies, I have learned from Prof. Jean-Francois Geleyn (Mèteo France, MF). My thanks are due to colleagues and co-authors in the mountain studies: Robert Sigg (Swedish Meteorological and Hydrological Institute, Swedish Defence Research Agency), Eric Bazile (MF), Anastasia Senkova (Russian State Hydrometeorological University) and Mariken Homleid (Norwegian Meteorological Institute). Special thanks are due to Kai Sattler (DMI), whose name never occurred first in our common reports, but who is the master in filtering and processing the different scales of the earth's orography.

During these years, Prof. Hannu Savijärvi (UH) and Dr. Carl Fortelius (FMI) have always been ready to comment and discuss the problems of modelling and diagnostics, helping with their advice and sharing ideas and tools. Thanks to HIRLAM colleagues and leaders of the international HIRLAM programme for applying the results of my studies, thus giving the meaning to this work. My thanks are due to FMI and its Meteorological research, Dr. Juhani Damski, Profs. Mikko Alestalo and Yrjö Viisanen, for providing an excellent working environment and all kinds of support. Thanks to all colleagues and friends in Finland and abroad - I have not forgotten you, simply the list of your names would not fit to this page.

I am grateful for the valuable and encouraging comments, made by the pre-reviewers of this thesis, Prof. Christoph Schär (ETH Zürich) and Dr. Martin Miller (European Centre for Medium Range Weather Forecasts). I am looking forward for the critical comments by Prof. Branko Grisogono (Zagreb University), who has agreed to be the opponent in the defence of this thesis.

Last but not least, thanks to my family: Anatoli and our daughters Natalia and Helena, for support and taking good care of themselves while mum has been busy with mountains and HIRLAM, and not only during the regular office hours.

Helsinki, the 15th of September 2007

Laura Rontu

Contents

LIST OF ORIGINAL PUBLICATIONS

This thesis consists of an introductory review followed by four research articles. The papers are reproduced with the permission of the journals concerned.

I Rontu L., K. Sattler and R. Sigg (2002): Parametrization of subgrid-scale orography effects in HIRLAM. *HIRLAM Technical report*, 56, 46 pp.

II Rontu L. (2006): A study on parametrization of orography-related momentum fluxes in a synoptic-scale NWP model. *Tellus*, **58A**, 68-81.

III Senkova A. S., L. Rontu and H. Savijärvi H. (2007): Parametrization of orographic effects on surface radiation in HIRLAM. *Tellus* **59A**, 279-291.

IV Rontu L. (2006): Vorticity budget over mountains diagnosed from HIRLAM analyses and forecasts. *Meteor. Z.*, **15**, 199-206.

1 INTRODUCTION

Numerical models, used for atmospheric research, weather prediction and climate simulation, describe the state of the atmosphere over the heterogeneous surface of the Earth. Several fundamental properties of atmospheric models depend on orography, i.e. on the average elevation of land over a model area. The higher the models' resolution, the more the details of orography directly influence the simulated atmospheric processes. This sets new requirements for the accuracy of the model formulations with respect to the spatially varying orography.

Orography is always averaged, representing the surface elevation within the horizontal resolution of the model. In order to remove the smallest scales and steepest slopes, the continuous spectrum of orography is normally filtered (truncated) even more, typically beyond a few gridlengths of the model. This means that in the numerical weather prediction (NWP) models there will always be subgrid-scale orography effects, which cannot explicitly be resolved by numerical integration of the basic equations, but require parametrization. On the subgrid-scale, different physical processes contribute on different scales. The parametrized processes interact with the resolved-scale processes and with each other. In the present-day NWP models, orography-related parametrization schemes represent buoyancy waves, turbulence and also differential heating of slopes due to radiation. They influence three-dimensional momentum fluxes and surface radiation fluxes.

The objective of this thesis is to develop and apply methods for handling the orographic effects in a NWP model. The main attention is paid to parametrization of subgrid-scale momentum fluxes, related to waves and turbulence, in the High Resolution Limited Area Model (HIRLAM, Undén et al. [2002]). Representation of orography, scale-dependencies of the simulated processes and interactions between the parametrized and resolved processes are discussed. From high-resolution digital elevation data, orographic parameters are derived for both momentum and radiation parametrizations. Tools for diagnostics and validation are developed and presented.

This introductory review is organized as follows. Ch. 2 introduces the scales of orography, related atmospheric processes and their representation in a NWP model. Ch. 3 discusses some aspects of modelling the airflow over resolved and unresolved orography. The next two chapters (Ch. 4 and Ch. 5) concentrate on parametrization of subgrid-scale momentum and radiation fluxes. Derivation of variables, required by the parametrization schemes, from high-resolution orography data is presented in Ch. 6 while Ch. 7 is devoted to methods of diagnostics and validation. Ch. 8 summarizes the main results of this thesis.

Throughout the review, references will be made also to HIRLAM newsletters and workshop reports, which are not peer-reviewed publications. However, they contain material essential to the present thesis and are all available for readers in electronic form, as detailed in the list of references.

2 SCALES OF OROGRAPHY AND MODEL

2.1 SCALES OF OROGRAPHY AND ATMOSPHERIC PROCESSES

Fig. 2.1 represents a profile of the Earth's surface elevation around the globe (180°W ... 180°E) along the 45th northern latitude (45°N), based on Shuttle Radar Topography Mission Elevation (SRTM) three arc-second (3" $\approx$ 65 m at 45°N) horizontal resolution data (Rodriguez et al. [2005], see Ch. 6.2 of this review for details). This profile contains 432 000 data points. Oceans and main mountain systems of the Earth can be seen in the picture (along with gaps, eventually representing still existing deficiencies of the data set). However, this kind of raw profile is not very informative. A better insight may be acquired from a spectral analysis of the data.

The corresponding orography spectrum, i.e. variance of surface height as a function of horizontal scale, is shown in Fig. 2.2. Atmospheric processes related to the different scales of orography variation may be classified to the planetary (O(1000-10000 km)), synoptic (O(100-1000 km), meso (MSO, O(10 km) and small (SSO, O(1 km)) scales. It is evident that the main part of the orography variance falls under the planetary and synoptic scales. Orographic effects related to these scales are expected to be the most important for the global weather and climate. However, there is variance in all scales, without significant gaps in the spectrum, till the maximum resolution covered by the data set. The small- and mesoscale orography variations may have large influence on the local weather and climate.

The upper horizontal scale of Fig. 2.2 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 in weather forecasting within a few years from now, will not see orography features smaller than ca. 6 - 15 km. Saying that the "model sees" 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 scales larger than this 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)Δx [Skamarock, 2004]. Resolution and smoothing will be discussed in detail in Chs. 3.2 and 6.3.

An attempt to summarize typical orography-related atmospheric processes of different scales is made in Table 2.1. NWP and climate models are expected to handle correctly processes related to all scales of underlying topography. In the coarse-resolution global, hemispheric and regional models the subgrid-scale processes are parametrized in different ways. In the fine-resolution local models, a large part of the local effects is explicitly resolved, while the planetary and synoptic scale effects enter through the domain boundaries from large-scale host models (large-scale closure, see Laprise [2003]. The smallest-scale turbulent effects require parametrization in all models (small-scale

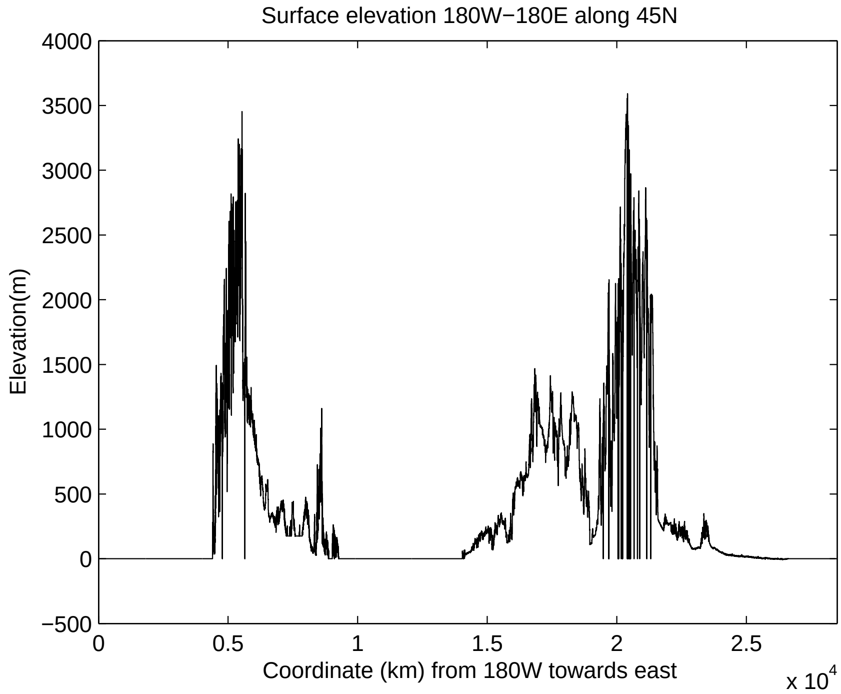

FIGURE 2.1. Surface elevation along the latitude 45° N, based on SRTM 3" data.

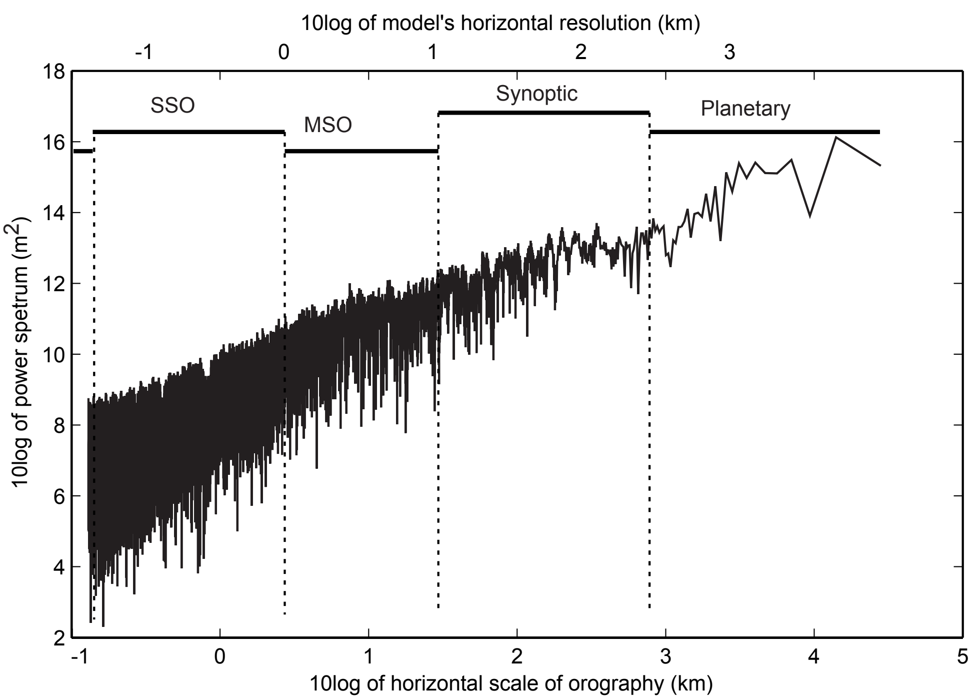

FIGURE 2.2. One-dimensional power spectrum of global orography cross-section along the latitude 45° N, based on STRM 3" data.

closure).

2.2 Resolved and parametrized flow

The equation of horizontal hydrostatic motion in a pressure-based, terrain-following hybrid vertical ζ-coordinate system [Simmons and Burridge, 1981] is written, following Kasahara [1974]:

$$\frac{\partial \vec{v}}{\partial t} = -\vec{v} \cdot \nabla_\zeta \vec{v} - \dot{\zeta}\frac{\partial \vec{v}}{\partial \zeta} - \frac{1}{\rho}\nabla_\zeta p - \nabla_\zeta \Phi - f\vec{k} \times \vec{v} - \frac{g}{p_s}\frac{\partial \vec{\tau}}{\partial \zeta}, \tag{2.1}$$

where $\vec{v}$ is the horizontal wind, $\dot{\zeta}$ is the generalized vertical velocity $\dot{\zeta} = \frac{\mathrm{d}\zeta}{\mathrm{dt}}$, ∇_ζ is the gradient operator applied along the constant ζ-surface, $\vec{k}$ is the unit vector in direction of $\vec{g}$, g is acceleration due to gravity, $\Phi = gz$ is geopotential, ρ is density of air, p is pressure and p_s surface pressure. The terms of Eq. 2.1 describe, from left to right, the local tendency (change in time) of the horizontal wind, horizontal advection, vertical advection, two components of the pressure gradient term, Coriolis term and vertical divergence of the subgrid-scale vertical momentum fluxes. $\vec{\tau} = -\rho\overline{\vec{v}' w'}$ is the stress vector related to the subgrid-scale vertical momentum fluxes; w is the geometric vertical velocity, an overline denotes gridbox average and a prime $'$ subgrid-scale deviation.

On the other hand, the tendencies of the horizontal wind $\frac{\partial \vec{v}(x,y,z)}{\partial t}$ given by a NWP model can be divided to contributions from explicitly resolved dynamics and physical parametrizations of subgrid-scale processes:

$$\frac{\partial \vec{v}}{\partial t} = (\frac{\partial \vec{v}}{\partial t})_d + (\frac{\partial \vec{v}}{\partial t})_p \tag{2.2}$$

where the indexes d and p refer to dynamics and parametrized physics. The dynamical tendency now contains the terms describing advection, pressure gradient and Coriolis forces. In addition, it is influenced by the accuracy of the numerical schemes, smoothing, boundary relaxation, interpolations etc. The parametrized tendency can be represented as a sum of momentum fluxes due to different subgrid-scale processes,

$$(\frac{\partial \vec{v}}{\partial t})_p = -\frac{g}{p_s}\frac{\partial \vec{\tau}}{\partial \zeta}, \qquad \vec{\tau} = -\sum_{j=1}^{n} \rho(\overline{\vec{v}' w'})_j \tag{2.3}$$

where the three-dimensional vector $\vec{\tau}(x, y, z)$ is the sum of momentum fluxes due to n different physical processes, denoted here by the index j. Eqs. 2.2 and 2.3 are useful for development of parametrizations and also for model diagnostics, which are discussed in Chs. 4 and 7.

Table 2.1 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[1] Local (thermal) circulations Orographic convection Fog and low clouds	Hours - Day	1 - 100 km	[1]stable stratification hydrostatic $\longrightarrow$ nonhydrostatic rotating $\longrightarrow$ nonrotating directional effects
Small Micro	Turbulent eddies	Minutes - Hours	100 m - 1 km 10 m	non-hydrostatic non-rotating isotropic

3 MODELLING THE FLOW OVER OROGRAPHY

3.1 RESOLVED-SCALE OROGRAPHIC EFFECTS

In the following, a short review of issues related to the modelling of the resolved-scale orography is presented. These problems require increasing attention when the model's resolution grows higher. This review intends to provide a background to the rest of this thesis, which will concentrate on the parametrized processes only.

VERTICAL COORDINATE AND LOWER BOUNDARY CONDITION. The basic hydrodynamic equations of the atmospheric models are generally formulated in some kind of a terrain-following coordinate system, based on the surface pressure or surface elevation [Phillips, 1957; Kasahara, 1974; Gal-Chen and Somerville, 1975; Simmons and Burridge, 1981; Mesinger et al., 1988; Konor and Arakawa, 1997; Gallus and Klemp, 2000; Schär et al., 2002; Steppeler et al., 2002]. These coordinate systems have been developed to enable an accurate formulation of the models' lower boundary condition, allowing the air to flow smoothly along the uneven surface. On the other hand, it is desirable that the influence in the atmospheric dynamics of the terrain details would decrease when the distance from the surface increases. Depending on the numerical methods applied for solution of the basic equations, several problems arise in connection to the terrain-following coordinate systems. For example, the problems related to the formulation of the momentum equation in the widely used (also in HIRLAM) pressure-based hybrid (η) coordinate are well known: the single pressure gradient term of the geometric coordinate system is split into the compensating terms of pressure and geopotential gradients, requiring careful numerical treatment over steep orography. This is especially the case when applying semi-lagrangian, semi-implicit time integration schemes within spectral models. Here, a nonlinear orography term, including multiplication of surface geopotential gradient with the near-surface wind, complicates the solution of momentum equations.

LATERAL BOUNDARY CONDITIONS. Formulation of the lateral boundary conditions for the limited area models is a subject of intensive discussion and development, see e.g. McDonald [2005] and references therein. The problem is demanding even over the flat surface. Nesting of models over mountainous domain leads to additional practical problems of horizontal and vertical interpolation between grids of different resolution. In HIRLAM, a method adapted from the Canadian MC2 model [Benoit et al., 1997] is applied to rearrange the standard boundary relaxation and that of the orography fields [McDonald, 2003; Järvenoja, 2003b,a].

UPPER BOUNDARY CONDITION. Formulation of models' upper boundary condition is indirectly related to the orography. Mountains represent the main source of vertically propagating atmospheric buoyancy (gravity) waves. Buoyancy waves, created by the air flow over mountains, propagate upwards carrying momentum and kinetic energy and may reflect from the physical or artificial discontinuities of the model. The upper boundary condition should be formulated so that unphysical reflections from the top of the model domain are minimized. The radiative upper boundary condition (RUBC) was first suggested by Bougeault [1983] and Klemp and Durran [1983]. Formulation of a true RUBC for a NWP model is a complicated task, depending crucially on the formulation of the basic equations and numerical methods of solution. Gassmann and Herzog [2007] report about the implementation of a RUBC within the split-explicit numerical scheme of Lokal-Modell (German Weather Service). In practice, solutions using some kind of dissipative (sponge) layer in the upper part of the model domain, are generally applied instead of the RUBC. The sponge layer should damp all waves approaching the top of the model domain. In HIRLAM, such a layer is created by enhanced horizontal diffusion, otherwise used for filtering of the the shortest and fastest buoyancy waves (noise) during the model integration [Undén et al., 2002].

HORIZONTAL DIFFUSION. NWP models apply different methods of smoothing in order to maintain the kinetic energy balance, reduce noise and control the non-linear instability during the model integration. In addition to the smoothing inherent to the (semi-lagrangian, semi-implicit) numerical schemes, higher-order horizontal diffusion schemes are commonly used. Formulation of the horizontal diffusion over steep orography requires special consideration, in order to avoid smoothing of meteorologically significant vertical gradients. Solutions for different types of fine-scale models have been suggested by Zängl [2002] and Vaña et al. [2007]. When the model's horizontal and vertical resolution increases, formulation of the horizontal diffusion ceases to be a purely numerical problem. In this case, turbulence should be treated as three-dimensional, especially in conditions of strong static stability or strong wind. Three-dimensionality creates a new aspect in the interactions between the physical parametrizations and resolved dynamics.

FILTERING OF OROGRAPHY, INITIAL AND BOUNDARY DATA. To avoid problems and noise due to the initial and boundary conditions, filtering the model's surface elevation, initial and boundary data is often applied to damp the features of smallest temporal and spatial scale. In HIRLAM, after the data-assimilation step, a (temporal) digital filter is used [Huang and Yang, 2002]. A digital filter might be applied also to the boundary data. In order to remove orography features of horizontal scales smaller than about two gridlengths, a Raymond filter [Raymond, 1988] is used in HIRLAM.

DATA ASSIMILATION. At the observation sites, the real surface elevation differs from the averaged model orography. This influences the use of (surface-based) observations in data assimilation and also the verification of forecasts. In the upper air and surface data assimilation, the three-dimensional statistical structure of the observation and background (forecast) errors depends on orography.

3.2 A CARPATHIAN EXAMPLE

Terrain-following coordinate systems have been used in the atmospheric models already for about fifty years. As shown by Kasahara [1974], any single-valued monotonic

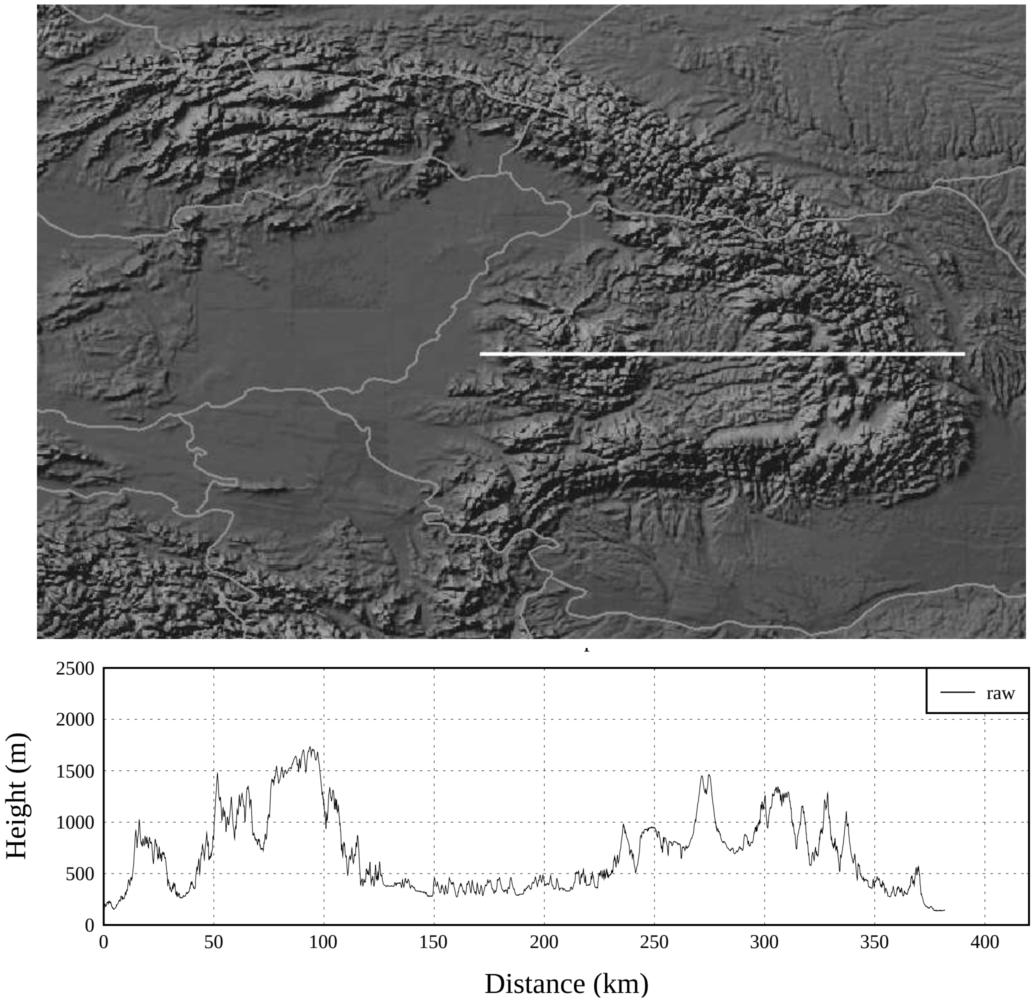

FIGURE 3.1. Topographic map of Carpathian mountains and cross-section along the latitude 46.5 °N (light line). The cross-section is based on 3” SRTM data (see text for details).

function of geometric height can be used as coordinate variable. It is also generally assumed that both the earth’s surface and model top are coordinate surfaces. In practice, solution of the equations requires sufficient smoothness of the coordinate surfaces.

A profile of surface elevation along the latitude 46.5 °N over the Carpathian mountains is shown in Fig. 3.1. The original 3” SRTM data has been thinned, by picking every 20th point, to a resolution of 1 arc minute, corresponding to a resolution of ca. 1.3 km at this latitude. Quite many details and possibly some noise are seen in the resulting profile. The vertical coordinate based on these raw data would evidently not fulfil a requirement of smoothness. Using such a coordinate in a high-resolution atmospheric model would most probably create numerical noise and problems by introducing too steep slopes.

To avoid these problems, most (high-resolution) models apply smoothing of sur-

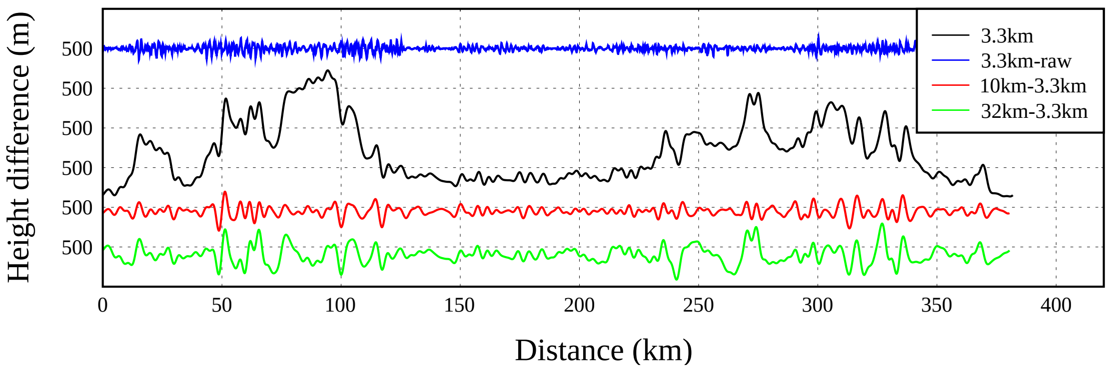

FIGURE 3.2. *The basic curve (black) represents the profile where scales smaller than 3.3 km have been filtered out. The blue curve shows the difference between the 3.3 km and raw data profiles. Difference between the basic and 10 km (32 km) profile is shown in red (green). The horizontal resolution of the x-axis is 1 arc minute (ca. 1.3 km). Scale of the vertical axis: 500 m between the ticks, distances between the profiles are arbitrary.*

face elevation. To illustrate the possible effects of smoothing, we now perform one-dimensional spectral filtering of the Carpathian profile (Fig. 3.2). The basic smoothed profile represents orography scales larger than about 3.3 km. The differences between the basic curve and those representing the raw and smoothed to 10 km and 32 km resolution data are shown. The highest-resolution models, which would be able to handle the filtered profiles, would be approximately of 1 km, 3 km and 10 km horizontal resolution, respectively, assuming that a NWP model is unable to explicitly resolve orography scales smaller than a few gridlengths.

We continue by building a hypothetic vertical coordinate both on the raw data and smoothed profiles. The level heights z_i shown in Fig. 3.3 are defined analogously to the pressure-based hybrid coordinate of HIRLAM as $z_i = A(z) + B(z)z_s$, where A(z) and B(z) are constants at each level and z_s is the surface elevation. The coefficients are defined so that there are more levels closer to the surface than in the upper atmosphere and that the levels approach to constant elevation surfaces in the upper atmosphere. Note that in Fig. 3.3 only a section of the whole profile is shown.

Intuitively, one could expect the vertical coordinate based on the smoothed mountain profiles to be computationally more reliable than that based on the highly variable highest-resolution orography data. The problem is now, that in the smoothed profiles we have filtered out all the details shown by the difference curves of Fig. 3.2. Thus our fine-scale model, perhaps of kilometre-resolution, would only be able to represent explicitly effects due to the orography scales of several kilometres and larger. In principle, the smallest-scale orographic effects may influence the large-scale flow (e.g. momentum flux and related drag due to the buoyancy waves or flow blocking), or only the local weather (e.g. strong downslope winds related to the large-amplitude buoyancy waves). The former are important in the models of any resolution and should be prop-

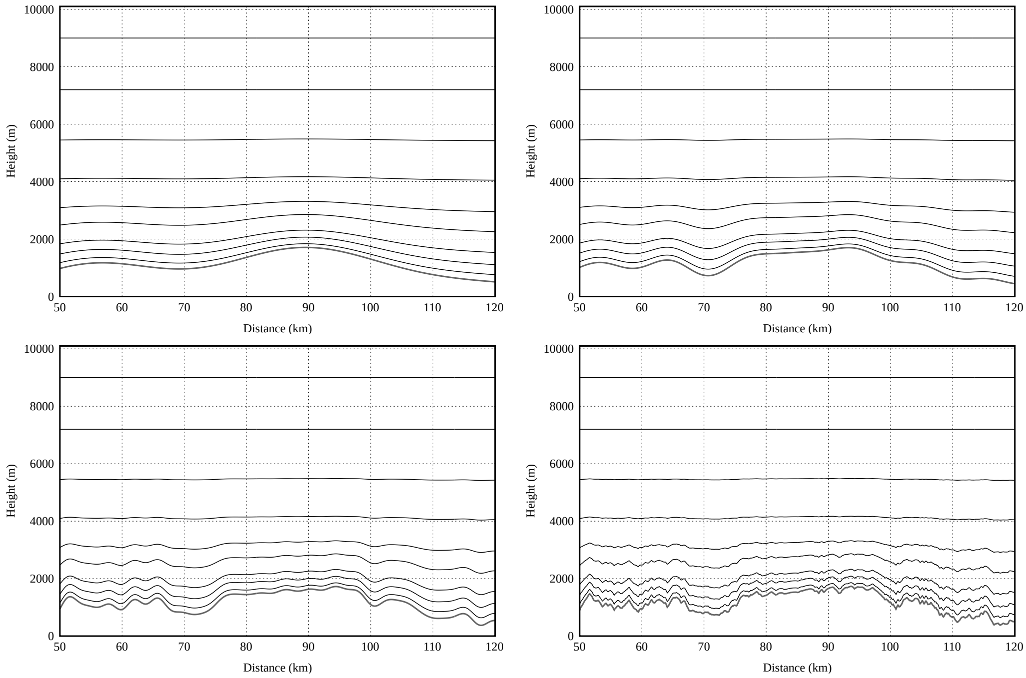

FIGURE 3.3. Hypothetic vertical coordinate based on Carpathian profiles (smoothing to the resolution of 32 km, 10 km, 3.3m and raw data, see Fig. 3.2). A section from 50 km to 120 km of the profile in Fig. 3.1 is shown.

erly parametrized. The highest resolution models are expected to represent correctly also the latter. To analyse the possible effects of the details of orography on the airflow, we will now use the Carpathian profiles as input for a two-dimensional, semi-analytic nonhydrostatic mountain wave model.

3.3 A FINITE-AMPLITUDE MOUNTAIN WAVE MODEL

The finite-amplitude mountain wave model [Rontu, 1986] is of so-called Long-type [Long, 1953, 1955], but with a radiative upper boundary condition. In the model, the adiabatic and frictionless equations for the Boussinesq flow are combined to a single, mathematically linear Helmholtz-equation for the streamfunction, without making conventional assumptions of infinitesimality of the obstacle. As shown by Smith [1977], nonlinear interactions in the atmospheric flow disappear because of the assumed stationary and constant in height upstream velocity. In two-dimensional domain, a semi-analytic solution of the equations is obtained from the free-slip lower boundary condition. In the horizontal direction, disturbances are assumed to disappear far upstream and downstream from the obstacle. In practice, an integral equation is solved at the lower boundary to define the stream function in the whole domain, as suggested by Raymond [1977]. The horizontal and vertical wind components and the surface drag along the profile are derived from the streamfunction, using finite differences. There may be from one to three layers of different stability in the model; only one is used in the present study.

The main advantage of this kind of model - compared to the classical mountain-wave solutions over linearised bell-shaped mountains - is in the possibility to obtain simple wave solutions for the flow over any mountain profile. The solution contains also the shortest nonhydrostatic waves. Because of its basic assumptions, implying absence of wave breaking and transient effects, the model ceases to give results directly comparable to observations when the nondimensional mountain height G_h (also referred to as inverse Froude number, see below) grows significantly larger than unity, i.e. in the high-drag (blocked-flow) regime. The solution method requires that the lowest streamline follows the mountain profile exactly, thus excluding the possibility of explicit calculation of the blocking effects. Thus, the model can indicate the onset of blocking and wave breaking but not handle the (time-dependent) evolution of these phenomena.

Fig. 3.4 shows the streamlines given by this model over the smoothed Carpathian profiles in a moderately high-drag situation with G_h = Nh_m/U, $\approx$ 1.2, based on maximum mountain height h_m = 1.7 km, upstream wind velocity U = 15 ms^{-1} and stability defined by buoyancy (Brunt-Väisälä) frequency N = 0.012 s^{-1}. In all cases, the horizontal and vertical resolution used in calculation of the functions, needed for the semi-analytic solution, are 1.3 km and 50 m, respectively.

The main features of the flow are similar over the different profiles. Wave amplification and overturning over the main ridges and flow acceleration over the lee slopes are observed in all cases. The higher is the orography resolution, the more details are seen in the solution. Fig. 3.5 depicts the near-surface wind relative to the constant upstream wind, V_s/U. Local wind maxima and minima are enhanced over steep slopes, which remain unresolved in the coarse resolution case. However, the mean values of wind components (u and w, not shown) averaged over the whole domain do not change with changing orography resolution. This suggests that in a NWP model, smoothing of the underlying orography could locally decelerate the strong winds and accelerate the weaker ones. In high-resolution models, compensating this decrease of amplitude by some kind of parametrization might be complicated, and has eventually not yet been tried.

Dependency of the calculated buoyancy-wave drag on the resolution of the mountain profile is summarized in Table 3.1. Results for both a high-drag (G_h>1) and a low-drag (G_h<1) case are shown. It can be seen that in the high-drag case the total drag increases about 50 % when the orography resolution increases from 32 km to 3.3 km. The difference between the drag over the raw profile (1.3 km) and the highest-resolution smoothed profile (3.3 km) is insignificant. In the low-drag case, the drag increase with improving resolution is smaller. Here also the linear estimate of the drag ($D_{lin} = \rho N U h_m^2/a$, where h_m is the difference between minimum and maximum elevation along the transection of length a) is closer to the value given by the model, although the former remains smaller than the latter. The results indicate that smoothing

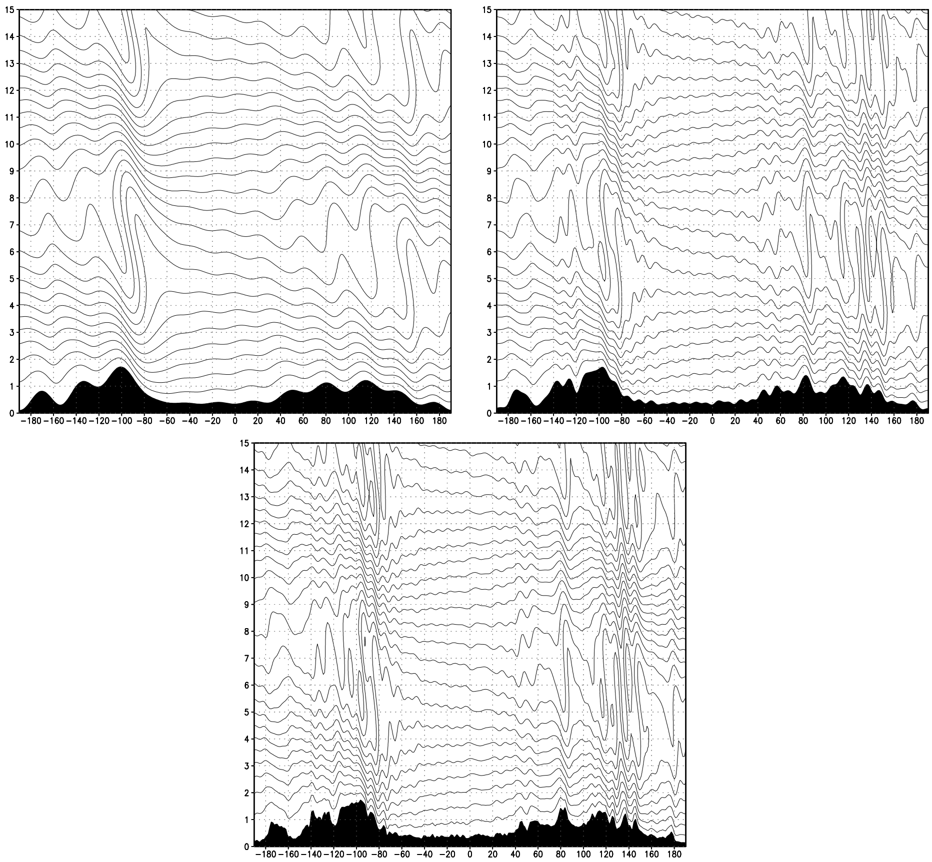

FIGURE 3.4. Streamlines over the Carpathian profile with different resolutions: orography smoothed to 32, 10 and 3.3 km, see text and Fig. 3.2. Atmospheric parameters: U=15 ms$_{-1}$, N=0.012 s$_{-1}$, constant surface temperature. Height (y-axis) and distance (x-axis) given in km.

of the orography would reduce the resolved wave drag, thus influencing the larger-scale flow in a NWP model. This reduction of the explicitly calculated drag might need compensation by the orographic parametrizations also in the kilometre-scale models.

These results are in line with the findings by Davies and Brown [2001], obtained with the fine-resolution hydrodynamic research model BLASIUS, largely applied for boundary-layer studies. The authors concluded that models are capable of handling orography features larger than 4-6 gridlengths and suggested filtering of the smallest scales.

The preliminary conclusions, based on the results of the semi-analytic model, would require confirmation by full high-resolution NWP simulations. There, several effects, not included into the present solution, will modify the results. The most important of such factors would presumably be related to the three-dimensionality of the flow and the full nonlinearity of the solution, to the surface friction and rotation of the earth. In the numerical simulations, interactions between parametrizations and resolved-scale flow during the model integration could be expected to influence the results.

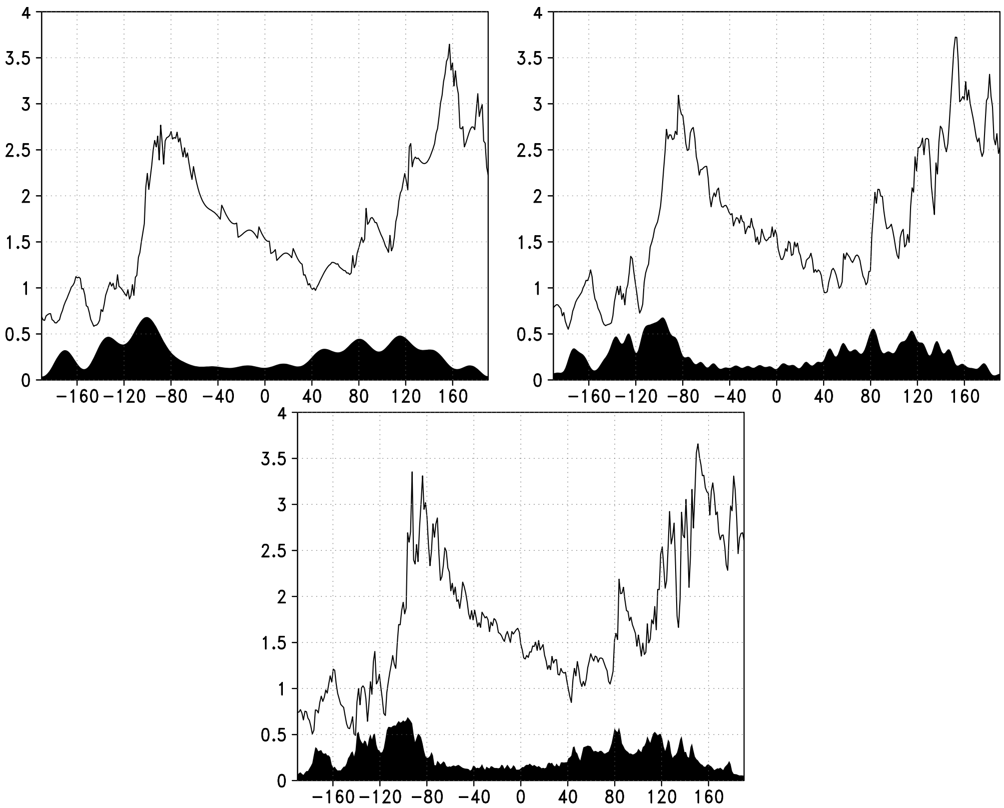

FIGURE 3.5. Relation of the near-surface wind velocity to the constant upstream flow V_s/U (y-axis) along the Carpathian profiles of different resolution (see Fig. 3.4). The underlying surface elevation profiles are scaled so that the scaled elevation corresponds to 0.4h, h is mountain elevation in kilometres.

Table 3.1 Mountain wave drag

smoothing of profile	nondimensional mountain height	D (Pa)	D/D_{lin}
raw	1.20	9.3	6.5
3.3	1.22	9.4	6.3
10	1.19	8.4	6.0
32	1.23	6.1	4.0
raw	0.72	8.0	3.4
3.3	0.73	7.8	3.2
10	0.71	7.9	3.4
32	0.74	7.1	2.8

The drag D expressed as pressure difference (unit Pa) is obtained assuming that the drag force affects the whole length a=384 km of the transection.

4 PARAMETRIZATION OF SUBGRID-SCALE MOMENTUM FLUXES

In PAPER I, a review of the orography-related parametrizations in NWP models was presented, reflecting the situation till the year 2001. During the last five years, new developments in this area have taken place both in the operational and research models. More attention has been paid to the interactions between resolved and parametrized, wave and turbulent processes. A comprehensive review of gravity-wave parametrizations by Kim et al. [2003] brings together the approaches of stratospheric researchers and NWP modellers, who develop parametrizations of transient and stationary buoyancy waves for the upper atmosphere and over mountains.

Recent articles report about improvements to the parametrization schemes of the subgrid-scale orography effects in several operational NWP and climate models. Webster et al. [2003] describe improvements to the representation of orography in the Met Office Unified Model. Beljaars et al. [2004] present the new parametrizations for the turbulent form drag in the ECMWF model, using a spectral approach for handling of the smallest-scale orographic effects. Kim and Doyle [2005] extended the orographic drag parametrization of U.S. Navy global model to include anisotropy and flow blocking effects. Catry et al. [2007] document the renewed ARPEGE-ALADIN mountain drag and lift parametrization scheme, reporting improved validation results. Rontu [2006] (=PAPER II) describes the parametrizations of mesoscale and small scale orography effects in HIRLAM. Liang et al. [2006] introduce parametrization of subgrid topography effects into the climate version of Weather Research and Forecast (CWRF) model.

All these applications contain new developments and formulations, but give different weight to the various aspects of the parametrization. Some elements are common for different models. For example, HIRLAM now shares the parametrization scheme of the MSO effects of ARPEGE-ALADIN and uses an approach to the SSO parametrizations close to that of the ECMWF model. Within each model, these parametrizations are adapted and tuned to its framework of resolved dynamics and physical parametrizations. Intercomparison of the results of such heterogeneous approaches would be interesting but quite a demanding task. It might be possible to compare the magnitude of the parametrized subgrid-scale momentum fluxes due to the orography-related and non-orographic processes in the different models.

Among the recent research papers, Wilson [2002] suggests representation of drag on unresolved terrain features as internal (rather than enhanced surface) momentum sink. The author offers an elegant theoretical argument for the direct parametrization of small-scale orography effects (turbulent form drag), proposed by Wood et al. [2001] and implemented by Beljaars et al. [2004] and PAPER II, see also discussion in 4.3.

Interactions between turbulence and waves and their influence in the structure of the atmospheric boundary layer (BL) have been actively studied during the recent years. Athanassiadou [2003] revises and expands the linear theory of surface pressure drag over orography of small amplitude. The author shows how the wave drag and turbulent form drag operate together when the nondimensional mountain width $G_a = Na/U > 1$ (i.e., over sufficiently wide small- and mesoscale obstacles; a is a measure of obstacle width). In the earlier analysis [Belcher and Wood, 1996], only waves were assumed to significantly influence the flow in this regime.

Grisogono and Enger [2004] study the BL response to nonlinear orographic forcing with Coriolis effect, using a mesoscale numerical model. Wave breaking in the presence of rotation comprises a "double resonance phenomenon", which modifies the BL structure, and can extend the initial mesoscale forcing over the synoptic scale. Nappo et al. [2004] study the generation of BL turbulence due to breaking small-amplitude buoyancy waves. A wave-saturation parametrization is developed, where terrain height is adjusted in order to decrease wave amplitude and the model flow is modified by the divergence of the wave stress.

In the companion papers Smith et al. [2006] and Jiang et al. [2006] document and explain absorption of the trapped lee waves by the atmospheric BL, using numerical model and idealized two-dimensional approach. They show that horizontal friction shifts the near-surface wind disturbance, due to the lee waves, upstream compared to the disturbance in the free atmosphere. This changes the BL thickness, resulting in partial absorption of buoyancy waves. Ross and Vosper [2005] study neutral turbulent flow over forested hills. The authors suggest using a simple model of canopy near the surface instead of the traditional roughness length parametrizations. They show that the surface pressure perturbation is shifted and the related drag enhanced when the hill is narrow or the canopy deep.

An interesting case study, based on observations and fine-scale model (RAMS) simulations by Poulos et al. (2000, 2007), discusses systematically and with advanced diagnostics, the interaction of radiatively driven katabatic flow and mountain waves in a nocturnal boundary layer. Complicated time-varying dynamics, different from that of both pure katabatic flow and pure mountain waves, results from their nonlinear interplay. The authors present a conceptual model of this gravity wave - boundary layer interaction. They suggest that the mechanism may represent a more general source of variability of atmospheric boundary layer.

These studies are likely to contribute to the development of improved parametrizations of wave-turbulence interactions in the boundary layer. However, application of such improvements in NWP models seems not yet having been reported in the literature.

4.1 SURFACE FRICTION, FORM DRAG AND BUOYANCY WAVE DRAG

Parametrization of orographic effects in atmospheric motion aims at representing the stress (Eq. 2.1) with the help of orography features and the resolved-scale wind and stability. The vertical divergence of the parametrized stress is used to modify (retard) the simulated flow. In HIRLAM, the parametrization schemes of subgrid-scale orographic effects are based on a few assumptions:

1. Different subgrid scales of orography are related to effects of different physical character.

2. The parametrizations should provide the three-dimensional stress vector $\vec{\tau}(x, y, z)$ (see Eqs. 2.1 - 2.3), consisting of the sum of momentum fluxes due to the different physical processes related to orography.

3. Orographic effects may be parametrized by combining suitable atmospheric grid-scale variables with parameters representing variation of surface elevation in the given scale within the given grid volume, e.g. properly filtered standard deviation of surface elevation or average slope angle.

These assumptions differ from the historically developed, standard assumptions behind subgrid-scale orography parametrizations, by 1) differentiation of the subgrid orography scales and processes, and 2) considering all effects essentially three-dimensional. As discussed in the review of PAPER I, in earlier times, the bulk effect of all subgrid-scale processes was represented by the effective orographic roughness [Fiedler and Panofsky, 1972; Mason, 1985; Taylor et al., 1989]. Parametrization of the orographic gravity wave drag [Boer et al., 1984; Palmer et al., 1986] then followed. Additional improvements were reached with the application of so-called envelope orography [Tibaldi, 1986], that leads to enhancement of the resolved orography effects. The value of the orographic roughness, height of the envelope orography and the surface value of orographic drag were all based on the same standard deviation of orography height, representing all scales within each grid-square. The magnitude of this standard deviation was determined only by the model's horizontal resolution and availability of the fine-scale orography information. Different physical effects generated by mountains were obtained by the differently formulated dependencies of parametrized wave and form drag on the grid-scale atmospheric parameters. However, these formulations were developed independently of each other. A systematic analysis of the possible interactions seems to be lacking in these early parametrizations.

Information in Fig. 3.2 (see also Table 2.1) allows to refine the first assumption about the different processes. We will further assume that the smallest-scale variations, due to orography of the scales below a few kilometres (blue curve) can be described as turbulent form drag. Parametrization of small-scale orography (SSO) effects is formulated to take care of this effect. The scales between a few kilometres and a few grid-scales (red or green curve, depending on the horizontal resolution of the NWP model) are related to vertically and horizontally propagating orographic buoyancy waves and flow blocking. Parametrization of mesoscale orography (MSO) effects is intended to handle the resulting buoyancy wave drag and mesoscale form drag. Below the smallest scale, there remains the turbulent surface friction due to trees, rocks and other elements of the rough surface. The classical parametrizations of the turbulent surface layer should take care of this surface stress, by using the concept of (vegetation) roughness. Above the MSO scale, the model's resolved dynamics is responsible for modelling of the orographic effects.

Division of the processes and flow dynamics only according to the horizontal scale of the orography is a simplification. In fact, when the effects of earth's rotation are neglected, two nondimensional parameters govern the behaviour of the mesoscale orographic flow: the nondimensional width G_a and height G_h. Both of these parameters combine the upstream flow velocity and stability with the scale of the mountain. The relation $G_h : G_a$ reduces to the simple relation of the height and width of the obstacle (aspect ratio or mean slope h/a). A schematic diagram (Fig. 4.1) classifies orographic phenomena according to these parameters. (Note that, in the present context, the upper left quadrant of the diagramme is not populated because orographic obstacles with a height greater than width are not common in nature.) In principle, a unified turbulence-wave parametrization should be able to handle the disturbances forced by the whole spectrum of the underlying orography in varying conditions of the resolved-scale stability and flow velocity. Development of such unified parametrization schemes remains a task for future research.

Development and application of the MSO parametrizations in HIRLAM was described in PAPER I. SSO effects were added in PAPER II. Technically, the two parametrization schemes are formulated to work independently within the system of physical parametrizations of HIRLAM. They will be first discussed separately in the context of the synoptic-scale model, followed by a short summary of validation of MSO-SSO parametrizations and remarks considering the application of orography-related parametrizations in the future operational kilometre-scale models. The scale-dependent approach poses new requirements on the quality and processing of the fine-resolution digital elevation data. This aspect will be discussed in Ch. 6.

4.2 MESOSCALE OROGRAPHIC EFFECTS

MSO parametrizations in HIRLAM are based on the first version of the ARPEGE-ALADIN (AA) gravity-wave drag parametrization scheme [Geleyn et al., 1994]. The surface value of the drag is based on two-dimensional linear theory of mountain waves. Anisotropy (ellipticity) and direction (with respect of the upstream wind) of the obstacles is taken into account. The vertical profile of drag in each grid-column is obtained by taking into account wave dissipation at and reflection from critical levels. The effect of flow blocking is accounted for below the level of estimated mountain tops, using the approach of Lott and Miller [1997].

In the HIRLAM application, first presented by Sigg et al. [2001] and Rontu and Sigg [2001], systematically documented in PAPER I, the MSO parametrization scheme provides the drag due to the mesoscale mountain waves and mesoscale form drag due to the flow blocking effects. None of the new features of the updated AA scheme [Catry

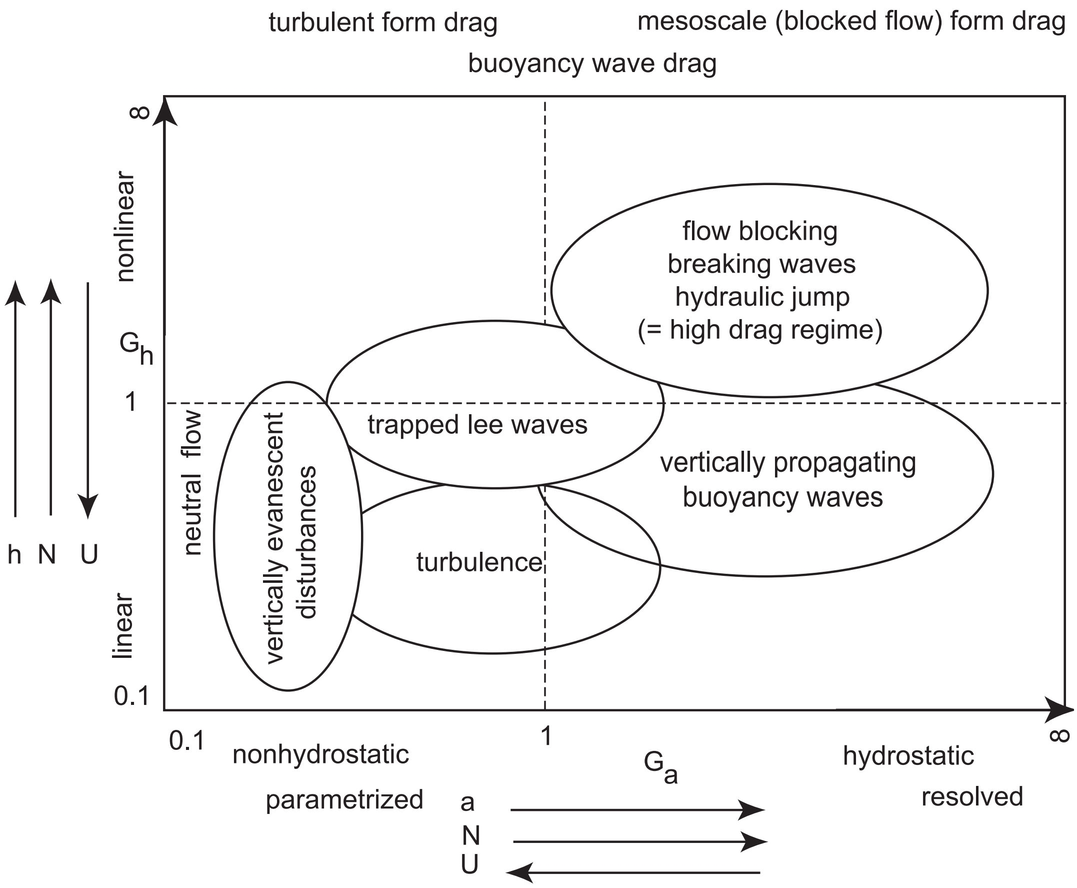

FIGURE 4.1. Orographic flow classified according to G_a (x-axis) and G_h (y-axis), c.f. text for details and discussion. Note that the existence of trapped lee waves or hydraulic jump would require vertically non-constant (layered) upstream stability/flow velocity.

et al., 2007] is applied in the present HIRLAM version.

The main differences between the HIRLAM formulation and the original AA scheme are:

- Scale-dependent derivation of the parameters for the MSO scheme (orography variance, anisotropy and direction) is applied in HIRLAM; the SSO effects are treated separately.
- The basic surface value of MSO stress is related to the square of the subgrid-scale orography (Eq. 5 of PAPER I) while a linear formulation is used in the AA scheme.
- The coefficients of the MSO scheme are tuned as required by the above modifications.

- Parametrization of the lift effect is not included into the HIRLAM scheme. Also the envelope orography has never been used in HIRLAM, in contrary to the earlier AA system, for which the original scheme was built.

The MSO scheme has not yet been used in the operational HIRLAM. However, it has been evaluated within several HIRLAM versions. PAPER I reports sensitivity studies and early verification of the MSO scheme, which was then combined with the (smallest-scale) orographic roughness. Rontu and Bazile [2003] present a case study comparing kinetic energy tendencies in ARPEGE and HIRLAM, with and without the MSO pararametrizations.

The main finding of these early comparisons was that the MSO parametrizations and the turbulent mixing effectively compensate each other in the lower troposphere. The net effect of both parametrizations together was found to be approximately the same as the effect of the turbulence parametrizations only in the reference experiments, which used the orographic roughness approach alone. The same kind of compensation has been reported in a global model by Kim and Hogan [2004]. Kim and Doyle [2005] noted that the distinction among various drag mechanisms near the surface has been rather vague in the literature. In PAPER I, Rontu and Bazile [2003] and PAPER II an explanation was suggested, that the orography-related parametrizations and resolved dynamics, each in within their own scales, may create vertical gradients, which the turbulence parametrizations tend to smooth, independently of their origin or scale. Also another possible mechanism of interactions was suggested in PAPER I: the surface friction retards the low level flow → the nondimensional mountain height increases → low level blocking starts → surface friction and surface wave drag decrease because of the decreased wind → approximate balance is established.

In the artificial and real cases studied in PAPER I, practically all parametrized MSO effects were shown to be due to the low troposphere blocking. Some parametrized wave breaking took place in the topmost layer of the model, without practical influence in the model results. It was concluded that in these circumstances the compensation between MSO and turbulence parametrizations means that the blocking parametrization becomes less dependent on the large-scale flow velocity, instead reflecting the changes of the local turbulence-modified wind. The result of the MSO parametrization thus resembles an additional surface friction, instead of describing the larger-scale blocking effects as intended.

Another finding of Rontu and Sigg [2001], PAPER I and Rontu and Bazile [2003] was the confirmation of the ability of the MSO scheme to handle breaking waves - uncommon, but nevertheless detected in the upper troposphere in some of the experiments. It was also found that the interactions between turbulence and MSO parametrizations in handling wave breaking processes in the upper atmosphere would require further evaluation and development.

The MSO scheme of HIRLAM, as the subgrid-scale orography parametrizations in all present-day synoptic-scale NWP and climate models, contains several simplifying approximations. Such a scheme does not aim at a detailed description of the buoyancy waves but provides the model with the subgrid-scale wave drag due to mesoscale obstacles. In principle, several aspects of the present scheme could be developed further. Application of the updated version of the AA scheme should be tested in HIRLAM, possibly also including the parametrization of the enhanced lift effect in the synoptic scale model. Combination of wave drag with the mesoscale form drag (blocked flow drag) is still done somewhat arbitrarily. Handling of wave breaking and reflection from the wave-induced and other critical levels is presently based on hypotheses whose validity and significance are not clear enough. Introduction of a parameter explicitly describing the mesoscale slope, possibly asymmetric, might improve the results. Description of wave-turbulence interactions in the boundary layer requires further attention.

Possible application of parametrizations of the subgrid-scale orography effects in kilometre-scale NWP models will be discussed further in Ch. 4.5.

4.3 The smallest scale orographic effects and turbulence

In the previous HIRLAM approach the orographic roughness $z_{o,oro}$ was calculated in each grid-square, based on the subgrid-scale orography variance. The related effects were treated as surface layer turbulent momentum fluxes. The main disadvantages of this approach are:

- Using the concept of orographic roughness means that all subgrid-scale orography effects are assumed to be essentially turbulent and two-dimensional (related to the surface layer), that does not correspond reality.

- The values of $z_{o,oro}$ depend on model's horizontal resolution and availability of high-resolution orography data, but are not strictly related to the physical processes the parameter is expected to represent.

- In the HIRLAM practice, in an attempt to reduce the systematic error of near-surface wind (according to the standard verification scores, the wind has been too strong), the values of $z_{o,oro}$ have been artificially increased. Over mountainous areas they reach several tens of metres, i.e. possibly larger values than the typical surface layer thickness in the model. In practice, this also resulted in too strong retardation of wind over mountains.

- Orographic roughness approach, relying on the complicated formulation of the of surface layer turbulence theory, is quite an indirect way of handling orography-related momentum fluxes. It also is not evident that e.g. the implicit stability-dependencies are applicable to orographic effects in unstable cases. Roughness is not an observable quantity, and its calibration using for example ten-metre wind observations is not necessarily an easy task.

In HIRLAM, $z_{o,oro}$ has been directly applied only to the calculation of momentum fluxes, while vegetation roughness ($z_{o,veg}$) has been used for estimation of heat and moisture fluxes. The surface turbulent momentum fluxes provide the lower boundary condition for the vertical diffusion scheme of HIRLAM, based on turbulent kinetic energy (so called CBR scheme [Undén et al., 2002]). This relaxes the two-dimensionality inherent in the orographic roughness concept. In principle, one might calculate $z_{o,oro}$ based on the smallest-scale orography variations only (assumed to relate to the turbulent processes) and use a parametrization of MSO effects to represent the mesoscale effects (related to buoyancy waves). Even then, last two of the above mentioned disadvantages would apply.

The approach by Wood et al. [2001] offers a possible solution here. The HIRLAM application of this SSO parametrization was documented in PAPER II. As discussed in Ch. 4.1, in HIRLAM only the smallest-scale orography features are assumed to create turbulent form drag, which is parametrized by the SSO scheme. Thus this scheme is applied together with the MSO parametrizations, although the former is formulated to work independently of the latter.

The surface value of the SSO stress $\vec{\tau}_{os}$ is related to the square of the smallest-scale slope, multiplied by the turbulent stress,

$$\vec{\tau}_{os} = C_o \frac{\vec{\tau}_{ts}}{\rho_s} s_t^2, \tag{4.1}$$

where C_o is the SSO drag coefficient, $\vec{\tau_{ts}}$ denotes turbulent surface stress, ρ_s is surface air density and s_t is the SSO slope parameter (tangent of the smallest-scale slope, see Ch. 6 for details).

In the latest version of the SSO scheme, a few modifications were made [Rontu et al., 2006a], compared to the description in PAPER II. First, the parametrized surface orographic stress is added to the surface turbulent stress and transmitted to the vertical diffusion scheme, instead of using the original simple exponential decay in vertical (Eq. (5) of PAPER II). Thus the three-dimensionality of the SSO stress is now realized via the vertical diffusion parametrizations only. (This means also that the SSO standard deviation σ_t is not needed by the scheme anymore. In PAPER II it was used because the vertical decay scale was set equal to $2\sigma_t$.) Second, the value of the the coefficient C_o was corrected and made dependent on the lowest model level wind velocity. Now $C_o = C_{oo}V_o/(V_{nlev} + V_o)$, where V_{nlev} denotes the lowest model level wind speed and the tunable parameters C_{oo} = 100 and V_o = 1 m/s. The idea was to increase the drag on the weakest winds by accounting for the surface layer wind shear. Third, the SSO slope is calculated as a part of HIRLAM physiography generation system, instead of using external to HIRLAM methods of the earlier tests (see Ch. 6 for details).

The formulation of Eq. 4.1 means that the SSO and turbulent stress vectors are assumed closely related and parallel. In the present HIRLAM, the turbulent stress direction is (pragmatically) rotated in the stable cases, according to the suggestion by Nielsen and Sass [2004]. Due to the link between the vertical diffusion and SSO schemes, this rotation now influences also the SSO stress both at the surface and higher in the boundary layer.

The main simplification of the HIRLAM version of the SSO parametrization, compared to the formulae proposed by Wood et al. [2001], is neglection of the direction differences of slopes and the effects of anisotropy inside the grid-squares. This is considered justified, because here only the smallest-scale orography (presumably isotropic) features are handled by the SSO parametrizations. Note that anisotropy and direction of the obstacles do affect the larger-scale MSO parametrization of HIRLAM. The value of the SSO drag coeffient C_o and its dependency on near-surface wind were chosen with the help of ten-metre wind observations, but may need further tuning. Comparison of the results obtained by using the original exponential decay profile and the new formulation (Eq. 4.1 + turbulent diffusion scheme) could be continued.

4.4 Evaluation of the MSO-SSO parametrizations

The suggested combination of MSO and SSO parametrizations has been validated in case studies and pre-operational tests of HIRLAM, reported in Rontu [2004, 2005] and Paper II. The latest modifications and tests before operational implementation were described by Rontu et al. [2006a] and Rontu et al. [2006b]. The main results of these reports are summarized below.

Standard verification scores (bias, rmse) and kinetic energy budgets were applied for comparison and validation in the preliminary experiments reported in Rontu [2004, 2005]. It was found that the SSO parametrizations alone are not sufficient to replace the (enhanced) orographic roughness. The results improved when MSO parametrizations were added. In the experiments, sensitivity of the SSO parametrizations to the changes of the basic turbulence parametrizations was also detected. Examination of the kinetic energy budgets showed again that the parametrizations, representing different subgrid scales, interact and partly compensate the effects of each other.

Systematic sensitivity tests and validation of the MSO-SSO parametrizations, with the first version of the SSO scheme, were reported in Paper II. The ECMWF version of the SSO parametrization was included in the comparisons, which concentrated on BL variables over the complex orography of Iceland. The analysis of surface momentum fluxes showed, as expected, that the influence of the MSO parametrizations decreases when the model's horizontal resolution improves. The surface drag due to the ECMWF SSO parametrizations was found to be significantly larger than that given by the HIRLAM SSO parametrizations or by the reference HIRLAM. The analysis of kinetic energy budgets confirmed the earlier result that the different parametrizations tend to compensate each other.

The analysis of forecast-observation differences showed that the orography-related parametrizations operate in quite a local scale. Over flat areas, only minor differences between the experiments were seen. Both the reference HIRLAM and the modified versions tend to overestimate weak and underestimate strong winds both in the coarse and the fine resolution experiments. A model version with the new MSO-SSO parametrizations was able to correct this distribution only slightly.

The results reported in Rontu et al. [2006a] and Rontu et al. [2006b] were obtained using the updated version of the SSO scheme (see Ch. 4.3 for the differences between the first and second version). Validation against Norwegian wind observations showed improved performance over the mountain stations, compared to the reference HIRLAM (v. 6.4.3). Overestimation of the dominating weaker winds, and underestimation of the few cases of very strong wind, was shown to remain a problem. It was suggested that this feature may be more related to the turbulence parametrizations in and above the surface layer than to the orography-related schemes.

4.5 Orographic effects in kilometre-scale NWP models

In the introductory review of Paper I, some considerations of the future of the orography-related parametrizations in the finest-scale NWP models were raised. The finding by Georgelin et al. [2000] that the resolved wave intensity tends to be overestimated and upstream blocking and related effects underestimated by mesoscale models (with a horizontal resolution of about 10 km) was commented there. In this model intercomparison study the best results were obtained by models with enhanced surface friction, i.e., enhanced orographic roughness. Criticizing the use of orographic roughness approach and envelope orography, Paper I questioned also the application of the present type blocking parametrizations to enhance resolved blocking in mesoscale models because in the nature, flow blocking is not caused by the unresolved small-scale orography features but by the integral properties of whole mountain systems. The question then remained: are some processes missing in the models' dynamics (formulation of the lower boundary condition), leading to the observed overestimation of wave intensity and underestimation of resolved blocking? How well does the fine-scale model feel the large-scale mountain effects?

Nowadays, it is evident that the SSO parametrizations, replacing the orographic roughness approach, are needed also in the kilometre-scale NWP models. The SSO scheme complements the turbulence parametrizations, by using relatively simple formulations and adding some minimum information of the smallest-scale orography features. The present parametrization aims at representation of the contribution of the viscous non-separated sheltering to the asymmetric pressure distribution around small-scale orographic obstacles. Due to the smoothing of the basic orography (see Ch. 3.2 and Ch. 3.3 for discussion of resolution and smoothing), such subgrid-scale obstacles will be present even in the kilometre-scale models. For description of the smallest-scale orography features, available satellite-based high-resolution data of surface elevation should be utilized.

The finest-resolution models are, in principle, capable of handling explicitly the generation of mountain waves and flow blocking. Thus, they do not need MSO parametrizations for this purpose. However, the existing MSO (buoyancy wave) schemes take care of both the creation and dissipation of the waves. It may not be possible to describe, in the whole atmosphere, the conversion of kinetic energy between the waves and turbulence, depending on the scales of (orographic) forcing, atmospheric stability and flow characteristics, with the present-day turbulence and surface layer schemes.

Moreover, the present day MSO parametrizations seem to be more oriented towards the extreme but rare cases of strong dowslope windstorms, hydraulic jumps, wave resonance from wave-induced critical levels and similar nonlinear dynamics. It is quite possible that breaking, dissipation and reflections of horizontally and vertically propagating buoyancy waves of different scales are everyday phenomena in the lower atmosphere, as well as in the upper troposphere and stratosphere.

All this calls for a unified approach of (three-dimensional) wave-turbulence parametrizations, taking care of the whole spectrum of effects due to the subgrid-scale forcing. Many building blocks for such next generation parametrizations within the mesoscale models already exist, but the unified formulation is still missing.

In the next chapter, we move from orography-related momentum fluxes to the radiation fluxes.

5 PARAMETRIZATION OF OROGRAPHIC EFFECTS ON RADIATION

Thermal effects related to orography are due to differential heating of (sloping) surfaces at different elevations, mainly due to the differences in solar radiation. Modelling of the orographic effects on surface radiation becomes 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.

The parametrized radiation effects enter into the model via the equation of thermodynamics, together with the parametrized turbulence and condensation:

$$\frac{\partial T}{\partial t} = -\vec{v} \cdot \nabla_\zeta T - \dot{\zeta}\frac{\partial T}{\partial \zeta} - \frac{1}{c_p}(\frac{g}{p_s}\frac{\partial F_r}{\partial \zeta} + \frac{g}{p_s}\frac{\partial F_t}{\partial \zeta} + F_c), \tag{5.1}$$

where F_r denotes the net radiation flux, $F_t = -\rho\overline{T'w'}$ is the turbulent sensible heat flux and F_c is related to the latent heat changes due to condensation and evaporation.

The aim of a radiation parametrization is to calculate the profile of the net radiation flux $F_r(z)$ in each grid-column, 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 in calculation of the surface energy balance over different types of surface. In HIRLAM, as in most of the operational NWP models, the radiation parametrizations have assumed that the surface is flat and effectively homogeneous.

PAPER III describes how the present HIRLAM radiation scheme [Savijärvi, 1990; Sass et al., 1994; Wyser et al., 1999; Räisänen et al., 2000; Järvenoja and Rontu, 2000; Rontu and Järvenoja, 2003; Rontu and Senkova, 2003] was enhanced to take into account the slope, shadow and sky view effects on surface radiation fluxes. Directional fraction of slopes and slope angle in each direction, directional coefficients and the average sky view factor are calculated from high-resolution digital elevation data and aggregated to the model grid (see Ch. 6 for the details). Time-dependencies of some of the parameters are converted to direction-dependencies by using the idea of directional fractions, introduced by Senkova and Rontu [2004] and Senkova [2004].

The HIRLAM orographic radiation scheme was first systematically presented in an unpublished Ph.D. dissertation by A. Senkova (Russian State Hydrometeorological University, February 2005, in Russian). This study was initiated by a suggestion and idealized calculations by Savijärvi [2003]. Development of such a scheme was started independently from Müller and Scherer [2004, 2005], who were the first to publish a subgrid-scale parametrization scheme of orographic effects on radiation for mesoscale models. In PAPER III, formulation of the basic equations, in particular definition of the shadow and sky-view factors, now follows the formulations by Müller and Scherer [2005]. In derivation of the orographic parameters for the HIRLAM scheme, we apply the experience gained in developing the MSO and SSO parametrizations (PAPER II, see also Ch. 6).

The orographic radiation calculations are integrated into the system of physical parametrizations of HIRLAM as described by Rontu et al. [2006b] and PAPER III. At each time step at each HIRLAM gridpoint, the time dependent solar position is first defined. Next, the main radiation parametrizations are applied for calculation of the three-dimensional radiative flux F_r, assuming the surface is flat and homogeneous. Grid-square averaged values of the needed model parameters are used, including surface elevation, albedo, emissivity, surface (skin) temperature. These are determined by the properties of vegetation and other surface properties. The downwelling shortwave and longwave fluxes over uneven terrain are then updated by using the orographic radiation scheme, utilizing (time-independent) information of the subgrid-scale slopes and slope directions. The updated fluxes enter to the HIRLAM surface scheme [Rodriguez et al., 2003], which calculates the surface energy balance, fluxes and tendencies of the soil and surface variables over the surface subtypes.

The first steps of validation of the proposed scheme were taken and reported in PAPER III. In the sensitivity experiments, relatively small effects on near-surface temperature and boundary layer clouds were detected due to the orographic radiation parametrization. More systematic validation and mesoscale model comparison studies over complex orography are needed. These could also shed light to the question of the relative importance of accurate representation of the clear-sky radiative transfer, cloud-radiation and surface-radiation interactions in the short-range mesoscale NWP models.

Possible dynamical feedbacks, i.e. the connection between the radiation fluxes, temperature and local circulations as well as triggering of convection and enhancement of precipitation, deserve further analysis and development. With this respect, connections between the orographic radiation parametrizations with the parametrizations of the orographic momentum-flux, turbulence and condensation could be studied and the results compared with wind, pressure, cloud and precipitation observations.

6 Representation of orography in atmospheric models

6.1 Description of resolved and subgrid-scale orography

Baines (1998, Ch. 7.2.1), defines five statistical parameters to represent orography in each grid-square of a NWP model: mean elevation, variance, direction of maximum mean-square gradient, anisotropy and mean-square slope. These parameters are determined by the high-resolution surface elevation data, covering the area of the grid cell. The last three parameters, i.e. the mean-square gradient, anisotropy and mean-square slope, stem from the orographic gradient correlation tensor.

In the present study, applying the scale-dependent approach (Ch. 4.1), these parameters (except the mean-square slope) are used for the MSO parametrizations and for definition of the resolved orography for the model dynamics. Following Scinocca and McFarlane [2000], it was decided already by Sigg et al. [2001] to remove both the lower and higher spectrum when calculating the orography parameters for the MSO scheme. The smallest scale orography structures create turbulence but no vertically propagating buoyancy waves (high end), and the HIRLAM dynamics can be expected to resolve those scales of orography which are represented by the model grid (low end).

Wood et al. [2001] suggested using the maximum slope for parametrization of the orographic stress. In the present study, this parameter is used for the SSO parametrizations. It is calculated based on the orography data, that represent the smallest scale (high end of the spectrum) only. However, SSO parametrizations might be as well based on some other statistical measure of the smallest-scale orography variation (mean-square slope, standard deviation). Contrary to the MSO parameters, no direction-dependencies are taken into account in this range of orography spectrum. Thus the mean-square gradient and anisotropy, which could be derived from the orography gradient correlation tensor, are not needed here.

For parametrization of the orographic effects on radiation, slopes and local horizon in the different directions are required (Paper III). These properties, determining the slope, shadow and sky-view factors for the orographic radiation scheme, are derived from unfiltered high-resolution orography data. This is because separation of the orography scales is considered irrelevant for the radiation processes.

Table 6.1 shows all these orographic parameters and the relevant scales. Methods for calculation of the parameters will be presented in Ch. 6.3, after introduction of sources of the fine-resolution orography data in Ch. 6.2.

Table 6.1 Orography-related parameters used in HIRLAM

parameter	description	unit	usage	scale (km)	filtering
s_t	mean maximum small-scale slope	rad	SSO	$<$ 3 km	high-pass
σ_t	mean small-scale standard deviation	m	SSO	$<$ 3 km	high-pass
σ_m	mean mesoscale standard deviation	m	MSO	3 km . . . $k\Delta x$	band-pass
α	coefficient of anisotropy	-	MSO	3 km . . . $k\Delta x$	band-pass
θ	x-angle of orography gradient	rad	MSO	3 km . . . $k\Delta x$	band-pass
$H_{k\Delta x}$	mean surface elevation	m	dynamics	$> k\Delta x$	low-pass
$\gamma_{m,i}$	mean slope angle in direction i	rad	radiation	full resolution	none
f_i	fraction of slopes in direction i	-	radiation	full resolution	none
$\gamma_{h,i}$	local horizon in direction i	rad	radiation	full resolution	none

Typically, the empirical coefficient k in the terms kΔx is given a value between 2 and 4.

6.2 Sources of high-resolution orography data

During last ten years, detailed global or near global data on surface elevation have become available. The resolution of these data is 100 m - 1 km. In addition, local data sets exist with even higher (ca. 10 m) horizontal resolution. Three basic data sets, suitable for the use in atmospheric modelling, are shortly characterized here.

GTOPO30 [USGS, 1998] is a global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometre). GTOPO30 was developed through a collaborative effort led by U.S. Geological Survey and completed in 1996. It is based on a variety of sources of topographic information, including digital terrain elevation data, elevation maps and models. GTOPO30 contains the field of surface elevation, given in regular latitude-longitude grid. It is still the only existing truly global high-resolution elevation data set.

Hydro1K [USGS, 2003] is a 1 $\times$ 1 km resolution geographic database derived from GTOPO30 data. The database aims at providing hydrologically correct DEMs along with ancillary data sets for use in continental and regional scale modelling and analyses. Basic and derived data include the surface elevation, slope angle and azimuth (direction), flow direction, basins, streams etc. The data is arranged to continent-wide suites and given in Lambert azimuthal equal area projection. Because of the area-conserving properties of this projection, the data set is well suited for use in the rotated latitude-longitude coordinate system of HIRLAM. Hydro1K data cover the whole globe excluding Greenland and Antarktis.

Shuttle Radar Topography Mission Elevation (SRTM, Rodriguez et al. [2005]) provides orography data with a horizontal resolution of three arc-seconds (3”). SRTM digital raster elevation covers the globe between latitudes 60°N and 56°S. The data are given in regular latitude-longitude grid. Examples of these data were discussed in Ch. 2 of this review. In the future, it might be relatively easy to utilize SRTM data in

HIRLAM experiments of limited midlatitude or tropical domain.

6.3 SCALE-DEPENDENT DERIVATION OF PARAMETERS

Each of the orographic parameters shown in Table 6.1 is derived from properly filtered high-resolution source data and represents orography features within one grid-square, in some cases covering also the surroundings within kΔx. Scale-dependent methods for calculation of the orographic parameters have been developed both within the HIRLAM physiography generation system (PAPER I, Rontu et al. [2006a], Rontu et al. [2006b]) and outside it [Rontu, 2003].

The reference HIRLAM physiography generation system, shortly described in Undén et al. [2002], uses the original GTOPO30 data set [USGS, 1998] as the source of orography-related information. These data have been converted into a uniform grid, rotated or regular latitude-longitude, depending on the geographical area. Physiography generation tools can be applied for creation of input data for any model resolution and domain over the globe. Filtering of source or target data is applied when creating the fields of orographic parameters. Spectral properties of the filters and filtered orography data are analysed and discussed (by K. Sattler) in PAPER I, Rontu et al. [2006a] and Rontu et al. [2006b].

The HIRLAM physiography generation system is operational, optimized and universal, but not immediately applicable for derivation of new parameters. That is why temporary external programs were prepared to calculate parameters required by the new orographic parametrizations. In the following, this approach is presented, based on Rontu [2003], in order to explain the basic assumptions and methods. The calculations are built on the continent-wide Hydro1k data sets and are thus restricted by the coverage of these data.

The data handling procedures and conversion between Hydro1k and HIRLAM grids are illustrated in Fig. 6.1. Averaged variables are calculated at a HIRLAM grid point centred at $(\lambda_{HI}, \phi_{HI})$ and represent the area of Δx $\times$ Δy, except the mean height and the MSO parameters, which are averaged over an area $k\Delta$x $\times$ $k\Delta$y. The original and derived 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]).

From the basic Hydro1K data, only the terrain elevation h is used for calculation of the resolved orography and subgrid-scale parameters for MSO and SSO schemes. First, the average elevation (h_9) over the point and its 8 neighbours is calculated at each Hydro1k point. The difference between the original and average elevation ($h' = h - h_9$)

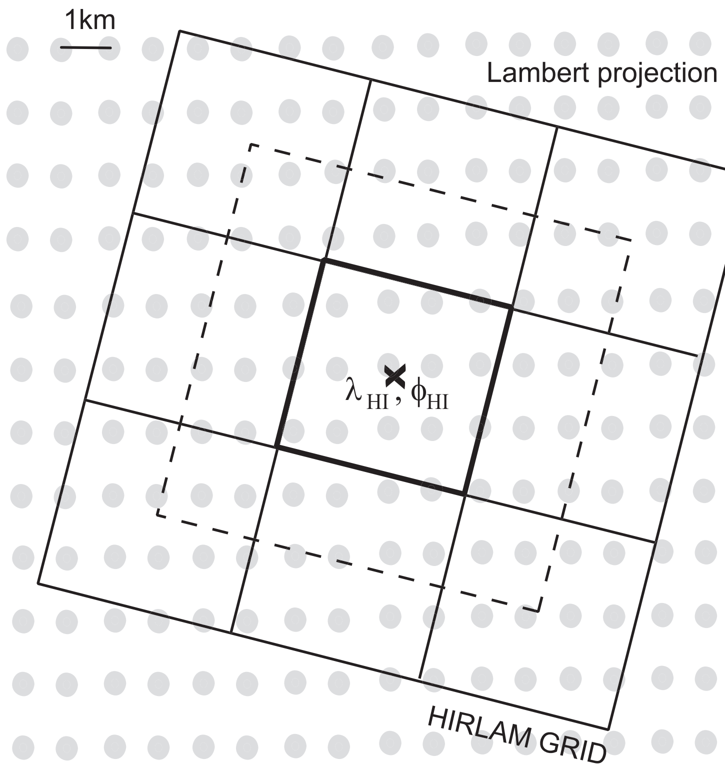

FIGURE 6.1. *Derivation of variables from Hydro1K digital elevation data to HIRLAM grid. The grey balls represent a Hydro1K data square of 1 km × 1 km, containing the original and derived elevation data. The innermost square represents a HIRLAM grid-square centred at λ_{HI}, ϕ_{HI}. Its center is marked with a cross and the length of its sides is Δx=Δy. The square with dashed sides represents an area $k\Delta$x × $k\Delta$y, k=2. The HIRLAM coordinates may be rotated with respect to the Lambert equal area azimuthal grid of Hydro1K. Figure copied from Rontu [2003].*

is obtained, and the maximum small-scale slope (s_{max}) is found by using values of h' at the point and around it. Slope elevation (h_m) and direction (a_m) angles provided by Hydro1k are utilized for definition of the orographic radiation parameters. Thus, at each Hydro1k point we now have five parameters: the original elevation h, smoothed h_9, smallest-scale h' and s_{max}, full-resolution h_m and a_m. The rest of the variables (Table 6.1) are based on these five:

The mean elevation $H_{k\Delta x}$ is calculated for every HIRLAM grid-square, based on values of h_9 at all Hydro1K data points whose centre falls inside the square of $k\Delta$x × $k\Delta$y (see Fig. 6.1). Because of the double filtering, the resulting mean elevation field is quite smooth.

The standard deviation of mesoscale orography σ_m, anisotropy α and angle θ between model's x-axis and the principal axis (direction of maximum gradient) of the mesoscale orography are calculated using the formulae explained in PAPER I but based on the differences h_9-$H_{k\Delta x}$ instead of the filtered source elevation.

The mean maximum small-scale slope s_t for SSO parametrizations is obtained as a simple grid-average of the high-resolution s_{max}. This leads to some smoothing, that needs to be taken in account when defining the coefficients in Eq. 4.1.

Calculation of the slope angles $\gamma_{m,i}$, directional fractions f_i, local horizon $\gamma_{h,i}$ and derived from these slope, shadow and sky-view factors for orographic radiation parametrizations is described in detail in PAPER IV.

The described method provides a quick and simple filtering of the source data and aggregation of the needed parameters to the HIRLAM grid. The simultaneous processing of the resolved and subgrid-scale parameters ensures consistent treatment of the parameters representing different scales. However, the spectral properties of the filtered orography and the resulting parameters have not been systematically studied in this framework.

Instead, in the HIRLAM physiography generation system, the MSO and SSO parameters are calculated from the filtered surface elevation. The aggregation of s_t consists of a simple averaging of the field s_{max} provided by HIRLAM physiography data base. This field of the maximum small-scale slope has been determined with the same simple high-pass filtering as described above. The parameters for the MSO parametrization are derived from band-pass filtered orography. The band-pass filter is described in PAPER I and its approximated form in Rontu et al. [2006a]. σ_m and the tensor of orographic gradient correlation [Baines, 1998] are aggregated during physiography generation, the latter using the methodology of subdivided aggregation grid, described in section 2.2.2 of Sattler [2001]. In the reference HIRLAM, the mean elevation is smoothed to represent only orography scales larger than $2\Delta x$, by applying an implicit filter by Raymond [1988]. Calculation of the parameters for the orographic radiation scheme has not yet been implemented in the HIRLAM physiography generation system.

7 METHODS OF DIAGNOSTICS AND VALIDATION

Validation of new developments in a NWP model is a nontrivial task, which could be divided to several steps. In general, a new scheme is first tested in the simplified, possibly single-column, stand-alone mode. Analytic solutions, artificial data, special observations and similar data are used for comparison, to make sure that the suggested scheme behaves physically and technically in a correct and expected way. Second, the scheme is embedded in the environment of physical parametrizations, dynamics and data-assimilation of the NWP model. One-dimensional and three-dimensional sensitivity studies and comparison with observations should allow to understand the behaviour of the new parametrizations in interaction with all other components of the model. The third step consists of parallel experiments during selected test periods, using standard verification scores for comparison between model results and observations or the numerical analysis.

Especially in the first and second steps, advanced diagnostic tools are necessary for understanding the behaviour and value of the suggested parametrizations. In this thesis, the methods applied for comparison, diagnostics, validation and analysis of the model interactions, include:

- Analysis of the results of the stand-alone radiation scheme and time-integrating single-column HIRLAM, using real and artificial input data (PAPER III).
- Analysis of artificial three-dimensional flow over real Scandinavian mountains (PAPER I).
- Comparison of the predicted wind, surface pressure, surface stress, temperature components of surface energy balance etc. between different model experiments (PAPER I-PAPER III).
- Analysis of predicted momentum and kinetic energy budgets in three-dimensional HIRLAM experiments of different setups (PAPER I and PAPER II).
- Comparison of analysed and predicted vorticity budget (PAPER IV).
- Standard and enhanced station verification against SYNOP and sounding observations (bias and rms-error, possibly classified according to the observed values) (PAPER I and PAPER II), comparison of observed and simulated parameters at individual stations (PAPER III).

Methods of budget studies, further developed and applied in this study for the analysis of momentum flux parametrizations, are now briefly presented.

7.1 VERTICALLY INTEGRATED MOMENTUM BUDGET

Averaging Eq. 2.1 over long enough period of time allows to estimate the response of model dynamics to the forcing due to the physical processes. The three-dimensional wind tendency (Eq. 2.3) due to physical processes can be integrated vertically to obtain the corresponding surface stresses, assuming that there are no vertical momentum fluxes at the top of the model atmosphere. Diagnostics, collected at each time step of a HIRLAM experiment, include accumulated tendencies of model variables, such as wind components or derived from these resolved scale kinetic energy, plus independently accumulated surface fluxes.

In PAPER I, the area-averages of the momentum equation (Eq. 2.1) were integrated vertically from surface to the top of the atmosphere in order to define the integrated (surface-level) momentum budget. The tendency equations of the vertically integrated horizontal wind components were written as a sum of terms describing the vertically averaged dynamical forcing, surface pressure drag and parametrized surface momentum flux. In a stationary situation without dynamical forcing, the surface pressure drag and the parametrized surface momentum flux would balance each other.

The method of diagnostics, applied in PAPER I, allowed to separate the influence of model dynamics and physical parametrizations as well as estimate the pressure drag from the model output. The dynamical forcing term was estimated as a residual. The components of the integrated momentum budget were calculated along selected cross-sections over Scandinavian mountains, based on real and artificial HIRLAM experiments, using different model resolutions and various combinations of subgrid-scale momentum flux parametrizations (PAPER I, Tables 3-5). Analysis of the results helped to understand the interactions between the parametrized and resolved momentum fluxes and surface drag.

Direct diagnostics of the (vector) momentum equations, applied in PAPER I (and earlier discussed in some detail by e.g. Hereil and Stein [1999a], Hereil and Stein [1999b] and Beau and Bougeault [1998]), is somewhat complicated way of analysing the behaviour of the model's momentum budget. Kinetic energy and vorticity budgets offer a possibility to use scalar variables for this purpose.

7.2 KINETIC ENERGY BUDGET

In PAPER I and PAPER II, the budget of resolved-scale kinetic energy was introduced and used as the main tool of analysis of the results. Vertical profiles of the area-averaged resolved-scale kinetic energy tendencies due to model dynamics, turbulence and MSO-SSO parametrizations, were calculated based on series of HIRLAM forecasts (with lead times between 36 and 48 h). The results have been discussed in Ch. 4.4.

The true sources and sinks of the atmospheric kinetic energy represent the work done by frictional forces, i.e. the parametrized turbulence, mesoscale and small scale orography effects. It can be estimated based on the values of wind components and their accumulated tendencies:

$$(\frac{\partial k}{\partial t})_j = \frac{\partial \frac{\rho}{2}(u^2+v^2)}{\partial t} \approx \rho u(\frac{\partial u}{\partial t})_j + \rho v(\frac{\partial v}{\partial t})_j, \tag{7.1}$$

where k=$\frac{\rho}{2}(u^2+v^2)$ denotes the (diagnostic) resolved-scale kinetic energy and the index j denotes any of the different processes so that $j = d, t, o, m$ refer to dynamics, turbulence, SSO or MSO parametrizations, respectively. The total tendency, due to the model dynamics and all parametrizations, is obtained from the difference of two model states. Averaged over long enough time it is expected to be close to zero so that the dynamical and parametrized tendencies balance each other.

In the future, comparison of the resolved-scale kinetic energy and turbulent kinetic energy budgets might help to understand the interactions between the model dynamics and parametrizations. Analysis of the kinetic energy spectra in the models (Skamarock [2004]) would offer another perspective.

7.3 Vorticity budget

Application of the gradient operator $\vec{k}\cdot\nabla_\zeta\times$ to Eq. 2.1 gives an equation for the vertical component of absolute vorticity η as a sum of relative ($\xi = \vec{k}\cdot\nabla_\zeta\times\vec{v}$) and planetary ($f$) vorticity, $\eta = \xi + f$ (see e.g. Haltiner and Williams [1980]; Bourke [1974]):

$$\underset{(a)}{\frac{\partial\xi}{\partial t}} = \underset{(b)}{-\vec{v}\cdot\nabla_\zeta\eta} \underset{(c)}{-\dot{\zeta}\frac{\partial\eta}{\partial\zeta}} \underset{(d)}{-\eta\nabla_\zeta\cdot\vec{v}} \underset{(e)}{-\vec{k}\cdot\nabla_\zeta\dot{\zeta}\times\frac{\partial\vec{v}}{\partial\zeta}} \underset{(f)}{-\frac{1}{p_s}\frac{\partial J(p,\Phi)}{\partial\zeta}} \underset{(g)}{-\frac{g}{p_s}\frac{\partial(\vec{k}\cdot\nabla_\zeta\times\vec{\tau})}{\partial\zeta}} \tag{7.2}$$

Here, $\dot{\zeta} = \frac{\mathrm{d}\zeta}{\mathrm{dt}}$ is the vertical velocity in the ζ coordinate system and $J(a,b)$ denotes a Jacobian, defined as $J(a,b)=\frac{\partial a}{\partial x}\frac{\partial b}{\partial y} - \frac{\partial b}{\partial x}\frac{\partial a}{\partial y}$. The hydrostatic assumption $1/\rho = -\frac{\partial\Phi}{\partial p}$ was used in derivation of Eq. 7.2. The terms of the vorticity equation represent the local time change of vorticity (a), horizontal (b) and vertical (c) advection, stretching (d), tilting induced by the nonuniform vertical velocity (e), change of vorticity due to baroclinity (f) and frictional forces (g). Only the two last terms represent true sources and sinks of vorticity, the rest describe its redistribution.

In the model, the baroclinity term (f) appears in interaction of the flow with the resolved scale mountains and the frictional torque is related to the parametrized momentum fluxes. This gives a possibility to apply the three-dimensional and vertically integrated vorticity equations for model diagnostics. In Paper IV, the terms of the vorticity equation, based on HIRLAM analyses, were compared with those based on the forecasts. The terms (a)-(f) were calculated by postprocessing numerical analyses or forecasts, while the frictional torque (g) was estimated as a residual (in analysis and forecast) or given by the parametrizations (in forecast).

The comparison allowed to measure the quality of momentum flux parametrizations and their interactions with the resolved dynamics. It was found, in particular, that the parametrized subgrid-scale torque (term g) was smaller than the residual term based on analyses. This was in line with the routine verifications of the reference HIRLAM of the same period (February 2004), pointing to a missing low-level subgrid-scale drag mechanism in the forecast model. Indeed, it turned out later that in the HIRLAM version in question (v. 6.3), by mistake no orography-related drag parametrization was used. Only the turbulent momentum fluxes over the rough surface were accounted for, by using the vegetation roughness as the basic parameter.

PAPER IV contains a systematic analysis of the underlying assumptions and discussion about the advantages and disadvantages of the method. The main disadvantage is related to the conceptually and numerically complicated nature of the vorticity budget in the terrain-following coordinate system. In the future, the method could be applied to comparison of the subgrid-scale momentum flux parametrizations, i.e. the turbulence and the new MSO and SSO schemes. Output of the three-dimensional parametrized fluxes (tendencies) from the model would allow deeper analysis of the interactions than was possible using the surface level and integrated variables only in PAPER IV).

8 CONCLUSIONS

Consistent formulation of scale-dependent parametrizations for orographic effects, development of the related methods for processing of orography data and application of diagnostic methods, capable for evaluation of interactions, are the most important outcome of this thesis. The main findings and conclusions can be summarized as follows.

SCALES OF OROGRAPHY AND MODEL. An attempt to build a consistent, scale-dependent system of orography-related parametrizations for HIRLAM has been undertaken. The basic equations and physical parametrization schemes of an atmospheric model use the smoothed surface elevation for building the vertical coordinate. Beyond the smoothed orography, the different subgrid-scales of orography may be related to different physical processes in the atmosphere. In the NWP models of any resolution, consistent handling of the orography scales and related resolved and parametrized processes is a necessity. However, this consistency is not always achieved in practice, because the models combine components, individually developed during perhaps several decades.

REPLACEMENT FOR THE OROGRAPHIC ROUGHNESS APPROACH. In this thesis, $z_{o,oro}$ of HIRLAM has been completely replaced by the parametrizations of mesoscale (MSO) and small-scale orography (SSO) effects. The results support the conclusion that the enhanced orographic roughness approach should not be used for parametrization of subgrid-scale orographic effects in the present-day high-resolution NWP models.

INTERACTIONS BETWEEN DYNAMICS AND PARAMETRIZATIONS. It was found, by using area-averaged momentum, kinetic energy and vorticity budgets and other diagnostic methods, that in HIRLAM the parametrized subgrid-scale momentum fluxes (turbulence, SSO, MSO), tend to compensate each other and resolved-scale fluxes. The exact reason for such compensation was not revealed, although it is not unexpected in view of the complicated nature of nonlinear interactions within the model.

METHODS FOR PROCESSING OF HIGH-RESOLUTION OROGRAPHY DATA. Simple tools for calculation of the scale-dependent orographic parameters for the parametrizations of orographic momentum and radiation fluxes were introduced in this study. The tools might be relatively easily be modified to handle different sources of finest-resolution digital elevation data, and to be applied also outside HIRLAM. However, because of the restrictions of these simple tools, they cannot replace e.g. the existing global physiography generation system of HIRLAM.

CONVERTING TIME-DEPENDENCIES TO DIRECTION-DEPENDENCIES. In the orographic radiation parametrizations, introduction of the idea of directional fractions, allows to optimize calculation of the slope factor. Slope factor is the main orography-dependent parameter, representing the different heating of slopes by shortwave radiation. It depends on the solar elevation and azimuth as well as on the steepness and direction of the slopes, i.e. on three spatial and one time dimension. The time-dependency was removed by definition of the directional fractions of slopes in the grid-squares.

DIAGNOSTICS FOR UNDERSTANDING AND VALIDATION OF THE MODEL. In this thesis, methods for advanced diagnostics and validation of the momentum flux parametrizations have been developed, based on momentum, kinetic energy and vorticity budgets. The commonly used standard statistical verification scores (bias, rms-error of model compared to available conventional observations) are necessary for monitoring the quality of operational NWP model results, but insufficient for understanding the effect of new developments.

Some future challenges, which could be attacked by applying and developing further the ideas and tools of this thesis, could be mentioned:

THE PROBLEM OF BREAKING WAVES AND THE ROLE OF TURBULENCE PARAMETRIZATIONS. When the models' resolution increases, generation of the mountain waves will be resolved with sufficient accuracy. However, wave dissipation (breaking, conversion to turbulence) remains to be parametrized. Three-dimensional turbulence parametrizations, capable of handling the whole spectrum of wave-turbulence interactions in the atmosphere, should be developed and properly combined with the SSO (orographic turbulence) parametrizations.

UNDERSTANDING AND PARAMETRIZING THE BLOCKING EFFECTS OF DIFFERENT SCALES. The (mesoscale) flow blocking and the related three-dimensional upstream and downstream effects (with friction and rotation included) requires deeper understanding, to allow correct handling of these nonlocal orographic effects in fine-resolution NWP models. In this respect, it may be necessary to take into account the interplay of resolved and subridscale dynamics when formulating the lower and upper boundary conditions and representation of the basic equations (spectral or grid-point formulations) in the model.

VORTICITY AND POTENTIAL VORTICITY DIAGNOSTICS. Analysis of the potential vorticity budget based on the numerical analyses and forecasts, combining both thermodynamic and momentum flux aspects, may offer new insight into the interactions between parametrized and resolved processes of different scales. Vorticity and potential vorticity diagnostics could be applied in the fine-resolution limited-area models and over complex terrain.

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GLOSSARY AND DEFINITIONS

In the glossary, short definitions are given for some terms used in this thesis.

BOUSSINESQ APPROXIMATION. Fluid is assumed incompressible, except in the buoyancy term. This restricts the vertical scale of (linear) motion to be much smaller than the atmospheric scale height.

BUOYANCY FREQUENCY. Same as Brunt-Väisälä frequency (N, unit s^{-1}), $N^2 = \frac{g}{\theta}\frac{\mathrm{d}\theta}{\mathrm{dz}}$

BUOYANCY WAVE. Same as GRAVITY WAVE, in which buoyancy acts as the restoring force on parcels displaced from hydrostatic equilibrium.

CRITICAL LEVEL. A level (layer) of discontinuity, where the upstream flow velocity (U) equals the horizontal phase speed (c) of a vertically propagating wave, U(z)=c. There is no significant transmission of wave energy through the critical layer (see discussion by Baines, 1998, Ch. 4.11).

ENVELOPE OROGRAPHY. Empirically defined grid-scale orography where the (multiplied by a constant) standard deviation of subgrid-scale orography is added to the grid-averaged surface elevation.

FORM DRAG. Drag due to the form of the obstacles. In this thesis, the SSO effects are referred to as turbulent form drag and the mesoscale flow blocking as mesoscale form drag.

INVERSE FROUDE NUMBER. Same as NONDIMENSIONAL MOUNTAIN HEIGHT (G_h) or WIDTH (G_a).

FRICTION DRAG. Drag force due to the (smallest-scale) surface roughness. In this thesis, also referred to as turbulent stress.

GRAVITY (BUOYANCY) WAVE DRAG. Force due to the momentum flux divergence related to breaking of (vertically) propagating buoyancy waves, handled by the gravity wave drag parametrizations. In this thesis, parametrization of MSO effects includes parametrization of the buoyancy wave drag combined with the parametrization of the drag due to mesoscale blocking effects (mesoscale form drag).

HYDRAULIC JUMP. In the atmosphere, related to orography: a large-amplitude, stationary or downstream-propagating, low-level mountain wave generated within a stable layer capped by less stable air. The nondimensional mountain height exceeds unity, flow enters the high-drag regime.

INERTIA-GRAVITY WAVE. Large-scale hydrostatic buoyancy wave influenced by Earth's rotation, with a frequency restricted by the Coriolis parameter and buoyancy frequency, $f < \nu < N$.

INVISCID FLOW. Flow without (internal) friction, characterized with large Reynolds number. In the atmosphere, flow above the boundary layer may be assumed inviscid.

LEE WAVES. Same as mountain waves. Sometimes this definition is restricted to the shortest (nonhydrostatic, trapped, horizontally propagating) waves.

LIFT FORCE. Component of form drag force, perpendicular to the flow. In this thesis, used to denote the force due to the interaction of the (quasi-geostrophic) synoptic-scale flow with mountains.

MOUNTAIN WAVES. In this thesis, used to denote hydrostatic and nonhydrostatic, vertically and horizontally propagating stationary waves created by orographic obstacles.

NONDIMENSIONAL MOUNTAIN HEIGHT/WIDTH. Nondimensional parameters relating buoyancy frequency (N) and mountain with (a) or height (h) to the upstream flow velocity (U), $G_h = Nh/U$ and $G_a = Na/U$. See Fig. 4.1 and related discussion.

OROGRAPHIC BLOCKING. Blocking of the stable airflow upstream of mountain ridges, creating mesoscale form drag. In this thesis, blocked-flow drag is handled by the parametrization of MSO effects, combined with the buoyancy wave drag.

OROGRAPHIC CONVECTION. Convective precipitation triggered by orography.

OROGRAPHIC PRECIPITATION. (Non-convective, stratiform) precipitation caused by the upstream lift ascent of air forced by mountains and hills.

OROGRAPHIC ROUGHNESS. Empirically defined enhanced roughness parameter, aimed at parametrization of the subgrid-scale orography effects as surface-layer turbulence. In HIRLAM, orographic roughness has been applied only to the parametrization of subgrid-scale momentum fluxes.

OROGRAPHIC STRESS. In this study, same as TURBULENT (SMALL-SCALE) FORM DRAG.

OROGRAPHIC TURBULENCE. Turbulence related to flow over over small-scale obstacles (such as smooth hills), creating asymmetric pressure distribution and related pressure drag. In this thesis, drag due to the orographic turbulence is taken care by the parametrization of SSO effects.

PRESSURE DRAG. Same as FORM DRAG.

SURFACE STRESS. In this study, same as FRICTION DRAG.

VEGETATION ROUGHNESS. In this thesis, used to denote the roughness parameter due to the smallest-scale surface features like vegetation, rocks, buildings. In HIRLAM, vegetation roughness influences the momentum fluxes and is used as a basis for derivation of the roughness parameter for heat and moisture.

WAVE STRESS. Same as GRAVITY WAVE DRAG.

SUMMARIES OF THE ORIGINAL PUBLICATIONS

I Rontu L., K. Sattler and R. Sigg (2002): Parametrization of subgrid-scale orography effects in HIRLAM. *HIRLAM Technical report*, 56, 46pp.

PAPER I describes implementation of a new parametrization scheme of the mesoscale orography (MSO) effects into the High Resolution Limited Area Model (HIRLAM). This scheme originates in Mèteo France global atmospheric model system (ARPEGE-ALADIN). In the introductory review, main aspects of the orography-related parametrizations in atmospheric models are discussed in general. Parametrization of the mountain waves and blocking effects and related orographic parameters are described. Special attention is paid to the distinction of different horizontal scales below the horizontal resolution of the model equations. Description of the model experiments is preceded by a short introduction to diagnostic methods used in the analysis of the results. The rest of the report is devoted to the analysis and validation of the suggested parametrizations. Both real and artificial flow cases over Scandinavian mountains are studied. Based on the report, a new MSO parametrization scheme has been prepared and accepted for implementation into HIRLAM.

AUTHOR'S CONTRIBUTION. The author of this thesis was responsible for preparation of the manuscript, wrote the review, performed most of the model experiments and analysed their results. The coauthors wrote the description of mesoscale orography parametrization scheme, derived the basic orographic variables and contributed to the analysis of the results as well as to the formulation of the manuscript.

II Rontu L. (2006): A study on parametrization of orography-related momentum fluxes in a synoptic-scale NWP model. *Tellus*, **58A**, 68-81.

PAPER II aims at a systematic presentation of the different subgrid-scale processes and their interactions in the synoptic scale HIRLAM. Methods for parametrization of the smallest-scale orography (SSO) effects are introduced and discussed. A new SSO parametrization scheme is being implemented into HIRLAM following the suggestions of this paper.

III Senkova A.S., Rontu L., Savijärvi H. (2007): Parametrization of orographic effects on surface radiation in HIRLAM. *Tellus*, **59A**, 179-191.

PAPER III is devoted to the parametrization of surface shortwave and longwave radiation fluxes over complex orography. Special attention is paid to a consistent derivation of the needed orography-related parameters from the high-resolution digital elevation data. Applicability of the methods in an atmospheric model of any horizontal resolution and model domain is achieved. The suggested new parametrizations are currently being implemented into HIRLAM.

AUTHOR'S CONTRIBUTION. The author wrote the general description of the methods. She was responsible for the preparation of the orography-related parameters as well as the design of the model experiments and related diagnostic methods. The author participated in performing the model experiments and analysing of the results. The coauthors did the basic work in formulation of the equations and methods, in performing the experiments and preparing the figures.

IV Rontu L. (2006): Vorticity budget over mountains diagnosed from HIRLAM analyses and forecasts. *Meteor. Z.*, **15**, 199-206.

PAPER IV contains an attempt to apply the budget of absolute vorticity to the analysis of resolved and parametrized surface torque in the synoptic scale HIRLAM. The budget, based on numerical analyses of the model, is formulated in the hybrid coordinate system of HIRLAM. Large part of the paper is devoted to discussion of advantages and disadvantages of the proposed method. The method described in the paper could be developed and applied in validation of parametrizations of momentum fluxes.

In Appendix (Corrigendum) are listed minor errors, found in PAPER I - PAPER IV after publication.

Appendix: Corrigendum

Paper I

Paper I is included into this thesis in the form containing the original corrigendum, concerning pages 8 and 14. p. 22 first paragraph, p. 26 second paragraph: instead of the tendencies of wind components (u- and v-tendencies), in Fig. 6 and all consequent vertical profile figures, the tendencies of resolved-scale kinetic energy are shown, as correctly explained in the figure captions. The last sentence at p.26 “The area averaged wind speed decreases ...” should be deleted.

Paper II

SSO slope values shown in Table 3 and Fig. 3 contain a conversion error: they should be multiplied by a coefficient 5.7, i.e. s_t(correct)=5.7 s_t(article) Reference to Wilson, 2003, J.Atm.Sci,99,... should be replaced by Wilson, 2002, J.Atm.Sci.,59,...