REQUEST FOR A SPECIAL PROJECT 2012–2014

MEMBER STATE: Austria

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Project Title: Numerical modelling of boundary layer processes over complex terrain

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ________________	
Starting year: (Each project will have a well defined duration, up to a maximum of 3 years, agreed at the beginning of the project.)	2012	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2012-2014: (The maximum project duration is 3 years, therefore a continuation project cannot request resources for 2014.)	**2012**	**2013**	**2014**
High Performance Computing Facility (units)	230000	230000	
Data storage capacity (total archive volume) (gigabytes)	1800	1800	

An electronic copy of this form ***must be sent*** *via e-mail to:* *special_projects@ecmwf.int*

Electronic copy of the form sent on (please specify date): 28th April 2011

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[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide an annual progress report of the project's activities, etc.

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Extended abstract

It is expected that Special Projects requesting large amounts of computing resources (500,000 SBU or more) should provide a more detailed abstract/project description (3-5 pages) including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The Scientific Advisory Committee and the Technical Advisory Committee review the scientific and technical aspects of each Special Project application. The review process takes into account the resources available, the quality of the scientific and technical proposals, the use of ECMWF software and data infrastructure, and their relevance to ECMWF's objectives. - Descriptions of all accepted projects will be published on the ECMWF website.

In recent years, large-eddy simulations (LES) have been frequently used to improve the knowledge of micrometeorological phenomena occurring over non-homogeneous terrain. The range of possible applications is extremely broad: initiation of deep moist convection over modest orographic obstacles (Kirshbaum, 2011); dynamical response of valley breezes to changes in the curvature of the valley axis (Weigel, et al, 2006); advective and turbulent heat transfer processes within the convective boundary layer in valleys (Serafin and Zardi, 2010); sensitivity of katabatic winds to changing slope angle or transversal ambient flow (Smith and Skyllingstad, 2005); interaction between gravity waves and the boundary layer (Doyle and Durran, 2007).

The focus of the present proposal is on two further topics in mountain meteorology that require high-resolution simulation of boundary-layer dynamics: (I) The characterization of turbulent anabatic flow and of its sensitivity to forcing factors such as slope angle and background stability, surface roughness, surface heat fluxes, transverse ambient flow. (II) The study of wave-induced boundary-layer separation in the lee of orographic obstacles and of the dynamics of the related rotor circulations and highly turbulent sub-rotor vortices.

In both research lines, idealized simulations will be carried out with state-of-the-art numerical weather prediction codes with LES capability. The study will lead to a greater insight in the properties of atmospheric turbulence in mountain regions, both in conditions of strong buoyant turbulence production (research line I) and in conditions of strong dynamic forcing (line II).

The long-term aim of the proposed research is to help improve boundary-layer parameterizations in coarse-resolution numerical weather prediction and climate models, which still today adopt approaches that are only appropriate above flat ground – and therefore not rigorously applicable to large portions of the Earth's surface. In particular, findings from this project are expected to provide useful information for improving the parameterization schemes of vertical heat fluxes and of subgrid-scale orographic drag in general circulation models. Answers to the following questions will be sought: how do slope and valley breezes interfere with convective heat transfer in the boundary layer (research line I)? How do boundary-layer separation and low-level wave breaking impact the vertical transport of momentum (research line II)?

I. Turbulent anabatic flow

Serafin and Zardi (2010) recently used LES to investigate the different diurnal development of the convective boundary layer over flat land and over mountainous terrain. They introduced the concept of a "valley boundary layer", where the vertical transport of heat is determined by the interplay between turbulent convection at the valley floor and advective transfer along the valley walls (through upslope winds) and within its core (through compensating subsidence). This depiction of the flow field suggests that the pressure gradient that causes valley breezes would not be caused by the confinement of the surface energy input below mountain tops, as commonly postulated, but rather arise as a consequence of the downward mixing of potentially warm air masses from even higher altitude. Besides being a key factor in creating the density imbalances that drive valley breezes and plain-to-mountain winds, slope circulations strongly affect the ventilation of valleys and therefore the dispersion of pollutants in their vicinity: upslope winds detach from the ground at mountain tops or at sharp variations in the slope angle, forming plumes that can transport pollutants from the valley towards the free atmosphere. However, the relevance of upslope winds for the thermodynamic structure of the lower and middle atmosphere, as well as for the transport of pollutants, is not completely understood: very few quantitative studies of the heat and mass fluxes between a valley and the free atmosphere have been carried out so far (e.g., Noppel and Fiedler, 2002). This motivates further analysis of the salient features of anabatic flow.

The phenomenon is very common in the atmospheric boundary layer over hilly and mountainous areas during clear-sky days: when the near-surface atmosphere is subject to heating from the ground, density and pressure gradients are established between the air in the immediate vicinity of the slope and the air at the same level in the valley core. In these conditions, the vector sum of the buoyancy force (related to density perturbations) and of the pressure gradient force (related to pressure perturbations) is such that air parcels near the ground are subject to upslope acceleration.

The first model of upslope flow was provided by Prandtl (1952), who defined a simplified equation set expressing the conservation of momentum and of thermodynamic energy for a fluid near a heated (or cooled) sloping surface, under the hypothesis of laminar flow and constant thermal forcing from the ground. Prandtl’s seminal treatment neglected a lot of important features of natural upslope flows, in order to make the problem amenable to analytical solution. Such features include the invariably turbulent nature of near-surface motion and the effect of spatial and temporal variations in several important parameters. These include: (1) the surface heat flux, (2) the slope roughness, (3) the background atmospheric stability and (4) the possible occurrence of a transverse ambient flow. A complete investigation of the impact of these factors is only possible by means of numerical modelling.

The only known research effort in this direction was made by Schumann (1990), who implemented a three-dimensional LES model of turbulent flow in a cartesian, rotated reference frame (with one axis parallel to the slope), and examined the impact of changing slope angles and surface roughness on the turbulent structure of the upslope boundary layer. In the present project, Schumann’s work will be extended considering a wide range of variability for the slope angle and for each of the four variables outlined above.

LES with a modified version of the ARPS model, where the coordinate system is transformed to allow for sloping lower boundaries, will lead to a complete characterization of atmospheric turbulence within the upslope flow region. The study will include an evaluation of the statistical properties of turbulent fluctuations in the upslope flow and will allow assessing the validity of the Monin-Obukhov Similarity Theory in sloping boundary layers. A detailed examination of the slope-normal variation of all terms in the turbulent kinetic energy budget will be performed. A preliminary investigation of the possible occurrence of coherent structures in upslope-boundary-layer turbulence (e.g. roll vortices moving upslope) will also be undertaken.

II. Wave-induced boundary layer separation

Adverse pressure gradients associated with lee waves may force the atmospheric boundary layer to separate from the ground surface on the lee side of orographic obstacles. Near-surface winds blowing opposite the prevalent flow downstream of the separation line are often observed in this case. The regions of recirculation of the flow about a horizontal axis beneath wave crests are known as rotors and may pose serious threats to aircraft, due to the severe intensity of turbulence encountered therein. While the first observations of atmospheric rotors date back to the ’30s, the investigation of their dynamics by means of numerical simulation was undertaken only recently, highlighting that extreme turbulence is related to subrotor vortices forming along the separation line, due to strong shear and the related Kelvin-Helmholtz instability (Doyle and Durran, 2007). Recent advances in the characterization of atmospheric rotors, both from an observational and a modelling point of view, followed the T-REX campaign held in the lee of the southern Sierra Nevada (eastern California, USA) in spring 2006 (Grubišić et al, 2008).

As mentioned, numerical simulations allowed considerable advance in understanding the dynamics of wave-induced boundary-layer separation. However, virtually all of the numerical experiments carried out so far considered flow over idealized, essentially two-dimensional topography (e.g. a linear mountain range with axis normal to the prevalent flow). Recently, observations of rotor and subrotor vortices in the lee of a three-dimensional orographic obstacle were performed with an airborne W-band Doppler cloud radar in the vicinity of the Medicine Bow range (Wyoming, USA; Grubišić et al 2009). The availability of these observational data provides a unique opportunity to study boundary-layer separation in the lee of three-dimensional obstacles, and a benchmark for the verification of model simulations in a physically more realistic framework. Observations show that significant displacements of the separation line on the lee of the mountain can occur in a rather short time frame (8 km in around half an hour), despite a relatively steady flow upstream.

Theoretical analyses (Ambaum and Marshall, 2005) and wind tunnel observations (Baines and Hoinka, 1985) of flow past a 2D obstacle show that wave-induced boundary layer separation occurs preferentially on the lee of relatively high obstacles (in terms of a non-dimensional height Nh/U, h being the obstacle height, N the Brunt-Vaisala frequency and U the wind speed) with gentle slopes. However, the process causing the onset of a non-stationary regime is still unclear. Preliminary two-dimensional simulations suggest that the intensity of the surface momentum flux may play an important role in this behavior. Dynamical effects related to the 3D structure of the flow field may also be important (Doyle and Durran 2007).

Semi-idealized simulations will be performed using the CM1, WRF and ARPS models in order to gain further insight in the dynamics of boundary-layer separation. Model runs in domains with smoothed realistic 3D topography will be initialized with vertical soundings representative of the flow field at the time and place of the available observations (southern Wyoming, January 2006). Sensitivity runs with different air-land interaction schemes and varying friction parameters (e.g., increasing or spatially variable surface roughness) will be performed, in order to identify appropriate scaling functions and investigate the parametric range under which non-stationary boundary-layer separation may occur.

Technical details

Several numerical models will be employed in the present project. They include the ARW-WRF and CM1 models, developed and maintained by NCAR; and the ARPS model, developed and maintained by the Center for Analysis and Prediction of Storms at the University of Oklahoma. All models have been widely tested on a variety of computing platforms and can easily be optimized in different compilation environments, including XLFortran. All models support MPI parallelization through a 2D Cartesian domain decomposition, and automatic OpenMP shared-memory parallelization at compilation time. Therefore, they can be run as mixed MPI/OpenMP applications, fully exploiting the simultaneous multi-threading capabilities of computing nodes. Data I/O, managed by a single processor in all three models, is either in NetCDF or in HDF format. Preliminary simulations suggest that the average requirement for a typical 3D LES run is on the order of 1200 CPU hours, i.e. approximately 23000 ECMWF SBUs. We plan to perform around 20 such runs (10 in research line I and 10 in research line II): ECMWF computing facilities would only be used for production runs, after carrying out preliminary tests in house. This plan motivates a request of 460000 SBUs for the years 2012-2013. The average output size from a single LES may be of around 100 gigabytes, implying the necessity of a total storage capacity of approximately 3.5 terabytes (3584 gigabytes).

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