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LIST OF ABSTRACTS

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Quantifying the influence of local meteorological conditions on air quality in Zagreb using generalized additive models

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The research area which defines the influence of meteorological parameters on air quality in Croatia has developed rapidly over the last decade. This paper presents an estimated response of hourly air pollutants (carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter (PM_{10}) in Zagreb, Croatia to local scale meteorology in the period 2006-2012. High concentration of these pollutants has a major impact on human health and air quality. The increase of concentration in urban areas is not just a result of sudden emission, but also a result of meteorological conditions which can prevent dispersion or accumulate pollutants at a particular site.

A general model is presented, where the logarithm of hourly concentration of an air pollutant is modelled as a sum of non-linear functions of meteorological and several time variables. Time variables have been included to control emissions. The model can be estimated within the framework of generalized additive models (GAMs) and is additive on the logarithmic scale, which results in multiplicative effects on the original scale. Although the model is non-linear, it is simple and easy to interpret. It quantifies how meteorological conditions and emissions influence the level of air pollution. A measure of relative importance of each predictor variable and a statistical evaluation of the model are also presented.

Overall, results found that the most important predictor variables are those related to emissions. The aggregate impact of meteorological variables in the model explained 45% of the variance in CO, 14% in SO_2, 25% in NO_2 and 24% in PM_{10}. This indicates that meteorology, at a local scale, is a relatively strong driver of air quality in Zagreb. Stable atmospheric conditions, in the urban area, go in favor of higher concentration of air pollutants, having a negative impact on human health. The convection processes dominate in unstable conditions and ventilate the boundary layer.

Anthropogenic influence on mesoscale weather – an example of construction of the man-made lake

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The mesoscale Weather Research and Forecasting (WRF) model (Version 3.3) was used in order to assess possible modifications of the surface meteorological conditions due to construction of a small, man-made lake in midlatitudes. WRF was applied to four real typical synoptic situations for which the area of interest was under the influence of a wintertime anticyclone, summertime anticyclone, wintertime cyclone and a summertime cyclone. Each of these four real synoptic setups was simulated twice – once with assuming the present state and again with assuming the existence of the new lake. To better represent complex topography and other surface characteristics of investigated heterogeneous area, double-nested simulations with three domains were performed, where results obtained at the finest horizontal resolution (1 km) were considered relevant. Results showed noticeable changes in the surface temperature and relative humidity as well as a small increase of the mean surface wind speeds in the air above the newly constructed lake. At other portions of the investigated area average differences produced by the new lake were neglectable. However, in individual hours, the differences were occasionally quite high, especially for cyclonic episodes. Finally, results suggest a slight enhancement of slope winds produced by existence of a new lake.

Imbalance of the Surface Energy Budget and role of the terrain heterogeneities

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The surface energy budget (SEB) at the atmosphere-surface interface is a tool widely used in a large number of applications, ranging from numerical modelling to agricultural managing or remote sensing algorithms. It is customarily taken as an equilibrium equation between the main forcing term (the net radiation) and the three major response mechanisms (sensible and latent heat fluxes and heat flux in the soil). This approach implicitly assumes stationarity (no storage term) and homogeneity of the interface (flat terrain with no different land characteristics - patchiness).

However, the emerged lands are neither flat nor homogeneous, and the mentioned hypotheses may be questionable. In fact, it is now accepted that imbalances between 5 and 20% are common using half-hour averages, even in almost flat terrains with a low degree of land use heterogeneity. In this talk the imbalance is computed for two measuring sites. The first one, at the south side of the Pyrenees, is in a locally flat area and with a low degree of heterogeneity (crops). For it, the imbalance is computed and compared with the main terms of the budget. It increases linearly with the value of the other fluxes and amounts approximately 20 to 30% of the value of the Net Radiation. The imbalance has similar values as the turbulent and ground heat fluxes.

The second site, at the Northern foothills of the Pyrenees, is located in a locally flat area, but with a relatively large land-use heterogeneity. Here the data gathered during the BLLAST experiment during June and July 2011 are used estimating the order of magnitude of the advection term, which is customarily neglected in the SEB equation. We make use of data provided by model runs, satellite images and thermal cameras on board remotely-controlled aerial systems to evaluate the temperature variability and infer the order of magnitude of the advection term. Results indicate that, at scales close to 100 m, the terrain heterogeneities may generate persistent circulations that could contribute with several tens of W/m^2 to the SEB equation, therefore explaining partially part of the observed imbalance.

Influence of WRF parameterization on air quality modeling

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Within the research with the NWP *WRF* model, various tests were made with implementation of the new, improved mixing length in MYJ PBL scheme. Default and modified setup of the NWP *WRF* model were both later coupled with dispersion models. This study presents the continuation and exploration of the research by application of regional and high resolution air quality models. On larger scale regional *EMEP* model was used to simulate long range and trans-boundary transport of various pollutants during the episode of high PM10 values when observed daily values reached ~ 140 $\mu g/m^3$ at stations in continental part of southeastern Europe. Furthermore *CAMx* high resolution model was applied to evaluate the contribution of local anthropogenic sources. Experiments with AQ models encompassed different time periods. Using complex atmospheric chemistry models it was possible to analyze the main processes contributing to the relatively high concentration on regional and local scale and to compare the performance of two different air quality models.

A nested large-eddy simulation study of the Ora del Garda wind in the Alps

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High-resolution numerical simulations performed with the Weather Research and Forecasting (*WRF*) model are analyzed to investigate the atmospheric boundary layer (ABL) structures associated with the development of a lake-breeze and valley-wind coupled system developing in the southeastern Italian Alps, the so-called “Ora del Garda” wind. Five domains were nested for the simulations: three mesoscale domains, forced by reanalysis data field, are used to drive the finest two domains, in which the large-eddy technique is used, achieving a final horizontal resolution of 0.133 km. Model results complement an existing dataset composed of a series of measurement flights and surface observations. The flights explored specific valley sections at key locations in the study area, namely over the lake’s shore, at half valley and at the end of the valley where the breeze blows. Model results display a good agreement with the experimental dataset. In particular, the surface diurnal cycles of radiation, wind, air temperature and sensible heat flux are satisfactorily reproduced, despite some discrepancies in the timing of thermally-driven circulation onset and offset. The typical structure of the valley ABL, characterized by shallow or even absent mixed layers surmounted by slightly stable layers extending up to the lateral crest level, is also well reproduced in the simulated fields. Moreover, the simulations confirm characteristic local-scale features of the thermally-driven wind field suggested by the analysis of the airborne dataset as well as from previous observations in the area. For example, the model shows the development of inhomogeneities in the cross-valley thermal field, caused by the propagation of the lake breeze and by the different heating between the sidewalls of the valley, as well as the formation of a hydraulic jump in the area where the Ora del Garda flows down into an adjacent valley from an elevated saddle.

New developments of Prandtl model for simple slope flows

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The model of Prandtl combines concisely the 1D stationary boundary-layer dynamics and thermodynamics for pure katabatic and anabatic flows over simply inclined surfaces by assuming the balance between buoyancy and turbulent friction. A weakly nonlinear version of Prandtl model is developed recently by the authors (QJRMS 2014, in press). There, a small parameter, that is estimated carefully, controls feeding of the flow-induced potential temperature gradient back to the environmental potential temperature gradient since the former, under the katabatic jet, can be ~ 50 times stronger than the latter, background or free-flow gradient. Hence, the near-surface potential temperature gradient becomes stronger and the corresponding katabatic jet gets somewhat weaker and at a lower height than that in the classical Prandtl solution.

The new model is compared to the glacier wind data from Pasterze, the Austrian Alps. Further discussion includes gradient Richardson number and an application to simple anabatic flows. The effect of weak nonlinearity, although noticeable, seems to be of a lesser importance than the effect of a prescribed, gradually varying eddy diffusivity/conductivity, K(z), considered within the usual validity of the zero-order WKB approximation. We also tackle the energetics of Prandtl model in order to further elicit the interplay among turbulent production, diffusion, dissipation and temperature-wind interaction. Questions on how to implement Prandtl model, as a sub-model for inclined surface layers, into mesoscale models will be raised and possibly promoted.

Evaluating regional climate models over complex topography

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Several examples of the evaluation of regional climate models (RCMs) over complex topography will be presented. These include: (1) evaluation of an ensemble of RCMs at the 25-km horizontal resolution over the Croatian Adriatic coast against 2m air temperature and total precipitation measurements from the operational DHMZ network; (2) sensitivity study of an increasing resolution (50, 25, 12 and 6 km) in RCM RCA3 on the realism of the simulated total precipitation field over regions of complex topography; (3) estimation of the systematic errors in a 50-km and 12-km simulations using RCM RegCM4 in comparison to a suite of satellite-based products. Both limitations in regional climate models and observational datasets will be stressed and possible impacts of the systematic errors on the projected climate changes will be discussed.

Bora flow over the complex terrain of the mid-Adriatic area

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While severe northern-Adriatic downslope windstorms are since long in the focus of interest, strong bora winds in the hinterland of mid-Adriatic coast are much less studied, yet frequent and equally severe phenomena. The predictability of these events is considerably lower than for its northern counterpart due to the inflow complexity induced by the upwind chain of secondary orographic steep mountain sub-ranges and deep valleys.

A strong late-winter anticyclonic bora event at the mid-Adriatic was analyzed with the use of ultrasonic measurements, a SODAR and numerical sensitivity experiments carried out with the *WRF* model. The three-dimensional bora flow was characterized by a shallow bora layer, a pronounced directional vertical wind shear, and interaction with valley circulations in deep valleys. Sensitivity simulations with several secondary mountain sub-ranges individually withheld from a set of simulations reveal that bora flow downstream of the primary mountain range is largely determined by the secondary orography, which promote the the hydraulic-jump type of flow recovery. Nevertheless, this may not necessarily imply significant non-local effects, such as for bora strength over the Adriatic Sea. During the event, two regimes of sub-mesoscale pulsations were found: i) Regime A – pulsations observed predominantly during the night and morning hours with periods of 5 – 8 minutes and ii) Regime B – pulsations observed predominantly during the afternoon with periods of 8-11 minutes. According to the model simulation, pulsations of regime A propagated far away from the point of origin, while pulsations of regime B quickly dissipated during the stable nighttime conditions. The roles of gravity-wave breaking, Kelvin-Helmholtz instability and surface fluxes were analyzed to study the formation and development of pulsations. Finally, main differences in the bora subtle structure, there and over the northern areas, the latter pertaining to more known bora cases, are pointed out.

Evaluation of the ability of progressively finer MNWP models to reproduce wind regimes over complex terrain

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In the complex terrain of the eastern Adriatic where wind climate is governed by regional/local winds, it is beneficial to utilize a chain of numerical models to refine the associated wind predictions. The principal questions we address are (i) whether an increase of model chain resolution improves the accuracy and (ii) could simplified, computationally cheaper mesoscale meteorological models be used in the model chain for assessment and forecasting of wind properties?

To answer the above questions wind forecasts from Aire Limitée Adaptation dynamique Développement InterNational (*ALADIN*) Mesoscale Numerical Weather Prediction (MNWP) model with 8 km horizontal grid spacing were used in period 2010-2012. Those forecasts were further refined to 2 km grid spacing using: i) full physics model forecasts, and ii) so-called dynamical adaptation method (DADA) over subdomain that covers broader area around Croatia. Statistical and spectral verification were performed for three different forecasting setups using measured wind speeds from several meteorological stations that represent different climate regimes of Croatia.

Based on variety of statistical scores as well as spectral measures inferred in frequency domain, the performed verification suggests that the results generally improved with increasing the model resolution. The largest portion of errors can be attributed to phase errors. The most significant increase of accuracy was found for statistical scores related to wind variability, in particular for diurnal periods of motions. Furthermore, DADA forecasts have proven to be successful in forecasting wind properties on a majority of stations, but at some stations near the very coast and steep terrain, the DADA method showed less appropriate to represent regional/local wind systems than the full-physics model. Finally, kinetic energy, vorticity and divergence spectra were studied to provide scale-dependent measure of model properties as well as to study the gross effects of horizontal diffusion on the effective model resolution.

Development of eddy diffusivity method based on LES simulations in convective atmospheric boundary layers

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Parameterization of eddy diffusivity introduced by the turbulence closure theory that represents strength and intensity of vertical mixing in the atmosphere is very important for air quality simulations. The vertical eddy diffusion coefficient (Kz, where z is height) is usually the main quantity in numerical models of the atmosphere for vertical distribution of different atmospheric properties and pollutants. Not much is known about the structure and the strength of mechanical vertical diffusion in convective conditions. The main goal of our work is to introduce a robust exponential approach to the Kz calculation that is applicable in stable as well as in convective conditions. Work is an extension of relatively recently developed method that was applied for stable conditions. Advantages of this relatively new analytical form of are confirmed with large-eddy simulation (LES) data. New scheme has also been applied in the atmospheric chemical Unified *EMEP* model to test their impact on the simulation of surface concentrations.

A multipurpose microcontroller-based data acquisition system for meteorological measurements

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In order to explore and evaluate a number of different meteorological models and parameters, a quality high-speed data suitable for such purpose needs to be collected and processed.

This paper presents a novel general-purpose meteorological data acquisition and logger system. It is implemented based on a Texas Instruments TivaC microcontroller, and has a possibility to scan up to 16 analogue and 4 digital sensors together. Analogue inputs have the voltage range from 0 to 5V, possibility of operation in differential and single-ended mode with a resolution up to 23 bits and sampling rate up to 1 kHz. Digital inputs are RS485 and RS232 compatible, with hardware handshaking and flow control. The system has a GPS receiver and a backup real-time clock built-in for the purpose of off-line measurement synchronization (data samples time-stamping) between several geographically distributed measurement locations. Analogue and digital data time stamping resolution is 1us. The measured data is stored in a removable, non-volatile random access memory (SD card) each hour for one month. Measurement set-up, control and monitoring is done over the mobile data network. This system is versatile and easily transportable. To verify its operation and specification, a number of measurement system performance tests and a comparison with another commercial data-acquisition system have been carried out and presented.

Wind forecast verification during bora events at the Dubrovnik airport

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The bora flow is prominent in the lee side of Dinaric Alps where several airports are situated. Essentially related phenomena such as severe gusts, turbulence or wind shear are can disrupt air traffic at the airports. It is emphasized even more if wind is perpendicular to the runway direction as is case at the Dubrovnik airport. Some results of wind forecasts verification of the routine forecast will be shown.

The data used for the verification are TAF and METAR reports during the period 2009-2013. They contain hourly values of short-range forecasts (24 hours) and observed reports every half-hour. A method similar to the Austro Control TAF verification system is applied in Croatia Control Ltd. Moreover, ALADIN model results is used for determine type of flow (shallow or deep). The bora is dominantly driven by large scale, hence it is rather well forecasted. The wind roses of observation, model and human forecasts are similar. Inferior forecasts are found at the end of the forecast period and when significant influence of small mesoscale phenomena exists. The most severe gusts have higher False Alarm Ratio that is inherent to a rare (observed) event. The verification results according to type of flow show better scores for in-situ forecasters then for the allocated ones. Although the bora flow is essentially turbulent, verification of 10minutes wind direction is very good according to aviation requirements.

MET service provision challenges related to bora at the Dubrovnik airport

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Bora wind is the most significant and the most dangerous wind at Dubrovnik Airport. It is characterized by wind gusts, with direction which is perpendicular to the runway. The mean wind speed of bora is often above the maximums for crosswind set by airlines and aircraft manufacturers causing many problems in flight operations such as diverting and even cancelling flights which is especially troublesome issue since the city and region of Dubrovnik are in an isolated position in Croatia and EU, surrounded by sea and non-EU states. Besides all aforementioned it is estimated that over 60% of tourist nights in Dubrovnik area are realized by the tourists arriving by air traffic, and tourism is by far the principal source of income for the city and its region.

The orography around Dubrovnik Airport is very complex. Mountain ranges as high as 1000 meters above the runway elevation lie very close (~1-2 km) and perpendicular to the runway and the aircraft approach direction, making the area very challenging for NWP, especially for operational mesoscale models. Different heights of the terrain upstream of the bora flow at different sides of runway cause different surface wind measurements during bora episodes at different runway thresholds. Also, two types of bora episodes have been recognized by the aeronautical forecasters over the years: shallow bora and deep bora (with or without the critical level above). It has been shown by measurements that the wind at the surface is much more variable in mean wind speed, direction and gusts during deep bora events, which presents a bigger safety issue during air traffic operations.

Croatia Control Ltd. and its MET Department (MET service provider in Croatia) are headlining an efforts to start a research project related to the above mentioned issues aiming to create a detection and forecasting decision-making system for aeronautical forecasters and users to increase safety, capacity and efficiency.

Wind-tunnel experiments on flow and turbulence in complex terrain

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An extensive set of experiments was carried out in the CRIACIV boundary layer wind tunnel in order to characterize flow and turbulence in the wake of an offshore wind turbine placed in the vicinity of a complex coastal terrain. The wind-tunnel simulation of the atmospheric boundary layer (ABL) flow and turbulence developing upwind from the coastal mountain was achieved by using the *Counihan* method including castellated barrier wall, vortex generators and surface roughness elements. Once a well-developed ABL simulation has been created, wake characteristics of a single offshore wind turbine placed downwind from the coastal mountain were studied for three different mountain models. A configuration without the mountain was tested as well in order to investigate flow and turbulence around an offshore wind turbine placed downwind of a plane coast. The wind turbine was in the parking position (no rotation of the rotor blades) in order to simulate wind characteristics for a strong wind situation. The experimental results indicate a velocity decrease and stronger turbulence in the wind-turbine wake in presence of a coastal mountain.

Characterization of the solar irradiation field for the Trentino region in the Alps

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Well-developed thermally driven flows (like up-slope and up-valley winds) are typically observed during daytime on fair-weather, sunny days. They are driven by the differential heating of the air column respectively over flat and sloping terrain, and over a plain and inside a valley. These differences greatly depend on the spatial heterogeneity of the solar irradiation field, as well as on the complex morphology and the land use of the underlying terrain. As matter of fact, the above factors produce a heterogeneous distribution of sensible heat fluxes at the ground surface, determining the fingerprint of the local thermally-driven wind systems. For example, differences in insolation between two valley slopes may induce asymmetric up-slope circulations, which may even “degenerate” into a unique cross-valley circulation, leading to situations highly different from what foreseen by ideal circulation schemes. Moreover, solar irradiation represents not only one of the primary factors in determining spatial and temporal patterns of local thermally-driven winds, but also the structures and the evolution of the associated atmospheric boundary layer (ABL).

In order to understand the processes inducing the typical variability of slope and valley winds as well as of the associated ABL structures developing over complex terrain, a proper characterization of the local field of solar irradiation is needed. This contribution presents a set of high-resolution (200 m), climatological maps of monthly mean solar irradiation for the small Alpine region of Trentino (Italy). The maps are calculated on the basis of ground-based observation of global radiation from the local radiometric network, by combining the use of a clear-sky radiation model (r.sun, GRASS GIS software) and geostatistical mapping methods (residual kriging). They are part of the Solar Atlas of Trentino, which is intended to represent a useful tool for the assessment of available solar resource, e.g. for photovoltaic applications.

Some features of near-ground bora turbulence

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Bora wind creates considerable difficulties for structures, traffic and human activities. Further research is therefore required to fully elucidate Bora wind characteristics. In this study, an analysis of unique 3-level high-frequency Bora measurements was performed. The obtained results indicate a good agreement between the average velocity profiles of the Bora wind with the power-law and logarithmic-law approximations. An interesting feature is an increase in the power-law exponent and aerodynamic surface roughness length, and a decrease in friction velocity with decreasing Bora wind velocity. This suggests a rural-like velocity profile for larger wind velocities and an urban-like velocity profile for smaller wind velocities. Variations in velocity profiles at the same site during different wind periods are interesting for itself, as in the engineering community it has been commonly accepted that the aerodynamic characteristics at a particular site remain nearly the same during various wind regimes. Bora turbulence proved to be predominantly generated mechanically due to an intense mixing, while the thermal effects were observed to be negligible, as the stratification of the atmospheric surface layer is near-neutral. Another interesting feature is an increase in turbulence intensity and a decrease in turbulent Reynolds shear stress with decreasing Bora wind velocity and vice versa.

Inter-annual variability of CO_2 fluxes measured at mixed forest of pedunculate oak with eddy covariance

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Estimating annual net ecosystem productivity (NEP) with traditional forestry methods is difficult and virtually impossible at shorter time scale, therefore a different approach is necessary. Micrometeorological method of eddy covariance (EC) has become a standard method for measurement of net ecosystem exchange (NEE) of CO2 i.e. direct, high-frequency (typically half-hourly), measurement of NEP (NEP =   NEE).

In September 2007 we have set up EC tower in a 35-year-old mixed stand of pedunculate oak (Quercus robur L.) for estimating NEP. In addition, we have set up a soil respiration (Rs) measurement system and a conducted a series of periodic ancillary measurements (dendrometer bands, litterfall) in order to obtain independent estimate of NEP.

We present here the results of three years (2008 – 2010) of measurement of NEE. Measured raw fluxes of NEE were checked for quality and gapfilled according to Reichstein et al. (2005) to obtain estimate of annual fluxes. NEP was partitioned into gross primary productivity (GPP) and ecosystem respiration (Reco) according to Lasslop et al. (2010). Gapfilling and flux partitioning was performed with on-line tool of Max Plank's Institute of Biogeochemistry. NEP in 2008, 2009 and 2010 was estimated to 280, 393 and 221 gC m-2 yr-1, respectively, while GPP was 1424, 1424 and 1482 gC m-2 yr-1. Reco was estimated to 1143, 1031 and 1261 gC m-2 yr-1, while measured Rs amounted to 999, 993 and 984 gC m-2 yr-1 in 2008, 2009 and 2010, respectively. Of the investigated three years, the 2010 was the wettest one and soil saturation with water was frequent during vegetation season. At the same time, for 2010 we obtained highest Reco and lowest Rs. Such result is counter-intuitive, since Rs is part of Reco. One of possible explanations is that overestimation of GPP and Reco occurs during soil saturation events when both GPP and Reco are limited by hypoxic condition in soil, indicating that existing gapfilling and flux partitioning should be re-evaluated. Further research is needed in improving of gapfilling and flux partitioning methods.

Investigation of land surface atmosphere feedback combining WRF simulations with water vapor DIAL measurements

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Land-surface-atmosphere (LSA) feedback is a key controlling factor of weather and climate from local to global scales. Between most variables in the LSA system a two-way coupling exists, such as between soil moisture and precipitation. In contrary to this, often atmospheric variables have been considered as “forcing” of land surface models (LSMs), which led to substantial errors in the simulations of land-surface exchange such as evapotranspiration. Better understanding of LSA feedback processes will improve performance of the weather and climate models, and therefore it is essential to investigate the whole model chain across all compartments of the LSA system.

In the WRF model planetary boundary layer (PBL) schemes and LSMs are strongly coupled, since surface fluxes calculated in a LSM represent lower boundary condition in a PBL scheme. We investigate sensitivity of the model to 5 PBL schemes and 2 LSMs in simulating the PBL features such as the grid-cell averaged humidity profiles, the PBL height, the PBL development in the course of a day, etc. Seven simulations were carried out in 36-hour cycles over 26-day period for western and south-western Germany on 2 km horizontal resolution and with 89 vertical levels. For process studies and model verification we use high resolution measurements performed with water vapor differential absorption lidar (WVDIAL) of University of Hohenheim.

We will demonstrate advantages of the WVDIAL measurements in investigating the PBL features. One day case study showed significantly higher sensitivity of WRF to the LSMs than to the PBL options, which is evident not only in the lower PBL, but it extends up to the entrainment zone and the lower troposphere. Furthermore, we deploy the mixing diagram approach as introduced in Santanello et al. (2009) to demonstrate the simulated influence of the land-surface and the entrainment on the PBL evolution on diurnal timescales.

Persistency as a reference in determining rare event forecasting skill

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In this work skill score with persistency forecasting as a referent model (SSp) is defined using several verification measures such as accuracy, critical success index, polychoric correlation coefficient and other widely used skill scores (Heidke skill score, SEEPS, etc.). Persistency forecasting used in determining skill, unlike random chance, gains from information of current weather. Question that needs to be answered is: will SSp appropriately describe skill of rare event forecast?

Score SSp is tested at climatologically different locations on daily cumulative precipitation forecasts of two numerical models:

• *ALADIN* (Aire Limiteé Adaptation Dynamique dévelopement InterNational) regional model with 8 km horizontal resolution

• *ECMWF* (European Centre for Medium-Range Weather Forecasts) global model with 0.25° grid spacing.

Precipitation is considered as a categorical predictand with three categories: dry, light and heavy precipitation. Dry category dominates the contingency table, while heavy precipitation is considered as rare event. Skill score defined in this way inherits characteristics of original measure (M) that is used to create it, but it has lower value than M. Difference between SSp and M enlarges if average M value reduces or if value of original measure for persistency forecasting (P) enlarges. The latter is important because P is high for climatologically frequent categories such as dry weather, but low for rare event categories. This way correct forecasting of rare event is rewarded more than correct forecasting of common event. Including information about current weather in determining skill efficiently reduces sensitivity to climatological probability of defined categories. Consequently, SSp appropriately describes the skill of rare event forecasting and should be used for evaluation, validation or inter-comparison of different numerical and physical schemes.

Wind speed ensemble predictions with an analog-based method in complex terrain

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The chaotic nature of the atmosphere and the imperfections of mesoscale models mean that there is a need to improve them even more, as well as provide information about their uncertainty. Analog ensemble (AE) method can do both. The first step to build AE method is the search for similar (i.e. analogs) past predictions across several variables (e.g., wind speed, wind direction, temperature) to the current prediction. Then, the measurements corresponding to the analogs form the AE. The AE can be used to generate both deterministic and probabilistic short- or medium-range forecasts. The AE was generated by *ALADIN* mesoscale model run over two nested domain with 8 and 2 km horizontal resolution, respectively and simplified, dynamically downscaled model with 2 km grid spacing (DADA). Several different deterministic AE forecasts were tested (AE mean and median, AE weighted mean, Kalman filter of AE means etc.) at three climatologically different regions across Croatia for point-based wind speed predictions at 10 m height. Results were verified and compared to starting model to address the following questions:

- How many analogs is needed to produce the optimal results?
- How much these analog – based methods improve starting model and what is the difference between them?
- What is the impact of the starting model on the performance of the AE?

The verification procedure includes several metrics computed considering wind speed as continuous and categorical predictand. This study shows that deterministic AE predictions, compared to model used to generate it and Kalman filter of a starting model, improve rank correlation coefficient between predictions and measurements and reduce bias and root-mean-square error, especially in complex terrain. They produce similar results regardless of the starting model. Also, probabilistic AnEn predictions provide reliable information about their uncertainty.

On the boundary layer structure over mountainous complex terrain

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Both numerical weather prediction and regional climate modeling are using ever higher spatial grid spacing in their simulations so that local phenomena such as exchange processes in the boundary layer become more and more important. Boundary Layer parameterizations in these models, however, are largely based on the assumption of a flat and horizontally homogeneous surface (similarity theory). Moreover, with better resolution the terrain in the model becomes steeper (i.e., more realistic in mountainous terrain) leading to all kinds of numerical problems.

All this leads to the question concerning our knowledge of the boundary layer structure in complex, mountainous terrain and the associated exchange processes and whether this is sufficient to build new exchange parameterizations for mountainous terrain (or even test the existing ones which are known to be flawed – at least in principle). An attempt will be made to lay out the major obstacles on our way to potentially necessary new parameterization for boundary layer processes in complex terrain, to review a number of recent findings (or 'glimpses' into potential pathways) and, in particular, to refer to missing puzzle pieces. The focus will be on the success of (or otherwise) of 'scaling', i.e. the question to what degree similarity concepts can be used in complex, mountainous terrain.

Dynamics of rotor formation in single layer flows over topography

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Boundary layer separation (BLS) may occur when a strong adverse pressure gradient force is imposed on boundary layer flow, leading to strong deceleration and detachment of streamlines from the surface. This process commonly occurs at the salient edge of very sharp obstacles. In stably stratified flows, pressure perturbations strong enough to cause BLS can also be induced by internal gravity waves such as mountain waves.

A well-known phenomenon related to wave-induced BLS is that of leeside atmospheric rotors, i.e., boundary-layer zones characterized by strong turbulence, surface wind direction reversals, large values of spanwise vorticity and near-neutral stability. Due to the high intensity of turbulence, atmospheric rotors are known to pose a hazard to general aviation and road traffic.

We use the CM1 model to systematically explore the impact of different mountain flow regimes on the size and strength of rotors. A set of two-dimensional quasi no-slip simulations shows that the rotor height and strength generally increase with the non-linearity of the flow. However, there is also a strong variation depending on the vertical aspect ratio of the mountain. We use linear theory to explore the impact of the mountain shape on the rotor height and strength.

Rotor streaming is another aspect in the process of rotor formation and describes the occurrence of a train of consecutive rotors downstream of the leading rotor. The phenomenon occurs in most of our numerical simulations and is remarkably persistent over time. The underlying dynamics have not been clarified yet, although different processes like self-induced wave ducts or undular bores have been suggested in literature to play an important role. Based on numerical experiments we will shed some light on the driving processes of rotor streaming.

A NWP-based mesoscale climatology of boundary-layer processes over complex terrain

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Granite Peak, in western Utah, is an isolated mountain rising ~800 m above the surrounding terrain, with main axes respectively ~10- and ~6-km long. It is located in an area with significant land-surface variability, with a salt plain (playa) to the west and northwest, and a broad valley covered by herbaceous vegetation to the east. Furthermore, the arid grassland east of Granite Peak is surrounded almost completely by other prominent mountain ranges.

These geographical features favor the onset of diverse local wind systems in the atmospheric boundary layer (BL). On nights with relatively weak synoptic forcing, drainage flows typically develop. Due to stable stratification in the whole air column, a variety of dynamically-forced phenomena may also affect near-surface flow in the nighttime. During daytime instead, differences in sensible heat flux between the playa and the sagebrush plain drive "salt breezes", and the development of the convective BL and the spatial variability of the mixing height are significantly affected by the uneven topography.

This study outlines an approach to elaborate a climatological characterization of some aspects of BL flows in the Granite Peak area, by exploiting a multi-year archive of operational numerical weather predictions with resolution of ~1 km in space and 1 hour in time. Favorable areas for the nocturnal occurrence of boundary-layer separation and the formation of convergence lines, responsible for vigorous mixing even in stable conditions, are tracked down by elaborating climatographies of wind speed, temperature and pressure gradients. Furthermore, the spatial variability of the mixing height during daytime is quantified, and the impact exerted by land-surface properties and topography on the CBL development is examined.

I-Box: Issues with studying boundary layers in very complex terrain

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Very complex mountainous terrain poses a significant challenge to numerical modeling, but also to turbulence measurements, both in situ and remotely. Still, the lack of significant advances on the issues of boundary layers in complex terrain is mostly fuelled by limited availability of long-term datasets that would enable a systematic approach to addressing these issues. i-Box (short for Innsbruck Box) is a platform for studying boundary layer processes in complex terrain designed to bridge this knowledge gap through providing a long term data set for studying turbulence at sites of different complexity and high resolution numerical modeling. Located in the Inn Valley, the six i-Box measurement sites cover representative topographic features of different slope (0 - 30°), elevation (600m - 2000m), exposition (N and S) and surface characteristics, ranging from valley bottom to mountaintop. Apart from the in situ measurements, continuous remote sensing allows for truly three-dimensional boundary layer study. The accompanying numerical modeling efforts focus on idealized and real case LES simulations.

In this talk we will present the *i*-Box concept, with a special focus on measurement issues in complex terrain (such as measurements representatively, coordinate systems, post-processing of turbulence data, uncertainty assessment, corrections etc.). Using more than a year of data from several stations, we will look at the effect of these issues on the results and conclusions about the applicability of flat terrain theory in complex terrain.

Mountain wave-induced turbulence: "Lower turbulent zones" revisited

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In their seminal 1974 paper on "Lower Turbulent Zones Associated with Mountain Lee Waves", P. F. Lester and W. A. Fingerhut attempted to characterize regions of low-level turbulence in the lee of mountain ranges, commonly associated with large amplitude mountain waves aloft. Ever since that study, scientists have been re-examining and refining the conceptual model of the lower turbulent zone (LTZ) in order to shed more light on the structure and origin of turbulence therein.

The Terrain-Induced Rotor Experiment (T-REX, Sierra Nevada, CA, 2006) is the most recent, major effort organized to investigate the characteristics of LTZs by studying the coupled mountain-wave, rotor, and boundary-layer system. During the T-REX Intensive Observing Periods (IOPs), the University of Wyoming King Air research aircraft documented the variation of the complex mountain flow along multiple flight legs across the Sierra. High-rate in situ measurements from T-REX missions allow to examine the structure of the LTZ and the turbulence within it at unprecedented spatial resolution.

In this study, we make use of the extensive T-REX datasets from cases with strong gravity wave forcing in order to revisit the LTZ concept. In the analysis, particular emphasis is laid on the character of mountain waves in the lower and mid-troposphere lee-side of the Sierra as revealed, for example, by energy flux wavelet diagnostics. The complete study of all relevant T-REX cases calls for augmenting the classical picture of the LTZ by several additional elements, including the effective dimensions of the primary wave-generating obstacle, properties of the valley atmosphere (stable vs. convective), and the influence of the secondary ridge on the wave field aloft.

High-resolution numerical simulations of wintertime atmospheric boundary layer processes in the Adige Valley during an ALPNAP project field campaign

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High-resolution simulations are performed with the Weather Research and Forecasting (*WRF*) model, coupled with two different land surface models (LSM), Noah and Noah_MP, to reproduce meteorological conditions leading to a severe pollution event during the winter season in the Alpine Adige Valley. Model results are compared against data collected during a measurement campaign performed close to the town of Aldeno, within the project ALPNAP. Particular attention is focused on assessing the model ability to reproduce the 2-m temperature and the terms composing the surface energy budget. Validation of model results highlights that WRF poorly reproduces near-surface temperature over snow-covered terrain, with an evident underestimation. Furthermore it fails to capture specific atmospheric processes, such as the development of ground-based thermal inversions and the different thermal range between the sidewall and the valley floor. The main cause of these errors is the overestimation of the amount of snow on the ground and the consequent too high fraction of reflected solar radiation calculated by both the LSMs. Modifications to them are then performed to improve model results, by intervening in the initialization of snow cover and land use and in the calculation of the surface temperature. Thanks to these changes in the parameterization of snow-related influences on the surface energy budget, a significant improvement in the comparisons between model results and observations is observed. In fact, the proposed changes in the LSMs lead to a better reproduction of both the radiation fluxes composing the surface energy budget and of the near-surface temperature. In particular, for the latter variable, errors found are comparable to those reported in previous investigations of atmospheric processes in complex terrain with high-resolution atmospheric models. Moreover, results highlight that, with the proposed modifications, the model is able to reproduce correctly important atmospheric processes strictly connected with air pollution dispersion.

The prognostic deep convection parameterization for operational forecast in horizontal resolutions of 2, 4 and 8 km

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The parameterization schemes of deep moist convection assume that the deep convective cells occupy a small portion of the grid cell. This assumption could be valid as long as the model resolution is above the so called grey zone, i.e. in the range from 3 to 8 km or similar. In general, models run with grid meshes lower than 3 km fully resolve convective motions and the parameterization of deep convection is not needed at those resolutions. However, there are convective motions associated to atmospheric fronts that are large and organized so that they are well resolved even with horizontal grids larger than 8 km. On the other hand, moist convective motions that lead to the precipitation can have horizontal extent of less than 3 km and are not resolved with models at that resolution. The extent of the grey zone is therefore dependent on the weather. A scheme that parameterizes deep convection in a way that the above assumption is not needed has been implemented in the *ALADIN* model. The scheme is modular multi-scale micro-physics and transport (3MT) scheme. It is used for operational forecast in Meteorological and Hydrological Service of Croatia. Both moisture convergence and CAPE closure are available as well as a combination of them, the first one performs better for severe convection, while the other is better for light sub-grid showers. The combined closure is the one used operationally since it allows optimal forecast in both weather patterns. The operational turbulence scheme uses prognostic turbulent kinetic energy and interacts with deep convection in multiple ways through closure and fluxes. It also parameterizes contribution of shallow convection.

Observations of the bora-wind turbulence using the hot-wire anemometer

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During a bora event, i.e., a famous downslope windstorm at the eastern Adriatic coast, difficulties often emerge in traffic, industry and, generally, in everyday life. This is mainly due to bora persistency and severe gustiness (the wind-speed maxima may surpass even 70 m s−1), which makes bora a subject of intensive scientific research. In the past few decades, statistical, synoptic and main mesoscale characteristics of the bora flow have been comprehensively studied, but some aspects of bora dynamics are still insufficiently investigated, especially its turbulence. The main reason for such situation has been the lack of suitable measurements which are needed to asses these aspects. In this work we address the near-surface bora turbulence.

We mounted a single point 1D hot-wire anemometer (HWA) (Dantec Dynamics Multichannel CTA Anemometer System) and 3D ultrasonic anemometer (USA) (Gill Instruments WindMaster) at the north-eastern Adriatic coast in Vratnik Pass (44.98°N, 14.98°E, 700 m above MSL) on the mast 2.8 m above the ground. We measured a moderate bora event that occurred on 25 September 2014. We gathered 267 min of data (1451 – 1918 LST). HWA sampled streamwise wind speed component with sampling rate of 50 kHz while USA sampled all three wind speed components using 10 Hz sampling rate. We performed an in situ calibration of the HWA voltage data using the wind speed data from the collocated USA. In this work we focus on calculation of turbulence kinetic energy dissipation rate, ε. We calculate and compare ε using the direct dissipation technique and two indirect dissipation techniques: the inertial dissipation technique and the Kolmogorov's four-fifths law. The goal is to find out which of the two indirect techniques provides better results for bora-wind turbulence because the use of indirect techniques significantly reduces expenses needed for the reliable estimation of ε.

Where do we slope?... Some elementary thoughts on our present understanding of thermally driven slope flows.

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Thermally driven atmospheric flows over simple slopes offer a basic archetypal situation in the wide variety of thermally driven flows over complex terrain, as they are one of the simplest situation of nonhorizontal terrain, and provide useful conceptual schemes for insights, based on a local analysis, into more complex situations including finite-extent slopes (e. g. valley sidewalls, regions connecting two plateaus, etc.)

For many reasons, downslope (katabatic) winds have received much more attention than upslope (anabatic) ones. One of the reasons may be that convection makes these flows much deeper than drainage winds, and field measurements designed so as to capture the whole extent of upslope flows are difficult to perform. However even extensive high-resolution numerical simulations are rare, and not much progress has been made after Schumann's (1990) LES model runs. As a consequence we still don't know much about TKE budgets associated with upslope flows, as well as on the slope-normal structure and appropriate scaling of mean velocity, temperature, and higher order moments.

Analytical solutions, such as Prandtl (1942), rely on severely restrictive assumptions (parallel flow, constant or slowly varying eddy viscosity and diffusivity, along-slope invariance of the ambient factors). Extensions of such solutions relaxing those restrictions are still limited.

A few ideas on open questions and possible topics to address for future research are outlined and discussed.