Book of abstracts

32nd International Conference on Alpine Meteorology

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KRANJSKA GORA
June 2013

Book of Abstracts
32nd Intenational Conference on Alpine Meteorology

Izdajatelj:
Ministrstvo za kmetijstvo in okolje
Agencija RS za okolje,
Vojkova ulica 1b, Ljubljana,
http://www.arso.gov.si
E naslov: gp.arso@gov.si

Tehnično urejanje in oblikovanje:
Tanja Cegnar, Gregor Skok

CIP - Kataložni zapis o publikaciji
Narodna in univerzitetna knjižnica, Ljubljana

551.5(234.3)(082)
551.582(234.3)(082)

INTERNATIONAL Conference on Alpine Meteorology (32 ; 2013 ; Kranjska Gora)
Book of abstracts / 32th International Conference on Alpine Meteorology, Kranjska Gora, June, 2013. - Ljubljana : Ministrstvo za kmetijstvo in okolje, Agencija RS za okolje, 2013

ISBN 978-961-6024-60-0

267303680

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Current and future fire weather risk in Tyrol

David Leidinger, Institute for Meteorology, University of Natural Resources and Life Sciences, Vienna
Herbert Formayer, Institute for Meteorology, University of Natural Resources and Life Sciences, Vienna

Corresponding author: David Leidinger, david.leidinger@boku.ac.at

Forests are an important economic factor in Austria and are a valuable ecosystem. They provide protection from natural hazards like avalanches and rockfalls. Wildfires are a serious threat for forests. The risk of wildfires is predicted to increase with climate change. Fire weather indices (FWI) are a proxy for the risk of wildfires and are calculated using a combination of quantities such as temperaturte, precipitation, relative humidity, wind, and phenological data. Various FWI were calculated for Tyrol on a 1x1 km grid using INCA-data and three bias-corrected, localized climate-models to determine the current and future hotspots for the climate-prone risk of wildfires, which is one of many factors driving wildfires. We show an increasing trend in the number of days with high fire weather risk, and that the risk reaches areas, which are not yet affected, such as at high elevations.

Dust storms in the Icelandic highlands

Pavla Dagsson Waldhauserova 1,2, Haraldur Ólafsson 1,3,4, and Ólafur Arnalds 2
1 University of Iceland, Department of Physics, Reykjavik, Iceland. 2 Agricultural University of Iceland, Faculty of Environment, Hvanneyri, Iceland. 3Meteorological Office of Iceland, Reykjavik, Iceland. 4 Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway.

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

Manned weather observations in NE-Iceland have been explored in order to investigate the intensity and frequency of dust storms emanating from the Icelandic highlands in strong southerly winds.

A total of 2201 dust days were reported in Iceland in 1949-2011. The annual mean of 35 dust days pr. year in Iceland is similar to that found in dust-active parts of China, Mongolia or Iran.

As glaciers retreat in a warming climate, new dust sources emerge and dust storms may become an increasing problem.

Understanding and forecasting air pollution episodes in Slovenia

Rahela Žabkar, Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia and Center of Excellence SPACE□SI, Ljubljana, Slovenia
Luka Honzak, Center of Excellence SPACE□SI, Ljubljana, Slovenia
Marko Rus, Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia

Corresponding author: Rahela Žabkar, rahela.zabkar@fmf.uni-lj.si

Slovenia is known for its large topographical and climate diversity, where over an area of only 20 thousand square kilometers Mediterranean, Continental and Alpine climate zones are present. It is well known, that modeling air quality over geographically complex areas can be especially challenging. In the present contribution three modeling approaches used for air quality modeling in Slovenia are presented and evaluated: statistical regression model, regional scale modeling with in-line coupled meteorological-photochemistry WRF-Chem model and with off-line coupled ALADIN/CAMx modeling system. With the use of different approaches we investigate the characteristics of the temporal and spatial dynamics of the high O3 and PM10 episodes with the purpose to understand and forecast air quality in Slovenia. We also present the first results of the operational WRF/Chem and ALADIN/CAMx air quality forecasts running experimentally since January 2013.

Which weather situations are favouring high air pollution levels of PM10 and ozone in Ljubljana?

Anton Planinšek, Slovenian Environment Agency
Tanja Cegnar, Slovenian Environment Agency

Corresponding author: Tanja Cegnar, tanja.cegnar@gov.si

In 2013, the Year of the air, clean air is the focus of EU environmental policy discussions. According to the Eurobarometer survey, the impact of air pollution is something that European citizens feel strongly about. Data collected by the European environment agency show that lives are being cut short by air pollution and chronic respiratory disease makes life miserable for many across the continent. In spite legislation has led to improvements in many cases, we still register days with exceeded daily limit from time to time. The purpose of our study was to find out the main cause for high air pollution levels in Ljubljana. The hypothesis that the particular weather situation is the main cause for high air pollution has been tested.

Air pollution levels of PM10 and ozone vary from year to year. Criterions for it are limit and target values, set for health protection. Long-range transport depends from direction where air mass comes from. Emissions do not vary very much; therefore the main factor determining air pollution level must be the local weather, especially in such basin where Ljubljana lies.

Air pollution level for PM10 is defined with number of days with exceeded daily limit value. Allowed are 35 cases in calendar year. Similar is at ozone, where 25 exceedances of target value is allowed. Because of daily limit and target values are set, it is necessary to find daily weather situation favourable for exceeding of limit and target value. We took into account some weather parameters in 5 years series and compared them with daily PM10 concentration in winter and with maximum 8-hourly ozone concentration. We got fairly good agreement between number of yearly exceedances of PM10 limit value and ozone target value respectively with number of days that are favourable for such events. The result could be used for prediction purpose and to explain variation in number of days with air pollution exceeding the air pollution threshold.

Flow over partially forested ridges

Andrew N Ross, Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, UK
Tim Baker, Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, UK

Corresponding author: Andrew N Ross, A.N.Ross@leeds.ac.uk

Many areas of complex terrain are at least partially covered by forests. Interactions between the flow in the forest-canopy and in the boundary layer above are important on the local scale for understanding transported process in forest canopies and interpreting measurements from flux towers over forests. They are also important on the larger scales as the canopy flows impact on orographic drag. Previous theoretical and modelling work has focussed almost exclusively on fully forested hills with uniform canopies. Here we present results from numerical simulations, supported by theory, to study the effect of partial forest cover on the local flow and the orographic drag caused by flow over idealised two dimensional hills. The placement of the forest on the hill can have a large impact on the local flow and transport over the hill. This will have important implications for placement and interpretation of flux tower measurements over complex, heterogeneous terrain. The placement of the forest can also lead to significant differences in the orographic drag caused by the hill. For large scale hills where there is a scale separation between the horizontal scale of the topography and the lengthscale over which the flow adjusts at the forest edge that the effects of the hill and the forest edge can be considered separately. This gives a simple method of predicting the drag over a hill with an arbitrary forest cover and could form the basis of a new drag parametrisation including the effects of partial forest canopy.

Boundary-layer characteristics over complex terrain observed by remote-sensing systems during HyMeX

Bianca Adler: Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT)
Norbert Kalthoff: Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT)

Corresponding author: Bianca Adler, bianca.adler@kit.edu

The evolution of the convective boundary layer (CBL) in complex terrain varies significantly from the evolution over homogeneous terrain. Thermally-induced circulations and advective processes impact the CBL growth and cause interactions between the boundary layer and the layers above. As part of the HyMeX field campaign in the Western Mediterranean Sea 2012 the KITcube observation platform was installed at the mountainous island Corsica. KITcube combines various in-situ and remote-sensing systems that allows to measure the interactions of different thermally-induced circulations and the CBL growth.

During the day upslope winds caused strong subsidence in the valley atmosphere, which suppressed the CBL growth. Furthermore, they advected moisture from the lower part of the valley atmosphere along the slopes towards the ridges into the free atmosphere and resulted in the formation of clouds. Above the CBL vertical movements were measured by remote-sensing systems. Occasionally, the movements got coupled with CBL convective cells which resulted in a effective vertical mixing of moisture from the CBL into the free atmosphere above. A conceptual model of the typical diurnal evolution of the valley atmosphere and exchange processes is presented.

Weakly-nonlinear Prandtl model for simple slope flows

Branko Grisogono, Univ. of Zagreb, Fac. of Sci., Department of Geophysics, Zagreb, Croatia
Toni Jurlina, University of Zagreb, Faculty of Science, Department of Geophysics, Croatia
Željko Večenaj, Univ. of Zagreb, Faculty of Science, Department of Geophysics, Zagreb, Croatia
Ivan Guettler, Meteorological and Hydrological Service, Zagreb, Croatia

Corresponding author: Branko Grisogono, bgrisog@gfz.hr

Prandtl model couples, perhaps in the most succinct way, basic boundary-layer dynamics and thermodynamics for simple anabatic or katabatic flows over inclined surfaces. This 1D analytic model assumes steady-state balance between buoyancy (positive for anabatic, negative for katabatic flows) and turbulent friction. While the classical Prandtl model is linear with a priori assigned vertically constant eddy diffusivity and heat conductivity, in this analytic work we partly relax both of these assumptions.

Focusing on katabatic flows, one of the main weaknesses of Prandtl model is that strong, near-surface flow-induced finite-amplitude potential temperature gradient does not feed back to the assigned environmental potential temperature gradient in the thermodynamic equation, even though the induced gradient below the katabatic jet can be 20 to 50 times stronger than the related environmental gradient. This issue is tackled by using a weakly-nonlinear approach where a small parameter controls feeding of the flow-induced potential temperature gradient back to the environmental potential temperature gradient. An appropriate range of values for the small parameter controlling the weak nonlinearity is provided. In this way, the near-surface potential temperature gradient becomes stronger and the corresponding katabatic jet somewhat weaker (at a slightly lower height) than that in the classical Prandtl solution.

The other issue of constant eddy coefficient K in the classical Prandtl model is treated by a given gradually varying K with the height above the surface, all within the validity of the zero-order WKB approximation. The new model is compared to data from PASTEX-94, Austria. Besides other potential applications, this modified Prandtl model may help in parameterizing inclined boundary layers in climate models since there is only little confidence on the projected changes in future wind fields and the corresponding extremes.

Time scales of the atmospheric boundary layer evolution in an idealized valley

Johannes Wagner
Alexander Gohm
Mathias Rotach

Corresponding author: Daniel Leukauf, Daniel.Leukauf@uibk.ac.at

In recent years, the mechanisms of thermally-driven wind systems over complex terrain have been investigated through a series of idealized numerical simulations. The numerical models used in these studies were typically initialized with an atmosphere at rest and a simplified thermal stratification. In some studies, constant forcing was applied at the surface which does not allow for the evolution of a full daily cycle and these simulations were typically integrated only over a few hours. On the other hand, there are studies which use radiative forcing and capture the day and night cycle but in most cases these models were integrated over less than two days. The question remains whether the simulation period is long enough to capture a quasi-steady state (QSS) or, in other words, how strong the conclusions drawn from these studies are affected by the chosen analysis time. This question is fundamental if one aims at developing a parametrization of exchange processes based on bulk fluxes of heat, moisture and other properties from the valley to the free atmosphere evaluated from such idealized simulations.

In this study we want to determine the time scales for reaching a QSS in the evolution of the atmospheric boundary layer (ABL) as a function of various forcing parameters. A QSS is characterized by a daily cycle of the ABL that is essentially identical from one to the next day, e.g, the same maximum ABL height in the afternoon. For this purpose we conduct large eddy simulations with the Weather Research and Forecasting (WRF) model of thermally-driven flows in an idealized valley and compare the results to the ABL evolution over flat terrain. An important aspect of the study is the impact of the soil moisture content on the QSS time scale (QSSTS).

The chosen valley geometry consists of two sine-shaped mountain ridges which form a 20-km wide and 40-km long valley with a flat valley floor. As the terrain is homogeneous in the along-valley direction and periodic boundary conditions are used, only slope winds but no valley winds evolve. We use full physical parametrizations including radiation and surface-atmosphere exchange processes to represent realistic forcing. The initial vertical profiles are characterized by a constant buoyancy frequency, a constant relative humidity and zero winds.

In addition to the valley simulation the model is run with flat terrain using a three times smaller domain and all simulations are carried out over five full days. It can be shown that the ABL reaches a QSS typically after three days for relatively dry soil (semi desert). Using the QSS ABL profile of the flat-terrain simulation as initial conditions for the valley simulation shortens the spin-up time by about one days. On the other hand, for a moist soil the ABL does not reach a QSS within the five days of simulation and boundary layer heights are much smaller.

A climatological analysis of the “Ora del Garda” wind in the Alps

Lorenzo Giovannini (1,2), Lavinia Laiti (1,2), Dino Zardi (1,2) and Massimiliano de Franceschi (1,2,3)
(1) University of Trento, Department of Civil, Environmental and Mechanical Engineering, Atmospheric Physics Group, Trento, Italy
(2) National Consortium of Universities for Atmospheric and Hydrospheric Physics (CINFAI), Rome, Italy
(3) Diocese of Bolzano-Bressanone, Major Seminary, Bressanone, Italy

Corresponding author: Dino Zardi, Dino.Zardi@ing.unitn.it

The “Ora del Garda” is a coupled lake and valley breeze, which flows very regularly, during clear-sky days in the warm season, from the northern shorelines of Lake Garda. Hence it propagates into the valleys nearby, until it reaches, through an elevated saddle, the River Adige Valley north of the city of Trento, where it interacts with the local up-valley winds, producing a strong and gusty flow.

Typical features of this wind are outlined by means of a climatologic analysis of data from two representative surface weather stations – one located on the shores of lake Garda, and one 30 km inland – covering a 10-year period. Furthermore, to assess the impact of the synoptic wind on the development of the lake breeze, wind speed and direction at 850 hPa level from reanalysis are analysed.

Clear lake-breeze days are identified in the period April-September by means of a set of objective criteria, based on the analysis of surface radiation and observations of wind speed and direction at the two surface stations.

It is found that the Ora del Garda develops on the shores of the lake in about 70% of the days from April to September, with higher values in summertime. Moreover in about 90% of days in which the lake breeze develops on the lake shores, it also reaches the inland weather station. Average wind strengths on Lake Garda shores are in the order of 4-6 m s-1, with maximum intensities reaching frequently 10 m s-1. The wind typically starts blowing on average at 1100-1200 LST (but the onset time is progressively delayed from spring to summer), and lasts until 1700-2000 LST (with earlier cessation times occurring more frequently in April and September). The lake breeze takes on average 3.5 h to get to the inland weather station, where it lasts until 2000-2100 LST.

The analysis of wind speed and direction at 850 hPa from reanalysis highlights that the lake breeze is on average stronger and its duration is slightly longer when the synoptic wind blows onshore. Moreover the lake breeze propagates faster, and arrives earlier at the inland weather station, under synoptic winds blowing onshore.

A remotely piloted aircraft for investigation of mountain flows

Joachim Reuder 1, Marius O. Jonassen 1 and Haraldur Ólafsson 1,2,3
1 Bergen School of Meteorology, Geophysical Institute, University of Bergen, 2 University of Iceland,
3 Icelandic Meteorological Office

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

In recent years, the Small Unmanned Meteorological Observer SUMO has been developed as a flexible tool for atmospheric boundary layer (ABL) research to be operated as sounding system for the lowest 4 km of the atmosphere. Recently two main technical improvements have been accomplished. The integration of an inertial measurement unit (IMU) into the Paparazzi autopilot system has expanded the environmental conditions for SUMO operation. The implementation of a 5-hole probe for determining the 3D flow vector with 100 Hz resolution and a faster temperature sensor has enhanced the measurement capabilities.

Results from two recent field campaigns are presented. During the first one, in Denmark, the potential of the system to study the effects of wind turbines on ABL turbulence was shown. During the second one, the BLLAST field campaign at the foothills of the Pyrenees, SUMO data proved to be highly valuable for studying the processes of the afternoon transition of the convective boundary layer.

Inside the Reykjavík shelter

Marius Opsanger Jonasson, Bergen School of Meteorology, Geophysical Institute, University of Bergen, Haraldur Ólafsson, University of Iceland, Icelandic Meteorological Office and Bergen School of Meteorology, Geophysical Institute, University of Bergen, Hálfdán Ágústsson, University of Iceland, Icelandic Meteorological Office and Institute for Meteorological Research and Ólafur Rögnvaldsson, Institute for Meteorological Research

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

The Reykjavik shelter
The city of Reykjavík is located at the west coast of Iceland, with mountain ranges some 10 km to the south, southeast and northeast. The wind climate of Reykjavík is analyzed with ground-based observations, reanalysis data and by observations from a remotely piloted aircraft.

The mountain range to the northeast provides a remarkable shelter, while the mountains to the southeast do not. In northeasterly flows, Reykjavík is inside a wake and the mean surface wind speed is only about 35% of the wind speed at 850 hPa and this ratio is sensitive to the static stability. In southeasterly flow which also is downstream of a mountain range, the mean surface wind speed is about 50% of the 850 hPa winds and this ratio is independent of the static stability. A case of northerly flow is explored with a remotely piloted aircraft and a complex stratified wake structure is revealed.

Sensing the thermal PBL evolution in complex terrain using a passive microwave profiler

Ivana Stiperski, University of Innsbruck
Giovanni Massaro, University of Innsbruck
Mathias W. Rotach, University of Innsbruck

Corresponding author: Ivana Stiperski, ivana.stiperski@uibk.ac.at

Boundary layers in non-flat terrain are characterized by complex spatio-temporal evolution connected with diurnal variations due to valley- and slope-wind systems, layers of different stability caused by secondary circulations, inhomogeneities due to local terrain characteristics etc. Such complex boundary layer evolutions are impossible to resolve with standard daily or at best three-hourly radio-soundings. Airplane or tethered balloon measurements during specific field campaigns also give only limited information due to their finite duration and scope.

A passive microwave temperature/humidity profiler provides continuous measurements of mean temperature and humidity profiles at high temporal resolution able to resolve sub-synoptic scale phenomena and the rapid temperature/humidity evolution associated with them. With its high resolution and vertical reach it out-performs radio-soundings and other types of measurements in this respect.

As part of the Innsbruck Box (i-Box) project, a platform for studying boundary layer processes in complex terrain, such a passive microwave temperature/humidity profiler (HATPRO) is operated for the first time, in very complex terrain over a longer period of time (spanning several years). In line with the governing philosophy of i-Box, the profiler is operated continuously, mapping the changing PBL vertical structure at very high temporal resolution and adequate vertical resolution. It also provides information in the middle of the valley atmosphere where measurements are scarce or non-existent. Given that the profiler measures instantaneous volume-integrated temperature and humidity structure directly above the measurement location it is also an especially valuable tool for model validation. However, a particular challenge lies in the fact that statistical algorithms HATPRO relies on for retrieving the profiles are limited to the range of atmospheric conditions for which they have been trained. In this contribution we will address the advantages and especially challenges of using HATPRO in complex terrain. The instrument was trained on the basis of a long database of nearby radio soundings (over 4000) and accuracy for different height ranges of the profile measurements was compared to that resulting from the instrument's "standard calibration". In particular, we will address the instrument's ability to detect (multiple) inversions and show novel strategies to improve this accuracy and assess their potential. First results of measurements in Innsbruck (i.e., probing the Inn Valley boundary layer) started last in autumn of 2012 will be presented.

The impact of valley geometry on thermally driven flows and vertical heat fluxes

Johannes Wagner(1), Alexander Gohm(1), Mathias Rotach(1), Daniel Leukauf(1), Christian Posch(1)
(1) Institute of Meteorology and Geophysics, University of Innsbruck, Austria

Corresponding author: Johannes Wagner, johannes.wagner@uibk.ac.at

In this project thermally driven flows in complex terrain are studied. The overall goal is to investigate the role of different valley geometries on slope and valley winds and on horizontally averaged valley bulk heat flux profiles. The study is based on idealised large-eddy-simulations (LES) of heated valley topographies, which are performed with the Weather Research and Forecasting (WRF) model. In a first step a simplified setting with a constant surface heat flux forcing and an infinitely long valley is used to compare the simulation results to another LES-study, which used the Advanced Regional Prediction System (ARPS) with the same domain set-up (Schmidli, J. submitted). The model comparison shows that both models agree well in the averaged and resolved-scale turbulent flow structures and in the heating of the valley atmosphere. In a second step the valley depth and width is varied to examine the impact of valley shape on slope winds and bulk fluxes. It is found that the well known three-layer thermal structure with two superposed circulation cells only occurs in deep valleys and that bulk vertical turbulent heat fluxes exhibit a secondary maximum near ridge height. In a third step the simulation is extended to a valley plain topography to allow for the development of along valley flow.

Scaling the quasi-steady along-valley wind

Juerg Schmidli, Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland
Richard Rotunno, National Centre for Atmospheric Research (NCAR), Boulder, USA

Corresponding author: Juerg Schmidli, jschmidli@env.ethz.ch

The quasi-steady-state limit of the diurnal valley wind system is investigated over idealized three-dimensional topography. Although this limit is rarely attained in reality due to ever-changing forcings, the investigation of this limit can provide valuable insight, in particular on the mass and heat fluxes associated with the along-valley wind. We derive a scaling relation for the quasi-steady-state along-valley mass flux as a function of valley geometry, valley size, atmospheric stratification, and surface sensible heat flux forcing. The scaling relation is tested by comparison with the mass flux diagnosed from large-eddy and mesoscale simulations of the valley wind system. Good agreement is found. The results also provide insight into the relation between surface friction and the strength of the along-valley pressure gradient.

Near-surface wind shear over the complex terrain: observational analysis

Kristian Horvath, Meteorological and Hydrological Service, Gric 3, 10000 Zagreb, Croatia
Darko Koracin, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512
Craig Smith, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512

Corresponding author: Kristian Horvath, kristian.horvath@cirus.dhz.hr

Although analysis of winds and wind regimes in complex terrain has received considerable attention, near-surface wind shear has been considerably less studied primarily due to scarcity of the observed data. Nevertheless, the importance of near-surface wind shear for air pollution, wind energy, transport and infrastructural design, as well as the increasing number of wind towers and ground-based remote sensing measurements promotes a more detailed focus on the analysis of near-surface wind shear.

Four meteorological towers in west-central Nevada, equipped with cup and vane anemometers at 10 m, 20 m, 30 m 40 m and 50 m AGL, provided an excellent dataset for analysis of the near-surface wind shear. Mean wind speed on average increased with height at all analyzed wind towers. The average wind shear decreased with height, however, the decrease was not necessarily monotonous. The temporal variability of wind shear was much higher during the night than during the day, while maximal wind shear values (both positive and negative) were found during episodes of nocturnal winds. Furthermore, relationship between wind shear and wind speed was qualitatively different during daytime and nighttime. Finally, a considerable portion of nighttime events with a negative wind shear suggests the presence of shallow nocturnal circulations, but negative wind shear can likewise occur during daytime and for the entire range of the wind speed distribution.

Reconstruction of high-resolution meteorological fields from airborne observations: a comparison of different techniques

Lavinia Laiti - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy
Dino Zardi - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy
Massimiliano de Franceschi - Major Seminary, Diocese of Bolzano-Bressanone, Bressanone, Italy

Corresponding author: Lavinia Laiti, laitil@ing.unitn.it

Light aircrafts represent valuable measurement platforms for atmospheric research, for they are able to provide high temporal and spatial resolution observations of the atmosphere. In particular, they are very suitable tools for the observation of atmospheric boundary-layer (ABL) structures in complex terrain, which are typically characterized by a fine-scale, fully 3D variability. Indeed, thanks to their good maneuverability, they allow to perform both vertical profiles and horizontal surveys. Various techniques have been used in the literature to remap data taken along flight trajectories onto regularly spaced, high-resolution 3D grids. In the present contribution the application of a geostatistical interpolation technique called Residual Kriging (RK) is proposed for the mapping of airborne measurements of scalar quantities. In RK the dominant (vertical) drift component underlying the original data is first extracted from the original data to filter out local anomalies, then the residual field is separately interpolated through an Ordinary Kriging algorithm and finally added back to the drift. In RK the determination of interpolation weights relies on the estimate of the characteristic covariance function of the residuals through computation and modeling of their semivariogram function. RK implementation inherently accounts for the characteristic anisotropy of the target field, and it also allows for an estimate of the interpolation error. A dataset from flights of an equipped motorglider, exploring ABL structures in the valleys near the city of Trento (in the southeastern Italian Alps) on fair-weather summer days, is adopted as test-bed database. RK method is used to reconstruct 3D high-resolution fields of potential temperature and water vapor mixing ratio for specific vertical slices of the valley atmosphere, integrating also measurements from the nearest surface weather stations (when present). From RK-interpolated meteorological fields, fine-scale local features of the valley ABL developing in connection with the occurrence of thermally-driven slope and valley winds are detected. RK's performance is tested against the performances of other mapping methods commonly adopted for this application, i.e. methods based on Inverse Distance weighting or on Delaunay triangulations. A comparative evaluation, carried out by means of cross-validation procedures and in terms of physical plausibility of results, identifies RK as best-performing technique.

An investigation of the Ora del Garda wind in the Alps by means of Kriging of airborne and surface measurements

Lavinia Laiti - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy
Dino Zardi - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy
Massimiliano de Franceschi - Major Seminary, Diocese of Bolzano-Bressanone, Bressanone, Italy
Gabriele Rampanelli - Depuration Agency, Autonomous Province of Trento, Trento, Italy

Corresponding author: Lavinia Laiti, laitil@ing.unitn.it

The present study investigates a coupled lake-valley wind, known as Ora del Garda, which typically arises in the late morning on clear-sky days along the northern shorelines of Lake Garda and then channels northward into the Sarca and Lakes valleys, until breaking out into the Adige Valley north of Trento city (southeastern Italian Alps), where it interacts with the local up-valley wind in a complex fashion. This thermally-driven circulation displays great regularity, marking the local climate with a strongly mildening influence. A series of targeted measurement flights, performed by means of an instrumented motorglider, allowed to explore the valley atmosphere thermal structure at selected vertical sections, namely over the lake's shore, at half valley, at the end of the valley, and at the junction with the Adige Valley. Dominant vertical profiles of potential temperature were inferred from airborne data, while 3D potential temperature fields were mapped over high-resolution regular grids for each explored section, through the application of a Residual Kriging (RK) technique both to airborne and to surface data from weather stations disseminated along the valley floor. These procedures allowed to identify atmospheric boundary layer (ABL) features typical of most diurnal valley winds. In particular, rather shallow convective mixed layers, surmounted by deep stable layers, occur up-valley. On the other hand, closer to the lake the advection of colder air tends to stabilize the atmosphere throughout the whole valley ABL depth. Small-scale features of the thermally-driven wind field produced by the coupling between the lake breeze and the up-valley circulation into a unified mesoscale flow were revealed by RK-interpolated potential temperature 3D fields; the development of a lake-breeze front structure was captured in the shoreline area, while up-valley sections displayed cross-valley thermal asymmetries, mostly amenable to the different irradiation of the valley sidewalls and to inhomogeneities in the surface coverage, but also to the curvature of the valley in its final part. Lastly, RK-interpolated fields suggested the occurrence of a hydraulic jump structure at the end of the Lakes Valley, where the Ora del Garda potentially cooler air overflows from an elevated saddle down to the underlying Adige Valley floor, producing there an anomalous and gusty cross-valley flow.

Numerical simulations of the Ora del Garda wind in the Alps: a comparison with surface and airborne measurements

Lavinia Laiti - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy
Lorenzo Giovannini - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy
Dino Zardi - University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy

Corresponding author: Lavinia Laiti, laitil@ing.unitn.it

In order to investigate the atmospheric boundary layer (ABL) structures associated with the development of a lake-breeze and valley-wind coupled system developing in the Lakes Valley (southeastern Italian Alps), the so-called “Ora del Garda” wind, a series of measurement flights were performed by means of an instrumented motorglider on four warm-season days. 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. Air pressure, temperature and relative humidity measurements were recorded. At the same time, surface observations from a number of local automated weather stations were collected. In order to get a complementary view of the phenomenon, high-resolution numerical simulations of the flights days were carried out using the model WRF. Five nested grids were used, achieving a final horizontal spacing of 0.5 km. High-resolution orography and land use datasets were adopted for the domain initialization, while NCEP reanalysis provided initial and boundary conditions for the meteorological fields. The simulations were initiated at 1800 UTC of the day preceding the flight. The Unified Noah land-surface model and the Bougeault-Lacarrere scheme for PBL physics were used. The preliminary results display a rather good agreement with the experimental dataset. In particular, the surface daily cycles of radiation, wind and air temperature are satisfactorily reproduced, despite some discrepancies in the timing of thermally-driven circulation onset and offset, probably due to initialization inaccuracies. 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 qualitatively well reproduced in the simulated fields. Moreover, the simulations confirmed characteristic local-scale features of the thermally-driven wind field that were suggested by the analysis of the airborne dataset. For example, the model showed the development of a well-defined lake breeze front in the lake’s shoreline area, as well as the formation of a hydraulic jump structure in the area north of Trento city, i.e. at the end of the Lakes Valley, where the Ora del Garda denser current flows down into the nearby Adige Valley from an elevated saddle (elevation difference: 400 m).

Numerical simulations of boundary-layer phenomena and urban-scale processes in the Alpine city of Trento

Giovannini Lorenzo, Atmospheric Physics Group, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy
Dino Zardi, Atmospheric Physics Group, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy
Massimiliano de Franceschi, Atmospheric Physics Group, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy and Major Seminary, Diocese of Bolzano-Bressanone, Bressanone, Italy
Fei Chen, National Center for Atmospheric Research, Boulder, CO

Corresponding author: Lorenzo Giovannini, lorenzo.giovannini@ing.unitn.it

Simulations with the Weather Research and Forecasting (WRF) model coupled with an urban parameterisation scheme are performed to evaluate the alterations caused by the urban area of Trento on boundary-layer processes in the Alpine Adige Valley. Simulations, with 500-m grid spacing, focus on a typical summer sunny day, when both valley winds and the urban heat island are well developed. Specific gridded datasets of urban morphology parameters and anthropogenic heat flux releases were created to provide high resolution input information to the urban scheme. Validation of numerical results against measurements from surface weather stations shows that the model is able to simulate reasonably well the development of valley winds, as well as the complex interaction occurring north of Trento between the local up-valley wind of the Adige Valley and an incoming lake breeze from a tributary valley. The urban heat island of the city is also well captured by the model, with strong intensities at night and low values in the central hours of the day. It is found that the city inhibits the development of the ground-based thermal inversion at night, especially in the city centre, displaying a denser urban morphology and higher buildings. Furthermore comparisons with an idealised simulation, where all the urban land use grid points are replaced by cropland, suggest that the city also affects the development of valley winds, modifying both the typical down-valley wind in the early morning, and the interaction between the up-valley wind flowing in the Adige Valley and the lake breeze. Finally sensitivity tests are performed to analyse in detail the impact of the gridded datasets of urban morphology and anthropogenic heat flux releases on the near-surface temperature and wind field.

Impact of mesoscale meteorological processes on the anomalous propagation conditions

Maja Telišman Prtenjak; Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia
Igor Horvat; Meteorological and Hydrological Service of Croatia, Zagreb, Croatia
Mladen Viher; Croatian Air Force HQ,Croatia

Corresponding author: Maja Telišman Prtenjak, telisman@gfz.hr

The occurrence of the anomalous propagation (so called anaprop) of radio waves: radioducts, superrefractions and subrefractions is created by the different properties of the atmosphere through the altitude difference in temperature, humidity and air pressure. Atmospheric variability is a result of large scale conditions, frequently modified by mesoscale structures that influence the height of boundary layer and produce local fronts with abrupt spatial changes in temperature and humidity.

Here we study the impact of 3 mesoscale phenomena (over the wider area of the northern Adriatic) on the occurrence of anaprop conditions: sea/land breeze, the bora wind and cumulonimbus clouds. The selected period that unites them is 13 - 20 August 2000. For the purpose of the analysis we used radiosoundings in Udine, with a sampling period of every 6 hours and numerical WRF-ARW model at the horizontal resolution of 1.5 km every hour. Results show that the model can successfully simulate the occurrence of anaprops in Udine, although their intensity is sometimes underestimated. The model has certain difficulties in reproducing the correct height and intensity of anaprops since the faithful vertical profile of the modified refractive index is the most dependent on the accuracy of the modeled vertical changes of relative humidity.

Spatial anaprop distributions show that the sea surface (between 30 and 100 m a.s.l.) is mainly covered by superrefractions and radioducts through the entire studied period. Sea breezes (SB) are continuously connected with the anaprop formations: (i) in the first 100 m above the ground within SB body where superrefractions and radioducts form due to advection of colder and moist air, (ii) in upper region of the SB front which are usually connected with elevated radioducts and superrefractions, (iii) inside transition layer between the SB body and anti-SB current with subrefractions. When a deep convection over land appears, we observe the elevated superrefractions and subrefractions between 0.5 and 1 km above ground. Subrefractions are caused by downdraft beneath the cumulonimbus cloud base in its mature phase that creates smaller pools of cold and dry air. Below subrefractions in the lowermost 200 m, the type of anaprop is changed from superrefractions to radioducts. The bora wind through by the advection of colder and drier air, in the shallow surface layer usually creates radioducts and superrefractions: over land and coast, inside the hydraulic jump, and over the sea and islands, in somewhat deeper layer. Bora is also associated with subrefractions: (i) over the sea surface along the edges of bora jets where a lateral exchange of air with various moisture content occur due to the convergence of flow and increased vorticity, and (ii) on the windward side of Dinaric Alps where the formation of the local vortices below the mountain top affect the moisture profile.

Flow Interactions Observed by a Very High-Resolution Surface Weather Station Network in Complex Terrain

Matt Jeglum, University of Utah; Sebastian Hoch, University of Utah; C. David Whiteman, University of Utah; Frank W. Gallagher, US Army Dugway Proving Ground

Corresponding author: Matt Jeglum, m.jeglum@utah.edu

Dugway Proving Ground, host to the observational portion of the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) program, operates a permanently installed array of 51 automated weather stations (miniSAMS) aligned on a roughly rectangular grid with a grid spacing of one mile. The dataset includes 1-minute averages of temperature, pressure, wind speed, wind direction and solar radiation at 2 m height and wind speed and direction at 2 m and 10 m heights. The array sits in a broad, flat-floored basin surrounded by mountainous terrain with relief on the order of 500 m in all directions except northwest. To the northwest lies nearly flat terrain, including unvegetated playa (dry alkali flats which fill with water seasonally to form shallow lakes).

The relatively high spatial and temporal resolution of the array allows investigation of atmospheric boundary layer structures that are either poorly observed or unobserved using typical surface networks. Data from the array shows signatures of synoptic cold fronts, diurnal slope and valley flows, and turbulent wakes, often interacting with one-another in complex ways.

The array data was analyzed for the MATERHORN Fall campaign period (25 Sept. through 21 Oct. 2012), but one illustrative day will be investigated as a case study. On 23 October 2012 a synoptic cold front associated with a 700-mb shortwave trough crossed the miniSAMS grid in the late afternoon, leaving moderate northwesterly winds in its wake. Shortly thereafter a second, weaker boundary propagated across the grid from the northeast, with northeasterly winds behind it. This boundary displayed traits common to downslope windstorms. This boundary was followed by the return of the pre-frontal southwesterlies, with a coincident rise in temperature despite the nighttime hours. Finally, northwesterlies again propagated across the grid, accompanied by a drop in temperature. Through the remainder of the night a confluence zone was maintained over the array, with northwesterly winds on the west side and northeasterly winds on the east side. As the confluence zone wavered back and forth, individual stations sifted from NW to NE and back.

The high spatial and temporal resolution of the miniSAMS observations offers a unique opportunity to characterize and study the contribution of differently forced flows and their interactions. The knowledge gained can be applied to meso- and micro-scale processes that occur elsewhere in the world.

High resolution modeling of katabatic wind and field campaign on an alpine slope

Sébastien Blein : LEGI, Grenoble, France
Christophe Brun : LEGI, Grenoble, France
Jean-Martial Cohard : LTHE, Grenoble, France
Maxime Litt : LTHE, Grenoble, France

Corresponding author: Sébastien Blein, sebastien.blein@legi.grenoble-inp.fr

High resolution numerical simulation is used to analyze the stable atmospheric boundary layer dynamic in mountainous region. The 3D spatial resolution is of 10m in the horizontal direction and 2m in the vertical direction above the ground surface. A 1D vertical model is coupled to the 3D model to access the flow dynamic in the region between the ground and the first atmospheric grid point. It allows a better description of momentum and temperature fluxes at this level. Within the air quality context, we focus on katabatic processes and their contribution on meso-scale motion and mixing for high polluted event during the winter on the Grenoble valley, France. The study is based on MesoNH realistic simulations (Meteo-france & Laboratoire d'Aerologie, Toulouse, France). To complete the numerical study, a field campaign (KACOSONIC, KAtabatic wind at Grand COlon mountain and SONIC anemometer data) was organized on November 2012. Measurements were performed during a strong particle pollution event. The field campaign consisted on 2 main sites. First, a Sodar was located at the slope bottom to catch the meso-scale behavior (mean wind profiles, shear layer...). It performs 600m high profiles with 6m resolution. Secondly, a 6m mast was located at the middle of the slope, were well established katabatic winds were observed. 4 sonic anemometers (20Hz) were used at 1m, 2m, 4m and 6m above the ground to describe the low level jet. Meteorological data were also stored. At the mast location (katabatic source location), the down-slope jet is of 10m high and the maximum is located between the 2m and the 4m mast point. With this configuration, the momentum and temperature fluxes are well described above and below the wind maximum height. The strong complementarity of numerical simulations and field campaign led us to study both approaches. The field campaign is temporally well defined and used to be easily trusted but lacks of spatial description, especially on the horizontal direction. This lack of spatial description is filled by the realistic numerical results which are themselves supported by in-situ data. This self-sufficient data-set permits boundary layer parametrization studies and to examine their applicability to realistic therefore complex configuration.

Climate change effects on temperature and ice of the lake Bohinj, Slovenia

Peter Frantar; Slovenian Environment Agecy

Corresponding author: Peter Frantar, peter.frantar@gov.si

Lake Bohinj is the biggest non-karstic natural lake in Slovenia. It is located in the Julian Alps 525 m asl. with maximum depth of 45 m and area of 3,2 km2. State monitoring of basic lake characteristics started near 1900 with water levels and ice monitoring and in 1939 with additional lake water temperature measurements. The analysis showed that climate change is having effects also on the lake ice duration and on the rise of lake water temperatures. Especially after the 1980 the ice is diminishing and the temperatures are growing. These 2 indicators can therefore be set also as climate change indicators for alpine space. We present the trend of lake ice duration, trend of yearly water temperature and the seasonal changes in water temperature regime.

Ensemble approach to the homogenisation of monthly temperature series in Slovenia

Gregor Vertačnik, Damjan Dvoršek, Renato Bertalanič, Mojca Dolinar, Mateja Nadbath (all Slovenian Environment Agency, Slovenia, Ljubljana), Matija Klančar (University of Ljubljana, Slovenia, Ljubljana)

Corresponding author: Gregor Vertačnik, gregor.vertacnik@gov.si

Many studies in recent years have stressed the importance of homogenous data series for assessing climate variability and climate change. Data series obtained from measurements of climate variables are rarely homogenous, mostly due to the relocations of weather stations and instrumentation changes. Homogenisation procedures are then often applied to correct for this kind of inhomogenities in the data series. While many statistical methods have been developed for the purpose, recent COST project HOME tried to evaluate them on the benchmark dataset. Some of best methods and practices for homogenisation were then packaged in a semi-objective homogenisation tool HOMER. To our knowledge no one has tried to estimate the subjectivity factor arising from the expert performing homogenisation procedure with this tool. In order to estimate this factor in the homogenised series, several experts performed homogenisation on the same dataset of real monthly series of mean, daily maximum and daily minimum temperature series.

Additionally, three subsets of mean temperature dataset were homogenised to assess the impact of network density on the final results. Analysis of homogenised series revealed only few significant differences in derived climate features between different experts and datasets. On the other hand, the ensemble approach indicated the need for high-quality and continuous climate measurements as well as the importance of dense network grid.

Calculation of Snowline Climatology over the Alpine Region from ECMWF ERA-Interim reanalysis

Imran Nadeem, Institute of Meteorology, University of Natural Resources and Life Sciences, Vienna
Herbert Formayer, Institute of Meteorology, University of Natural Resources and Life Sciences, Vienna

Corresponding author: Imran Nadeem, imran.nadeem@boku.ac.at

Snow is a key element within the Alpine region, which not only affects the ecosystem, but has an important economical factor in the Alps. For many adaptation measures in several economic sectors, information about the snow conditions is needed. In most climate impact assessments, snow conditions are simply a function of the elevation. But within the Alpine region, this elevation dependency is only correct for snow melt. The elevation of the snow level (elevation where falling snow melts to rain) highly depends on the air mass causing the precipitation. Air masses in the Alps coming from the Mediterranean or the Atlantic are several degrees warmer during winter than air masses arriving from the North or Baltic Sea. Correspondingly the elevation of the snow level is much higher in regions, where precipitation is caused from air masses from the Mediterranean or the Atlantic.

An algorithm has been developed to calculate snow line from pressure level data of temperature, relative humidity and geopotential. The algorithm calculates wet-bulb temperature (WB) at each pressure level during the precipitation event and then looks for the elevation where WB is zero. The algorithm also takes into account the melting of the snow in the atmosphere and evaporational cooling when melting starts. For the present study we used 3-hourly ECMWF ERA-Interim re-analyses at pressure levels of 700, 850, 925 and 1000 hPa. The snowline has been calculated for the period 1979-2012 over the whole Europe domain. For analysis we will present results only for the Alpine domain. A comparison of the last three decades will be presented which allows a quantification of the climate change impact on snow level within the Alpine region. A comparison of the effect on the snow level with the general warming within this period gives some findings, if dynamical effects have been relevant for the Alpine domain. The same method can be applied to regional climate model data. This will give a tool for comprehensive analyses of the climate change impact on the elevation of the snow level during the 21st century.

Climate change scenarios of precipitation extremes in mountain regions of Europe based on ENSEMBLES regional climate models

Jan Kyselý, Institute of Atmospheric Physics & Technical University of Liberec, Czech Republic
Ladislav Gaál, Institute of Atmospheric Physics & Slovak University of Technology, Slovakia
Romana Beranová, Institute of Atmospheric Physics & Technical University of Liberec, Czech Republic

Corresponding author: Jan Kysely, kysely@ufa.cas.cz

Mountain regions and areas with complex orography are particularly prone to heavy precipitation and floods, and uncertainties in possible changes associated with climate change may be enhanced due to complexity of interactions between orography, atmospheric circulation, and local processes. The study examines possible changes in high quantiles of precipitation amounts in scenarios of late 21st century climate in an ensemble of regional climate model (RCM) simulations over Europe from the EU-FP6 ENSEMBLES project. The RCMs have a resolution around 25 km and are driven by several global climate models. The projected changes are evaluated in winter and summer seasons, and on a wide range of time scales from hourly to multi-day amounts. The region-of-influence method is applied as a pooling scheme when estimating distributions of seasonal maxima of precipitation, which leads to spatial patterns of high quantiles that are smoothed compared to local analysis. We focus on a comparison of results (scenarios) for several mountain and lowland regions of Europe, and evaluate altitudinal dependence of the projected changes of precipitation extremes. Specific attention is paid to the performance of the pooling scheme, particularly how the regional homogeneity criterion is met in areas with complex topography. Uncertainty of the projected changes due to inter-model variability is also assessed and compared for the selected regions.

Daily air temperature range analysis for the Slovak Tatra Mountains part and scenarios up to the year 2100

Marian Melo (Comenius University in Bratislava, Slovakia)
Ivan Bastak-Duran (Czech Hydrometeorological Institute, Prague, Czech Republic)
Martin Gera (Comenius University in Bratislava, Slovakia)
Milan Lapin (Comenius University in Bratislava, Slovakia)

Corresponding author: Marian Melo, melo@fmph.uniba.sk

An analysis of daily maximum and minimum temperatures as well as of daily temperature range at selected meteorological stations in the Slovak part of the Tatra mountains region in 1951-2010 are studied. Mean daily temperature range is defined as a difference between the daily temperature maximum and minimum. Time series of temperature range means have been analyzed by trend analysis and other statistical tools. In the second part of contribution daily outputs of two regional climate change models (Dutch KNMI and German MPI, both with ECHAM5 boundary conditions) have been used for design of climate change scenarios (daily maximum and minimum of air temperature and daily range of air temperature) for selected stations in this region and the period 1951-2100. Comparisons of measured and modeled temperature characteristics (daily extremes and daily range) are included.

Analysis of recent snow cover and skiability conditions in a few mountainous areas of Slovenia

Massimiliano Fazzini - University of Ferrara - Department of physics and earth sciences - Via Saragat, 1 - 44100 Ferrara - Italy
Paolo Billi - University of Ferrara - Department of physics and earth sciences - Via Saragat, 1 - 44100 Ferrara - Italy
Tanja Cegnar – Slovenian Environment Agency, Ljubljana
Gabriele Avancini - University of Ferrara - Department of physics and earth sciences - Via Saragat, 1 - 44100 Ferrara - Italy

Corresponding author: Massimiliano Fazzini, fzzmsm@unife.it

In eastern Alpine system, nivometric measurements, carried out during the last three decades, indicate a decreasing trend of seasonal accumulation; for the same time interval, a marked increase in temperatures (more than 0.7 °C) of the winter semester has caused a patent rise of the snow limit, a decrease of snow permanence on the ground, hence of natural skiability, at least for elevations less than 1500 m a.s.l. Aim of this study is to analyze these parameters also for a few mountainous areas of Slovenia by means of time series ranging from 1980 to 2010 and characterized by no or very limited data gaps. Nine meteo-nivometric stations were selected. They are located in all the main mountain sectors of Slovenia (Julian Alps, Karavanke, Pohorje and other isolated mountains) at elevations between 480 and 2520 m a.s.l. and a few of them (Ratece, Krvavec, Vojsko, Vogel) are included in important skiing resort districts. For the meteo station of Ratece, located within the famous skiing district of Kranjska Gora, a longer time series is available, hence the data analysis regarded the 1950 – 2010 interval. The analysis of daily thermometric and higrometric data has confirmed the possibility to produce artificial snow whenever the natural snow cover is not enough for alpine skiing sports. In fact, it has been observed that the amount of snow is decreasing significantly and constantly, at between two to four centimeters per season whereas the number of skiing days is decreasing from 0.7 to 1.4 per season, with the exception of Krvavec station where no negative trend is observed. We confirm that the skiing threshold of 100 days per years is reached only in the skiing sites located at an elevation higher than 1500 m a.s.l., whereas below such elevation the need of artificial snow is becoming more and more impelling. At the Ratece station, the number of natural skiing days equals 70 but, with the support of artificial snow, a total number of 100 skiing days is easily reached. Such a threshold is considered as the minimum condition for the economic developent of the skiing district.

Winter 2012-2013, exceptional snowfall in Trentino Dolomites: the example of Fiemme Valley

Massimiliano Fazzini - University of Ferrara, Department of physics and earth sciences - Via Saragat 1 44100 Ferrara - Italy
Sergio Zeni - ITAP Pampeago, Tesero (TN) Italy
Gérard Beltrando - * Université Paris Diderot, UMR 8586 (PRODIG) du CNRS (cc 7001) 75205 Paris cedex 05

Corresponding author: Massimiliano Fazzini, fzzmsm@unife.it

Notwithstanding the winter season is not over yet, it has shown uncommon meteoclimatic features with often perturbed and cold weather and very abundant snowfall also at low elevations. The seasonal values of the last ten years are characterized by a wide nivometric variability with the 2008-2009 season as the most snowy on average since 1951. A first analysis of nivometric parameters, carried out on data of a several stations located in the skyiing district “Ski Center Latemar” (Fiemme Valley, eastern Trentino), which includes the snow fields of Pampeago, 1760 m a.s.l., Monsorno, 2000 m a.s.l., Naturale Agnello 2080, m a.s.l., Tresca, 2180 m a.s.l., Gardoné, 1655 m a.s.l. and the snow fields of Alpe Cermis, 2100 m a.s.l., Passo Rolle, 2000 m a.s.l. and Passo Valles. 2040 m a.s.l., shows that the highest values of 2008-2009 season have been locally exceeded in terms of snowy days and fresh seasonal snow accumulation. In particular, by comparing the nivologic data of 2008-2009 and 2012-2013 a marked difference in temporal distribution and intensity daily results. The 2008-2009 season was characterized by a first trimester, spanning from the end of November to the end of February, with extreme abundant snowfalls, whereas during the second part of the season enough dryer and colder conditions prevailed. In the current 2012-2013 season, the snow precipitation spectrum has been cyclic and uninterrupted since the last days of October to the end of March. These conditions have been favored by the constant occurrence of the zonal flow, with an undulatory polar jet stream at latitudes lower than expected, whereas the extremely abundant snowfall event that characterized the beginning of the 2008-2009 winter season, determined by prefrontal massive advections of Mediterranean air, was absent.

Recent snow and synoptic situations bearers of heavy snowfall on the mountains of Sicily island

Massimiliano Fazzini - University of Ferrara, Department of Physics and earth sciences, Via Saragat, 1 - 44100 Ferrara;
Antonino Paladino - Corpo Forestale della Regione Siciliana
Vincenzo Romeo - Corpo Forestale dello Stato - Servizio Meteomont - Rome - Italy
Antonio Cardillo - Regione Molise - ARPC
Carmela Vaccaro - University of Ferrara, Department of Physics and earth sciences, Ferrara

Corresponding author: Massimiliano Fazzini,Antonino Paladino, Vincenzo Romeo, Antonio Cardillo, Carmela Vaccaro, fzzmsm@unife.it*

Sicily covers over 25,000 square kilometers in the Mediterranean basin, which appears to be the largest Island; it has a population of over 5 million inhabitants. The mountain domains stretch for 24% of the total area, and they appear to be numerous and diversified elevation, morphology and geology. In the northern part of the region, overlooking the Tyrrhenian Sea, stands the mountainous alignment Nebrodis-Peloritani-Madonie that rises up to 1980 m of Pizzo Carbonara. Along the east coast there is the active volcano Mount Etna - 3,343 meters high. Given a typically Mediterranean rainfall regime, with cool and very rainy winters - despite the latitude between 37 and 39 degrees north - in these domains mountains, snow is quite generous and above 1800 meters it is possible the practice of ski. On the top of Mount Etna, the snowpack remains generally from late October to mid-June. In the period 1960-1992, the Regional Hydrographic Service has monitored the condition of the snowpack in the winter resort of Floresta - located on Nebrodi Mountain at over 1200 meters above sea level. There are measures the height of the snow on the 10th, 20th and 30th of the month and the duration of snow while you do not have measures relating to the cumulative of fresh snow. First analyzes of the data shows that the snow is conspicuous at least above 1500 meters above sea level; the sum of snow varies between 150 and 250 cm while the snow remains on the ground for an average period of 55 -100 days. In the last two seasons, the snowfall the snowfalls were very abundant due at the frequent advection of continental or intermediate polar air which affected also the central and southern areas of the Mediterranean basin. In the mid-March 2012, the height of the snow on the ground has exceeded 250 cm. The study of the synoptic conditions bearers of heavy snowfall occurred in the last two seasons, completed those relating to historical snowfall which also affected the plains and hilly areas of the region in the last fifty years, completed the study.

Climate change in Slovenia in the period of 1961–2011

Mojca Dolinar, Renato Bertalanič, Gregor Vertačnik, Damjan Dvoršek, Mateja Nadbath (all Slovenian Environment Agency, Slovenia, Ljubljana), Matija Klančar (University of Ljubljana, Slovenia, Ljubljana)

Corresponding author: Mojca Dolinar, m.dolinar@gov.si

Climate records have become increasingly important in the last 20 years, mostly due to the impacts of anthropogenic climate change. Analysing of historical data sets for the purpose of climate change monitoring is an immense task. Slovenian Environment Agency launched a project in 2008 to study climate variability since 1961 in Slovenia. It began with a thorough quality control and metadata collection. Bad quality data series were discarded from the further analysis, while the rest were homogenised and analysed. The most striking feature is a strong positive temperature trend of about 3.3 °C per century in the analysed 51-year period. The trend is slightly higher in eastern Slovenia. All seasons, except autumn, have warmed significantly. Precipitation sum is more variable, with the linear trend on seasonal scale being mostly insignificant. Snow cover depth has been the most variable and challenging climate element studied. Sunshine duration shows mostly increasing trend.

The relevance of cut-off low systems to manifestation of large scale extreme precipitation events in the Alpine region

Nauman K. AWAN and H. Formayer
Institute of Meteorology, Department of Water, Atmosphere and Environment, University of Natural Resources and Applied Life Sciences (BOKU), Vienna

Corresponding author: Nauman Khurshid AWAN, nauman.awan@boku.ac.at

In this study we attempt to highlight the relevance of cut-off Low systems (CoLs) to large scale extreme precipitation events. The CoLs are detected with the aid of a numerical algorithm which is based on the physical characteristics of CoLs. The European Center for Medium-Range Weather Forecasts (ECMWF) ERA-40 re-analysis dataset is used as an input. The output of the algorithm contains the co-ordinates of centers of CoLs. The main outcomes of this study are: 1) a detailed climatology (1971-1999) of CoLs for the European region, 2) contribution of CoLs to large scale extreme precipitation events in the Alpine region, 3) identification of regions mostly affected by large scale extreme precipitation, 4) identification of regions of CoLs recurrence, 5) identification of regions where presence of CoLs is related to extreme precipitation in Alps. For evaluating precipitation Swiss Federal Institute of Technology Zürich dataset is used. The findings of this study suggest that CoLs occur quite often in the Alpine region. They also have a significant influence on the climate of this region. However, they are more often in Summer then in any other season (more than 80 % of the events occur in summer season). The area around the Alps and West of Spain (over the Atlantic Ocean) is the most favored region. The most affected regions are in the East and North of the Alps.

Evaluation of a 10-year Cloud-resolving climate simulation for the greater Alpine region

Nikolina Ban, ETH Zürich
Jürg Schmidli, ETH Zürich
Christoph Schär, ETH Zürich

Corresponding author: Nikolina Ban, nikolina.ban@env.ethz.ch

Large uncertainties in current regional climate model integrations are partly related to the representation of clouds, moist convection, and complex topography. Experience with numerical weather prediction generally shows that increased spatial resolution, and switching from parametrized convection to cloud-resolving models, leads to a better forecast. For climate simulations, however, the potential of cloud-resolving models is not yet sufficiently investigated. Recent studies using cloud-resolving models in climate mode have shown highly promising results. Here we present a cloud-resolving simulation for a 10-year long period (1998-2007) integrated with the COSMO-CLM (Consortium for Small-Scale Modeling in Climate Mode). Two one way nested grids are used with horizontal resolution of 2.2 km for a cloud-resolving simulation (CRM) on an extended Alpine domain (1100km x 1100km) and of 12 km for a regional climate simulation (CPM) which covers Europe. The CRM is driven by hourly lateral boundary conditions from the CPM run while the CPM run is driven by 6-hourly lateral boundary conditions from ERA-Interim reanalysis data. To eliminate spin-up issues, initial soil moisture is taken from the CPM simulation which has been integrated over the 1993-2007 period. We will present evaluation results in terms of differences between the cloud-resolving simulation CRM and the parametrized convection run CPM. Particular consideration will be given to the inter-comparison of the precipitation distributions from the two simulations over complex terrain, including an assessment of extreme precipitation events.

Long-term variation of large-scale circulation and its relation to climate changes at the Kola peninsula

Demin V.I., Polar Geophysical Institute of RAS, 14, Fersmana St., Apatity, 184209 Russia
Chernous P.A., Center for Avalanche Safety, "Apatit" JSC, 33a, 50-years of October St., Kirovsk,184250 Russia
Moroz N.V., Center for Avalanche Safety, "Apatit" JSC, 33a, 50-years of October St., Kirovsk,184250 Russia

Corresponding author: Pavel Chernous, pchernous@phosagro.ru

All variety of atmospheric processes can be organized into several classes. G. Vangengeim generalized all types of atmospheric processes into three so-called circulation forms – zonal (W) and two meridianal (E and C). These circulation forms are represented as specific patterns of global baric and thermal fields in the troposphere. It is important that there are long-term changes in the frequency of circulation forms which are named as a circulation epochs. Their periods have a length of about ten and more years. During circulation epochs the frequency of one (or two) circulation form(s) exceeds the long-term mean value. Changes of the circulation epochs cause the long-term trends of regional weather conditions. Thus this factor should be taken into account for the detection of regional climate variations.

In this research long-term changes of air temperatures at the Kola Peninsula were analyzed separately in different homogeneous groups of the circulation processes (W, E and C). It is shown that mean anomalies of winter air temperature on the top of the Lovchorr Mountain (the Khibiny Mountains, 1091 m.a.s.l.) for periods of 1991-2011 are more 1.7, 07 and 0.9 °C than ones for period of 1961-1990 for the forms W, E, C correspondingly. Increases of mean anomalies of summer temperatures for same periods are 1.6, 0.4 and 1.3°C. Analogue results were obtained for other stations of the Kola Peninsula. Thus the modern warming in the region is very difficult to interpret as a result of changes atmosphere circulation since the increase of air temperatures is observed for all circulation forms.

An increase in the upper tree limit in the Khibiny mountains (Kola peninsula, Russia) and climate change

Demin V.I., Polar Geophysical Institute of RAS, 14, Fersmana St., Apatity, 184209 Russia
Chernous P.A., Center for Avalanche Safety, "Apatit" JSC, 33a, 50-years of October St., Kirovsk,184250 Russia
Moroz N.V., Center for Avalanche Safety, "Apatit" JSC, 33a, 50-years of October St., Kirovsk,184250 Russia

Corresponding author: Pavel Chernous, pchernous@phosagro.ru

Changes of vertical temperature distribution in the Khibiny Mountains (Kola Peninsula, Russia) were analyzed on the basis of measurements at the mountain meteorological stations. It is shown that mean summer temperature in the Khibiny Mountains for period of 1961-2011 is 0.3-0.4°C higher than one for period of 1881-1960. This change is corresponds to movement of summer isotherms by 30-50 m upward. At the same time a comparison of the old and contemporary photos of mountain slopes shows that since the end of 19th century the upper tree limit in the Khibiny Mountains has risen up by 100-150 m. It has been found that the forest expansion continued also during the periods of cooling of 1940-1970. Most likely upper tree limit was located lower than possible thermal boundary, i.e. movement of tree limit has the time lag relatively to the temperature changes.

It is suggested that the observed rise of upper tree limit in the Khibiny Mountains is resulted of long-term (centuries) climate changes mainly and in a lesser degree is a response to short-term (decades) climatic variations including the present-day warming in the region which is started from the second half of 1980’s.

Thermal comfort analysis in the Alpine region

Reinhold Steinacker and Dieter Mayer, Department of Meteorology and Geophysics, University of Vienna, Austria

Corresponding author: Reinhold Steinacker, reinhold.steinacker@univie.ac.at

Besides the basic state variables of the atmosphere, complex quantities which need several variables for its computation are of special interest for applications in applied climatology. One of these specific quantity is the thermal comfort index for men, which is determined for both, cold and warm conditions. For its full determination the air temperature, humidity, wind speed and solar radiation is required. As the diurnal range of the relevant quantities may vary dramatically, it does not make sense to compute such indices on a daily or even monthly basis. At least three hourly - or even better hourly observations have to be taken to decribe the thermal comfort for men. With the aid of the hourly VERA (Vienna Enhanced Resolution Analysis) fields, we have started to determine the hourly fields and statistics of the comfort index - at present without considering the solar radiation - for the whole Alpine region with a very high resolution. To avoid a more or less pure topographic field distribution due the extreme hight differences, we focus in one display on the low lands and Alpine valley floors, where the vast majority of people live. The fields for 2012 show interesting and partly unexpected details in the occurrence and frequency of different levels of discomfort due to cold and hot weather conditions. We intend to recompute fields of thermal comfort for the last 30 years to see the corresponding trends and impacts of the climate change.

High resolution simulations of cold air pooling in small-scale valleys

John Hughes, Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, UK
Andrew N Ross, Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, UK
Simon Vosper, Met Office, Exeter, UK
Adrian Lock, Met Office, Exeter, UK

Corresponding author: A.N.Ross@leeds.ac.uk

COLPEX (COLd-air Pooling EXperiment) was a large field campaign studying cold air pooling and fog formation in small-scale UK valleys with a width of ~1-2km and a depth of ~200m depth. A series of 100m resolution simulations were performed with the MetUM (the UK Met Office unified model). In addition to running IOP case studies, a 2 month long continuous run was performed to allow a more systematic assessment of the performance of the model at this high resolution over a range of different conditions. The data has been used to understanding the processes leading to cold air pool formation and development in these valleys. The results are also being used to understand the impact of these small scale processes on the parametrised fluxes in lower resolution models. Results from the high resolution simulations are coarse grained to a lower resolution and compared with results from simulations run at lower resolutions. The aim is to improve the parametrisation of these sub-grid cold air pooling processes in lower resolution weather and climate models. This paper will present results from the cold air pool heat budget study along with initial results from the coarse graining.

Idealized simulations of canyon exit jets in Utah

Allison Charland, University of Utah
C. David Whiteman, University of Utah
Manuela Lehner, University of Utah

Corresponding author: Allison Charland, allison.charland@utah.edu

Nocturnal wind jets have been observed at the exit of Weber Canyon to the east of the Great Salt Lake Basin in Utah during late summer and early fall on clear, undisturbed nights. These canyon exit jets develop 1-3 h after sunset and can reach maximum wind speeds of 15-20 m s-1 overnight, then weaken after sunrise. Idealized simulations using CM1, a 3D, time dependent, non-hydrostatic numerical model, have been analyzed to determine the causes of the formation and dissipation of the canyon exit jets.

Simulations show the formation of a valley-exit jet around 1900 MST, about 1 h after sunset, which weakens in the late morning hours the next day. Cold, stable air builds up in Morgan Basin, upstream of Weber Canyon, overnight due to a down valley flow. The air drains through the canyon and accelerates as it is compressed downward at the canyon exit. Simulations show the development of a hydraulic jump at the canyon exit with high wind speeds present beneath the region of the hydraulic jump. The jet maximum, downstream of the hydraulic jump, occurs between 50-100 m above the ground.

High wind speeds extend nearly 10 km horizontally into the Great Salt Lake Basin from the canyon exit and are partially deflected northward due to a plateau located south of the exit region. There is also a second, weaker exit jet that develops out of Ogden Canyon, north of Weber Canyon.

The influence of a depth of a very shallow cold air pool lake on the nocturnal cooling

Jože Rakovec,Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia and Center of Excellence SPACE□SI, Ljubljana, Slovenia
Gregor Skok, Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia and Center of Excellence SPACE□SI, Ljubljana, Slovenia

Corresponding author: Gregor Skok, Gregor.Skok@gmail.com

A five-layer thermodynamic model for a very shallow (few meters deep) Cold Air Pool (CAP) is presented. The model has two stationary layers with constant temperature (an atmosphere layer above the CAP and a deep soil layer) and three non-stationary layers: one thin soil layer at ground surface and two very shallow air layers. The model is applied either to a shallower CAP (only one layer 3 m deep) and a deeper CAP (two 3 m layers, together being 6 m deep) CAP. The model shows that air in the deeper CAP cools more than the air in the shallower CAP. The difference between the equilibrium temperature of deeper and shallower CAP is shown to be strongly dependent on the humidity of the air inside the CAP and humidity of the atmosphere - more humidity of the air inside CAP or the atmosphere results in greater difference in cooling. The difference is also somewhat dependent on the soil heat conductivity and on temperature deep in the ground – an increase in heat conductivity results in smaller difference. In the end the model results are compared with measurements from a 10-month field experiment which consisted of simultaneous measurement of temperature and humidity at three locations inside a very large shallow CAP. The measurements confirm the importance of depth of CAP on equilibrium temperature but also hint that other factors, especially local concavity (position in a local depression), might play an equally important role in the strength of nocturnal cooling.

Observed and modeled nocturnal wind and temperature oscillations in the lower Inn Valley

Irene Schicker, Institute of Meteorology, University of Natural Resources and Life Sciences, Vienna
Petra Seibert, Department of Meteorology and Geophysics Vienna, University Vienna

Corresponding author: Irene Schicker, irene.schicker@boku.ac.at

The propagation of sound and the dispersion of pollutants in basins and valleys is influenced by the local wind systems as e.g. slope and valley winds. Another parameter influencing is the location and height of the cold air pool layer. Nocturnal wind and temperature oscillations measured during an intensive observation period (IOP), November 20 2005 to March 10 2006, in the Austrian Inn Valley are investigated using the observations taken during the IOP and a meteorological model. Several events of sudden drops of the nocturnal temperature were observed during the IOP. During such events temperature decreases of more than 3 K within less than 5 – 10 minutes were found. These events occurred when the wind direction changed from downslope to upslope thus advection the cold air of the valley floor towards the observation sites indicating an swashing forth and back of the cold air pool. Also, changes in the sign of the sensible heat flux were observed. These temperature oscillations are observed at all three sites but not necessarily at the same time. At the lowest site, the temperature drops are observed more often than the ones located at the slightly higher sites. Here, a microscale change of the air masses is observed which are not only relevant for the transportation of pollution and noise but also relevant for e.g. growth of fruits.

Three measurement sites close to Jenbach, located 5 – 30 m above the valley floor along the northern and southern slope are used. At each site measurements of temperature and wind at two levels at small towers were carried out. At one site and ultrasonic anemometer was used additionally. Results and findings of an earlier case study were some basic MM5 simulations were carried out were used in addition. Besides the observations a very high resolution simulation using the WRF ARW v3.3.1 is carried out to investigate the evolution of selected events. The WRF simulations shown here use re-mapped CORINE land-use data and high resolved DEM data for the innermost modeling domain.

Modelled variation of cold air pooling processes at various grid resolutions

Paul Burns (1)
Charles Chemel (1,2)

1 Centre for Atmospheric & Instrumentation Research, University of Hertfordshire, UK
2 National Centre for Atmospheric Science, Centre for Atmospheric & Instrumentation Research, University of Hertfordshire, UK

Corresponding author: Paul Burns, p.burns@herts.ac.uk

Elucidating cold air pooling processes forms part of the long-standing problem of parameterising the effects of complex terrain in larger-scale models. The Weather Research and Forecasting model has been setup and run at high resolution over an idealised alpine-valley domain of order 10 km, to investigate the four dimensional variation of key cold air pooling drivers, under de-coupled stable conditions. Model results indicate that downslope flow characteristics are sensitive to model grid resolution, and a convergence of solutions enables a strategic model grid resolution selection. Three regimes of long-wave radiative flux divergence contribution, C_rad, to total average valley-atmosphere cooling have been identified. Starting about one hour before sunset, there is an initial 40 min period of C_rad dominance, as the flow establishes itself and when the other energy balance terms generally sum to a heating contribution. A period of instability follows, lasting for approximately one hour. Finally, there is a gradual reduction of C_rad over a period of 380 min from 60% to a final contribution of 32 %. The simulation average C_rad is close to 50 %, but is 38 % for the period of gradual decline, with maximum and minimum values, occurring at the start and close to the end of the simulation, of 233 and 16 %, respectively. The C_rad values for the final period and its average contribution are in the range of values reported in the literature. The contribution of the other energy balance terms will be discussed, together with the dependency on model resolution.

Numerical modelling of valley cold air pools

Peter Sheridan, Met Office, UK
Simon Vosper, Met Office, UK

Corresponding author: Peter Sheridan, peter.sheridan@metoffice.gov.uk

Valley cold air pools which form on calm, clear nights in complex terrain represent a significant problem, enhancing the likelihood of road-ice formation, crop damage and harmful pollution episodes. Cold air pools form in valleys over a wide range of scales and geometries, and may have a very different character in different locales, presenting different forecast problems. In small UK valleys, for instance, cold pools are diurnal and the scale is less than the grid spacing of operational numerical weather prediction (NWP) models, while in many large US basins, cold pools may persist for days, and the complex interplay of processes involved in their evolution may be difficult for NWP models to forecast accurately. Here, high resolution idealised model simulations will be used to examine how cold air pool behaviour depends on factors such as valley scale and geometry as well as upstream wind and temperature profile, in order to investigate different regimes in a controlled manner.

Influence of topography on the diurnal cycle of summertime moist convection over its near-and far-field regions

Hassanzadeh Hanieh, Institut for Atmospheric and Climate Science, ETHz University
Schmidli Jürg, Institut for Atmospheric and Climate Science, ETHz University
Langhans Wolfgang, Climate Sciences Department, Berkeley University
Schär Christoph, Institut for Atmospheric and Climate Science, ETHz University

Corresponding author: Hanieh Hassanzadeh, hanieh.hassanzadeh@env.ethz.ch

The influence of the topography on the diurnal cycle of summertime moist convection is investigated in an idealized framework using a cloud-resolving model (CRM) with a horizontal grid spacing of 2km. In this framework, the atmosphere is continuously relaxed towards prescribed reference profiles of temperature, specific humidity and wind speed. This relaxation mimics the influence of a large-scale advection. The strength of the relaxation varies with height, with a relaxation time of 1 day in the upper troposphere and much weaker relaxation at lower levels. The simulations are run for 30 days. During the last 20 days a quasi-steady diurnal cycle is obtained, the diurnal equilibrium. Here, we investigate the influence of topography on the diurnal equilibrium evolution of clouds, precipitation and the associated net vertical fluxes of energy and water. As expected the influence is large, in terms of cloud and precipitation amount as well as in terms of timing of the diurnal cycle. In comparison to flat terrain, clouds and heavy precipitation occur earlier in some regions over the topography, but other adjacent regions receive very little precipitation. In this work, a particular focus will be on the analysis of the mountain effects as a function of the distance from the mountain (e.g. near-field and far-field effects) and a detailed investigation on the evolution of moist convection including an analysis of the dominant precipitation mechanisms over each region.

Orographic triggering and mesoscale organization of extreme storms in subtropical South America

Kristen L. Rasmussen - University of Washington, Seattle, WA
Robert A. Houze, Jr. - University of Washington, Seattle, WA
Anil Kumar - NASA Godard Space Flight Center, Earth System Science Interdisciplinary Center, Greenbelt, MD

Corresponding author: Kristen Lani Rasmussen, kristen@atmos.washington.edu

Extreme convection tends to form in the vicinity of mountain ranges, and the Andes in subtropical South America help spawn some of the most intense convection in the world. An investigation of the most intense storms for 11 years of TRMM Precipitation Radar (PR) data shows a tendency for squall lines to initiate and develop in this region with the canonical leading convective line/trailing stratiform structure. On average, South American mesoscale convective complex cloud shields are 60% larger than those over the United States and they have larger precipitation areas than those over the United States or Africa. The synoptic environment and structures of the extreme convection and MCSs in subtropical South America are similar to those found in other regions of the world, especially the United States. In subtropical South America, however, the topographical influence on the convective initiation and maintenance of the MCSs is unique. The Andes and other mountainous terrain of Argentina focus deep convective initiation in a narrow region. Subsequent to initiation, the convection often evolves into propagating mesoscale convective systems similar to those seen over the Great Plains of the U. S. and produces damaging tornadoes, hail, and floods across a wide agricultural region.

Numerical simulations conducted with the NCAR Weather Research and Forecasting (WRF) Model extend the observational analysis and provide an objective dynamical evaluation of storm initiation, development mechanisms, dynamics and microphysics. A capping inversion in the lee of the Andes is important in preventing premature triggering. The South American Low Level Jet impinging on low mountains to the east of the main Andes ranges triggers extremely deep and intense convection. Mesoscale organization into leading line/trailing stratiform system occurs as the storms propagate eastward. The simulated mesoscale systems closely resemble the storm structures seen by the TRMM satellite as well as the overall shape and character of the storms shown in the GOES satellite data. A sensitivity study removing small-scale topographic features that are hypothesized to focus deep convective initiation determines the role of the topography in triggering and geographical focusing the extreme convection. Preliminary results of the numerical experiment in which smaller mountain features are removed will be presented at the conference.

Wind patterns associated with the development of daytime thunderstorms over Istria

Maja Telišman Prtenjak
Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia
Gabrijela Poljak
Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia
Marko Kvakić
CNRM-GAME, Meteo-France/CNRS URA 1357, 42 Avenue Gustave Coriolis, 31057, Toulouse Cedex, France

Corresponding author: Maja Telišman Prtenjak, telisman@gfz.hr

This study investigates the impact of the combined large-scale wind and thermally induced local wind on the moist convection development (cumulonimbus clouds) over the northeastern (NE) Adriatic. Former analyses revealed that the NE Adriatic, particularly the Istrian peninsula, is the area with (i) the highest frequency of thunderstorms in Croatia, typically during three wind regimes on a large scale (from the southwest (SW), northeast (NE) and northwest (NW)), and (ii) frequent appearances of sea breeze along the coast (every other summer day on average). The highest density of lightning strikes was observed in the NE mountainous part of the peninsula. Therefore, the three selected cases (one for each type of dominant large-scale wind) were analyzed using the available near-surface and remote measurements. They were simulated also by WRF high-resolution numerical model and examined by the sensitivity tests.

In all cases, the near-surface wind patterns consisted of sea breezes along the coastline that generated a narrow eastward-moving convergence zone along the Istria. When the large-scale SW wind (as an onshore wind) dominated in the upper troposphere, the thunderstorm event was the shortest and weakest with only a minor impact on the sea breeze. This was confirmed by the sensitivity tests without microphysics. The origins and locations of storm cells were completely controlled by the low-level convergence zone and the upward advection of low-level moisture at the sea breeze front. In the other two examined cases with offshore large-scale winds from the NE and NW, the mountain range hastened the beginning of convection and affected its intensity. Except for the low-level convergence zone, the advection of large-scale wind influenced the lifetimes and movements of the initial convective cells. Thus, while the local front collision with the NE wind advection caused the thunderstorm to propagate southward, the convergence zone and fronts interaction determined the afternoon northwestward storm movement against the NW large-scale wind.

Dependency of convection on environmental conditions over complex terrain during HyMeX

Norbert Kalthoff: Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT)
Bianca Adler: Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT)

Corresponding author: Norbert Kalthoff, norbert.kalthoff@kit.edu

In mountainous areas various thermally and dynamically produced processes occur simultaneously and interact on different scales. Beside the large-scale atmospheric conditions these processes influence the evolution of convection. As part of the HyMeX field campaign in the Western Mediterranean Sea 2012 the KITcube observation platform was installed at the mountainous island Corsica. KITcube combines various in-situ and remote-sensing systems that allows to measure the process chain from energy exchange at the surface via turbulent transport to the formation of clouds and precipitation.

In contrast to days with weak synoptic winds, gravity waves formed in the lee of a high mountain ridge when strong synoptic winds prevailed. This waves were associated with a downward transport of warm, dry and aerosol-free air and strong momentum from the free atmosphere into the lower parts of valley atmosphere. They interacted with the boundary-layer structure and suppressed convection in the valley center.

Regularly, moist convection formed above the mountain ridges due to moisture transport up the slopes and mountain venting. Depending on the large-scale conditions (e.g., stability, humidity content) shallow convection also persisted above the valley center. Finally, we analyzed the differences between days with shallow and deep convection.

The Interaction of Convective Storms with Complex Terrain: A Case Study of an Alpine Supercell

Phillip Scheffknecht, Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria
Stefano Serafin, Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria
Vanda Grubišić, Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria and Earth Observing Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

Corresponding author: Phillip Scheffknecht, phillip.scheffknecht@univie.ac.at

In this study we examine the interaction of a convective storm with complex terrain. On 2 August 2007 a supercell storm moved north of and along the Alpine main ridge for over 8 hours, passing over several individual peaks in excess of 2000 m. The event is very well suited to identify the ways in which topography influences the development of a convective system.

WRF simulations with a maximum horizontal resolution of 833 m are performed. Model output is verified with surface weather station data and radar imagery. We analyze how the intensity of the supercell's updraft is affected by the distribution of CAPE and moisture in the valleys and over mountains along the storm track.

The real case simulation produces a convective system whose development is very similar to the observed one. The storm intensity variations correlate with the altitude variations of the underlying terrain and with CAPE availability along the storm track. The depth of the moist layer tends to be higher over mountaintops than over valleys. In fact, thermal circulations push the warm and moist air out of valleys ahead of the storm and concentrate it along convergence lines. The storm updraft intensifies every time it crosses one of these areas.

In addition to the real case (control) simulation, two sensitivity tests are made to examine the effect of the terrain on the supercell development. Results from these semi-idealized simulations suggest that the Alpine ridge as a whole influences the wind field in such a way that the wind shear is favorable for the formation of a supercell. On the other hand, smaller-scale valleys and ridges influence the storm by supporting thermally driven circulations, which redistribute moisture in the boundary layer favoring an exceptionally long-lasting event.

Extended intensive rainfall in Rijeka due to local orography

Martina Tudor, Kristian Horvath, Stjepan Ivatek-Šahdan
Croatian Meteorological and Hydrological Service

Corresponding author: Stjepan Ivatek-Šahdan, ivateks@cirus.dhz.hr

A heavy precipitation event occurred over the north-eastern Italy, Slovenia and north-west Croatia in the afternoon and evening of 12th September 2012. The event was associated to a warm and moist low level air-mass from the Adriatic Sea and a cold front. Rain-gauges recorded 24 hourly precipitation exceeding 100 mm, up to 160 mm over north-eastern Italy, but reaching 220 mm in Rijeka, Croatia. That area received the most intensive rainfall during this event according to the data from the rain-gauges and TRMM.

In the morning, a cold front, associated to a pressure through moving eastward, interacted with warm and moist low level air and initiated severe deep convection first over northern Italy. The system moved eastward, according to the lightning maps.

Operational forecasts using ALADIN at CMHS did forecast rainfall amounts exceeding 100 mm in 24 hours, but most forecast runs put the area of maximum intensity over Slovenia, and only one operational forecast run moved the high intensity precipitation towards Rijeka. According to ombrograph, precipitation intensity was the highest from 21 to 22 UTC (85.3 mm/h), with 20.6 and 51.7 mm/h in the previous and the next hour.

The band of intensive rainfall moved eastward over flat plain of Po valley, more intensive above land than above water of northern Adriatic. But when it approached more complex terrain, secondary bands of intensive rainfall form in front of it, according to radar data. At the same time satellite figures show formation of cumulonimbus clouds. This intensive rainfall band reaches Trieste and Slovenia according to radar figures at 19:30 UTC and merges with the rainfall band that formed above Trieste at 18 UTC. Another rainfall band forms above Istrian peninsula at 19:30 UTC. Intensive rainfall spreads to Rijeka and remains there for several hours. During that time other rainfall bands form and arrive to Rijeka intensifying the precipitation and prolonging the period of high precipitation intensity.

The high resolution non-hydrostatic operational forecast shows upward motions all along the coastal mountains of Croatia and an approaching band associated to the rain band.

The impact of data assimilation of different observation types on forecast of severe precipitation in the northern Adriatic during Hymex IOP 16

Antonio Stanesic (Croatian Meteorological and Hydrological Service)
Kristian Horvath (Croatian Meteorological and Hydrological Service)
Stjepan Ivatek-Sahdan (Croatian Meteorological and Hydrological Service)
Tomislav Kovacic (Croatian Meteorological and Hydrological Service)

Corresponding author: Antonio Stanesic, stanesic@cirus.dhz.hr

During IOP 16 of the HYdrological cycle in the Mediterranean Experiment – Hymex, a heavy precipitation event occurred over the northern Adriatic region and surrounding mountains and lasted from 26 Oct – 28 Oct 2012. The areas most affected by the event were the municipality of Rijeka in Croatia and regions near Italian-Slovenian border, where the accumulated precipitation in those two days reached more than 200mm. This event was used to perform the initial analysis of the impact of the mesoscale data assimilation of different observational data types, including targeted observations, on the forecast accuracy using the Observing System Experiments (OSE) approach.

Simulations were performed using the operational hydrostatic model implemented at DHMZ, which is ALARO with 8km horizontal grid spacing and 37 vertical levels. The data assimilation system used in this study consists of the surface assimilation (OI) and the upper-air assimilation (3DVar) within the ALADIN model framework. The observation dataset used in this study includes SYNOP, SYNOP-SHIP, radiosoundings, MSG AMW winds and satellite radiances from NOAA (AMSU-A, AMSU-B) and MSG (SEVIRI). Furthermore, additional Data Targeting System extra-soundings performed during the IOP16 were used to study the potential for targeting heavy precipitation events in the northern Adriatic area. Forecasts were validated against rain-gauges and remote sensing instruments.

METEOMET: metrology for data quality in climate and meteorological observations

Domen Hudoklin, University of Ljubjana, Faculty of Electrical Engineering, Ljubljana, Slovenia
Janko Drnovšek, University of Ljubjana, Faculty of Electrical Engineering, Ljubljana, Slovenia
Gaber Begeš, University of Ljubjana, Faculty of Electrical Engineering, Ljubljana, Slovenia
Jovan Bojkovski, University of Ljubjana, Faculty of Electrical Engineering, Ljubljana, Slovenia
Fabio Bertiglia, Istituto Nazionale di ricerca Metrologica - INRiM, Torino, Italy
Giuseppina Lopardo, Istituto Nazionale di ricerca Metrologica - INRiM, Torino, Italy
Guido Roggero, Istituto Nazionale di ricerca Metrologica - INRiM, Torino, Italy
Francesa Sanna, Istituto per le macchine agricole e movimento terra IMAMOTER, Consiglio Nazionale delle ricerche - CNR, Ferrara, Italy
M. Carmen Garcia Izquierdo, Centro Espanol de Metrologia, Tres Cantos, Spain
Andrea Merlone, Istituto Nazionale di ricerca Metrologica - INRiM, Torino, Italy

Corresponding author: Domen Hudoklin, domen.hudoklin@fe.uni-lj.si

In October 2011, a joint research project called “MeteoMet - Metrology for Meteorology” (www.meteomet.org) started, bringing together a wide consortium of partners: 18 national metrology institutes and 6 universities as partners plus 29 collaborators, including national meteorological organizations, research institutes associations and instruments companies. The project is aiming to respond to the needs for new stable and traceable measurement standards, protocols, sensors and calibration procedures, and uncertainty-evaluation methods, to enhance data reliability and reduce uncertainties in climate models. This project is part of the European Metrology Research Program (EMRP) coordinated by the European Association of National Metrology Institutes (EURAMET).

The activities that are on their full way now, comprise of investigation of new humidity sensors for upper air measurements with setting up a traceability chain based on tuneable diode laser absorption spectroscopy (TDLAS); development of novel methods and instruments for the measurement of temperature, humidity, and pressure in lower and upper atmosphere; development of traceable measurements methods and protocols for temperature, humidity, pressure and airspeed ground-based measurements needed for climate studies and meteorological long–term and wide scale observations; etc. Additionally, the project deals also with the construction of a facility for in-situ traceable calibration of weather stations. Three models of this facility have been developed for different uses, including extreme environmental conditions: one of those chambers will be transported and used at the Pyramid laboratory/observatory of Mount Everest, for the calibration of sensors positioned in the Himalayan area.

As the project will terminate in 2014, initial steps were already taken to start a follow-up project, which will place even more focus on alpine meteorological issues related to metrology. At present, several high mountain stations located mainly in alpine environment are run by different services or institutions without commonly agreed procedures for measurements, instruments involved and site characteristic, which hardly complies with the WMO directive. The particularity of high mountain environment requires new kind of site and instrument validation processes. A proposed reference station in high mountain alpine area, combined with other kind of monitoring (permafrost, water lakes/springs, etc.), is necessary in order to analyse the best way the relationship among atmosphere, geosphere, cryosphere, hydrosphere and biosphere in alpine region, particularly sensitive to climate change and where their effects are more pronounced. A pilot surface site in support of high mountain programs and in conjunction with the permafrost monitoring network would improve the quality of weather and climate parameters recorded in high alpine. The evaluation of mutual relations at seasonal, annual, long-term level would be possible.

For the measurement of the high mountains lakes temperature of the water and ice mantles it is proposed the definition of specific systems, best practice, calibration and measurement uncertainty evaluation, for a practical reference example to be implemented through instruments and calibration campaigns. Dedicated instruments calibration for temperature and soil moisture probes and assessment of calibration and measurement uncertainty are proposed too. A methodology to achieve calibration target uncertainty in the order of 0.01 °C is proposed for permafrost monitoring studies.

The adoption of standard equipment and procedures for alpine stations, would benefit the work of the European nations belonging to the Alps Convention in their common mission of climate and weather observations.

These ambitious objectives are planned to be discussed also in the scope of a first International workshop on traceability and uncertainty evaluation for meteorology, climatology and earth observations which is scheduled for late spring 2014.

HyMeX SOP1, the field campaign dedidicate to heavy precipitation and flash-floods in Northwestern Mediterranean

Véronique Ducrocq CNRM/GAME, Météo-France, Toulouse, France
Evelyne Richard Lab. d'Aerolgie, CNRS & University of Toulouse, Toulouse, France
and the HyMeX EC-ISC Team

Corresponding author: Evelyne Richard, Evelyne.Richard@aero.obs-mip.fr

The Mediterranean region is frequently affected by heavy precipitation events associated with flash-floods, landslides and mudslides each year that cost several billions of dollars in damage and causing too often casualties. Within the framework of the 10-year international HyMeX program dedicated to the hydrological cycle and related processes in the Mediterranean (http://www.hymex.org), a major field campaign has been dedicated to heavy precipitation and flash-floods from September to November 2012. The 2-month field campaign took place over the Northwestern Mediterranean Sea and its surrounding coastal regions in France, Italy and Spain. The observation strategy aimed at documenting four key components leading to heavy precipitation and flash-flooding in that region: (i) the marine atmospheric flow that transport moist and conditionally unstable air towards the coasts; (ii) the Mediterranean Sea as a moisture and energy source; (iii) the dynamics and microphysics of the convective systems; (iv) the hydrological processes during flash-floods.

During the field campaign about twenty precipitation events were monitored, including mesoscale convective systems, Mediterranean cyclogenesis, shallow-convection orographic precipitation. Three aircraft performed about 250 flight hours for a survey of the upstream flow, the air-sea fluxes and the convective systems. About 700 additional radiosoundings were launched either from HyMeX sites or from operational RS sites in Europe, as well as about 20 boundary layer balloons were launched to monitor the low-level flow over the Mediterranean Sea and the ambient atmospheric conditions. Gliders, Argo floats, drifting buoys and ocean soundings from vessels monitored the Mediterranean Sea during the field campaign. Atmospheric and hydrological instruments such as radars, LIDARS, radiometers, wind profilers, lightning sensors, were deployed over 5 regions in France, Italy and Spain.

The presentation will present the general observation strategy and instrumentation deployed during the campaign, as well as the weather forecast component of the field operations coordination. An overview of the Intensive Observation Periods (IOP) will be then presented, together with first highlights on some observations and events.

Perspectives from field experiments in Iceland in recent years

Haraldur Ólafsson et al.
University of Iceland, Icelandic Meteorological Office and Bergen School of Meteorology, Geophysical Institute, University of Bergen

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

Several observational campaigns have been carried out in Iceland and between Iceland and Greenland in recent years. The experiments were based on portable network of weather stations, manned and unmanned aircrafts, supported by radar and an ever-increasing amount of data from remote sensing and a permanent network of ground-based observations. In all these campaigns mountains played important, but different roles. A review of highlights of results from these campaigns will be given, including thermally driven mesoscale flows, wakes, gravity waves, drag, local jets and the interaction of some of the above features.

Comparison of NWP-model chains by using novel verification methods

Manfred Dorninger, Departement of Meteorology and Geophysics, University of Vienna, Vienna, Austria
Theresa Gorgas, Central Institute for Meteorology and Geodynamics, Vienna, Austria
Reinhold Steinacker, Departement of Meteorology and Geophysics, University of Vienna, Vienna, Austria

Corresponding author: Manfred Dorninger, manfred.dorninger@univie.ac.at

Forecasts of a set of three model chains characterising a variety of model versions and types are evaluated. Each model chain consists of three models with increasing resolution nested into one another. Rules for a fair model inter-comparison have been defined. Inter alia, they refer to the use of NWP-model independent analyses as reference data which, in this study, are provided by the VERA (Vienna Enhanced Resolution Analysis) system. Observational data and model data have been collected in a combined effort of COPS (Convective and Orographically induced Precipitation Study) and D-PHASE (Demonstration of the Probabilistic Hydrological and Atmospheric Simulation of flood Events in the alpine region). Verification parameters are precipitation and the gradient of equivalent potential temperature as front indicator. The verification domain covers Central Europe. Verification periods range from half a year to single case studies. A choice of novel and traditional verification metrics has been implemented to examine multiple aspects of the model chains.The results only partly confirm previous findings that the models with the highest resolution usually outperform their counterparts of lower resolution. We find a rather different behaviour from model chain to model chain. Additional forecast skill is not stringently added by the nested models with the highest resolution. In the case of frontal propagation it is the coarsest model, which shows the best results. Wavelet transforms are used to study phase and modulus coherence of forecast and analysis on different scales.

Slope- and Valley Winds and their interaction – Observations with Doppler Wind LiDARs during MATERHORN

Sebastian W. Hoch, University of Utah, UT
Christopher Hocut, University of Notre Dame, IN
Amélie A. Klein, Ecole Normale Supérieure de Cachan, FR / University of Utah, UT
Yansen Wang, US Army Research Laboratory, MD
C. David Whiteman, University of Utah, UT
Harindra J. Fernando, University of Notre Dame, IN

Corresponding author: Sebastian W. Hoch, sebastian.hoch@utah.edu

The characterization of local drainage flows on an alluvial fan on the eastern slope of Granite Peak, and their interactions with the diurnal up- and down-valley circulation was a goal of Doppler Wind LiDAR measurements during the first experimental phase of MATERHORN (Mountain Terrain Modeling and Observation Program) conducted at Dugway Proving Ground, Utah, in Fall 2012.

LiDAR observations on the synoptically quiescent night of 1-2 October 2013 are presented. They show the formation and development of a shallow drainage flow on the eastern slope of Granite Peak, undercutting the previously dominating up-valley circulation by ~1800 MST. A down-valley flow becomes established by ~2100 MST bringing much colder air to the study area and undercutting the local drainage/slope flow. The interaction between the two flows includes the development of Kelvin-Helmholtz waves at their interface. During the course of the night, the shallow local drainage/slope flow becomes reestablished several times, mainly on the upper part of the slope seen by the LiDARs. The drainage flow appears to be separated from the surface and rides up onto the colder air put in place by the down-valley flow. The down slope flow can be followed for 1.5 km after separating from the slope and turning into the down-valley direction.

Surface Energy Balance Observations during MATERHORN

Sebastian W. Hoch, University of Utah
Derek Jensen, University of Utah
Eric Pardyjak, University of Utah
C. David Whiteman, University of Utah
Harindra J. Fernando, University of Notre Dame

Corresponding author: Sebastian W. Hoch, sebastian.hoch@utah.edu

Observations of the earth's surface energy balance have long been a focus of atmospheric research. The partitioning of the available energy from the sun varies widely by geographic location, land surface type, exposure, soil properties, and available moisture. The energy balance near the surface ultimately controls boundary layer development and evolution, and spatial energy balance differences lead to the formation of thermally driven circulations, such as sea-, lake- and playa breezes, slope- and valley wind circulations. Most of the time, when all components of the energy balance (net radiation, ground heat flux, turbulent sensible and latent heat fluxes) are measured directly, the energy balance is not closed and a residual term remains.

All components of the surface energy balance were directly measured at three different sites using some of the best available instrumentation during the experimental phase of MATERHORN (Mountain Terrain Modeling and Observation Program) conducted at Dugway Proving Ground, Utah, in Fall 2012. One site is located in a large sparsely vegetated arid basin, a second on a playa (dry alkali flats which fills with water seasonally to form shallow lakes). The third site is located on a sparsely vegetated slope of an alluvial fan of Granite Peak.

Besides the measurements of the individual short- and longwave components of the radiation balance and eddy-covariance measurements of the turbulent fluxes, our special focus was directed to the soil heat flux. Pairs of self-calibrating heat flux plates were uses at all sites, and the heat storage term above the flux plates was calculated from soil temperature measurements at three levels along with direct observations of the soil's volumetric heat capacity.

Albedo differences between the sites are the main cause of variations in energy input, but we also show how variations in soil properties lead to large differences in the energy balance. Differences in the energy balances among the three sites and their implications for boundary layer evolution will be discussed, along with measurement uncertainties and the residual term.

Characterizing regimes of strong terrain-induced winds in the vicinity of the Hong Kong International Airport

Alexander Gohm, Institute of Meteorology and Geophysics, University of Innsbruck, Austria
Lukas Umek, Institute of Meteorology and Geophysics, University of Innsbruck, Austria
Victoria Fetz, Institute of Meteorology and Geophysics, University of Innsbruck, Austria

Corresponding author: Alexander Gohm, alexander.gohm@uibk.ac.at

The Hong Kong International Airport (HKIA) is frequently affected by strong terrain-induced winds that develop downstream of the mountains on Lantau Island. These winds occur when the large-scale lower tropospheric flow is from the wind sector east to south west, often with a capping inversion located slightly above crest height and a less stable layer below. The resulting flow pattern in the vicinity of HKIA is rather complex and may be characterized by downslope windstorms, gap flows, rotors, vortex formation and shedding. Associated turbulence and rapid change in the mean wind speed and direction along the flight path are aviation hazards to the aircraft flying into and out of HKIA. In recent years, a series of case studies have been conducted based on the dense observational network at HKIA as well as high resolution numerical simulations to better understand these phenomena. However, a systematic study that relates various possible flow regimes to the atmospheric background state is missing. Such a study could be the basis for a simple and efficient forecasting tool that predicts a certain flow regime based on the predicted background state represented in a coarse resolution numerical weather prediction model and a regime diagram complied a priori by a series of high resolution semi-idealized simulations.

Our goal is to develop such a regime diagram. In a first step, we apply a single-layer shallow-water model (SWM) to the terrain of Lantau Island. Compared to a conventional three-dimensional numerical model, the SWM is less computationally intensive and allows for a higher number of different simulations. Hence, the effect of a change in the upstream background state – represented by the upstream Froude number (Fr), the layer depth (H), and the flow direction – can be explored in more detail. We find that the highest flow variability in space and time is associated with vortex shedding and occurs especially for southerly flow (within the range Fr=0.15 to 0.6 and H=0.25 to 1.2 km) and less for easterly flow. Shedding occurs only downstream of the two highest mountain peaks for moderate Froude numbers (approx 0.2 to 0.4) and layer depths of about 1 km. For higher Fr and lower H the predominant vortex forms at the southwestern edge of the island. The vortex size (between about 2 and 10 km) and the shedding period (between about 10 and 60 min) is a function of the background state. Strong gap winds and associated jets and wakes near HKIA occur for Fr between 0.2 and 0.6 and H smaller than 0.8 km. In a second step, we will evaluate our SWM results for selected regimes with three-dimensional large eddy simulations.

What really causes föhn warming? - A quantitative evaluation of the causes of leeside warming using the case study of the Antarctic Peninsula

Andrew Elvidge, UEA
Ian Renfrew, UEA
John King, BAS
Andrew Orr, BAS
Mark Weeks, UK Met Office

Corresponding author: Andrew Elvidge, a.elvidge@uea.ac.uk

Leeside warming during westerly cross-barrier flow across the Antarctic Peninsula is investigated and, for the first time, a thorough quantitative comparison of the importance of the various mechanisms responsible for föhn warming is presented. Three föhn events (A, B, C) during the Austral summer of 2010/11 have been observed in aircraft observations and simulated at high resolution by the UK Met Office Unified Model. Warming contributions are calculated using a novel approach which makes use of data derived from a Lagrangian model (Lagranto). In Case A, isentropic drawdown (due to the differential advection of air from aloft, as a result of low-level upwind flow blocking) constitutes the dominant warming mechanism for 5 out of 6 sample regions. In Case B, due to the sourcing of föhn air from low level, moist regions upwind (in association with a relatively linear flow regime), latent heat provides the greatest warming contribution. For two Case C sample regions and the remaining Case A sample region, sensible heat due to turbulent mixing – a mechanism that has previously been overlooked or underestimated – provides the greatest contribution due to the combination of a relatively low upwind source region and a relatively dry air mass. The implication is that there is no dominant föhn mechanism. Which mechanism dominates depends upon the relative humidity of the approaching air mass and the linearity of the cross-barrier flow regime.

What type of föhn event causes the highest melt rates on the Larsen C Ice Shelf, Antarctica?

Andrew Elvidge - UEA
Ian Renfrew - UEA
Thomas Lachlan-Cope - BAS
John King - BAS
Andrew Orr - BAS
Mark Weeks - UK Met Office

Corresponding author: Andrew Elvidge, a.elvidge@uea.ac.uk

Two contrasting cases of westerly flow across the Antarctic Peninsula are investigated with regard to the distribution of leeside warming and the consequent effect on Larsen C Ice Shelf melt rates. Data is derived from aircraft observations, AWS measurements and the UK Met Office Unified model run down to a horizontal resolution 1.5 km. In Case A relatively weak southwesterly cross-Peninsula flow determines a non-linear föhn event. The consequent strongly accelerated flow above, and hydraulic jump immediately downwind, of the lee slopes lead to high amplitude warming in the immediate lee of the AP, downwind of which föhn warming diminishes greatly due to the upward ascent of the turbulent föhn flow. Melt rates are insignificant on the Larsen C away from the AP. Case B defines a relatively linear ('deep') case associated with strong northwesterly winds. There is no laterally extensive hydraulic jump and föhn flow is able to flow at low level right across the ice shelf. Melt rates are high due to a combination of large solar flux (providing the largest surface flux) in association with a dry cloudless lee, and sensible heat flux due to the warm relatively well-mixed near-surface föhn flow. The implication is that whilst non-linear föhn events cause intense warming at the base of the lee slopes, linear föhn events cause more extensive near-surface warming in the downwind direction and consequently greater ice melt rates on the Larsen Ice Shelf.

Longitudinal vortices in the bora wind

Danijel Belušić, School of Mathematical Sciences, Monash University, Melbourne, Victoria, Australia
Željko Večenaj, University of Zagreb, Faculty of Science, Department of Geophysics, Zagreb, Croatia
Margaret A. LeMone, National Center for Atmospheric Research, Mesoscale and Microscale Meteorology Division, Boulder, Colorado, USA

Corresponding author: Danijel Belušić, danijel.belusic@monash.edu

The bora downslope windstorm dynamics has been studied at several different scales, ranging from the synoptic scale, through various mesoscales, where the interaction with mountains occurs that generates jets and wakes and the related PV banners, wave breaking and rotors, down to turbulence scales and wind gusts. However, a rather narrow range of scales has been overlooked despite a large body of previous studies. Our results indicate that bora generates longitudinal roll vortices above the Adriatic Sea with the wavelength of about 1 km. The bora flow setup is ideal for the formation of rolls - cold air outbreak over the relatively warm sea, with moderate to strong winds and wind shear. It thus comes as a surprise that rolls have not been assumed nor reported in previous bora literature. The most likely cause of this omission is the absence of the distinctive clouds streets that are usually associated with the roll vortices. This study examines the characteristics of the bora rolls observed by the Electra aircraft on 07 November 1999 during the MAP experiment.

The Novaya Zemlya Bora

G.W.K. Moore
Department of Physics
University of Toronto

Corresponding author: G.W.K. Moore, gwk.moore@utoronto.ca

Novaya Zemlya is a large and mountainous island in the Eastern Arctic that separates the Barents and Kara Seas. Weather station data indicates that surface wind speeds in excess of 15m/s occur approximately 50% of the time during the winter months. The air-sea interaction that occurs within a polynya that forms along the eastern shore of the island is thought to play an important role in Arctic thermohaline circulation and the water mass transformation of the incoming Atlantic water that passes by the island enroute to the central Arctic Ocean.

Although it has been proposed that a bora is responsible for these high winds, there have been no quantitative analysis of these winds and their impact on the environment.

Here we use the recently completed Arctic System Reanalysis (ASR) with its 30km spatial resolution to provide the first detailed high-resolution climatology of the surface wind field in the Novaya Zemlya region. The highest surface wind speeds are found on the western side of the island during easterly flow that is associated with a low-pressure system centered over the western Barents Sea. The high wind events are associated with a reversal in the zonal wind direction with height.

We show that the vertical structure of these high wind events shares many characteristics with idealized models of downslope windstorms associated with environmental critical layers as well as observations of the Yugoslavian Bora. In this regard, the high static stability of the upwind flow over the ice covered Kara Sea acts to increase the effective height of the topographic barrier thereby contributing to the acceleration of the flow that on the lee side of the island.

The highest wind speeds are most commonly found in the region where dense water is observed to form and we show that during high wind events, there is an approximate doubling, as compared to winter mean values, in the magnitude of the turbulent heat transfer from the ocean to the atmosphere. It is therefore proposed that the winds associated with this bora and the concomitant intense air-sea interaction contributes to the dense water formation in the Barents Sea.

Foehn diagnosis goes probabilistic

Georg J. Mayr, Institute of Meteorology and Geophysics, University of Innsbruck
David Plavcan, Institute of Meteorology and Geophysics, University of Innsbruck
Achim Zeileis, Department of Statistics, Faculty of Economics and Statistics, University of Innsbruck

Corresponding author: Georg J. Mayr, georg.mayr@uibk.ac.at

Diagnosing the occurrence of foehn at a particular has evolved from manually searching time series of temperature, relative humidity and wind speed and direction to objective methods (Vergeiner, 2004). What remains particularly difficult is to distinguish nocturnal downvalley or downlsope flow from relatively weak foehn winds. We will describe an objective scheme that can also deal with such situations by ascribing a probability to the occurrence of foehn.

A new windgust record in a downslope windstorm in Iceland

Hálfdán Ágústsson (1,2,3) and Haraldur Ólafsson (1,2,4)
(1) Háskóli Íslands (Univ. of Iceland), Reykjavík, Iceland (haraldur68@gmail.com), (2) Veðurstofa Íslands (Icelandic
Meteorol. Office), (3) Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway, (4) Reiknistofa í veðurfræði (Institute for Meteorological Research), Reykjavík, Iceland

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

On 1 November 2012, 10 min mean winds of 38 m/s and a wind gust of 71 m/s were recorded at the coast of Hamarsfjörður, Southeast-Iceland. This is the strongest windgust ever recorded by a reliable instrument close to sea level in Iceland. The atmospheric conditions leading to the strong windgust are explored and described.

The flow is statically stable and there is strong gravity wave activity on scales ranging from the scale of Iceland (>100 km) to the scale of the Hamarsfjörður fjord (<10 km). At mid-tropospheric levels, there is a critical level in terms of wave energy trapping and on the 1 km horizontal scale, there is a lowering in topography. Both these features appear to contribute to the acceleration of the flow. The mean wind speeds are reasonably well reproduced in a high-resolution simulation, but the observed gusts are greater than predicted by the Brasseur method. Guided by the low level wind speed, the wind direction and the vertical profile of temperature, the frequency of similar events in future climate scenarios is explored.

A nice orographically generated wintertime temperature record

Haraldur Ólafsson1,3,4 & Hálfdán Ágústsson1,2,3,

1 Háskóli Íslands (University of Iceland), 2 Reiknistofa í veðurfræði (Institute for Meteorological Research), Iceland, 3Veðurstofa Íslands (Icelandic Meteorological Office), 4Geophysical Institute, University of Bergen

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

On 29 March 2012, a temperature recording of 20.5 C was made at Kvísker in Southeast-Iceland. This extreme event is analysed and described by a numerical simulation. The analysis of the event leads to identification of the following important characteristics:
a) A warm airmass
b) A low level inversion and strong winds at mountain top level leading to an upstream blocking and yet strong downslope flow
c) Weak winds (<2 m/s) leading to a superadiabatic surface layer
d) Snow-free and dry soil for a low albedo and a high Bowen ratio

Some of the above situations are infrequent, such as dry soil in March and warm and strong foehn winds over the slopes in SE-Iceland, but calm at the same time at the weather station in question.

The Reykjavík 2012 downslope windstorm

Einar Magnús Einarsson (1,2), Haraldur Ólafsson (1,2,3), Hálfdán Ágústsson (1,2,4), Ólafur Rögnvaldsson (3,4)
(1) Háskóli Íslands (Univ. Iceland) haraldur68@gmail.com, (2) Veðurstofa Íslands (Icelandic Meteorol. Office), (3) Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway,
(4) Reiknistofa í veðurfræði (Institute for Meteorological Research), Reykjavík, Iceland

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

An extreme downslope windstorm occurred in November 2012 in the area commonly known as the Reykjavik wake in northerly flow . Unlike in most northerly flows, the downslope windstorm which is usually confined to the foothills of the Esja mountain, propagated over the city of Reykjavik, more than 10 km downstream of Mt. Esja.

There was great temporal and spatial variability in the winds and this variability is to some extent reproduced in high-resolution numerical simulations. The fluctuations in the wind pattern downstream of Mt. Esja coincide with variations in the vertical structure of the flow, particularly the elevation of an inversion located close to mountain top level. The variations correspond to the flow pattern moving between Type E and Type S windstorm described in Agustsson & Olafsson (Meteorol. Atm. Phys., 2010) which makes this windstorm the first documented case of a single windstorm moving from one category to another.

On the downslope nature of wind extremes in Iceland and their variability

Birta Líf Kristinsdóttir 1,2 & Haraldur Ólafsson 1,2,3
1 Univ. Iceland, 2 Icelandic Meteorol. Office, 3. Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

Extreme winds are studied from observations of approximately 200 automatic weather stations in the complex terrain of Iceland. In spite of the detrimental effect of surface roughness on low-level winds, hardly any of the extreme windstorms are in winds blowing from the sea. On the contrary, about four out of five extreme windstorms are when winds are blowing downwards from a nearby mountain, indicating that gravity waves are a dominating factor in extreme winds in the complex terrain of Iceland. A second result is that extreme winds are significantly more frequent in the night than during the day. This confirms the importance of gravity waves, as the static stability is greater during the night than during the day. The pattern agrees with dynamic numerical downscaling of winds over Iceland.

Very high resolution idealized simulations of foehn wind conditions in Tatra mountains

Katarzyna Nurowska (Institute of Geophysics, University of Warsaw, Poland)
Szymon P. Malinowski (Institute of Geophysics, University of Warsaw, Poland)
Zbigniew P. Piotrowski (IMGW-PIB, Warsaw, Poland)

Corresponding author: Katarzyna Nurowska, katarzyna@igf.fuw.edu.pl

We present preliminary results of very high resolution (up to 60 m) modelling of foehn wind ("halny") conditions over Tatra mountain range in southern Poland and Slovakia. We set up EULAG model for geopfysical flows on a domain of 86 by 57 km with topography based on ASTER dataset. Simulations are initiated with spatially uniform atmospheric conditions derived from atmospheric sounding in Poprad. We choose situations representing reported cases of extremly high wind on the lee side of Tatras. We analize flow response, model robustness and computational performance for a series of horizontal resolutions ranging from 300 m to 60 m.
This research serves as a reconnaissance of a gray zone are between cloud resolving numerical weather prediction and LES, It is complementary to the implementation of EULAG model as a new soundproof dynamical core of COSMO framework, reported in the presentation of Piotrowski et al. and is planned to be later concluded with experimental simulations of full COSMO framework at such resolutions.

Downslope windstorms over the very complex orography: formation and development of pulsations

Kristian Horvath, Meteorological and Hydrological Service, Gric 3, 10000 Zagreb, Croatia
Zeljko Vecenaj, Geophysical Institute Andrija Mohorovičić, Horvatovac bb, 10000 Zagreb, Croatia
Branko Grisogono, Geophysical Institute Andrija Mohorovičić, Horvatovac bb, 10000 Zagreb, Croatia

Corresponding author: Kristian Horvath, kristian.horvath@cirus.dhz.hr

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 eqaully 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. Two regimes of 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 dispersed and 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. Furthermore, the secondary orography appeared as essential for the propagation of the bora flow away from the primary mountain range, by promoting the hydraulic-jump type of flow recovery. 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.

Initial simulations of flow over a small crater basin in preparation of an upcoming field experiment

Manuela Lehner (University of Utah)
Richard Rotunno (National Center for Atmospheric Research)
C. David Whiteman (University of Utah)

Corresponding author: Manuela Lehner, manuela.lehner@utah.edu

Measurements taken during the METCRAX (Meteor Crater Experiment) field campaign in 2006 revealed the occurrence of nocturnal downslope-windstorm-type flows in the almost circular and approximately 1-km wide and 170-m deep basin of Arizona's Meteor Crater. The plain surrounding the Meteor Crater slopes slightly upward to the southwest toward the Mogollon Rim. This sloping surface leads to the regular development of a drainage flow on the plain during clear-sky nights. The southwesterly drainage flow impinges on the crater rim, which extends about 30-50 m above the plain, causing the build-up of a cold-air pool upstream of the crater rim. Under certain conditions the interaction of the drainage flow with the crater topography causes downslope-windstorm-type flows in the lee of the upwind crater rim, with increased wind speeds, an intrusion of warmer air from above the plain, and a hydraulic jump in the upwind half of the crater basin.

Model simulations are run using CM1 in preparation for a second field campaign (METCRAX II) at the Meteor Crater in fall 2013, which will focus on the formation and evolution of these downslope-windstorm-type flows in the crater basin. The primary goals of the simulations are to study the impact of the crater topography, of the wind and temperature structure within the approaching drainage flow, and of the temperature structure in the crater on the development of the downslope-windstorm-type flows and to provide guidance for the deployment of the field equipment. In this presentation we will show preliminary results from these simulations, including the flow behavior upstream of the crater. As the drainage flow interacts with the crater topography and with the cold-air pool upstream, part of the flow splits around the crater, while part of it goes over the crater rim. The simulations show that the flow in the lee of the crater rim depends strongly on the vertical wind and temperature profiles within the approaching flow, indicating the importance of correctly modeling the drainage flow and the surface inversion over the plain.

METCRAX II - An upcoming field investigation of downslope-windstorm-type flows on the inner sidewall of Arizona's Meteor Crater

C. David Whiteman, University of Utah; Sebastian Hoch, University of Utah; Manuela Lehner, University of Utah; Allison Charland, University of Utah; Matt Jeglum, University of Utah; Rich Rotunno, National Center for Atmospheric Research; Tom Horst, National Center for Atmospheric Research; Steve Semmer, National Center for Atmospheric Research; Bill Brown, National Center for Atmospheric Research; Ron Calhoun, Arizona State University; Norbert Kalthoff, Karlsruhe Institute of Technology; Bianca Adler, Karlsruhe Institute of Technology; Roland Vogt, University of Basel

Corresponding author: Sebastian W. Hoch, sebastian.hoch@utah.edu

The recently initiated METCRAX (Meteor Crater Experiment) II research program has as its main goal the improvement of understanding of hydraulic-analog atmospheric flows that produce downslope-windstorm-type events. The overall research program will combine modeling with field research to improve understanding of these flows. This presentation will focus on the design of a field program to investigate katabatically driven hydraulic-type flows at Arizona's Meteor Crater in a one-month experiment scheduled for October 2013.

Arizona's Meteor Crater is a near-circular basin with a diameter of 1.2 km and a depth of 170 m. The crater's rim projects 30-50 m above an extensive surrounding plain, which is tilted upward to the southwest. During clear undisturbed nights, a shallow mesoscale drainage flow comes down this plain from a collection of plateaus and mesas (the Mogollon Rim) to interact with the crater topography. Hydraulic flows over the crater's rim lead to occasional downslope-windstorm-type events on the inner southwest sidewall of the crater, and a hydraulic jump sometimes forms locally over the sidewall. These katabatically driven events were discovered serendipitously in a previous field program at the crater, but the characteristics of the flows were not well observed with the instruments deployed during those experiments.

The METCRAX II field measurements have been designed on the basis of initial observations and model simulations, and will determine the changes in the approaching katabatic flow that lead to the intermittent downslope-windstorm-type events. Two tall instrumented towers, a radar wind profiler/RASS, a Doppler SoDAR, a vertically pointing wind lidar, rawinsondes, and tethersondes will measure the changing dynamic and thermodynamic characteristics of the approaching flow. The channeling of the flows around the crater and over the rim will be measured with a Doppler lidar, tethersondes and automatic weather stations. The downslope-windstorm-type flows that form intermittently in the lee of the crater rim will be sensed remotely with two additional Doppler lidars, and lines of temperature and pressure sensors. Much of the meteorological instrumentation will be operated continuously during the 1-month-long experimental period. Nighttime Intensive Observational Periods (IOPs) will provide additional detailed flow information.

Separation of the turbulence from the mean bora flows at the NE Adriatic coast

Željko Večenaj, University of Zagreb, Faculty of Science, Department of Geophysics, Zagreb, Croatia
Danijel Belušić, School of Mathematical Sciences, Monash University, Melbourne, Victoria, Australia
Branko Grisogono, University of Zagreb, Faculty of Science, Department of Geophysics, Zagreb, Croatia

Corresponding author: Željko Večenaj, zvecenaj@gfz.hr

Bora is a downslope windstorm that blows at the Eastern Adriatic coast from the northeastern quadrant, most often during winter seasons. It possesses a wide spectrum of average wind speeds, and due to its gustiness the speed maxima may surpass 60 m/s. During a bora event, the turbulence is strongly developed in the lee of the mountains. So far the bora wind has been intensively studied in terms of its spatio-temporal statistics as well as macro- and meso-scale dynamics, but its turbulence characteristics still remain relatively unexplored.

In order to investigate turbulence, a suitable time/space averaging scale has to be deployed in order to define turbulent perturbations which are then used for calculation of turbulence statistical moments. This study addresses the turbulence averaging scale determined by applying several different approaches on the four cases of bora events using three different data sets. These four events are: winter bora case that occurred in November 1999 and was recorded offshore above the Adriatic Sea by the National Center for Atmospheric Research Electra aircraft, two winter bora cases that occurred in February 2005 and January 2006 and were recorded by the single point ground based measurements in Senj and Vratnik Pass, and summer bora case that occurred in July 2010 and was recorded on the three-level tower on Pometeno brdo in the hinterland of the city of Split. According to the results obtained from those four typical bora episodes, it appears that there is no unique averaging scale for determination of the bora turbulence statistics.

On the turbulence integral scales for the bora flows at the NE Adriatic coast

Željko Večenaj, University of Zagreb, Faculty of Science, Department of Geophysics, Zagreb, Croatia
Danijel Belušić, School of Mathematical Sciences, Monash University, Melbourne, Victoria, Australia
Branko Grisogono, University of Zagreb, Faculty of Science, Department of Geophysics, Zagreb, Croatia

Corresponding author: Željko Večenaj, zvecenaj@gfz.hr

Single point 3D high frequency wind measurements were conducted at the north-eastern Adriatic coast in the town of Senj (44.99°N, 14.90°E, 2 m above MSL, 13 m above the ground, March 2004 – June 2006), and Vratnik Pass (44.98°N, 14.98°E, 700 m above MSL, 10 m above the ground, Oct. 2004 – Sep. 2005), using WindMaster ultrasonic anemometers (Gill Instruments). These instruments recorded the data with a sampling frequency of 4 Hz. They were continuously operational for more than two years in Senj and almost a year in Vratnik Pass, recording all kinds of airflows. Using these data sets, we have a great opportunity to investigate turbulence characteristics of the local wind in this region.

We estimate turbulent kinetic energy and its dissipation rate for bora events in both Senj and Vratnik Pass between the coastal mountains. Using these estimations, we estimate integral turbulence length scale and integral turbulence time scale (a total eddy lifetime) through the turbulence closure techniques. The relationships between these scales and turbulence dissipation scales are investigated and compared with the relationships already reported in the literature. Among other reasons, these quantities are important for numerical model evaluations and turbulence parameterization scheme improvements.

Changes in surface water amounts considering climate change in Slovenian mountain region

Florjana Ulaga, Slovenian Environment Agency
Mira Kobold, Slovenian Environment Agency

Corresponding author: Florjana Ulaga, florjana.ulaga@gov.si

Monitoring and studying the hydrological conditions and events have become in recent years, when the frequency of flood and drought events due to climate change is more noticeable, more relevant. Temporal changes in water quantities in Slovenian rivers were analyzed with trends of river discharge as an important indicator of changes in the hydrological regime. The analysis was performed for small, medium and large flows measurement with a set of data over 30 years. Results show a general reduction of water, but trends throughout Slovenia are not statistically significant, nor are all declining. Statistical classification of mean annual flow of Slovenian rivers suggests five balanced groups of stations, each of which represent the largest group of stations in the basins of northwestern Slovenia. This group merging gauging station the Soča catchment, Sava catchment and upper part of the catchment Savinja. They are characterized by strong, statistically significant decrease in mean annual flows, the decline of small flows and large flows increase. The trend is most significant at the gauging stations in upper Sava and upper Soča catchment, where the impact of the Alpine mountain hinterland is most pronounced.

Can a point measurement represent the snow depth in its vicinity? A comparison of areal snow depth measurements with selected index sites.

Grünewald Thomas; WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 35, 7260 Davos, Switzerland and Cryos, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, GRAO 402 - Station 2, 1015 Lausanne, Switzerland
Lehning Michael; WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 35, 7260 Davos, Switzerland and Cryos, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, GRAO 402 - Station 2, 1015 Lausanne, Switzerland

Corresponding author: Grünewald Thomas, gruenewald@slf.ch

Information on the amount of snow stored in a catchment or on a mountain is an important issue for hydrology, climatology, natural hazards, winter tourism or mountain ecology. The snow cover is shaped through the processes of deposition, redistribution and ablation. These processes strongly interact with the local terrain and result in a strong spatial variability of the snow depth distribution. Typical patterns are deeper snow packs in sheltered locations or an increase of snow depth with elevation. Area-wide measurements of the snow depth in an appropriate spatial and temporal resolution are usually not available as they are costly and difficult to obtain for larger areas. In practice one needs to rely on few, selected point measurements, very often connected to meteorological stations, which give snow depth at a specific location. One then assumes that these index sites represent the snow cover in their vicinity. Such index sites are usually located in flat and sheltered terrain and it has been questioned if such places are really capable to represent the snow cover of their larger surrounding. In this study we use a large data set of areal snow depth measurements obtained by airborne LiDAR in six different mountain regions. With a spatial resolution of 1 m and an accuracy of few decimetres, the data sets are well representing the real snow distribution at the time of the survey, which was close to the peak of the accumulation season for most sites. By applying moving window techniques on digital elevation models and snow depth maps for each study area, we automatically identify flat places with homogeneous snow cover. We then define these locations as virtual index stations and analyse, if the snow depths at the sites do represent the real snow amount in the direct vicinity and of the entire catchment. We show that single stations are not able to represent the snow cover and that most index stations tend to clearly overestimate snow depth. There are, however, also index sites which measure much smaller snow depths than the mean in the surrounding area. Such stations are typically wind-exposed. We also show that elevation gradients of snow depth are qualitatively captured by index sites, even though there often occur large differences in comparison to the real gradients.

Characterisation of snowpack for better understanding of water balance in Julian Alps (Slovenia)

Iztok Sinjur, Slovenian Forestry Institute, Ljubljana, Slovenia (iztok.sinjur@gozdis.si)
Gregor Vertačnik, Slovenian Environment Agency, Ljubljana, Slovenia (gregor.vertacnik@gov.si)
Jaka Ortar, Anton Melik Geographical Institute, Ljubljana, Slovenia (jaka.ortar@zrc-sazu.si)
Mihael Brenčič, University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of geology, Ljubljana, Slovenia (mihael.brencic@geo.ntf.uni-lj.si)
Polona Vreča, Jožef Stefan Institute, Department of Environmental Sciences, Ljubljana, Slovenia (polona.vreca@ijs.si)

Corresponding author: Iztok Sinjur, iztok.sinjur@gozdis.si

The area of Julian Alps (NW Slovenia) represents the upper catchment area of river Sava, a tributary to Danube. The area is locally characterised as one with the highest annual precipitation amount in Europe, rapid runoffs, low evaporation and regular snow cover. The storage of precipitation in snowpack in alpine areas, and the subsequent melting, substantially impacts the water cycle and the important part of the annual runoff takes place in connection with the spring melt. Recent climate warming and changes in atmospheric circulation patterns have resulted, also in Slovenia, in reductions in the duration of the snow cover season, the amount of water stored in the snowpack, a widespread trend toward earlier melt as well as in changes in discharge regime. However, these processes, spatial and temporal variability of snow, as well as snow cover contribution to the water balance in Julian Alps remain poorly investigated. Therefore, the main objectives of the on-going research are 1) to better characterise the snowpack properties, 2) to determine the isotopic composition of snow and other components of water cycle (precipitation, groundwater and surface water) and finally 3) to improve understanding of influence of snow and snowmelt on infiltration and recharge of important Slovene karstic aquifers and the dynamics of springs recharged from these aquifers.

Preliminary snow investigations started in 2011 at different locations at altitudes of 1300 – 1600 m asl but with different climatic conditions (Komna and Pokljuka) in the recharge areas of rivers Savica and Radovna, the two important tributaries to river Sava. We focused on sampling at frost hollow at Komna and at two locations with different canopy structures at Pokljuka (i. e. clearing and forest stand). Selected sampling locations were in vicinity of automated weather stations which are on sites for many years. First results showed spatial and temporal variability of snow characteristics, including isotopic composition, that were related to different precipitation events and to processes that change the initial isotopic signal. Results showed that more detailed investigations are needed for appropriate evaluation of snow and snowmelt influence on runoff. In winter 2011/12 we continued with investigations but they were limited due to extremely dry winter. In winter 2012/13 sampling was expanded to more locations and due to high snowpack (150 – 300 cm) investigations are still in progress.

Orographic effects on snowfall patterns in mountainous terrain

Rebecca Mott, WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
Danny Scipion, Ecole Polytchnique Federale de Lausanne (EPFL), School of Architecture and Civil Engineering (ENAC), Environemntal Remote Sensing Laboratory (LTE), Lausanne, Switzerland
Marc Schneebeli, Federal Office of Meteorology and Climatology MeteoSwiss - Radar, Satellites and Nowcasting, Locarno, Switzerland.
Nicholas Dawes, WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
Alexis Berne, Ecole Polytchnique Federale de Lausanne (EPFL), School of Architecture and Civil Engineering (ENAC), Environemntal Remote Sensing Laboratory (LTE), Lausanne, Switzerland
Michael Lehning, WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland; Ecole Polytchnique Federale de Lausanne (EPFL), School of Architecture and Civil Engineering (ENAC), Laboratory of Cryospheric Sciences (CRYOS), Lausanne, Switzerland.

Corresponding author: Rebecca Mott, mott@slf.ch

Orographic lifting of air masses and other topographically modified flows induce cloud formation and preferential deposition of precipitation. In this study, we examine orographic effects on small-scale snowfall patterns in Alpine terrain. A polarimetric X-band radar was deployed in the area of Davos (Switzerland) to determine the spatial variability of snowfall. In order to relate measured snowfall fields to flow dynamics, we modeled flow fields with the atmospheric prediction model Advanced Regional Prediction System (ARPS). Additionally, we compared radar reflectivity fields with snow accumulation at the surface as modeled by Alpine3D. We investigated the small-scale precipitation dynamics for one heavy snowfall event in March 2011 at a high range resolution of 75 m. Polarimetric radar data suggest orographic snowfall enhancement near the summit region at the transition between the updraft and downdraft zone. Radar reflectivity increased in the presence of flow acceleration at windward slopes and decreased in the presence of flow deceleration at the leeward slopes. Measurements and numerical analysis also suggest preferred snow deposition on leeward slopes. Measurements show that the temporal variation of the location of maximum concentration of snow particles is strongly dependent on the magnitude of the horizontal wind velocity. For situations with strong horizontal winds, the concentration maximum is shifted from the ridge crest towards the leeward slopes. Qualitatively, we discuss the relative role of cloud micro-physics such as seeder-feeder mechanism versus atmospheric particle transport in generating observed snow deposition at the ground.

The influence of climate change on river discharge in Austria with application to hydropower production

Robert A. Goler - Institute of Meteorology, University of Natural Resources and Life Sciences, Vienna, Austria; alpS Centre for Climate Change Adaptation Technologies, Innsbruck, Austria.
Simon Frey - alpS Centre for Climate Change Adaptation Technologies, Innsbruck, Austria; Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Life Sciences, Vienna, Austria.
Herbert Formayer - Institute of Meteorology, University of Natural Resources and Life Sciences, Vienna, Austria.
Hubert Holzmann - Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Life Sciences, Vienna, Austria.

Corresponding author: Robert A. Goler, robert.goler@boku.ac.at

Electricity produced from hydropower represents a primary source of renewable energy within the Alpine region. Approximately 55% of Austria's electrical energy is produced from hydropower. The utilisation of this energy source depends strongly on the spatial and temporal distribution of water in both its solid and liquid forms. Climate change is expected to result in an increase in temperature across the Alpine region. However, the effect that climate change will have on yearly precipitation totals still remains uncertain, although changes in the seasonal distribution of precipitation seem to be consistent. Thus it is highly probable that climate change will affect river discharge and hydropower production within the Alps.

In this study the river discharge characteristics in several catchment areas within Austria are modelled using a conceptual hydrological model. Processes which are represented by the model include meltwater from snow and glaciers; surface, subsurface, and groundwater flows; and evapotranspiration. The model is driven using daily climate data generated from three regional climate models (ALADIN, RegCM3, REMO) over the time period 1951-2100 using the A1B emissions scenario. This data has been bias-corrected and downscaled to a spatial resolution of 1 x 1 km over Austria. The model is calibrated using Monte Carlo simulations in the time period 1996-2005 over which observations of the river discharge were available. Validation of the model is done using observational data from 2006-2010.

The model results show that towards the end of the 21st century changes in the river discharge will be significant. For catchment areas whose discharge is dependent on water stored in snow and glaciers, there will be a general shift in the time of maximum river discharge to earlier in the year as the snow and ice melt earlier. During the winter months the discharge is forecast to be higher than at present, which would be advantageous for hydropower production as the number of days of low discharge will be reduced. However, due to the earlier snow melt the available water for the summer months will decrease, leading to lower discharges than present, which would be disadvantageous for hydropower production.

Throughfall in different forest types during extreme precipitation event in November 2012

Urša Vilhar, Gozdarski inštitut Slovenije – Slovenian Forestry Institute, Več na pot 2, SI-1000 Ljubljana
Iztok Sinjur, Gozdarski inštitut Slovenije– Slovenian Forestry Institute, Večna pot 2, SI-1000 Ljubljana
Primož Simonč ič, Gozdarski inštitut Slovenije– Slovenian Forestry Institute, Večna pot 2, SI-1000 Ljubljana

Corresponding author: Urša Vilhar, ursa.vilhar@gozdis.si

Extreme precipitation events in the mountainous regions are risk factors with consequences such as flooding of populated valleys, erosion, avalanches, debris flow and landslides. Because their effects could be significantly buffered by forest cover, therefore forest management practices should aim towards decreased surface runoff and soil erosion. In Central Europe, many pure Norway spruce stands, established on primary beech sites, were converted back into mixed stands over the last decades. The conversion of forest management from spruce monocultures into mixed deciduous-coniferous forests changed the forest structure dramatically. These changes could influence the hydrological processes on the catchment scale, associated with major river flooding following extreme precipitation events.

In this study, which focuses mainly on extreme precipitations with devastating floods in November 2012, the effect of forest management on the partitioning of rainfall into throughfall and stemflow in coniferous and mixed deciduous-coniferous stands on Pohorje mountains (NE Slovenia) were investigated. Four spruce Picea abies (L. Karst) stands were compared to four mixed spruce-beech Fagus sylvatica (L.) stands. In order to estimate the throughfall under forest canopies, among these results the monthly throughfall from totalisators and half-hourly throughfall from automated rain gauges in growing seasons from 2008 till 2012 were analyzed. In the mixed spruce-beech stands the monthly stemflow on beech trees was also measured.

There were small differences in throughfall during growing season between the coniferous and mixed deciduous-coniferous stands. Seasonal stemflow on beech trees was 4 to 5 % of the bulk precipitation amount. An illustration using half-hourly throughfall data during extreme precipitation events also showed small differences in throughfall intensities among the coniferous and mixed deciduous-coniferous stands. We assume that differences in cumulative throughfall during extreme precipitation event in November 2012 are more related to topography than to different forest types. The implementation of hydrology-oriented sylvicultural measures via a more accurate prediction of the impacts of tree species conversion on throughfall in this type of mountain forest is discussed.

Objective forecast verification of WRF compared to ALARO and the derived INCA-FVG outputs

ARTURO PUCILLO OSMER - ARPA FVG
AGOSTINO MANZATO OSMER - ARPA FVG

Corresponding author: AGOSTINO MANZATO, agostino.manzato@meteo.fvg.it

INCA is a nowcasting software developed by ZAMG (Austria) that merges extrapolated observations by stations and radar with model outputs, in order to overcome the LAM (Local Area Model) spin-up problem with a computationally "light" system. This software is particularly interesting for areas with a high density of surface stations and possibly covered by meteorological radars, because the 3-Dvar or 4-Dvar assimilation of these kind of data (radar in particular) is still difficult in modern LAM and computationally hard.

OSMER - ARPA FVG runs operationally INCA at 1 km of spatial resolution, fed by the numerous surface stations available in Friuli Venezia Giulia (NE Italy) and by the Fossalon di Grado doppler radar, using the ZAMG ALARO 5 (at 4.4 km of spatial resolution) as background model. For a period of about 75 days of summer 2011, OSMER asked CETEMPS (L'Aquila University) to run twice a day a special version of Advanced Research WRF (Weather Research and Forecasting) model at 3 km resolution, that assimilates (with a 3D-var method) the same set of surface stations assimilated by INCA, plus some high resolution soundings, on a larger domain than that of INCA. On the other way, the WRF simulations do not assimilate the radar SRI data, that are a very important contribute to the INCA forecasts for the very first hours.

In this work the preliminary results of an objective verification of the INCA, ALARO and WRF rain forecasts are presented, using different methodologies, varying from an object-oriented verification to a nearest neighbor area verification and a punctual verification. The results show that there is a bit better nowcast performance shown by INCA-FVG system in the first 3 hours of model lead time, whereas in the farest lead times the WRF model seems better performing.

An Icelandic wind atlas

Nikolai Nawri, Icelandic Met Office, Reykjavik, Iceland
Guðrún Nína Petersen, Icelandic Met Office, Reykjavik, Iceland
Halldór Bjornsson, Icelandic Met Office, Reykjavik, Iceland
Kristján Jónasson, Department of Computer Science, School of Engineering and Natural Sciences, University of Iceland, Reykjavík, Iceland

Corresponding author: Guðrún Nína Petersen, gnp@vedur.is

Although there is ample wind in Iceland its use for energy production has been limited. However, recently there has been increasing interest in the potential of using wind power to supplement hydro- and geothermal power. A wind atlas has been developed for Iceland, to obtain estimate of the wind energy potential.

The atlas is based on the wind obervations, supplemented with mesoscale model runs produced with the Weather Research and Forecasting (WRF) Model and high-resolution regional analyses obtained through the Wind Atlas Analysis and Application Program (WAsP). The wind atlas shows that the wind energy potential is considerable, but, due to the orography of Iceland, the variations in space are large. The regions with the strongest average winds are though impractical for wind farms, due to lack of infrastructure and often harsh climate. The orography of Iceland and its location in the middle of the North Atlantic storm track makes the identification of the most suitable areas demanding, but at the same time these two factors also result in the estimated annual power densities of many areas that are among the highest in Western Europe.

Applications of cross-sections from operational high-resolution simulations for weather forecasting in mountainous areas

Bolli Pálmason, Icelandic Meteorological Office, Iceland
Guðrún Nína Petersen, Icelandic Meteorological Office, Iceland
Haraldur Ólafsson, University of Iceland, Iceland, Icelandic Meteorological Office, Iceland, and Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway

Corresponding author: Guðrún Nína Petersen, gnp@vedur.is

Systematic validation of high-resolution numerical weather forecasts made by several models for Iceland has shown that strong winds are often underestimated, particularly in the highlands. In order to improve the availability of information needed to forecast surface winds, cross-section of winds and temperature over Iceland are now a part of the visualisation of operational high-resolution numerical forecasts. These sections often show high winds aloft that the model is unable to bring to the surface. Currently this is being investigated further, especially the role of the surface roughness on high wind speeds. The cross-sections thus provide a guidance for the wind forecasts and increase the awareness of low level jets. They also reveal details in the patterns of important meteorological features such as orographic disturbances and atmospheric fronts.

Severe wet-snow storms in the complex terrain of Iceland: Simulations and observations

Hálfdán Ágústsson; Institute for Meteorological Research, Iceland; University of Iceland; Icelandic Metorological Office
Haraldur Ólafsson; University of Iceland; Icelandic Metorological Office; Bergen School of Meteorology, University of Bergen, Norway,
Árni Jón Elíasson; Landsnet, National Transmission Line Operator, Iceland,
Egill Þorsteins; Efla Consulting engineers, Iceland.

Corresponding author: Hálfdán Ágústsson, halfdana@gmail.com

Two severe wet-snow windstorms hit Northeast-Iceland on 10 September and Northwest-Iceland on 30 December 2012. Both events were associated with heavy snowfall and strong winds. There was extreme accumulation of wet snow on overhead electric conductors in the affected regions. Combined with strong winds, a large number of distribution line poles and transmission line towers broke due to the severe load.

The extreme snowfall so early in September was exceptional and poorly forecasted by most operational models. There was accumulation of wet snow in a relatively wide altitude interval, with rainfall below approx. 150 metres. Most of the farmers in the region had not gathered their sheep from summer grazing in the mountains, and thousands of sheep were consequently killed after being buried by the wet, heavy snow.

In contrast to the event in September, the heaviest wet snow accumulation in December was more localized and mainly observed in the immediate lee of the very complex orography characterizing the region. Presumably the heaviest accumulations was combined with drifting snow from upstream hills, mountains and other landscape features where the flow was locally enhanced.

Detailed data were collected on the accumulated wet snow load on the affected transmission and distribution lines. Furthermore, accurate measurements of the wet snow accumulation were obtained from several operational load cells. The collected load data are unique in the sense that they describe in detail both the exact timing and the magnitude of the mechanical load resulting from the extreme wet snow accumulation. The events are furthermore well described by meteorological observations from a dense network of weather stations.

The atmospheric flow during the events is further analyzed based on high resolution atmospheric simulations. The simulated data are used as input to a cylindrical wet snow accretion model, producing both icing maps of the accreted wet snow diameter as well as time series at chosen locations, which then are compared to observed or measured wet snow loading. The performance of the accretion model is analysed, highlighting strong and weak points of the accretion models, as well as some key aspects of the flow and accretion process that need further improvement.

The work presented forms a part of the Icewind-project and the COST-action WIRE.

Visualization of real-time simulations of the atmosphere for education

Haraldur Ólafsson (1,2,3), Bolli Pálmason (2), Hrafn Guðmundsson (2), and Trausti Jónsson ()
(1) Háskóli Íslands (Univ. Iceland) haraldur68@gmail.com,
(2) Veðurstofa Íslands (Icelandic Meteorol. Office), bolli@vedur.is, (3) Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway

Corresponding author: Haraldur Ólafsson, haraldur68@gmail.com

Following the three-dimensional evolution of the atmosphere in real time is motivating for students and a challenging for all people interested in weather and climate. Recently, the Icelandic Meteorological Office has started to provide a large collection of output from operational numerical models on the web in real-time. The products consist of plots of basic parameters such as pressure, temperature, winds and humidity as well as a series of functions of these such as vorticity, potential vorticity, thermal winds, turbulent fluxes and turbulence kinetic energy. The plots are suitable as a tool to deal with a wide range of tasks in dynamic meteorology, including elements such as barotropic and baroclinic flows, planetary to short-scale waves, orographic disturbances, quasigeostropic theory and atmospheric fronts. The plots illustrate processes ranging from mesoscale to hemispheric scale and are used increasingly for educational purposes. The plotting tools are VisualWeather, Magics++ and GrADS and the web address is brunnur.vedur.is/kort/spakort.

Background error matrix in the Adriatic region: Characteristics and seasonal variability

Kristian Horvath, Meteorological and Hydrological Service, Gric 3, Croatia
Antonio Stanesic, Meteorological and Hydrological Service, Gric 3, Croatia
Tomislav Kovacic, Meteorological and Hydrological Service, Gric 3, Croatia

Corresponding author: Kristian Horvath, kristian.horvath@cirus.dhz.hr

Numerical weather prediction of heavy precipitation events is typically very sensitive to the initial and lateral boundary conditions. Therefore, the initial conditions for mesoscale predictions are often improved by mesoscale data assimilation. In 3D variational data assimilation, information about the state of atmosphere introduced by the observations needs to be spread in space. The key component that determines the horizontal and vertical propagation of information gained from observations is the background error covariance matrix.

Six different formulations of multivariate background error covariance matrix were calculated and analyzed using limited area model ALADIN (Aire Limiteé Adaptation Dynamique dévelopement InterNational). First, a standard NMC and an ensemble type of background error statistics were compared for the same period using vertical profiles of standard deviations and correlation length-scales of the four control variables: vorticity, divergence, temperature and specific humidity. Mean vertical correlations and cross-covariances among control variables were further studied to assess the changes in the covariance matrix structure. Second, four different ensemble matrices were calculated to study the seasonal variability of the background error matrix. Conclusions were drawn on the properties of different formulations of the background error statistics and the underlying dynamical properties and physical aspects of their seasonal variability.

Lagrangian Perspective of Orographic Blocking

Michael Sprenger, ETH Zurich
Erica Madonna, ETH Zurich
Alexandre Roch, ETH Zurich

Corresponding author: Michael Sprenger, michael.sprenger@env.ethz.ch

In Alpine mountain meteorology, orographic blocking is important because of its impact on: a) leecyclogenesis; b) the passage and modification of warm and cold fronts; c) the geographical distribution and intensity of (heavy) precipitation events. Traditionally, orographic blocking is studied with Eulerian methods based on the estimation of the inverse Froude number or dimensionless mountain height F=N/HU, where N is the stratification, H the mountain height and U the usptream velocity. Here we present the Lagrangian perspective of orographic blocking.

Meteorological fields are taken from the high-resolution NWP model COSMO, which is operationally run at the Swiss weather service. Winds are taken from a three-year (2000-2002) reanalysis simulation with COSMO. Based on these winds, kinematic forward trajectories are started at a distance of 300 km all around the Alps and at two height levels (750 and 1500 m). The 24-h trajectories are then investigated in their capability to surmount the Alpine barrier.

The blocking climatology is separated into three weather classes: westerly flow, northerly flow and southerly flow, the latter being restricted to south Foehn cases. For each class the percentage of trajectories surmounting the Alps and the percentage of air parcels flowing around the Alps is determined. Furthermore, trajectory densities are calculated to show the different air streams which start from selected upstream positions. The blocking frequencies are compared for air streams starting at 750 m and at 1500 m.

Finally, the Lagrangian method to identify orographic blocking is compared to the Euerlian one. The advantages of the Lagrangian method are discussed, as well as its limitations.

Verification of radiation and cloudiness forecasts in mountain areas

Thomas Haiden; European Centre for Medium-Range Weather Forecasts, Reading, UK

Corresponding author: Thomas Haiden, thomas.haiden@ecmwf.int

Abstract: Accurate prediction of cloudiness is crucial in mountain weather forecasting. In the past, routine verification of cloudiness at ECMWF was largely based on SYNOP observations. Recently this has been extended to include satellite-derived products and data from a network of surface radiation stations. EUMETSAT Climate Monitoring Satellite Application Facility (CM-SAF) cloud and radiation products are used to analyse various aspects of cloud forecast skill in mountain areas covered by the Meteosat 2nd Generation (MSG) instruments. The verification focuses on daytime conditions since quantities primarily used here are downward solar radiation at the surface and top of the atmosphere reflected solar radiation. The analysis is supplemented by station data from the Baseline Surface Radiation Network (BSRN) and the Austrian Radiation network (ARAD). Two aspects of cloudiness which are difficult to correctly represent in numerical weather prediction models and which have particular relevance for mountain areas are wintertime low stratus / inversion fog, and the diurnal cycle of convection. It is shown how these specific processes affect forecast skill in mountain areas and over flat terrain. Three-way comparison between SYNOP observations of cloudiness, BSRN/ARAD solar radiation, and satellite derived downward solar radiation in the alpine area allows estimation of systematic and non-systematic error contributions. It also allows separation of errors under clear-sky conditions from those specifically due to cloudiness. With respect to downward longwave radiation it is shown to what extent a long-standing negative bias which is more pronounced in cold, dry atmospheres and which occurs both under clear-sky and cloudy conditions, has recently improved. An unexpected result with respect to practical forecasting applications is that use of the ECMWF ensemble forecast improves cloudiness forecast skill even in the short range.