Oral

O-01.2

The influence of an isolated ridge on a mid-latitude cyclone and upper level jet.

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Idealized studies of the influence of mountains on the atmosphere have primarily focused on the steady-state response to horizontally uniform flows encountering an obstacle. In this research, we extend previous studies of non-steady mountain waves to examine their generation, propagation, and influence on the mean flow when forced by a mid-latitude cyclone impinging on an isolated ridge. The cyclone is obtained by superimposing a localized finite-amplitude potential vorticity anomaly on a baroclinically unstable jet. An isolated ridge is placed in an initially quiescent region of the flow away from the initial PV anomaly. As maturing cyclone propagates towards the ridge, mountain waves are generated exhibiting strong time-dependent behavior. For a 2-km-high ridge, the pressure drag increases at 6 days and remains large for the remainder of the simulation. The low-level vertical momentum flux is significantly less than the pressure drag. This difference is balanced largely by ageostrophic forcing (equal to the sum of the pressure gradient and Coriolis terms in the momentum budget), and is related to the complex dynamics associated with blocking near the mountain. Extensive wave breaking is also present, and is predominately observed (1) at low levels in the lee of the terrain prior to frontal passage and (2) persistently in the stratosphere after frontal passage. This wave breaking causes significant removal of the cross-mountain momentum, and strong regions of deceleration are observed above the jet core. While gravity-wave breaking is not observed in the upper troposphere, localized patches of strong flow deceleration are also observed at this level. Despite the existence of several regions obvious flow deceleration, the total terrain-induced momentum changes, averaged horizontally over the full domain, are strongly influenced by the presence of small-amplitude perturbations distributed over a broad area.

O-01.3

An adiabatic Foehn effect

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Mountain waves produced by incident winds that are null at the surface are evaluated with models of increasing complexity. All models confirm that downslope windstorms and Foehn (i) can be a direct consequence of the presence of a critical level located just below the surface, (ii) are stronger when the surface flow is more stable (e.g. when the surface Richardson number *J* increases) and (iii) are not necessarily produced by upper level wave breaking or internal reflections, as often suggest popular theories.

The first model used in this study is a theoretical model which combines linear gravity wave dynamics with a nonlinear boundary condition (Lott, 2016). In this model the wave breaking does not feedback onto the dynamics by construction. Partial linear waves reflections can also be minimized by using smooth profiles of the incident wind and uniform stratification N^2, and even suppressed in the case of constant wind shears U_z. The second model used in this study is WRF, and we show that it predicts mountain wave-field that can be reproduced by the theoretical model, providing that we specify adequate boundary layer depth in the theory.

The dependence of the onset of downslope windstorms onto the parameter *J* rather than on a dimensionless mountain height is also explained. In the presence of shear, the local vertical gravity wave wavelength at the mountain top *H* scales like U_zH/N. It is smaller than the mountain height when $U_z/N<1$ (e.g. when $J=N^2/U_z^2>1$).

Lott, F., 2016: A New Theory for Downslope Windstorms and Trapped Mountain Waves. *J. Atmos. Sci.,* 73, 3585–3597, doi: 10.1175/JAS-D-15-0342.1.

O-01.4

Penetration and interruption of Alpine foehn (PIANO): Description of upcoming field experiment

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Alpine foehn is one of the world's most intensively studied downslope windstorm. However, previous research has primarily focused on the well-developed stage rather than the complex initial and final stage of foehn. Hence, the mechanisms of foehn penetration into valleys and of foehn breakdown as well as the associated interaction of foehn with cooler air in the valley are still poorly understood. Potential processes responsible for the breakthrough and breakdown of foehn are, e.g., (I) large-scale air mass advection, (II) cold-air pool displacement and outflow, (III) turbulent mixing at the top of the cold pool, (IV) daytime heating and (V) nocturnal cooling of the boundary layer. Some of the previous studies disagree on which are the dominant processes. Furthermore, it is not clear to which extent todays high-resolution NWP models are able to represent these processes and, therefore, to predict the time of onset and decay of foehn.
In the framework of the recently started research project "Penetration and interruption of Alpine foehn (PIANO)" we aim at answering some of these open questions. In this conference contribution we will present the motivation and goals of the project. Furthermore, we will give an overview of the associated field experiment that will take place in fall 2017 in the Inn Valley (Austria). More specifically, the target area is the city of Innsbruck. The most important observing systems are three to four Doppler wind lidars (Halo Photonics Streamline) as well as the research aircraft DLR Cessna Grand Caravan. In order to support the planning of the field campaign, high-resolution numerical simulations have been conducted with the WRF model. First modeling results will be presented in an separate contribution.

O-01.5

Penetration and interruption of Alpine foehn (PIANO): preliminary high-resolution numerical simulations

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In the framework of previous field campaigns, such as the Mesoscale Alpine Programme, a broad understanding of the well-developed phase of foehn in the Alpine region has been gained. However, the initial and final stage of foehn received far less scientific attention. These transient phases during the penetration of the foehn flow down to the valley bottom or the breakdown of foehn feature complex turbulent interactions between the foehn and cooler valley air. The research project "Penetration and interruption of Alpine foehn (PIANO)" aims at increasing the understanding of the governing processes during these periods based on high-resolution numerical simulations as well as observations collected during an upcoming field experiment in the Inn Valley (Austria). An overview over the project and the field campaign in fall 2017 will be given in a separate presentation, whereas this contribution will focus on aspects of numerical modeling.
Very-high-resolution numerical simulations of selected foehn events in the Alpine region around Innsbruck, Austria, are conducted with the Weather Research and Forecasting (WRF) model. The application and performance of the WRF model at the transition between very-high-resolution mesoscale simulations and large-eddy simulations (LES) will be evaluated based on a verification against routine observations. Results of the numerical simulations will also support the planning of the PIANO field campaign in fall 2017 and help to determine appropriate locations for the installation of various measurement systems (including Doppler wind lidars and scintillometers) as well as appropriate flight patterns for airborne in-situ measurements. A nesting approach will be presented that allows to capture all relevant mesoscale and microscale processes. The highly complex and steep terrain in the target area influences several atmospheric phenomena at various scales, e.g., rotor or cold pool formation. Hence, strategies to incorporate a realistic topography in the numerical model while ensuring numerical stability will be explored and presented. Moreover, the representation of turbulent processes within the model and the turbulent inflow at nested domain boundaries pose another challenge and will be investigated. At the conference we will present preliminary modeling results and an appropriate model setup which will be used to conduct numerical simulations of foehn events during the PIANO field campaign.

O-02.1

Broad spectrum mountain waves

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Recent airborne mountain wave measurements over New Zealand in the lower stratosphere during the DEEPWAVE

campaign allow improved spectral analysis of velocity (i.e. u, v, w), pressure and temperature fluctuations. The surprising aspects of these data are the breadth of the power spectra and their different spectral shapes.
Using idealized complex terrain as a guide, the spectra are divided into the long-wave “volume mode” arising from airflow over the whole massif and the short-wave “roughness mode” arising from flow into and out of valleys. The roughness mode is evident in the aircraft data as an intense band of w-power from wavelength . The shorter part of this band falls near the non-hydrostatic buoyancy cut-off ( ). It penetrates easily into the lower stratosphere but carries little u-power or momentum flux. The longer part of this roughness mode carries most of the wave momentum flux. The volume mode for New Zealand, in the range , is detected using the u-power, p-power and T-power spectra. Typically, the volume mode carries a third or less of the total wave momentum flux but it dominates the u-power and thus may control the wave breakdown aloft. Spectra from numerical simulations agree with theory and aircraft data.
Based on the DEEPWAVE results, we discuss how broad gravity wave spectra pose challenges for observing and parameterizing waves. Observations that measure T-power or u-power are biased with respect to momentum flux. Regarding parametrization, the volume mode controls the wave breakdown while the roughness mode carries most of the momentum flux; casting doubt on the concept of saturation momentum flux.

O-02.2

Influence of surface roughness on downslope windstorms and mountain waves

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Surface friction affects the flow over the mountains and reduces the amplitude of the mountain waves, the effect is stronger for lower mountains. Surface friction depends on the surface roughness. The surface roughness is a parameter field that depends on unresolved terrain features, type of surface, vegetation cover etc.
Here we analyse the effect of surface friction in a framework of the ALADIN System, particularly the version used for operational forecast at 2 km horizontal grid spacing with ALARO physics package and non-hydrostatic dynamics. The problem is analysed using real terrain and real meteorological conditions. Surface friction is controlled via the surface roughness field. In order to assess the relative importance of the surface friction to the turbulence scheme, experiments with two alternative turbulence schemes were performed: I) a pTKE scheme and II) more advanced TOUCANS, which includes additional prognostic equation for total turbulence energy, as well as the anisotropy effects among other. The quality of the fields describing the terrain height, surface roughness etc. depends on the quality and resolution of the input data. These fields described above were extracted from a rather old database of quite a low resolution, hence an interpolation procedure created rather non-physical fields. These fields were used in the operational forecast in the absence of better ones. Many recent developments in the model were implemented and tuned using the physiography fields from this old database. Here we show how the implementation of new roughness length data impacts the model forecast, particularly the formation of mountain waves and associated windstorms and validate the results for 10 m wind. The old roughness length was too smooth for the Dinaric Alps region and had unnatural pattern over the Alps. The roughness length computed initially from the new database in high resolution had much higher values over the Dinaric Alps, but lower maximum values over the domain. Alternative ways of computing the roughness length due to unresolved topography were tested and applied to 2 km horizontal grid spacing non-hydrostatic forecast using the ALADIN System and two different turbulence schemes. Results show that introducing new roughness length field has larger impact on the model forecast than more sophisticated turbulence scheme. The impact of modified roughness length was tested by running 31 consecutive forecasts at 2 km horizontal grid spacing starting from 00 UTC 1st of March 2016. The forecast using low roughness length (from the old database) occasionally produced excessive wind speed for location Knin in a valley downstream of mountain during bura. Simultaneously, wind speed was underpredicted for another location (Lokvine) which is in the lee of a mountain about 50 km westward from Knin. The experiments have shown that this windstorm develop due to too smooth mountains (which is unrealistic). The introduction of roughness length from the new database made the terrain rougher in general. Using this more realistic and larger surface roughness, the windstorm did not develop over Knin, but it did over Lokvine, which corresponds to the measurements better. Conclusion: more realistic surface roughness allowed for model dynamics to develop local features at appropriate place and time and produce correct forecast.

O-02.3

Mountain wave turbulence in the presence of directional wind shear over the Rocky Mountains

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Mountain wave turbulence occurring in the presence of directional wind shear over the Rocky Mountains in Colorado is investigated here. Pilot Reports (PIREPs) of turbulence were used to select cases in which moderate or severe turbulence encounters were reported in combination with significant directional wind shear in the upstream sounding from Grand Junction, CO (GJT). For a selected case, semi-idealized numerical simulations were performed using the WRF-ARW atmospheric model initialized with a single sounding, using the GJT atmospheric sounding, and the real orography profile. In order to isolate the role of directional shear in causing wave breaking, sensitivity tests were performed to exclude the variation of the atmospheric stability with height, the speed shear, and the mountain amplitude as dominant wave breaking mechanisms. Significant downwind transport of unstable air was detected in the flow cross-sections, resulting in mountain-wave-induced turbulence occurring at large distances from the first wave breaking point (and from the orography that originates the waves). The existence of an “asymptotic wake”, as predicted by Shutts (1998) for directional shear flows, was hypothesized to be the mechanism responsible for this downwind transport. Directional-shear-induced critical levels were further studied using spectral analysis of the magnitude of the horizontal velocity perturbation field. In these 2D power spectra, a rotation of the most energetic wave-modes with the background wind, as well as perpendicularity between the background wind vector and the wave-number vector of those modes at critical levels, can be found. Such behavior is explained by the mechanism leading to wave breaking in directional shear flows.

O-02.4

A simple model for the amplitude of lee waves on the boundary-layer inversion

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An analytical model for the amplitude of lee waves on the boundary-layer inversion in two-dimensional flow is presented. Previous linear lee wave models, in which the amplitude depends on the power spectrum of topography, can be inaccurate if the wave amplitude is large. Our model incorporates nonlinear effects by assuming that lee waves originate at a region of transition between super- and subcritical flow (internal jump) downstream of topography. Energy flux convergence at this location is compensated by the radiation of laminar lee waves. The available energy is estimated using a hydraulic jump model and the resulting wave amplitude is determined from linear theory. According to the new model, the amplitude of lee waves depends essentially on their wavelength and on the inversion height difference across the jump. Amplitude estimates from the model generally agree very well with two-dimensional numerical simulations. The conditions under which the wave amplitude exceeds the limits of linear theory are explained. The regime transition from lee waves (linear behaviour) to hydraulic jumps (nonlinear behaviour) is described by combining the Froude number and the non-dimensional mountain and inversion heights in a single nonlinearity parameter. A comparison between model predictions and the results of experiments in a stratified water tank is also presented.

O-02.5

Wake formation in the lee of a small but high island: modelling and observations

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South Georgia in the Southern Ocean is a small (~30km long,) but high (~3km peak height) makes an ideal natural laboratory for studying wake formation and gravity wave generation. Here we combine high resolution (1.5km horizontal grid spacing) numerical modelling with ASCAT scatterometer winds and radiosonde observations from the SG-WEX field campaign to study the development and structure of the wake in the lee of the island. The high resolution simulations were conducted using the Met Office Unified Model for three month-long field campaigns as part of SG-WEX. Each ASCAT pass typically only covers part of the island and its wake, but using 6 years worth of ASCAT data (2010-2015) a climatology of wake structure was constructed as a function of wind direction, and upstream Froude number (calculated using the ERA-Interim reanalysis). To account for differences in wind speed the fractional wind speed difference relative to the background wind was calculated. This shows a clear wake structure in the lee of South Georgia. The wake structure varies depending on the wind direction relative to the orientation of the island. Surprisingly only a relatively weak dependence on Froude number is observed, with slightly

weaker wakes for higher Froude number. This weak dependence is likely due to the fact that the height of the mountains almost always means the flow is in a low Froude number regime with flow blocking. The wake climatology in the high resolution numerical simulations shows a very similar pattern to the ASCAT observations suggesting the model is accurately capturing the flow processes leading to wake formation. The temperature structure of the wake is also studied using the model simulations. On average the wake can be up to a couple of degrees warmer than the surroundings, although the warming is slightly less for the higher Froude number cases.

O-03.1

Mountain waves and cloud bands: case studies of 21 May 1937 and 1 February 2014 within a long research tradition

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Airflow across mountain ridges can induce in a stably stratified atmosphere vertically oscillating motions, which are termed *mountain waves*. Such wave patterns can be stationary over hours and can have considerable extension downstream. When the ambient humidity is suitable, the wave crests are often marked by elongated *cloud bands*. These basic mechanisms have been gradually discovered and described in the 1930s, especially by German glider pilots and scientists. In a pioneering study, Küttner (1939) collected photographic evidence for wave clouds at quite a number of mountain ranges. Furthermore, he used no less than 22 barogrammes from gliders taking part in a regional competition to map out the vertical velocity field in the lee of the modest size *Riesengebirge* ridge at the border between Czechia (northern part of the Czech Republic) and Silesia (today in the southern part of Poland).
The dynamics of mountains waves in two- and three-dimensional settings with various degrees of idealization became a core topic of (mesoscale) dynamical meteorology. At the turn of the century, the state of the art linking data from different observational platforms with three-dimensional episode-type simulations was documented for the Alpine case of 25 Sept. 1999 during MAP-SOP (Volkert et al., 2003).
In recent years detailed, multi-channel satellite observations with high spatial resolution (MODIS-instrument on the TERRA and AQUA satellites) as well as high temporal resolution (SEVIRI instrument on Meteosat second generation) make possible the detailed documentation of waves generated cloud systems and help to infer their (quasi-)stationarity. Image sequences from mountain based web-cameras provide the human perspective from the surface. During the exceptional case of 1 February 2014 stationary cloud structures of various wavelengths could be detected embedded in the transient frontal cloud system within a southerly airflow over an area extending from the Alps to the *Riesengebirge* some 400 km further to the north (cf. self-steerable satellite loop under http://www.pa.op.dlr.de/~HansVolkert/GraWaves).
The presentation (oral preferred; poster possible in an abbreviated fashion) contains highlights from a research tradition spanning a period of more than 75 years and links its findings with the development of observation technology and research interests.
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O-03.2

Gravity waves generated at small Rossby number by large amplitude topography

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Our theoretical understanding for the nonlinear aspects of topographic waves owes much to the 1953 theory of Long, but does not include the effects of Coriolis rotation. A rotating analog of Long's theory is presented that illustrates the effects of nonlinearity, beyond the familiar 1948 linear results of Queney, to near-overturning flows. These steady 2D solutions give insight into how short waves are introduced into small Rossby number, geostrophic flow by large-scale topography. This work is in collaboration with J. Klemp at the National Center for Atmospheric Research (NCAR-MMM).

O-03.3

Detection of gravity waves across the Snaefellsnes Peninsula: A case study

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On October 20th 2016 the FAAM BAE-146 aircraft conducted a flight to observe mountain waves over the Snæfellsnes peninsula, Iceland. The pattern of the vertical velocity suggests that the waves were generated by the air flow over the peninsula (waves parallel to the peninsula) as well as by Snæfellsnesjökull glacier at the tip of the peninsula. A horizontal wavelength of 12-15 km was observed. A series of nested simulations of this gravity wave event have been performed using the Weather Research & Forecasting (WRF) model initialised using GFS analyses. The studies have focused on the resolution required to accurately simulate the observed waves and to explore the role of cloud-microphysical processes on the wave generation. Simulations carried out at two horizontal resolutions (2 km and 400 m) have demonstrated that the wavelength and wave amplitude are well simulated at both resolutions but that details of the wave close to the mountains are sensitive to resolution. This sensitivity also affects the phase of the wave downstream of the mountains. In order to better understand how the physical processes close to the wave generation region affect the evolution of the wave, a series of model simulations have been undertaken with different cloud microphysics and boundary-layer schemes. We will compare each of these simulations with the aircraft data in order to better understand the influence of the detailed physical processes close to the wave generation region on the downstream wave structure.

O-03.4

Mountain wave attenuation and momentum deposition in sheared environments

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Recently, mountain wave (MW) attenuation above the Southern Alps of New Zealand has been investigated during the entire DEEPWAVE period. Within this period, MWs were often strongly attenuated in a negative shear region in the lower stratosphere, where wind reduction causes mountain waves to steepen, attenuate, and deposit negative momentum. Occasionally, MWs propagated to altitudes greater than z = 35 km when lower-stratospheric negative ambient wind shear was minimized and positive ambient wind shear dominated.
The objective of this investigation is to study differences in MW breakdown or attenuation in no-shear, positive-shear, and negative-shear environments. MW attenuation is simulated using the non-linear WRF model in a 2-D idealized configuration. Compact single-mode and dual-mode 500 m high cosine terrains are used to launch waves in the sheared profiles. A unique aspect of this work is that the domains are horizontally periodic. While this is an unrealistic idealization, this boundary condition allows intuitive wave-mean flow interaction. The ambient wind speed reduction is the time integrated gravity wave drag.
In no-shear environments, MW attenuation/momentum deposition has multiple maxima in the vertical. In negative shear cases, attenuation is confined to the layer with negative shear and attenuation is smoother with height. The largest decelerations are seen in the positive shear cases, where wave steepening due to decreasing density is countered somewhat by increasing ambient wind. In simulations with a large-scale “volume” mode and a small-scale “roughness” mode, momentum deposition profiles are qualitatively similar to those with only the volume mode, suggesting the volume mode u’ modulates the environment of the smaller-scale roughness mode and controls where this mode attenuates. Conventional gravity wave saturation equations are not able to produce the WRF-computed ambient wind reductions.

O-03.5

The community foehn classification experiment

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“Is this foehn?”, was the question posed to human experts and to algorithms. The answer matters for studies of the

phenomenon itself but also for studies in a wide array of fields from air pollution to admission rates to hospital emergency rooms. Two different types of human experts provided answers; scientists studying foehn and orographic flows and Masters´ students of atmospheric science. Each group had about 20 - 30 participants. Time series of meteorological variables at five different foehn locations and a crest-station in Switzerland covering twelve 48-hour periods together with topographical maps and wind roses formed the common data set. The classification experiment allows to answer questions how well classifications from different experts and between the two types of experts agree, whether their classifications are repeatable, and whether they are distinguishable from two operational objective classification algorithms.

O-03.6

Origin of the lee-side hydraulic jump

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Laboratory observations of the hydraulic jump indicate it is composed of statistically stationary (and dissipative) turbulent motion in an overturning wave. From the point of view of the shallow-water equations, the hydraulic jump is a discontinuous increase in the height and decrease of the velocity of the fluid layer; at steady state, kinetic energy is dissipated at the jump. Questions concerning the physical origin of the hydraulic jump are necessarily outside the boundaries of any steady-state description. To provide an understanding of the origin of the hydraulic jump in the atmospherically relevant case in which a hydraulic jump forms on the lee side of an obstacle, three-dimensional numerical solutions of the exact fluid equations are carried out along with numerical solutions to the shallow water equations for the same physical initial-value problem. The simulations are carried out in a regime where a stationary lee-side hydraulic jump is expected from steady-state shallow-water theory. Starting from a constant-height layer flowing over an obstacle at constant speed, it is demonstrated that the solutions to the shallow water equations form a lee-side discontinuity owing to the collision of the upstream-moving characteristics launched from the lee side of the obstacle. The solution to the exact fluid equations indicates the lee-side hydraulic jump forms as a steepening, and then overturning, of the originally horizontal density interface; subsequent to this overturning, the fluid interface becomes statically unstable and eventually transitions to turbulence. Analysis of the initial-value problem in these solutions shows that the tendency to form either the lee-side height/velocity discontinuity in the shallow water equations, or the overturning density interface in the exact fluid equations, is a feature of the inviscid, nonturbulent fluid dynamics. Dissipative processes, which are associated with the lee-side jump and/or overturning wave at steady state, are properly understood as a consequence of the inviscid fluid dynamics that initiates and maintains the locally unstable conditions.

O-04.1

Heavy Precipitation and Flash Flood Events over Eastern Pyrennes

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Southeastern France is prone to heavy precipitation and flash-flood events. These high-impact weather events usually occur ahead of a trough directing upper-level southern flow and providing large-scale ascent whereas at the surface the moist and warm marine inflow is strongly influenced by the coastal orography. This presentation is focused on the events which affect the eastern tip of the Pyrenees. First, the climatology of these events is examined using ERAI reanalyzes together with precipitation and discharges time series. Unlike the events which hit the Massif Central or the Southern Alps, the eastern Pyrenees events are mostly associated with a low-level cyclone (located in the vicinity of the Balearic Islands). According to the climatological trends deduced from ERAI, the associated cyclones, tend to become deeper and to progress westward. Then, the results of various hydro-meteorological simulations are analyzed. Three past severe episodes have been investigated with the Meso-NH atmospheric model (500 m resolution) coupled with the MARINE distributed hydrological model. It is shown that the Meso-NH precipitation forecasts remain skillful even for small size water sheds (~1500 km2).

O-04.2

Forecast verification of precipitation and wind in complex terrain

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Verification of forecasted precipitation and wind fields over complex terrain presents a special challenge. This was recognized and addressed by the ongoing MesoVICT project. In recent years, new verification methods have been developed and one of these is the Fractions Skill Score (FSS). Firstly, we show how the FSS can be used to provide meaningful information about the displacement between precipitation in one field compared to another. Secondly, the FSS, as originally defined, can analyze only scalar variables and here an attempt has been made to extend the score so as to analyze wind vector fields in a meaningful way. The new score was calculated and analyzed for real cases in the greater Alpine region as well as idealized setups.

O-05.2

The Enhancement of Lake-Effect Precipitation over the Tug Hill Plateau during the Ontario Winter Lake-effect Systems (OWLeS) Field Program

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Improved understanding of the influence of orography on lake-effect storms is crucial for weather forecasting in many lake-effect regions. During December 2013 and January 2014, the U.S. National Science Foundation sponsored Ontario Winter Lake-effect Storms (OWLeS) field program examined lake-effect storms in the vicinity of Lake Ontario, including their enhancement over the Tug Hill Plateau (hereafter Tug Hill), which rises 500 m above lake level and experiences some of the most intense snowstorms in the world. This presentation provides an overview of key OWLeS-derived findings related to the enhancement of lake-effect precipitation over Tug Hill. In contrast to contemporary conceptual models of lake effect interacting with downstream orography, which typically emphasize an invigoration of lake-effect convection (i.e., deepening and strengthening) over downstream terrain features, profiling radar observations from OWLeS indicate an overall decrease in echo depth, decrease in turbulence, and increase in the frequency and uniformity of radar echoes over Tug Hill, consistent with a convective-to-stratiform transition. Significant variations in precipitation enhancement with lake-effect mode have also been identified. For example, strongly organized long-lake-axis parallel bands produce the highest precipitation rates but the smallest increase in precipitation from lowland to upland locations. In contrast, non-banded lake-effect periods exhibit smaller precipitation rates, but much larger increases in precipitation from lowland to upland locations. Although precipitation rates are weaker, these non-banded periods are more frequent and appear to be primarily responsible for the climatological precipitation maximum produced over Tug Hill. Implications of these findings for operational forecasting and our understanding of lake-effect and orographic precipitation will be discussed.

O-05.3

Characteristics of Easterly-Induced Snowfall in the Yeongdong region of Korea

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In general, Yeongdong in Korea has heavy snowfall in late winter because of high Taeback Mountains and an adjacent East Sea to the east. The synoptic setting for the heavy snowfall in winter are the Siberian High extended to East Sea and further northern Japan along with the Low system passing by the southern Korean peninsula, which eventually results in the northeasterly or easterly flows in the Yeongdong region. The basic mechanism to initiate snowfall around Yeongdong seems to be similar to that of lake-effect snowstorms around Great Lakes in Canada, and the United States, and also western Japan across the East Sea. Interestingly, snowfall appeared to begin in case of an air-sea temperature difference exceeding over 15°C.
We also attempted to investigate temporal variations of water vapor, liquid water and snowfall using ground-based Global Navigation Satellite System measurements, Microwave radiometer, and radiosonde systems. The results show that low-level clouds exist below 2~3km thickness with cloud base less than 1km, where northeasterly and northerly winds are consistent. The analysis has been made along with the classification of 3 dominant synoptic

patterns such as Low Crossing, Low Passing, and Stagnation types. The snowfall intensity of the largely easterly-induced Stagnation type is highest in spite of lower available water vapor. Late-winter snowfall is likely to have mixed precipitation, such as relatively heavier melting snow. In general, easterly-induced snowfall consists of mainly various kinds of dendrite habits along with frequently rimed particles through both an i-phone and a digital camera. Interestingly the clouds are confined with distinctive shear in wind direction below 2 ~ 2.5 km below the stronger inversion in equivalent potential temperature.

O-05.4

Simulations of convective flash flood events in southern Switzerland

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The Weather Research and Forecasting model (WRF) was used to perform high-resolution numerical simulations for nine convective events with high peak discharges and flash flooding of the Maggia River in the Lago Maggiore region of southern Switzerland. The dynamics and kinematics behind the observed convective echo training were studied in an attempt to obtain additional insight into the atmospheric conditions that produce these flash flood episodes.
Model verification was performed using radar-estimated rainfall totals (Panziera et al. 2015) and routine radiosonde observations from Milan, Italy. Seven of the nine simulations adequately depicted the location and amount of precipitation when compared to the observed elliptical precipitation totals.
Mean atmospheric characteristics were analyzed using temporal averaging of the WRF output fields during the periods of heaviest precipitation over the Maggia catchment for each event as determined by the model composite reflectivity. Confluence of low-level southerly and easterly jets was observed in the cavity of the Alps surrounding the Lago Maggiore region. Furthermore, model omega and mixing ratio fields indicated significant downsloping and drying of the flow on the northern lee slope of the Apennines which led to deflection of the flow and the formation of the easterly barrier jet. This barrier jet converged with the southerly LLJ from the Ligurian Sea. The flow pattern was enhanced by a lee cyclone in the Piedmont region of northwest Italy, and the amount of the convective triggering over the region was related to the intensity of the convergence of the low-level flow. The confluence of these flow features and resultant orographic lifting of conditionally unstable air in the southerly LLJ are likely the mechanisms for the frequent convective triggering leading to intense flash floods in the Lago Maggiore region.

O-05.5

Orographic effects of the subtropical and extratropical Andes on precipitating clouds

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The orographic effect of the Andes (35°S-50°S) on precipitating clouds from midlatitude frontal systems is investigated using surface and CloudSat satellite data. The Andes is a long mountain chain that extends in the north-south direction on the west coast of South America. Its crest descent from the subtropics to extratropics and its perpendicular disposition to the westerlies makes this barrier an excellent natural laboratory to investigate orographic effects on frontal precipitation systems. Seven transects of hourly rain gauges between 35°S and 45°S from the windward side (Chile) to the lee side (Argentina) were installed as part of a project initiated in 2016. Installed rain gauges were complemented with daily precipitation data managed by Argentinean and Chilean Weather and Water agencies, although these datasets do not sample well near the crest and in the immediate lee sectors of the Andes. Surface precipitation observations indicate orographic enhancement and suppression in annual total amount from the Pacific coast to the leeward slopes that varies with latitude. Hourly gauges and instantaneous satellite observations show that the cross-barrier increase and decrease in annual precipitation responds to increase and decrease in both the intensity and frequency of precipitation. In addition, CloudSat satellite data reveal cross-barrier variations in precipitating cloud properties that suggest orographic influences on the airflow dynamics and microphysical processes that will be discussed in the presentation.

O-05.6

Terrain-trapped airflows and orographic rainfall along the coast of northern California: Horizontal and vertical structures of kinematics and precipitation

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Land-falling extratropical cyclones are responsible for the majority of precipitation that falls in the western United States. The spatial distribution of precipitation from these storms is strongly influenced by the regions' complex terrain. A narrow channel of concentrated horizontal water vapor flux in the lowest 3-4 km MSL is often present immediately ahead of the cold fronts associated with extratropical cyclones. Upon impacting the terrain, these statically-neutral atmospheric rivers (ARs) can facilitate moist orographic uplift that leads to enhanced precipitation. While this relatively simple conceptual model can explain a significant fraction of orographic precipitation that falls in the region, it does not take into account the fact that mountains can produce their own mesoscale circulations that modify the spatial distribution of precipitation. One example is the presence of a terrain-trapped airflow (TTA), which is defined as a relatively narrow air mass flowing in close proximity and approximately parallel to the windward slope of a mountain barrier. TTA impacts on orographic precipitation have been studied extensively in association with several large-scale mountain ranges such as the European Alps, the Southern Alps of New Zealand, the Rocky Mountains of Colorado and the Sierra Nevada of California. In contrast, TTA impacts on orographic precipitation occurring in association with relatively small-scale mountains (altitudes below ~1 km MSL) has received much less attention. It is notable that orographic precipitation over small-scale mountains has the potential to produce rapid runoff and flooding due to the prevalence of precipitation in the form of rain (rather than snow) and the relative scarcity of flood control infrastructure. This is a particularly relevant issue along the coastal mountains of northern California, where unobstructed ARs can directly interact with the coastal terrain (~0.5 km MSL and oriented northwest to southeast) to produce intense rainfall that leads to significant economic impacts.
This study employs observations collected along the California coast north of San Francisco as part of the Hydrometeorology Testbed experiments operated by the National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL). The main observing system is a scanning X-band Doppler radar located on the coast at Fort Ross (FRS, 10 m MSL), which supplied reflectivity and radial velocity data in the horizontal and vertical throughout the evolution of seven land-falling storms. This information allows the detailed documentation of three-dimensional kinematic and precipitation structures associated with the impact of TTAs on orographic precipitation. Another important instrument is a 915-MHz wind-profiling radar located on the coast at Bodega Bay (BBY, 15 m MSL) that supplies hourly, high-resolution (~100 m) vertical profiles of horizontal wind up to ~4 km MSL. These data are used to identify TTA conditions based on the mean wind direction in the lowest 500 m MSL; values less than 150° lasting two or more consecutive hours are associated with TTA conditions while values not meeting those thresholds are associated with NO-TTA conditions. Supporting information is provided by and surface meteorology and rain gauge observations at FRS, BBY and in the adjacent coastal mountains at Cazadero (CZD, 478 m MSL).
The seven-storm composite analysis of TTA conditions with data from the scanning Doppler radar reveals an average kinematic structure characterized by a significant horizontal gradient of wind direction with southeasterly winds along the coast transitioning to south-southwesterly at a range of ~50 km from the coast. In the vertical, mean TTA kinematic structure indicates a low-level jet (LLJ) of ~20 m s^{-1} surmounting a weaker airflow of ~10 m s^{-1} corresponding to the TTA. The LLJ center is displaced upward by the TTA from ~0.5 km MSL (offshore) to ~1.0 km MSL (at the coast). Mean precipitation structures in the horizontal and vertical show an enhanced precipitation zone offshore and oriented roughly parallel to the coastline. The center of this zone is located ~15 km offshore and extended upward from the surface to ~0.5 km MSL.
In contrast, seven-storm composite analysis of NO-TTA conditions indicates an average kinematic structure characterized by southerly winds and only a small amount of directional shear in the horizontal. Precipitation enhancement during NO-TTA conditions is restricted to a zone within ~10 km from the coast and extends upward to ~1.0 km MSL. LLJ structures are not readily apparent in either the horizontal or vertical. This does not mean that LLJ structures are nonexistent during NO-TTA conditions. Rather, it indicates that LLJ structures are smoothed out by the averaging process due to their relatively short duration compared to the relatively large NO-TTA data sample.

O-05.7

Role of the orography in the generation of a tornadic supercell in the Mediterranean

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On 28 November 2012, a multi-vortex EF3 tornado occurred in southeastern Italy causing one casualty and estimated damage of 60 M€. At approximately 1050 LT (0950 UTC), this tornado, which initially formed in

association with an apparent supercell thunderstorm over the Ionian Sea, moved inland. The environment where the tornadic supercell developed was characterized by large vertical wind shear in the lowest 1 km of the atmosphere and moderate conditional instability. The WRF-model numerical simulations show that it is possible to produce the track, change in intensity, and evolution of a simulated supercell thunderstorm similar to the actual one that spawned the tornado in Taranto, southern Italy. The genesis of the simulated supercell is due to a combination of mesoscale-meteorological features: warm low-level air advected toward the Ionian Sea, combined with a mid-level cooling due to an approaching trough, increased the potential instability; the intense vertical shear favored the possibility of supercell development; boundary layer rolls over the Ionian Sea moved in phase with the cells produced by the orography of Calabria to supply moisture and heat to convection. An unusual feature of the present case of tornadogenesis is the central role of the orography, which was verified in a sensitivity experiment where the orography of Calabria was reduced by 80%. The upper-level vertical-vorticity couplets generated in the lee of the orography are evidence of updrafts in vertical wind shear for the cells triggered by the orography, which are essential for supercell dynamics.

O-06.1

Use of a sub-grid orographic rain enhancement scheme in the MetUM

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At low resolution, numerical models are unable to produce enough orographic rain due to their poor representation of surface height variations (Smith et al 2015). Therefore a subgrid parameterisation scheme has been designed to represent seeder feeder rain enhancement produced by unresolved hills (Smith et al 2016). An estimate of the extra orographic water produced by ascent over unresolved hills is used by the microphysics scheme to enhance the rain accretion rate. In Smith et al, the scheme was tested using the idealised Kinematic Driver (KiD) model and it was shown to perform well in the warm, moist low-level flow typically encountered during orographic rain enhancement over the UK. The scheme is now being coded into the Met Office Unified model (MetUM) and some initial results will be described.

O-06.2

Dual-pol radar based hydrometeor classification: analysis of orographic precipitation mechanisms

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In assigning a hydrometeor label to every radar sampling volume, the new MeteoSwiss semi-supervised hydrometeor classification algorithm [1] exploits the complementary information provided primarily by dual-pol radar moments: radar reflectivity (Z_H), differential reflectivity (Z_{DR}), specific differential phase (K_{dp}) and correlation coefficient (ρ_{hv}). By doing so, it distinguishes between nine different hydrometeor types: crystals, aggregates, light rain, rain, rimed ice particles, wet snow, vertically aligned ice particles, ice hail/high density graupel and melting hail. The presentation introduces the hydrometeor classification algorithm and shows its application to the study of selected 21 orographic heavy rainfall events in the Lago Maggiore area on the southern Alps, located in the vicinity of the Monte Lema MeteoSwiss operational radar. Spanning over six years (2011-2016), these events caused the discharge peaks of the river Maggia, ranging from 300 to 2300 m^3/s, and are therefore associated to the flooding of the local settlements [2].
Estimated spatial probability density functions (PDFs) of occurrences of different hydrometeor classes in the vertical cross sections above the valley of interest are shown. On one side, by estimating them over the entire event, we obtain a unique signature for every rainfall case. On the other side, by estimating PDFs at hourly scale, we can track their evolution during the event, providing us with an original insight into the microphysical and dynamical processes of the orographic rainfall. Associating the observed hydrometeor tendencies to the local topography is of great help in further understanding the orographic precipitation mechanisms.
[1] Besic, N., et al.: Hydrometeor classification through statistical clustering of polarimetric radar measurements: a semi-supervised approach, Atmos. Meas. Tech., 9, 4425-4445, 2016.
[2] Panziera, L., et al.: Mesoscale organization and structure of orographic precipitation producing flash floods in the Lago Maggiore region. Q.J.R. Meteorol. Soc., 141, 224–248, 2015.

O-06.3

Study on characteristics of snow crystal from the two-layer cloud structure in Yeongdong region of Korean Peninsula

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The Yeongdong region of Korean Peninsula is vulnerable to natural disasters that are mostly caused by high-impact weather events. Because of their complicated geographical characteristics and lake effect, heavy snowfall episodes have frequently occurred in winter season. Snow crystals play an important role in cloud physics because they affect the scattering of light and fall speed of solid precipitation, which is an essential element for improvement of numerical model. Riming process and seeder-feeder processes contribute significantly to the snowfall formation in mountainous regions, but “seeder-feeder” processes are mainly focused on the summer heavy rainfall rather than winter snow so far.
In this study, the high-resolution dataset of upper-air observations and photographs of snow crystals in the campaign of Experiment on Snow Storms At Yeongdong (ESSAY) were used to apply a new approach for the characterization of snow crystal involved in winter seeder-feeder mechanisms over the Yeongdong region. We also attempt to simulate the snowfall of two-layer cloud structure that occurred on 29-30 January, 2016 using a high-resolution cloud resolving model, namely Cloud Resolving Storm Simulator (CReSS).
The previous studies showed that the snow crystals in the ESSAY campaign were mainly dendrite, consisting of about 70% of the entire habits. This study demonstrated that the rimed habits were frequently captured specifically when two-layerd clouds were observed under conditions of the strong wind shear and inversion in equivalent potential temperature about 2~3 km altitude, such as a case of 29-30 January 2016. Rimed particles, however, tended to change to dendrite form as 850 hPa temperature decreased with time. The CReSS simulation well captured the variations of snow crystal habits as well as two-layer cloud structure. The strong vertical air motion in the low-level cloud represented in the CReSS model appears to play a critical role in producing graupel-like habits.

O-06.4

Numerical Study of Physical Processes Controlling Summer Precipitation over the Western Ghats Region

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Summer precipitation over the Western Ghats and its adjacent Arabian Sea is an important component in the Indian monsoon. To advance our understanding of the physical processes controlling the regional precipitation, we conduct a series of high resolution convection-permitting simulations using the Weather Research and Forecasting (WRF) model. Convection simulated in the WRF model agrees with TRMM and MODIS satellite estimates. Sensitivity simulations are conducted, by altering topography, latent heating, and sea surface temperature (SST), to quantify the effects of different physical forcing factors.
It is helpful to put India west coast rainfall systems into three categories with different causes and characteristics: (1) Offshore rainfall is controlled by incoming convective available potential energy (CAPE) in the monsoon westerlies and the SST of the Arabian Sea. It is not triggered by the Western Ghats. When present, it steals CAPE and reduces coastal rainfall. Strong (weak) offshore rainfall is associated with high (low) SSTs in the Arabian Sea, suggested by both observation and sensitivity simulations. (2) Coastal rainfall is forced by both the coastline and the Western Ghats topography. The Western Ghats enhances convection-induced rainfall over the mountains and produces a drier rain shadow to the east. Convection is the biggest overall rain producer. (3) Orographic stratiform rain dominates the precipitation on the crest of the Western Ghats.

O-06.5

Precipitation scavenging effects on Mt. Washington cloud chemistry

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With cloud deposition the largest source of atmospheric pollutants to many fragile alpine environments, understanding the processes that control mountain cloud-water chemistry is critical. Using 20 years of summer cloud and rainwater samples collected near the summit of Mt. Washington, New Hampshire, US, this study evaluates how condensation and precipitation during atmospheric transport influence pollutant concentrations in air masses arriving from different geographic sectors. To characterize the condensation history of air masses arriving at Mt. Washington, the analysis leverages the fact that isotopically heavy water molecules condense more readily than their lighter counterparts. The more condensate removed as precipitation, the “lighter” the remaining cloud water becomes. Thus, the water isotope ratios of the samples serve as proxies for the amount of rainout that occurs “upstream” of the mountain. HYSPLIT back trajectories suggest the majority of Mt. Washington samples are associated with air masses arriving from locations to the west and southwest of New Hampshire, from regions such as the Great Lakes, the industrial Ohio River Valley, and the Boston-Washington, DC urban corridor. Concentrations of pollutants like sulfate, nitrate, and ammonium are highest for these geographic sectors. Despite the fact that water isotope ratios vary strongly with latitude, regression models suggest condensation and precipitation during air mass transport explain a third of the variance in Mt. Washington cloud chemistry. The dependence of pollution on “upstream” rainout becomes even more apparent when samples are binned by geographic origin, providing compelling evidence that precipitation scavenging effectively removes pollutants from air masses en route to mountain environments.

O-07.1

The environment of orographic wave clouds in the lee of the Colorado Front Range (and Oklahoma)

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A selection of several thousand photographs of orographic wave clouds taken in the lee of the Colorado Front Range (and elsewhere) from 1984 – 2016 were subjectively grouped into a number of categories based on their physical appearance. The purpose of our study is to (1) describe the different categories and (2) identify the upstream, environmental conditions associated with each category. The ultimate goals are to be able to predict what type of wave clouds will form based on numerical model forecasts of the synoptic environment and to infer properties of the atmosphere based solely on cloud observations.
Rawinsonde and North American Regional Reanalysis (NARR) data were used to characterize the upstream environment in Colorado. The former were used to characterize the far environment crudely, but with high vertical resolution; the latter were used to characterize the near environment (within 50 km or less), but with lower vertical resolution. The data are analyzed in the context of the properties of lee waves. Our results are interpreted with some caution because some of the wave cloud forms observed lasted only for relatively short periods of time, sometimes as briefly as an hour or less. Also, some of the wave clouds were rather isolated. The results of our study will be presented.
Finally, there is a small sample of wave clouds that appeared in other locations such as Norman, OK, where there are no nearby mountains. Some attention will be given to the synoptic environment of these clouds and a hypothesis for what may have triggered them will be offered.

O-07.2

The Influence of Mountain-Forced Waves on the Atmospheric Kinetic Energy Spectrum

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The observed kinetic energy spectrum of the atmosphere exhibits a k^-3 wavenumber dependence at large scales that transitions to a k^-5/3 dependence in the mesoscale. The synoptic slope appears well explained by 2D turbulence theory, but there is no clear consensus on the processes that generate mesoscale k^-5/3 slope. Previous studies have suggested possibilities including an inertial cascade from a localized large- or small-scale source, or direct mesoscale forcing via gravity waves or convection.
Here we show that mountain waves can make a substantial contribution to the k^-5/3 portion of atmospheric kinetic energy spectrum. A prototypical midlatitude low pressure system is generated in an idealized basic state favorable for unstable growth after seeding with a finite-amplitude PV anomaly. A mountain is placed well downstream of the initial anomaly. The cold front impinges on the terrain, and a full lifecycle of mountain wave generation, propagation, and decay is simulated. In comparison to a no-mountain simulation, these orographic waves produce a distinct

shallowing of the KE spectrum towards a k^-5/3 slope. In simulations with higher ridges, this k^-5/3 slope is evident over a wider range of scales.
The spectral energy budget is calculated using Fourier transforms analogous to the methods used in Peng et al. (2014). Terrain-forced gravity waves propagating from the troposphere into the stratosphere inject energy directly into the mesoscale; this mechanism is much weaker in the absence of a mountain. These results are in accordance with the growing literature suggesting that gravity waves provide a pathway through which the k^-5/3 spectral slope can be directly forced on the mesoscale, and that inertial cascade arguments are not necessary for its production.
Peng J., L. Zhang, Y. Luo, and C. Xiong, 2014: Mesoscale Energy Spectra of the Mei-Yu Front System. Part II: Moist Available Potential Energy Spectra. *J. Atmos. Sci.*, **71**, 1410–1424.

O-07.3

Photogrammetric analysis of rotor clouds observed during T-REX

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Stereo photogrammetric analysis is a little utilized but highly valuable tool for studying smaller, highly ephemeral clouds. In this study, we make use of stereo digital photographs that were collected during the Terrain-induced Rotor Experiment (T-REX) but little used thus far. The data set consists of matched stereo pairs of photographic images obtained at high temporal (on the order of seconds) and spatial resolution (limited by the pixel size of the cameras). Using computer vision techniques we have been able to develop algorithms for camera calibration, automatic feature matching, and ultimately reconstruction of 3D cloud scenes.
Applying these techniques to images from different T-REX IOPs we can capture the motion of clouds in several distinct mountain wave scenarios ranging from short lived lee wave clouds on an otherwise clear sky day to rotor clouds formed in an extreme turbulence environment with strong winds and high cloud coverage. Tracking the clouds in 3D space and time allows us to quantify phenomena such as growth, and vertical and horizontal movement of clouds, turbulent motion at the upstream edge of rotor clouds, the structure of the lifting condensation level, extreme wind shear, and the life cycle of clouds in lee waves. When placed into context with the existing literature that originated from the T-REX field campaign our results complement and expand our understanding of the complex dynamics observed in a variety of different lee wave settings.

O-07.4

Trapped lee waves at an inversion in flow over axisymmetric hills: theory and laboratory measurements of the drag

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The drag produced by 3D lee waves trapped at an inversion in flow over an axisymmetric hill is calculated using linear non-hydrostatic theory. These waves may propagate in the atmosphere at the capping inversion existing at the top of the boundary layer, and are responsible for near-surface wave drag that may be mistaken for turbulent form drag. This drag receives contributions from a continuous range of wavenumbers excited by the orography, in contrast to 2D flow (where all possible trapped wave modes are discrete), since the waves may vary their angle of incidence to satisfy their dispersion relationship. Hence (contrary to 2D linear flow), the drag is non-zero for both subcritical and supercritical flow, and its maximum is attained for a Froude number slightly lower than 1. This drag maximum is less pronounced than in the hydrostatic limit, due to wave dispersion. The drag calculated from the theory agrees well with that obtained from measurements performed in laboratory flume experiments using axisymmetric obstacles of different heights, especially for the lowest obstacle. Agreement is best when the effects of both a rigid lid bounding the upper fluid layer and dissipative effects (modelled as a Rayleigh damping) are taken into account. The theory performs somewhat worse for the highest hill considered in the experiments, as this amounts to stronger nonlinearity of the flow. But even then the theory remains qualitatively correct, being much more accurate than 3D hydrostatic or 2D non-hydrostatic calculations. This supports the idea that 3D and nonhydrostatic effects are of decisive importance in the drag behaviour shown by the measurements. The waves associated with this drag behaviour are predominantly transverse waves for relatively small Froude numbers, form a dispersive “Kelvin ship wake” in the vicinity of the Froude number where the drag is a maximum, and are predominantly divergent waves for larger Froude numbers. The density interface defining the inversion has a maximum depression directly in the lee of the hill, by an amount that is significantly correlated with the drag magnitude. This is not surprising, since the flow

region beneath that depression is characterized by a pressure deficit that is the ultimate cause for the drag force exerted on the hill in the flow under consideration.

O-07.5

The impact of upstream flow on the boundary layer in a valley - observations and high-resolution simulations

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Comprehensive measurements on the mountainous island of Corsica were used to investigate how the mountain atmospheric boundary layer (mountain ABL) in a valley downstream of the main mountain ridge was influenced by the upstream flow. The data used were mainly collected during the Hydrological cycle in the Mediterranean Experiment (HyMeX) in 2012 and were based on various in situ, remote sensing and aircraft measurements. Two days in autumn 2012 were analysed in detail.
On these days the mountain ABL evolution was a result of convection and thermally-driven circulations as well as terrain-induced dynamically-driven flows. The observations indicate that during periods when dynamically-driven flows were dominant, warm and dry air from aloft with a large-scale westerly wind component was transported downwards into the valley. On one day, these flows controlled the mountain ABL characteristics for several hours, while on the other day their impact was observed for about 1 h only. To help explaining the observed phenomena, Consortium for small scale modelling (COSMO) simulations with 500 m grid-spacing were performed. Observations and simulations show that the spatio-temporal structure of such a mountain ABL over complex terrain, which was affected by various interacting flows on multiple scales, differs a lot from that of the classical ABL over homogeneous, flat terrain.

O-07.6

Observational and numerical analysis of pulsations and turbulence in a bora downslope windstorm event

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Turbulent downslope windstorm events are frequent phenomena over complex terrain of the eastern Adriatic coast. While severe northern-Adriatic downslope windstorms are since long in the focus of interest, strong bora winds in the hinterland of middle Adriatic coast are much less studied, yet frequent and equally severe phenomena. The predictability of these events is considerably lower than for its northern counterpart due to the inflow complexity induced by the upwind chain of secondary orographic steep mountain sub-ranges and deep valleys. The aims of this work are first to study sub-mesoscale pulsations embedded in the bora flow and second, to study sources and sinks of bora turbulence through the analysis of the turbulence kinetic energy (TKE) budget.
The analyzed event was a strong late-winter anticyclonic bora (28 Apr 2010) in the very complex terrain, characterized by three-dimensional flow, shallow bora layer, a pronounced directional vertical wind shear and interaction with valley circulations in deep valleys. Observational analysis, performed with the use of ultrasonic anemometers at Pometeno brdo hill at 10, 22 and 40 m AGL, suggested that two distinct regimes of pulsations exist: i) Regime A – pulsations observed predominantly during the night and morning hours with periods of 3 – 8 minutes and ii) Regime B – pulsations observed predominantly during the afternoon with periods of 8-11 minutes. Numerical analysis of the event used the WRF model with realistic initial and boundary conditions and multiple nested computational domains in two configurations. The first used a mesoscale model setup at a grid spacing reaching 333 m in the highest resolution domain and a Mellor-Yamada type of the Planetary Boundary Layer (PBL) scheme while the second used a multiscale setup at a grid spacing as fine as 37 m using explicit simulation of large turbulent eddies. The strongest simulated wind speed pulsations were of comparable periods as in the observations and originated beneath the primary mountain gravity wave. These pulsations propagated farther away from the point of origin during the daytime convective PBL than those during the statically stable nighttime conditions. The analysis of sensitivity simulations suggested that pulsations originate beneath the primary mountain wave due to Kelvin-Helmholtz instability. Additionally, during daytime they are also found in the upstream flow. While mechanical production and dissipation of TKE are the dominant terms of the TKE budget, other terms such as turbulent transport and advection play an important role for the TKE budget. Finally, main differences in the bora subtle structure over the middle and northern Adriatic coastal areas, the latter pertaining to more known bora cases, are pointed out, as well as main differences between results in mesoscale and multiscale simulations.

O-08.1

Atmospheric rotors, downslope windstorms and severe turbulence in a deep long valley

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Turbulent atmospheric rotors are frequently observed in Owens Valley, a deep long valley in the lee of the southern Sierra Nevada in California. This contribution presents a comprehensive analysis of strong mountain-wave activity cases from the 2006 Terrain-Induced Rotor Experiment (T-REX). The analysis reveals the rich variety of rotor-like turbulent flow structures that may form during periods of strong cross-mountain winds. Observations show that the elements of the classic rotor conceptual model are modulated and, at times, almost completely offset by dynamically- and thermally-driven processes in the valley.
A 5-yr climatology of westerly wind events in Owens Valley, derived from the semi-permanent 16-station mesoscale network managed by the Desert Research Institute (DRI), show that relatively strong westerly winds at the valley floor are most commonly observed in the afternoon hours in late spring and summer. However, intense and potentially damaging westerly wind storms can happen at any time of the day throughout the year. The temperature and humidity variations caused by westerly windstorms at the valley floor depend on the properties of the approaching air masses. In some cases, the windstorms lead to overall warming and drying of the valley atmosphere, similar to foehn or chinook intrusions.

O-08.2

Radar kinematic information as surrogate for isentropes in stratiform orographic storms

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This paper will illustrate that dual-Doppler-derived horizontal vorticity in stratiform (laminar) flow is structured in persistent, thin striations. The reason this has not been documented before is that scanning ground-based radars have rather poor and range-dependent vertical resolution. Here we use data from an airborne radar with a fine and constant vertical resolution. Geerts et al. (2017, in Mon. Wea. Rev.) have shown that Doppler-radar-derived vorticity (a kinematic conserved variable) may serve as a suitable proxy for thermodynamic conserved variables such as equivalent potential temperature in stratiform precipitation. Here we apply this observational technique to describe wave patterns over complex terrain, and we use it to validate numerically simulated flow over complex terrain.

O-08.3

The impact of resolution on the representation of wind field in the vicinity of large Greenlandic fjords

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Greenlandic fjords
East Greenland is characterized by complex local topographic that gives rise to a number of low-level high wind speed weather systems that are the result of topographic flow distortion. These systems include barrier winds, downslope windstorms and katabatic flow. Global atmospheric reanalyses have proven to be important tools in furthering our understanding of these orographic winds and their role in the climate system. However, there is evidence that the mesoscale characteristics of these systems may be missed in these global products. For example, the 1935-36 British East Greenland Expedition (BEGE) noted a sharp gradient in the wind field along the Kangerdlugssuaq Fjord. Here we compare and contrast the representation of the wind field in the vicinity of the Kangerdlugssuaq and Kangertittivaq (Scoresby Sund) Fjords, two of the large fjords along the east coast of Greenland, in the 30km and 15 km versions of the Arctic System Reanalysis (ASR). We introduce a new diagnostic, the decorrelation length scale (DCLS), that is used to characterize the impact that model resolution has on spatial variability in the wind field. We show that the 15km version of the ASR is better able to represent this variability

including the gradient in the wind field in the vicinity of the Kangerdlugssuaq Fjord that were identified by the BEGE. This gradient is shown to be the result with tendency for downslope windstorms to occur to east of the fjord, while katabatic flow is focused to its west. We also use the DCLS to show that the two weather stations in the vicinity of the fjords have wind climates that are not representative of the regional winds.

O-08.4

Observation plans of ICE-POP2018 and the preliminary results

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The 23rd Winter Olympic and the 13th Paralympic Games will be held in PyeongChang, Korea on February-March, 2018. The Games provide great opportunities for the meteorologists to understand mountain meteorology over complex terrain areas like PyeongChang. Therefore, KMA (Korea Meteorological Administration) and NIMS (National Institute of Meteorological Sciences) have been working on the International Collaborative Experiments for PyeongChang Olympic and Paralympic 2018 (ICE-POP2018) project, and the preliminary results from ICE-POP2018 will be used to improve the accuracy of nowcasting and very-short-range forecast systems around the mountainous region.
The HIWRC (High Impact Weather Research Center) is practically in charge of the observation part in the ICE-POP2018. In order to characterize lake-effect snowstorm and orographic enhancement on the evolution of snow clouds over the PyeongChang area, intensive observation campaign has been designed and will be carried out during winter from 2016 to 2018. Beside synoptic observations, radars, wind profilers, multi-purpose aircraft, observing ship, and mobile observation vehicles (MOVE) will be intensively used in this campaign. The data from MOVE could be especially provided specifically in areas of limited mountainous sites.
During the 29-30 January 2016, accumulated snowfall amount at the mountain site (Daegwallyeong) reached 5.5 cm, and the inversion in equivalent potential temperature and strong wind shear about 2~3 km altitude were observed from the upper-air soundings of MOVE. However, snow flurries were observed at the lowland site (Bokwang) of the western direction with the different vertical structure, which means that snow depends on the small scales flows, stability, and phase change in a low level. Analysis of the data collected by MOVE observing platforms combined with other remote sensing measurements will provide new insights into the mechanisms contributing to a unique perspective on snowfall over PyeongChang area.

O-09.1

Impact of Icelandic volcanic dust on cryosphere

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Iceland is extremely active dust region and with over 44,000 km^2 counts as the largest Arctic and European desert. Frequent dust events, up to 135 dust days annually, transport dust particles far distances towards the Arctic and Europe. Satellite MODIS pictures have revealed dust plumes exceeding 1,000 km. The annual dust deposition was calculated as 40.1 million tons yr^{-1}, which places Iceland among the most active dust sources on Earth. About 5.5 - 13.8 million tons is deposited annually over the oceans around Iceland covering wide areas of 370,000 km^2.
Despite the location of Iceland in the high-latitude cold region, half of the annual dust events in the southern part of Iceland took place at sub-zero temperatures or in winter, when dust may be mixed with snow. We observed a “Snow-Dust Storm” in March 2013 when dust was transported over 250 km and consequently was deposited on snow in Reykjavik. The snow was nearly black with several mm volcanic dust layer close to the dust source, while a clumping mechanism was found in thin layer of impurities in Reykjavik. This has been the first observation of such mechanism in natural conditions.
Icelandic dust consists of fine reactive volcanic materials. It is dark in color and it contains sharp-tipped shards, often with bubbles. About 75-80 % of the material is a volcanic glass. However, extreme dust storms in Iceland transport also large proportion of organic material or diatoms. We conducted several experiments during winter campaigns investigating changes in albedo, bidirectional reflectance factor and other snow properties monitored on the clean

snow and areas affected by the dust deposition through the following melting period. These experiments also included black carbon (BC) observations revealing that volcanic dust has similar effects on snow albedo as BC. Icelandic volcanic dust tends to act as a positive climate forcing agent, both directly and indirectly, which is different than concluded for crustal dust in the 2013 IPCC report. This suggests that the Icelandic dust may be a contributor to the Arctic warming.

O-09.2

Coherent structures in the alpine atmospheric surface layer coupled with blowing snow response

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Wind transport of snow is a turbulence driven phenomenon impacting mountain hydrology, glaciology, and avalanche safety. Furthermore, blowing snow behaves as a wind momentum sink, especially in the dense near-surface region where snow is in saltation. In two-way coupled atmosphere-blowing snow models, this transfer of kinetic energy from the wind to snow particles is typically accounted for as an increased roughness length in a log-linear wind model. When steady state, equilibrium transport models do not apply, however, understanding the timescales of particle response to turbulent gusts becomes increasingly important to know what turbulence statistics accurately characterize snow transport. Small variations in transport can translate to large variability in blowing snow deposition. Currently, there is limited understanding of the timescales relevant in the two-way coupling of wind and snow in complex terrain and in the presence of high turbulence intensity. Through laser illuminated high-speed videography, snow particle tracking velocimetry, and ultrasonic anemometry in an alpine setting, surface layer structures were observed and coupled with intermittent blowing snow events. This has allowed better understanding of the nonlinear relationships between time-dependent turbulence statistics of high and low frequency motions and subsequent snow transport.

O-09.3

Investigating time scales in the meteorological forcing on snow avalanche activity

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Snow avalanches are a major natural hazard in snow covered mountainous areas and are considered a meteorologically induced hazard. Forecasting snow avalanches therefore requires a detailed understanding of the meteorological forcing on avalanche activity. Data on avalanche activity are generally obtained through visual observations, which are imprecise and impossible when visibility is limited. This leads to large uncertainties in the number and exact timing of avalanches, resulting in rather poor correlations between avalanche activity and meteorological parameters. We therefore used unique avalanche activity catalogues obtained through seismic monitoring to establish links between avalanche activity and local meteorological parameters. To identify characteristic time scales associated with the onset of avalanche activity and relaxation time scales associated with a return to stability we performed a de-trended cross-correlation analysis (DCCA). Our results suggest that typical time scales for wet-snow avalanches in spring are on the order of several hours to one day, while for dry-snow avalanches in winter time scales are on the order of a few days. Furthermore, a moving window DCCA showed that different meteorological drivers are related to increased avalanche activity throughout a season. While air temperature and incoming solar radiation are the dominant drivers in early spring, wind and precipitation correlated best with avalanche activity during winter and in late spring. Overall, our results show that accurate avalanche activity data can be used to improve our knowledge on avalanche formation processes and ultimately improve their forecasting using readily available meteorological data.

O-09.4

MODIS snow cover data for calibration and evaluation of hydrological models in French mountainous regions

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The objective of this study is to assess the potential of snow cover data from MODIS satellite sensor for calibration and evaluating conceptual lumped and semi-distributed hydrological models. Primary, this investigation assesses the impact of model structure on flow simulation and snow modelling using two versions of a conceptual hydrological model called MORDOR: (i) a lumped and (ii) a semi-distributed structures. As a rule model intercomparison experiments are widely used to investigate and improve hydrological model performances. However, a study based only on runoff simulation is not sufficient to discriminate different model structures. The first objective of this study is to investigate in an evaluation mode, the impact of spatial discretization (lumped vs. semi-distributed approaches) on flow and snow simulation. The evaluation framework, founded on a multi-criteria split sample strategy, is enriched by a direct comparison of snow cover simulated by hydrological models and MODIS data. The results show that the semi-distributed approach provides better validation performances for snow cover area, snow water equivalent and runoff simulation, especially for nival catchments. The second goal of this work is to evaluate the use of MODIS snow cover data for calibrating the semi-distributed structure of MORDOR. We consider two different techniques: (i) calibration to runoff alone and (ii) calibration to both runoff and MODIS snow cover. The results indicate that the use of MODIS snow cover data improves the snow model performance without a noticeable degradation on flow simulation. This outcome is especially true for mid-mountain catchments where the streamflow data are not sufficient for calibrating parameters of snow model. The analysis is performed for an extensive dataset composed of 50 catchments located in French mountainous regions.

O-09.5

Hydrometeorological reconstruction of snow-influenced streamflow series in France since 1871

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The length of streamflow records is generally limited to the last 50 years, and therefore prevents studying the long-term evolution of streamflow regimes. In order to overcome this limit, this work takes advantage of a 140-year ensemble hydrometeorological dataset over France based on: (i) a 8 km daily ensemble precipitation and temperature downscaling of the global Twentieth Century Reanalysis over France (Caillouet *et al.*, 2016a), and (ii) a continuous hydrological modelling that uses these meteorological reconstructions as forcings (Caillouet *et al.*, 2016b). The resulting dataset, called *SCOPE Hydro*, provides an ensemble of 25 equally plausible daily streamflow – and hydrological state variable – time series for a reference network of more than 600 stations in France over the 1871-2012 period.
A subset of 184 catchments located in French mountain ranges (Alps, Pyrenees, Massif Central, Jura and Vosges) is specifically targeted here. This work aims at studying the long-term evolution of streamflow in mountainous catchments where the regime is largely influenced by snow accumulation and snowmelt processes. Results show a high interannual variability of the seasonal snowpack and the associated snowmelt, in terms of both intensity and timing. Spatial patterns also emerge across the different mountain ranges for specific years. This variability is modulated by a relatively large multidecadal variability highlighting periods with a large (1910s) or small (1950s) snowmelt component of streamflow. Results also highlight the reduced snowmelt component in the post-1980 period compared to the 150-year average. The *SCOPE Hydro* dataset thus allows putting into a historical perspective observations from the last few decades that show a declining trend in snowpack and an advanced snowmelt season.
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O-09.6

Parameterizing surface wind speed in complex topography for coarse-scale models

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Surface wind fields are altered over complex topography giving rise to sheltering or speed-up. Accurate wind speed estimates are important for various models in complex terrain, such as spatial snow melt predictions, since wind is an important component of the surface energy balance. The impact of unresolved topography on wind speed in coarse-scale models is usually accounted for by using subgrid parameterizions, based on a variety of terrain parameters. These parameterizations were generally validated on a limited number of measurements in specific geographical areas.
We therefore systematically investigated which terrain parameters most affect near-surface wind speed over complex topography. Wind fields under neutral conditions were simulated using the Advanced Regional Prediction System (ARPS) on Gaussian random fields as model topographies to cover a wide range of terrain characteristics. Coarse-scale mean wind speed, i.e., a spatial average over the large grid cell accounting for influence of unresolved topography, correlated best with sky view factor. We therefore parameterized coarse-scale wind speed using a previously suggested subgrid parameterization for sky view factor and results compared well with domain-averaged ARPS wind speed. To derive local wind speed, we further scaled the subgrid parameterized wind speed using local, fine-scale topographic parameters which correlated best with fine-scale ARPS wind speed. Comparing downscaled numerical weather prediction wind speed with measurements from a large number of stations throughout Switzerland resulted in overall improved correlations and distribution statistics.

O-09.7

Dynamical downscaling overcomes deficiencies in gridded precipitation products in the Sierra Nevada, California

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Uncertainties in gridded and regional climate estimates of precipitation are large at high elevations where observations are sparse and spatial variability is substantial. We explore these uncertainties for water year 2008 across California's Sierra Nevada in 10 datasets: six regional climate downscalings generated using the Weather, Research, and Forecast (WRF) model at convection-permitting resolution with differing lateral boundary conditions and microphysical parameterizations, and four gauge-based, interpolation-gridded precipitation datasets. Precipitation from these 10 datasets is evaluated against 95 snow pillows and a precipitation dataset inferred from stream gauges using a Bayesian inference method. During water year 2008, the gridded datasets tend to underestimate frozen precipitation on the windward slope of the Sierra Nevada, particularly in the vicinity of Yosemite National Park. The WRF simulations with single-moment microphysics tend to overestimate precipitation throughout much of the region, whereas the WRF simulations with double-moment microphysics tend to better agree with both the snow pillows and inferred precipitation estimates, although they somewhat overestimate the windward/leeside precipitation contrast in the northern Sierra Nevada. WRF simulations, in particular those with single-moment microphysics, better distinguish spatial patterns of wet-versus-dry pillows and watersheds over the water year than the gridded estimates. Our results suggest treating gauge-based datasets as 'truth' may give a misleading representation of model accuracy, since these gauge-based datasets often have issues of their own.

O-09.8

Glacio-hydrological modelling on few alpine catchments: from recent past simulation to scenarios of future evolution.

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On many alpine catchments, understanding the effect of glacier recession on streamflow response is crucial for modelling past hydrology and for predicting water resources in the next decades. This study aims to evaluate a glacio-hydrological model on both observed streamflow and glacier mass balance, on two partially glacierized catchments: the Upper Rhone in Switzerland (Rhone at Porte de Scex, 5237 km²) and the Arve in France (Arve at Arthaz, 1650 km²). In glacier hydrology, first challenge is the water balance closure, given that total annual runoff is affected by glacier mass balance. An empirical method derived from the Budyko approach is used to estimate a realistic rainfall input, consistent with an interannual glacier melt proxy. We then evaluate the performance of the MORDOR semi-distributed glacio-hydrological model to simulate river discharges, snow cover and glacier mass balance on long-term periods. Within this conceptual model, glacier melt is modelled by a classical temperature-

index method and glacier area may be considered constant or variable. Model calibration and evaluation are performed on the two catchments of interest, considering not only runoff simulation, but also snow and glacier simulations. On evaluation periods, we show a very strong agreement between model and observations. The model simulates daily, seasonal and annual streamflows very consistently. In the same time snow cover dynamic and proxy mass balance (Aletsch and Argentiere glaciers) are precisely reproduced over several decades. Pluvial, nival and glacier contributions to the hydrological response are well identified. In the last part of this study, we model future streamflow response for these catchments, considering several CMIP5 climate projections and contrasted glacier evolution scenarios.

O-10.1

Cooling by melting snowfall in Alpine valleys: could its predictability get improved in the near future?

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In cases of sustained heavy precipitation over the Alps, it occasionally happens even in early or late summer that the snow line descends down into some inner-Alpine valleys, despite the large-scale freezing level lying thousand metres or more above the valley floor level. A precondition for this phenomenon is that the airmass, from which the latent heat of melting is withdrawn, gets decoupled from the large-scale ascending flow generating the precipitation. The flow evolution related to this decoupling can be characterized as a bifurcation process: once the valley airmass starts to get decoupled and develops increasingly stable stratification within the melting layer, mixing with the ambient airflow is reduced and the decoupling and cooling get reinforced. On the other hand, nothing may happen in other valleys where the initial melting layer does not lie far enough below the local crest line for the decoupling process to be initiated. The bifurcational behaviour of this cooling phenomenon makes its prediction very challenging, even though experienced forecasters know in principle which valleys are susceptible to it. Likewise, correctly reproducing this process in a numerical model is very challenging because the model needs a dynamical core that allows resolving steep mountains with very little orography smoothing, and the model dynamics must not induce spurious circulations over steep slopes. Moreover, the model needs to get the mesoscale wind and precipitation fields approximately right. In this study, we investigated five striking cases of cooling by melting using DWD's new global and regional weather prediction model ICON, three (two) of which occurred in the northern (southern) Alps. We used ICON's multi-step nesting capability to scale down from a global mesh size of 20 km to 625 m over the Alps. Although we simply started from global analysis data without performing additional mesoscale data assimilation, four out of the five cases were predicted very well, whereas cooling was underestimated in part of the observed region in the fifth case. Using a coarser resolution (1.25 km instead of 625 m) somewhat degrades the forecast quality in agreement with expectation, but the forecast still would have been useful in the majority of cases. This makes us very optimistic that a skillful model prediction of cooling by melting in Alpine valleys will be achievable quite soon with the upcoming generation of high-resolution NWP models.

O-10.2

Real time bias correction of very high resolution weather forecasting models for nowcasting in complex terrain

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In recent years, various operational weather centers increased the resolution of their numerical weather prediction models (NWP) reaching now convection-permitting scales in the order of 1-2km. Specifically, MeteoSwiss is operating now COSMO-1 at 1.1 km horizontal resolution over the Alpine arch. The model is able to resolve complex alpine terrain and associated processes such as radiation, convective cells and topographic driven wind systems. Nevertheless, the local temperature and humidity biases even at analysis time can be substantial. For example, temperature and humidity values show significant biases in foehn cases due to non-perfect timing of foehn breakthroughs and non-accurate prediction of inversions erosions. Other difficult situations are very strong inversions and some convective situations.
MeteoSwiss uses the INCA system (Haiden et. al, 2011) for the bias real time correction of the NWP forecast during the nowcasting window (0-6h). INCA derives a temperature and humidity analysis through a real-time bias correction of the NWP model data in a two-step approach. In a first step, the fields of the NWP model are interpolated to the high-resolution INCA grid of 1km horizontal grid spacing. In a second step, differences between these high-

resolution fields and station observations are interpolated in space using an inverse-distance-squared weighting in the horizontal.
The INCA system has originally been developed to deal with NWP models having horizontal resolutions in the order of 10km. The new generation of NWP models reduce the differences between the NWP and INCA topography. Therefore, we suggest a more direct interpolation approach in order to better maintain the height of temperature inversions and to take into account the better NWP performance also on small scales. Additionally, the observed typical thermal differences between nearby valleys, such as confinement of valley-scale cold-pool layers and channeling of warm foehn air, suggest that an approach considering the obstruction of air mass exchange by topographic barriers would be more suitable to avoid erroneous corrections of the NWP model. For these reasons, we propose to use non-Euclidean distances that weight the vertical distance across mountains based on the vertical layering of the temperature, such as introduced by Frei (2013) for gridding daily mean temperatures.
We will present the newly implemented two-step INCA correction algorithm. Validation results are analyzed both for temperature and humidity fields, for different seasons and several selected case-studies with challenging temperature distributions. In general, the results show an improvement to the previous approach.

O-10.3

Sub-kilometer modelling in operational NWP for areas with complex orography

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In late 2016 Danish Meteorological Institute and Icelandic Meteorological Office launched jointly a mesoscale weather forecast model, IGA, for routine weather forecast of Iceland and South Greenland, with a grid resolution of 2.5 km. IGA is based on the forecast system HARMONIE-AROME (40h1.1) as released by the international research programme HIRLAM-C, based on joint model development with Meteo France, ALADIN and ECMWF. From verification, IGA has shown clear advantages over coarser resolution models in forecast and warning of hazards weather events frequently encountered in this regions, especially the high wind conditions often associated with complex landscape over Greenland and Iceland. On the other hand, operational experiences do reveal numerous situations where the IGA forecast for individual area deviates substantially from station measurement, often in form of over-prediction of storm conditions, sometimes a severe under-prediction. Preliminary examination indicates that, while the present IGA setup is able to simulate overall “large scale” flow condition rather satisfactorily, careful postprocessing is necessary to extract model information to describe weather condition for a geographic point. Moreover, the current IGA model at 2.5 km grid resolution appears insufficient, sometimes, to model the flow complex in areas with complicated orography and landscape. Several domain setup with HARMONI-AROME model and a 750-meter grid has been configured, centered around selected regions with small scale orography complex, such as Tasiilaq, Nuuk and Qaanaaq in Greenland, Westfjords pensinsula in Northwest of Iceland, and Vaga airport in Faor Island, to explore use of sub-km mesoscale NWP model for improved weather forecasting especially for hazards storm conditions. Preliminary results so far show an overall encouraging results, in which the sub-km model is seen to be able to simulate weather patterns with improved realism. Tests have also shown a satisfactory stability and reliability, hence operationally feasible in the near future. It is recognised that NWP model at sub-km involves numerous complex scientific challenges, such as those on data assimilation, nesting, model dynamics and physics, high resolution physiographic database, and postprocessing toward end forecast products. Hence, experiences to be reported here is only start of a long scientific endeavour.

O-10.4

Wind speed analog-based predictions in complex topography

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Post-processing techniques improve weather prediction by combining dynamical and statistical information. Research on statistical post-processing is predominantly focused on the average case, while rare or extreme weather events, which are of high socio-economic impact, remain a substantial challenge. In order to improve predictions of rare and extreme weather events, the focus in this work is on a group of stations in coastal complex terrain prone to high wind speeds (e.g. bora wind). The analog-based predictions generated by Aire Limitée Adaptation dynamique Développement InterNational model (ALADIN) are tested at several climatologically and topographically different regions of Croatia for point-based wind speed predictions at 10 m AGL (Above Ground Level). The verification procedure is formulated and used to assess and improve the performance of analog-based

wind speed predictions.
This study shows that deterministic analog-based predictions, compared to model used to generate them, improve the correlation between predictions and measurements while reducing bias and root-mean-square error. This is especially the case in the coastal complex terrain. Analog ensemble mean forecasts (AN) exhibit the highest correlation, while applying Kalman filter to the AN removes bias almost completely. Distribution of analog-based deterministic predictions of high wind speeds is more similar to the distribution of observations than the distribution of raw model or Kalman filter approach predictions, particularly for the small ensemble size. Furthermore, predictions of high wind speeds are improved by using additional predictors.

O-10.5

Anelastic and compressible EULAG solvers for limited-area numerical Alpine weather prediction in the COSMO consortium

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Research conducted at Polish Institute of Meteorology and Water Management – National Research Institute, in collaboration with Consortium for Small Scale Modeling (COSMO) have resulted in the development of a new prototype nonhydrostatic anelastic NWP model COSMO-EULAG (CE-A) [1]. The dynamical core of the CE-A model is based on the anelastic set of equations and numerics adopted from the EULAG [2] fluid solver. The model turned out to be capable to compute convection-permitting weather forecast in limited-area regional domains with steep orography and to provide competitive forecasts with respect to the equivalent COSMO model setup. Furthermore, it allowed to perform very high resolution simulations of realistic flows (up to 0.1km grid length) in small Alpine domains with slopes reaching 80 degree of inclination.
More recently, the research framework was extended with a new compressible EULAG solver. The compressible solver was developed at ECMWF [3]. Preliminary results obtained with the new model (CE-C) are accurate and promising.
Continuous growth of high-performance resources is expected to allow employing sub-kilometer grid spacing for operational forecasting in the coming decade. Today one can already test model performance for single case studies performed with very fine computational grids. Both CE-A and CE-C models allow to carry out experiments for horizontal grid lengths ranging from 2.2 km to 0.1 km in the convective and stable weather regimes. Our tests have a form of case studies as well as verification comparisons. Results show that computational grid and orography refinement has a noticeable impact on the representation of the flow field and convective development. In particular, finer orography modifies flow field in boundary layer and is a source of increased gravity wave activity. It alters upslope wind patterns which in turn modify location of single clouds and the transition phase between shallow and deep convection. Finally, computational grid and orography refinement has a noticeable impact on the timing of convective precipitation in the model.
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O-10.7

Mountains and meteorological and climatological extremes in Iceland

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Almost all extreme values in temperature, wind and precipitation in Iceland are influenced, if not a direct consequence of the impact of mountains on the atmospheric flow. On a local scale, there is generally direct forcing of vertical winds, acceleration, deceleration or damming of horizontal flow by nearby mountain ranges, while on a larger scale, Iceland and Greenland influence the airmasses, leading to vertical profiles or hotrizontal gradients that enhance the extremes. The dynamics of some of the extreme weather situations in recent decades are discussed in wiew of the above.

O-11.1

Experimental validation of a modelling chain simulating the dispersion of pollutants from the incinerator of Bolzano (Italy)

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The simulation of dispersion processes in complex terrain is still a challenging task due to the inherent difficulties in accurately reproducing all the physical phenomena involved. This contribution presents results from a study aiming at characterising dispersion processes from the incinerator of Bolzano (262 m a.s.l., 106000 inhabitants, Central Italian Alps). The experiment included a modelling chain, simulating both meteorological processes and pollutants dispersion, and field campaigns, performed to validate the simulated emission-impact scenarios against ground measurements of a gas tracer released from the incinerator stuck.
Meteorological simulations were performed with the Weather Research and Forecasting (WRF) model using four nested domains down to a horizontal resolutionof 500 m. In the innermost domain observational nudging was used to assimilate meteorological data from 7 ground weather stations, a temperature profiler, a SODAR and a Doppler wind lidar. Then the CALMET model refined the meteorological field up to the resolution of 200 m, in order to improve its adherence to the complex terrain. Finally, the dispersion processes and the emission-impact areas of the tracer were simulated by the CALPUFF model, a non-steady-state lagrangian gaussian puff model, and by the SPRAY model, which adopts a purely lagrangian stochastic particle scheme. Both models were fed with real time data of emission rates and temperature, measured at the incinerator.
Two 1h-long tracer emissions at constant release rate were performed in order to investigate the dispersion processes under two typical wintertime meteorological conditions. The first release was performed in the early morning, under stable atmosphere and Northerly winds, while the second release was performed in the early afternoon, under weakly unstable atmosphere and Southerly winds. During each release 14 teams collected air samples in the Bolzano basin for a total of 59 samples.Data from the different samples were analysed and used to calibrate and validate the modelling chain.

O-11.2

On the relationship between atmospheric dynamics and PM10 concentration in the Arve Valley around Passy

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During wintertime anticyclonic episodes the urbanized Arve valley in the French Alps displays a strong spatial heterogeneity in air pollution, which raises questions about the ventilation processes in this valley. The highest concentration levels are usually recorded in the city of Passy during these episodes, which motivates the present study. Our aim is to understand the role of valley geometry and of the tributary valleys in the ventilation processes and associated impacts on pollutant concentrations, considering that spatial and temporal variations in pollutant emissions are known. Field data are used for this purpose: the three velocity components recorded by a wind Lidar located at the valley floor in Passy and scanning from 40 m to about 500 m above ground level, the temperature recorded on a tethered balloon platform and in ground-based stations, and the ground-level PM10 concentration at a few routine monitoring sites managed by the local air quality agency. As an attempt to get a general view of the atmospheric dynamics in the valley during wintertime polluted episodes, three very polluted episodes are considered, in January 2015, February 2015 and December 2016. Realistic numerical modelling of the February episode (to be presented in a separate communication at this meeting) also helps in interpreting the field data. The February episode corresponds to an IOP of the PASSY-2015 field campaign (Paci et al 2016).

The geography of the Arve valley in its most polluted part, around Passy, is already very specific. This section of the valley is indeed nearly closed at both ends, with a strong narrowing downstream and a pass leading to Chamonix upstream, 500 m above the valley floor. Two tributary valleys open onto this valley section on its south side. Regardless of the episode considered, the analysis of the field data collected in Passy shows that the dominant wind close to the ground is down-valley for the most part of the day and displays oscillations about a very weak mean value, less than 1 m/s. Three factors account for this very weak wind: (i) the presence of the pass upstream, (ii) the very strong temperature gradient close to the ground (resulting in wind kinetic energy able to move the fluid upward by no more than 15 m) and, very likely, (iii) the narrowing of the valley downstream which strongly reduces the speed of the along-valley wind (Arduini et al., submitted). The analysis of the vertical structure of the wind above the valley floor shows that the along-valley wind flowing from the part of the valley upstream, beyond the pass, detrains above that valley floor, therefore leaving the near-surface atmosphere unperturbed and promoting pollutant accumulation. Mixing processes may however occur at the detrainment level, which are currently investigated.
While the link between atmospheric dynamics and PM10 concentration in the most polluted section of the Arve valley seems to be broadly understood from this analysis, the relationship with the detailed sub-diurnal evolution of the PM10 concentration (Chemel et al 2016) remains to be clarified. This point is currently under investigation and will also be discussed at the conference.
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O-11.3

Impact of along-valley orographic variations on the dispersion of passive tracers in a stable atmosphere: an idealized study.

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During wintertime, mountain valleys frequently experience very stable and dynamically-decoupled atmospheric conditions leading to air pollution episodes. Under such conditions, the valley-wind system (consisting of thermally-driven down-slope and down-valley flows) plays a key role in the ventilation of the valley atmosphere. High-resolution numerical simulations using the Weather Research and Forecasting model have been performed for two different configurations of three-dimensional valleys opening onto a plain. The first configuration corresponds to a single valley opening onto a plain (draining case). The second one consists in a system of two valleys sharing the same axis, one valley opening on a narrower valley which opens on the plain (pooling case); the former and latter valleys are referred to as the upstream and downstream valleys, respectively. The aim of this work is to investigate the response of the transport of pollutants, modelled as passive tracers, to orographic variations along the valley axis during night-time.
The difference in the thermal structure of the valley and the plain atmosphere generates a horizontal pressure gradient leading to the development of the down-valley flow. This flow is the major driver of pollutant dispersion within and out of the valley. Along-valley variations in the valley width produce diverse responses of pollutant transport, from a long-lasting stagnation in the pooling case to a full ventilation in the draining case. For the latter case however, results are very sensitive to the ambient stratification.
When considering the draining case, results show that both the down-slope and down-valley flows display temporal oscillations of similar frequency, which is set by that of the down-slope flow. Most importantly, these oscillations are imprinted on the tracer field (as is expected) with amplitude for some short time periods as high as 30% of the mean concentration value. Once the down-valley flow is fully developed, three independent layers can be identified along the vertical within the valley atmosphere regardless of the ambient stratification. The height of the first layer close to the ground is limited by the first jet maxima. Tracers released at ground level before sunset remain trapped within this first layer for the entire night. Regardless of the initial stratification of the atmosphere (from 1.5 K/km to 6 K/km), all layers appear to be completely independent of each other, leading to a mainly horizontal dispersion of the tracers released within each layer. For the strongest stratification considered, the down-valley wind is strongly reduced, leading to very weak pollutant transport and, in practice, a quasi-stagnation of the tracers close to their emission source.
For the pooling case, preliminary results show that the impact of the narrower downstream valley on the pollutant concentration field in the upstream valley is major. Ventilation can indeed be completely suppressed during the first 4 hours after sunset due to the development of an up-valley wind in the downstream valley. Further results will be discussed at the conference.

O-11.4

Investigation and evaluation of atmospheric processes in orographic terrain applying the WRF model with very high resolution: examples from selected cases

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Numerical models have long been used as tools to better understand atmospheric processes and their evolution. In recent years, simulations with finer and finer resolution have been applied for this purpose.
To serve process understanding and model evaluation, we apply the WRF model in a chain of simulations from the mesoscale down to a resolution of 100 m. In the fine scale domain, WRF is applied in Large-Eddy simulation (LES) mode with switched-off turbulence scheme. Advantage of WRF, as compared to "traditional" LES models, are the possibility to set up the system for real atmospheric cases, namely with realistic lower boundaries and meteorological forcing. Furthermore, a consistent set of physical parameterization is applied through the whole chain of simulations. Starting from the ECMWF analysis, we operate WRF with four nests from 2.7 km down to 100 m. The evolution of the convective boundary layer on a sunny spring day and the life cycle of supercell that developed over southwestern Germany on 30 June 2012 are selected as examples to present the capabilities of the system. The results are very promising and demonstrate that WRF can be applied at such high resolutions for detailed process studies.

O-11.5

Influence of horizontal grid spacing in mountainous terrain on simulated planetary boundary layer depths in large-scale transport models

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The difficulty of modeling atmospheric transport and mixing processes introduces significant uncertainties in the atmospheric fluxes estimated with carbon transport models. An important diagnostic for vertical transport and mixing is the planetary boundary layer (PBL) depth, the height above the surface up to which surface fluxes of heat, moisture, momentum, and trace gases such as CO2 are transported and mixed on a diurnal time scale. CO2-concentrations at the surface are inversely related to the PBL depth. PBL depths are known to vary considerably in mountainous areas. Atmospheric transport models used for CO2-flux estimations are typically run on coarse grid spacing (i.e. around 100 km horizontal grid spacing) and therefore miss terrain information needed for an accurate PBL depth calculation and so a correct CO2-budget estimation. We relate subgrid terrain parameters to differences in PBL depths between a 'coarse' (10 km horizontal grid spacing) and a 'fine' (3.3 km) grid domain. We focus on an area which consists of a mixture of flat and mountainous terrain, and investigate for a period of two consecutive years. PBL depths are larger in the coarse than in the fine grid domain. Most significant differences are found for areas with unresolved ridges and attain more than 200 m in summer, or a relative difference of about 10%, and are attributed to terrain smoothing and the resulting lack of physical and dynamical processes in the coarse grid domain. The PBL depth differences can only be partly removed after correcting for the fine grid terrain elevation in the coarse domain, or the use of PBL height. The choice of the parameter for evaluation of a coarse model depends greatly on whether the PBL follows the terrain elevation or not. On a longer term, the understanding of these differences would lead to an improved simulation and understanding of the location and quantification of North American and global carbon sources and sinks.

O-11.6

Large eddy simulation of snowfall preferential deposition over complex topography

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Snowfall preferential deposition is a significant control on the spatial variability of snow depth in complex terrain. As such, it plays a key role in avalanche formation, hydrologic response, and water resource management in alpine regions. Here, we investigate the role of near-surface flow-particle interactions, as opposed to larger scale orographic processes, in driving preferential deposition at hillslope scale. We perform large eddy simulations (LES) of turbulent flows over Gaussian hills, accounting for the effect of the complex topography with an immersed boundary method (IBM). We compute the trajectories of falling snow in the turbulent flow with a Lagrangian stochastic model (LSM) driven by the LES fields. We first validate our modeling approach against wind tunnel experiments of dust deposition over ranges of hills. We then apply the model to simulate snowfall deposition over isolated hills and study the sensitivity of the deposition pattern to variations in the particle Stokes number and Froude number. The model results suggest that snow depth is generally smaller on the slopes than on the flat terrain. Snow deposition on the leeward slope, however, increases with decreasing the Stokes number, that is, when flow advection becomes relevant with respect to particle inertia. Flow advection, in fact, keeps particles aloft in the updrafts over the windward slope and enhances settling in the recirculation region. Conversely, snow deposition on the windward slope increases with increasing the Froude number, i.e., when particle inertia becomes relevant with respect to gravity. We finally show that the deposition pattern is also significantly affected by the steepness of the hill. Overall, our study singles out and indentifies the controls of advection, inertia, gravity, and hill steepness on preferential snow deposition. As such, it can provide solid guidelines for improved quantifications of snow depth spatial variability in alpine terrain under different wind conditions.

O-11.7

The spatial variability of the temperature structure in a major east-west oriented valley in the Alps

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The thermal and dynamical structure of the valley atmosphere in the Inn Valley in Austria is investigated by means of airborne, as well as ground-based meteorological data. Therefore the observations of an instrumented airplane were used that conducted three measurement flights in summer 2013. The collected data of potential temperature and water vapour mixing ratio were interpolated to a regularly-spaced three-dimensional grid. For the interpolation the method of Residual Kriging (RK) was applied, which was found to be a better performing interpolation technique compared to Natural Neighbour interpolation. A time-correction was conducted that filters out the temporal trend of potential temperature (diurnal cycle of temperature) so as to ensure that interpolated temperatures from different flight legs do not reflect the different times of those legs. The amplitude of the temperature change was determined using a ground-based station (i-Box) in the centre of the observed area in combination with an estimate of the vertical decay of the daily cycle of temperature as assessed from profiler data.
With the aid of cross-sections through the interpolated volume and vertical profiles at specific locations the temperature characteristics of the valley atmosphere were investigated. The along-valley variability of vertical temperature profiles in the valley-centre (approx. east-west) was found to be much smaller (quasi-uniform) than that in cross-valley direction (approx. north-south). Despite the predominantly thermal forcing of the valley flow (small synoptic pressure gradients, strong irradiance), the mixed layer did not grow higher than some 500 m and was topped by a deep stable layer (still below crest height in the morning and exceeding crest height in the afternoon). A second elevated well-mixed layer (around crest height in the morning and above in the afternoon) was found to be strikingly similar to results from idealized simulations with relatively deep (narrow) valley geometry.

O-11.8

Limited-area ensemble forecasts during Sochi-2014 Winter Olympics: multi-model vs single-model approach

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In the framework of 2014 Winter Olympic Games, held in Sochi (Russia), the FROST (Forecast and Research: the Olympic Sochi Testbed) research project developed a number of initiatives. In the field of limited-area ensemble forecasting, six different forecast systems were implemented and deployed so as to assist the local meteorologists in the probabilistic prediction of high-impact weather events with a great spatio-temporal detail. The weather prediction systems were based on both European models (COSMO, HIRLAM, Aladin) as well as the Nonhydrostatic Multiscale Model by NCEP. Several forecast products by the different systems were displayed on FROST web site in real time

and are now available on the project archive. In this work, the added value of the multi-model with respect to the single-model approach is assessed by investigating the performance of the different ensemble systems over a case study basis as well as over the full Olympic season, from 15 January to 15 March 2014. The skill of the different systems, either running in convection-parameterised or convection-permitting mode, is mainly studied in terms of probabilistic prediction of precipitation for forecast ranges up to day 3. The relative benefits of higher resolution and/or larger ensemble size are quantified over the verification period as well as for the individual case studies.

O-12.1

Evolution of the temperature profile during the life-cycle of a valley-confined cold-pool in the Pyrenees

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During the Cerdanya Cold Pool experiment in 2015 (CCP'15, see companion presentation by Martínez-Villagrasa et al for a complete description), a number of cases of cold-pool (CP) formation were observed with the enhanced instrumention available. The campaign took place in early October, still without snow, with large thermal diurnal cycles of about 20 ºC, reaching negative temperatures at night.
The vertical structure of the CP could be sampled with the following devices: i) a Scintec WindRass that provided wind, temperature and turbulence profiles between 40 and 400 m above ground level (agl), ii) a tethered ballon which was operated between the surface and an approximate height of 300 m agl and iii) a remotely-piloted multicopter that was flown up to 200 m. Close to the surface, iv) a standard meteorological weather station was supplemented with v) a complete surface energy station, which allowed to estimate all terms of the energy budget (latent and sensible heat flux, net radiation and ground flux) and vi) a column of thermistors between 2m and the surface.
There were five Intensive Operation Periods, each corresponding to one night, which captured CP with diverse evolutions, described in the companion talk of Martínez-Villagrasa et al. The most frequent case consisted in moderate valley winds before and after sunset of mesoscale origin, which calmed between 1 to 3 hours after dawn, leading to the late development of the cold pool. The second type of CP was in absence of the mesoscale winds, which allowed a soft evening transition with almost calm winds at sunset and establishment of down-slope and down-valley winds along the night, and the CP development starting around dawn.
In this presentation we focus on IOP3, belonging to the second type, taken as the campaign's Golden Case, since most of the observed dynamics seem to be generated locally in the main Cerdanya valley, its slopes and its tributaries. The evolution of the temperature profile between late afternoon and next morning is described using the ensemble of available data and put in relation with the topographically generated circulations at the valley scale. The surface energy budget and the behaviour of the thermal profile below 2m allow to explore the interaction with the underlying surface.
Finally, the observed evolution is compared with the one provided by a high-resolution mesoscale simulation (horizontal grid of 400 m) of the same night, assessing the performance of the simulation and looking for the causes of the differences between model and observations.

O-12.2

Local and non-local controls on a persistent cold-air pool in the Arve River Valley

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The Weather Research and Forecasting numerical model is used to simulate the life cycle of a persistent cold-air pool (CAP) event that occurred between 9 and 14 February 2015 in the section of the Arve River Valley between Cluses and Servoz in the French Alps. This section of valley presents three major tributaries. During this period, an upper-level ridge from the Atlantic moved quickly over Europe, allowing a CAP to form and persist over time. Model outputs are in good agreement with observations collected during the PASSY-2015 field campaign, in particular the temporal evolution of the vertical structure of the CAP is well captured throughout the episode. The impact of the moving upper-level ridge on the flows through the tributaries and thus on the thermal structure of the CAP and the dynamics within the valley section is quantified, by examining the heat and mass budgets of the valley volume. The

real-case numerical results are contrasted with those from a semi-idealised numerical simulation initialised with a horizontally homogeneous atmosphere and the wind speed set to zero across the domain.
During the persistent stage of the CAP life cycle the flow from the tributary valleys controls by and large the nighttime valley-scale circulation. Indeed, the mass budget over the valley volume shows that mass fluxes through the tributaries account for 70 to 90% of the along-valley drainage out of the valley section when averaged over the course of the night. It can exceed 100% (resulting in a vertical transport of mass out of the valley) when the upper-level ridge passed over the area and a strong down-valley flow formed in one of the tributary valley. However, because of the strong stratification of the CAP the inflow from the tributaries detrain at the top of the CAP, thereby gradually eroding the CAP during nighttime and generating valley-scale standing waves (seiches) within the CAP.
The thermal structure of the near-surface inversion layer is primarily locally controlled by the divergence of the radiative and turbulent fluxes and advection from thermally-driven flows. The seiches within the CAP associated with the non-local effects resulting from the flows from the tributaries modulate the thermally-driven flows and so the near-surface drainage of cold air out of the valley section.

O-12.3

The thermally driven wind system of the Adige Valley in the Alps

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The Adige Valley is one of the main corridors connecting the Po Plain with the inner Alps. A series of permanent weather stations and one wind profiler provide a regular monitoring of air temperature, atmospheric pressure, global solar radiation, wind speed and direction over the 140-km valley length and in the adjacent plain. Data covering the period 2012-2014 are analysed, objectively selecting days in which favorable weather conditions allowed a full development of valley winds. The typical alternating pattern of diurnal upvalley winds –peaking in the afternoon– and nocturnal down-valley winds –weaker but persisting throughout the night– is clearly observed. This daily wind cycle is associated with a corresponding cycle of the horizontal pressure gradient, as shown by the daily oscillation of the surface-level pressure at the valley stations. In particular, the wind intensity depends linearly on the along-valley pressure gradient, supporting the concept of a quasi-steady balance between pressure gradient and surface friction. In accord with previous investigations, the amplitude of the surface pressure cycle increases in the up-valley direction, displaying the smallest and the largest values respectively over the Po Plain and in the uppermost valley, and causing the reversal of the horizontal pressure gradient twice a day. On the other hand, no appreciable differences in the amplitude of the near-surface temperature daily cycle are observed between the valley and the plain or between different sections of the valley. The combined analysis of temperature and pressure perturbations suggests that the increasingly larger surface level pressure perturbations in the upvalley direction are caused by the increased depth of the atmospheric layer subject to heating and cooling. Finally, the typical behaviour of valley winds is found to be locally altered by irregularities in the geometry of the valley, which presents narrower and wider sections. In particular, anomalous pressure gradients and a local modification of the typical cycle of down- and up-valley winds are observed in the vicinity of a large basin, where the valley widens significantly. Also the presence of major urban areas, which affect the temperature of the lowest atmospheric layers, is found to alter the development of down-valley winds, inducing local wind convergence over cities during nighttime.

O-12.4

Wintertime circulation in the Chamonix-Mont-Blanc valley from scanning wind lidar measurements (Passy-2015 field experiment) and numerical simulations

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Wintertime anticyclonic conditions lead to the formation of persistent stable boundary layers which may induce air pollution episodes in urban or industrialized areas. This phenomenon can be particularly severe in mountainous regions as in the Arve river valley (French Northern Alps) around the city of Passy (France, Haute-Savoie), 20 km down valley past Chamonix-Mont-Blanc.
This area is actually one of the worst place in France regarding air quality since the concentration of fine particles and Benzo(a)pyrene (a carcinogenic organic compound) regularly exceeding the EU legal admissible level during winter.
Besides air quality measurements, a good knowledge of the atmospheric boundary layer dynamics and processes at

the valley scale under these persistent stable conditions is crucial in order to improve our understanding on how it drives pollutant dispersion. These issues motivated the Passy-2015 field experiment which took place during the winter 2014-2015. A relatively large set-up of instruments was deployed over several sites in the valley.
The present study focuses on scanning wind lidar measurements during two intensive observation periods (6-14 February and 17-20 February 2015). The scanning strategy was established in order to get vertical and horizontal transects with a frequency of 10 to 30 min. Large aerosol concentrations are usually observed in the area under persistent stable conditions, so the lidar range was regularly over 6 km. This allows to cover most of the region of interest. Circulation patterns in the valley and its surrounding (slope winds, adjacent valleys) retrieved from the lidar measurements will be discussed with a particular focus on diurnal cycle and fine horizontal and vertical scales. Then, high-resolution Meso-NH numerical simulations will be evaluated and studied to provide a better understanding of the circulation origins.

O-12.5

Boundary-layer profiling with ceilometers in complex terrain

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Introduction
Since several years, ZAMG operates ceilometers to determine the mixing height (MH) from the analysis of aerosol backscatter (Lotteraner and Piringer, 2016) and stability classes from the cloud base heights and the cloud amount a ceilometer provides (Rau and Piringer, 2017). This manuscript gives first an overview of the measurement principles and shows the locations of the Austrian research ceilometers. This is followed by examples of the ABL structure detected by a ceilometer, both for an “ideal” and a “disturbed” day. Some peculiarities on MH determination in Alpine valleys and in special situations will also be discussed, followed by a few concluding remarks.
Material and method
ZAMG operates now a small network of Vaisala CL51 ceilometers (Baumann-Stanzer et al., 2017). Three of them are situated in Alpine valleys at the base of mountain tops with air pollution monitoring stations. The purpose of the ceilometers is to help investigate whether an air pollution episode at these mountain tops is primarily caused by advection or mixing from polluted valley floors. The most prominent mountain is Hoher Sonnblick (3106 m) with his well-known mountain observatory.
The ceilometer CL51 employs a diode laser lidar (Light Detection and Ranging) technology, with which short, powerful laser (Light Amplification by Stimulated Emission of Radiation) pulses with a wavelength of 910 ± 10 nm (infrared light) are sent out vertically. The laser source of the ceilometer CL51 is an eye-safe indium gallium arsenide diode. The single lens optics of the ceilometer enables detection in a measurement range above approximately 50 m above ground level, where a sufficient overlap of emitted and backscattered laser signals is given (Wagner and Schäfer 2015), up to 15 km.
The reflection of light, backscatter caused by clouds, precipitation, haze, fog, mist and virga, is measured as the laser pulses traverse the sky. The time delay between the launch of a laser pulse and the detection of the backscatter signal indicates the cloud-base height. The ceilometer CL51 is able to detect three cloud layers simultaneously. The backscatter profile is further used to detect up to three aerosol-layer heights by applying the so-called gradient method with a post-processing software (BL-VIEW), which contains an automated mixing-height detection algorithm described in Emeis et al. (2007). An improved algorithm to determine the mixing height from ceilometer aerosol layer heights is described in Lotteraner and Piringer (2016). Its basic assumptions are to take the first aerosol layer height above ground as the mixing height. Aerosol layer heights above 500 m above ground are not considered as mixing heights between sunset and sunrise, thus avoiding to detect the night-time residual layer as the mixing height. If the near-ground wind speed is below 3 ms^{-1}, even a lower limit of 250 m above ground is applied. If at night no near-ground aerosol layer heights are found over a period of at least six hours, no mixing height is determined. In this way, daily time courses of the mixing height are obtained. The mixing height time series is then averaged and smoothed for a consistent course over time. Data gaps over 6 hours are not filled up.
Examples of the ABL structure
The post-processing software BL-VIEW provides, on a daily basis, colour plots of the backscatter intensity. Light blue to yellow colour in the plot indicates the intensity of the aerosol backscatter signal (in units of 10^{-9} m^{-1} sr^{-1}). Black dots or lines indicate aerosol-layer heights, white-rimmed dots or lines indicate cloud heights determined by Vaisala`s software BL-VIEW. Red colour in the plot denotes precipitation and clouds. A bold yellow line indicates the mixing-height time series for the particular day calculated by the method mentioned in the last section.
In the presentation, two days of back-scatter profiles will be shown. The first shows the typical evolution of the convective boundary layer on a clear sky day on which the successful determination of the mixing height from back-scatter profiles observed by a ceilometer at Vienna is demonstrated. During daytime, the mixing layer rises due to convection and reaches its maximum in the middle of the afternoon. At night, enough low-level data points are available in this example to construct a continuous time series of the mixing height.
The second example demonstrates how the method to determine mixing-height performs on a day with a complex structure of aerosol-layer heights and with precipitation. This day was characterized by an overcast sky in the morning, broken clouds during daytime, and intermittent rain in the evening. Between sunrise and sunset, the

mixing-height course followed more or less the aerosol-layer height course, but in a smoothed form. In spite of several gaps in aerosol-layer height data and rain for several hours in the evening, a continuous mixing-height time series with 100% availability of mixing-height data could be calculated on this day by applying the method described in the former section.

Peculiarities on MH determination

Alpine valleys and basins are prone to low wind speeds, especially at night, and are often characterized by clear air. Both are not favourable for the build-up of ground-level aerosol layers. Therefore, very often no mixing heights can be determined at night at these sites. Then the ceilometer mixing height time series will be interrupted, especially when the data gap exceeds 6 hours. Examples for this behaviour will be given.

Ceilometers turn out as good tools to detect volcanic ash clouds or Saharan dust events. At the begin of April 2016, a Saharan dust cloud reached Central Europe, leading to enhanced PM10 concentrations and reduced visibility. The evolution of the atmospheric boundary layer (ABL) at the Eastern Alpine ridge is observed by a network of ceilometers. These data are especially valuable to distinguish whether PM10 concentrations are mainly influenced by long-range transport or by advection of aerosols from the ABL. Implications for MH determination on the peak day of the event will be shown.

Conclusions

Ceilometers are ground-based remote sensing devices important for the detection of the vertical aerosol distribution and cloud base heights. Based on this information, mixing heights and atmospheric stability can be determined. This presentation focused on the mixing height in complex terrain and analyzed the potential of ceilometers to detect a Saharan dust event over Central Europe. For the latter, the advantages of a ceilometer network could clearly be shown.

Acknowledgement

The investigations concerning the interpretation of ceilometer backscatter profiles and especially the mixing height estimation are significantly stimulated by the EU COST Action ES 1303(TOPROF), dealing with ground-based remote sensing systems and the integration of their data into NWP models.

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O-13.1

Trailing Mountain Waves

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Trailing waves are spectacular long wave beams frequently observed in the stratosphere over mid- to high latitude topography. Two trailing wave events documented over New Zealand during the DEEPWAVE experiment are examined using numerical simulations and theoretical analysis to better understand the trailing wave characteristics and formation mechanisms. The DEEP propagating gravity WAVE program (DEEPWAVE) is a comprehensive, airborne and ground-based measurement and modeling program centered on New Zealand and focused on gravity wave dynamics and impacts from the troposphere through the mesosphere and lower thermosphere. This program employed the NSF/NCAR GV (NGV) research aircraft from a base in New Zealand in a 6-week field measurement campaign in June-July 2014. During the field phase, the NGV was equipped with new Rayleigh and sodium resonance lidars and an advanced mesospheric temperature mapper (AMTM), a microwave temperature profiler (MTP), as well as dropwindsondes and a full suite of flight level instruments providing measurements spanning altitudes from immediately above the NGV flight altitude (~13 km) to ~100 km.

We utilized numerical simulations using the nonhydrostatic COAMPS and AIRS satellite observations to explore the dynamics of trailing waves. We find that trailing waves over New Zealand are orographically generated, and the formation of trailing waves is regulated by several aspects including the interaction between terrain and mountaintop winds, critical level absorption, wave reflection, and refraction. Among them, the interaction between topography and low-level winds determines the perturbation energy distribution over scales and directions near the wave source and it follows that trailing waves are sensitive to terrain features and low-level winds. Terrain induced perturbations are filtered by critical level absorptions associated with directional wind shear and when the wave intrinsic frequency approaches the Coriolis coefficient. The former plays a role in limiting the wave beam orientation, and the latter sets an upper limit for the permissible wavelength for trailing waves. Once entering into the stratosphere, the orographic

waves are subject to refraction associated with the meridional shear of the stratospheric westerlies, which tends to refract waves toward stronger winds. This effect stretches out the wave fronts pointing toward stronger winds, resulted in elongated trailing wave beams, and in the meantime, shortens the wave fronts pointing toward weaker winds. We further explore the dynamics of trailing waves using idealized simulations initialized with a zonally balanced stratospheric jet. The idealized results confirm the importance of horizontal wind shear for the refraction of the waves. Furthermore, the zonal momentum flux minimum is shown to bend or refract into the jet in the stratosphere as a consequence of the wind shear.

O-13.2

How essential are 3D shear effects for the representation of the turbulence kinetic energy (TKE) structure in an Alpine valley?

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The correct simulation of the boundary layer structure in complex terrain is still a challenge for numerical weather prediction (NWP) models. This is often related to the models' turbulence parameterizations, which were initially developed for horizontal homogeneous and flat terrain and consider vertical exchange only.
In our study, we evaluate the 1D and 3D turbulence parameterizations of the NWP model COSMO on a horizontal grid size of 1 km. Our location of interest is the Inn Valley, Austria, and the main focus of the model evaluation is the representation of turbulence kinetic energy (TKE) and its contributing budget terms. This is possible with the so-called Innsbruck-Box (i-Box) measurement sites, which consist of turbulence flux towers at various representative locations in the Inn Valley (valley floor, south- and north-facing slopes). We have chosen cloud-free days and nights, in which boundary layer processes dominate and a thermally-induced valley wind circulation is present. We test both the model's standard 1D turbulence parameterization and a hybrid turbulence parameterization, which also considers horizontal contributions to shear production of TKE.
During shear-dominated up-valley wind phases and during night-time conditions, when a stable boundary layer is present, we find an underestimation of TKE by the model with the 1D turbulence parameterization. The hybrid turbulence parameterization brings a much better agreement with the observations of TKE in these situations. On the slopes in particular, the TKE structure is more realistic, together with a better-simulated (3D) shear production term.
This leads to the conclusion that 3D effects are crucial for the correct simulation of turbulence structure in complex terrain.

O-13.3

Characteristics of the spectral gap in a valley convective boundary layer

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The notion of decomposing time series of winds and scalars into a mean and a fluctuating component, historically known as Reynolds decomposition, is essential for the determination of the turbulent fluxes in the atmospheric boundary layer. Proper estimates of these fluxes are crucial for a number of applications, including calculating the annual budget of the net ecosystem exchange or the development of new turbulence closure parameterizations for numerical weather prediction. Assuming that the turbulent, microscale motions of interest are separated from macroscale motions by a spectral gap, one can readily apply Reynolds decomposition. Several studies have reported a range of scales that fall into such a spectral gap, especially for flat terrain. However, spatial and temporal information of the spectral gap scales are still lacking, especially over complex terrain. Micro- and mesoscale flows in complex terrain, such as valley and slope flows, may degrade the presence of a spectral gap and/or shift it to scales that are different than those over flat terrain. Thus, more information is needed about the variability of gap scales over complex terrain.
The main dataset we analyze is comprised of measurements obtained during the Terrain-Induced Rotor Experiment, conducted in the spring 2006 in Owens Valley, CA. Specifically, we analyze time series of winds obtained on 16 weather stations spread out across the valley, as well as sonic anemometer measurements of winds and temperature at two locations. To these we apply two methods to determine the climatology of gap scales, including the fast Fourier transform and multiresolution flux decomposition. We also focus on several phenomena typical for

complex terrain, such as rotors and upslope flows, with the goal of determining if and how gap scales react to their occurence.
Our results indicate that the typical range of gap scales is between 17 and 29 min, with substantial cross-valley variability and along-valley homogeneity. At the high-frequency end of the spectral gap, rotors and the deepening of the convective boundary layer are found to be the main gap scale drivers. This work has also gained insight into the low-frequency end of the gap, where the valley-slope flow system was found to be the dominant phenomenon. Here, the dominant mode of upslope flow variability, ranging from 80 to 200 min, was both observed and modelled using a simple periodicity model.

O-13.4

Spatial variations in the diurnal cycle of turbulent fluxes in an east-west oriented valley

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Diurnal cycles of turbulent heat and moisture fluxes, as well as of standard meteorological variables, such as temperature and humidity, are strongly influenced by local net radiation under synoptically undisturbed conditions. In complex Alpine topography, they will thus be strongly dependent on the specific location of a given site within the valley and its exposure towards the sun. Additionally, indirect effects such as timing and strength of thermally driven flows will have an influence on those daily cycles.
As part of the i-Box project, which was designed to study the turbulence structure in complex terrain, long-term field measurements are being made at six sites within the approximately east-west oriented Inn Valley, Austria. The measurement sites are located within an approximately 6.5- km long section of the approximately 2-3-km wide valley. One of the sites is located at the almost flat valley floor, one site at a mountain top approximately 1500 m above the valley floor, two sites on the south-facing sidewall, and two sites on the north-facing sidewall.
In this presentation, we will compare the diurnal cycles of turbulent heat, moisture, and momentum fluxes at the six valley sites together with local radiation observations to determine spatial variations in the timing and magnitude of the turbulent fluxes within the valley during synoptically undisturbed conditions. Two of the measurement sites are equipped with sonic anemometers at different levels, which are used to investigate vertical variations and constancy throughout the diurnal cycle.

O-13.5

Integral length scales in atmospheric surface boundary layers

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In many NWP and climate models with prognostic turbulence kinetic energy (TKE) equation, one can find that the TKE dissipation rate is parameterized via suitable ratio of TKE and some kind of a length scale. This length scale is often referred to as the integral length scale, *l*, and, in this case, a constant of proportionality, *C*, is introduced in the parameterization equation (PE). Estimation of *C* from real datasets will therefore be sensitive to the choice of *l*, and this can lead to inconsistencies in parameterization of ε in NWP and climate models. Regarding *l*, one can find a variety of different formulations in the literature. Most frequently used are integral scales derived from autocorrelation functions (so called 1/*e* and zero crossing scales) and scales at which a normalized Fourier spectra achieve their maximum values. Therefore, it appears that there is no consensus in the scientific community on the unique definition of *l*.
This work was initiated with the goal to estimate *l* and, after that, *C* for bora flows. For the analysis of bora flows, we used data obtained in the town of Senj settled at the north-eastern Adriatic coast (44.99°N, 14.90°E, 2 m above MSL). In the period from March 2004 to June 2006, WindMaster ultrasonic anemometer (Gill Instruments) mounted 13 m above the ground (at the very coast in Senj) recorded 294 bora events with cumulative duration of almost 7000 h. Possessing such a large dataset gives us an opportunity to estimate *l*, as well as *C*, and test the PE for bora's surface layer flows. Prior to this analysis, we used certain reference data to test different formulations of *l* mentioned above and choose the one that is most suitable for bora flows. These reference data include well known CASES99 dataset (which is considered as the reference data for a flat, homogeneous terrain) and T-REX dataset (which is considered as the reference data for a complex, mountainous terrain). Our results suggest that 1/e scale performs best as the integral scale for bora flows.

O-13.6

Dependence of similarity theory on turbulence anisotropy

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Accurate numerical weather predictions are essential for many applications including: transportation, agriculture, wind energy, hydrology and military. For these applications, it is crucial that the region of the atmosphere closest to the land-surface (atmospheric surface layer, ASL) is well captured numerically. Within the ASL, land-atmosphere forcings are transmitted to the rest of the atmosphere via turbulent exchange of momentum and heat. The short time scale and limited spatial extent of the processes related to the turbulent exchanged make it impossible for traditional weather forecast models to completely capture them. The numerical weather prediction models therefore make use of similarity theories to compute surface fluxes of momentum, sensible and latent heat from the corresponding averaged quantities at a height (z). Strictly speaking, similarity relationships were originally developed for ensemble averages of statistically stationary and horizontally homogeneous surface layer flows. Still, the same similarity relationships are regularly applied in regions of heterogeneous and non-flat terrain. Furthermore, modern numerical methods rarely rely on the mean equations anymore but need more detailed information about the fluxes than simply a mean behavior, as boundary conditions. To be able to model real flows over heterogeneous and complex surfaces, theory and application must be reconciled under the principle of "*local*" homogeneity and statistical stationarity. Meaning, that over small enough regions, sampled long enough, what *a-priori* might resemble a heterogeneous surface, can ultimately be interpreted otherwise.
The validity of surface layer similarity relations have so far been evaluated in terms of required time averaging, the appropriate spatial/local averaging, stationarity and surface heterogeneity through several experimental field campaigns located in places ranging from quasi-perfect horizontal homogeneity to highly complex terrain and complex atmospheric conditions. From the results, procedures and rules-of-use have been developed to ensure appropriate use of similarity relationships.
Within this work we present an analysis of the range of validity of similarity relationships based on the anisotropy of the turbulence Reynolds stress tensor. Turbulence data from multiple field campaigns over flat and complex terrain are separated according to the different states of anisotropy (isotropic, two component axisymmetric and one component turbulence) and flux-variance relationships are tested. Results illustrate that different states of anisotropy correspond to different similarity relations, especially under stable stratification. Experimental data with isotropic turbulence match Monin-Obukhov similarity relationships well for all the datasets. On the other hand, strongly anisotropic turbulence significantly deviates from the traditional scaling relations. We connect these limiting states of anisotropy with different governing parameters and identify conditions in which they occur. We believe that this new perspective to the land-atmosphere turbulent exchange processes might lead to improved parameterizations, as well as help advance numerical modeling of the land-atmosphere interface.

O-14.1

The Impact of Mount Washington on the Vertical Structure of Temperature and Moisture and the Height of the Boundary Layer

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While low elevations are always in the boundary layer, higher elevations can experience considerable time in other air masses besides the boundary layer, including the entrainment zone, free troposphere, and localized surface boundary layers. Since each of these air masses can have distinct thermal, moisture, chemical, and cloud properties, it follows that the type of air mass exposure could be a significant driver of high elevation climate, air quality, and elevation dependent warming. Discrimination of air mass exposure type in montane environments can be a challenge and is not commonly performed, but is necessary to determine its importance on high elevation climate and air quality.
A five-week field campaign to measure air mass type exposure on the summit of Mount Washington (44.2706ºN 71.3033ºW, 1917 m asl), New Hampshire, USA was performed during August-September 2016. In addition to the regular meteorological observations that are taken at the summit (temperature, relative humidity, wind, pressure, sky coverage, cloud type, etc.) and several mesonet sites on the east and west slopes (temperature, relative humidity, and wind), water vapor stable isotopes were measured at the summit for the five week campaign as an additional indicator of air mass type. On 19 August, an intensive observation period (IOP) captured a detailed evolution of the

vertical structure of the lower troposphere using multiple variables: the isotope analyzer was driven up and down the Auto Road and radiosondes were launched from the base of the Auto Road from pre-sunrise to post-sunset.
The 19 August IOP was characterized by mostly clear skies and a high pressure ridge slowly approaching from the west. During the early morning of the IOP, a 15-20 m s^{-1} wind forced residual layer air up the slopes to the summit from an altitude above 1400 m asl. Meanwhile, radiosonde temperature and dewpoint profiles indicate the boundary layer top was below the summit elevation in the free atmosphere. Winds diminished rapidly by 1000 LST, and highly variable summit water vapor isotope ratios and dewpoint values indicate the entrainment zone descended upon the summit for two hours. Drier and isotopically depleted air briefly mixed as low as ~1219 m ASL on the lee slope. Around 1200 LST, the convective boundary layer grew through the summit elevation, as suggested by a rapid increase in dewpoint, lapse rates at or exceeding dry adiabatic, and homogenizing of wind direction at sites above treeline. While in the convective boundary layer, summit dewpoint values exceeded all values in the boundary layer of the free atmosphere, except close to the surface, indicating local surface evapotranspiration can be an important source of water vapor at the summit. In addition, this IOP reveals important thermal and air mass height differences between the free atmosphere and along mountain slopes.

O-14.2

Impact of higher boundary temperatures on simulations of atmospheric ice accretion on structures during the 2015-2016 icing winter in West-Norway

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Atmospheric icing has been studied for several decades now, not only due to the hazardeous consequences it can have to air traffic, but also due to the damage it can cause to human installations such as power lines, wind turbines and radio towers etc. Overhead structures that are built in mountaineous regions at mid and high latitudes are particulary vulnerable to the exposure of super-cooled water in clouds.. The aim of this study is to quantify the possible effects that increased, global temperatures may have on atmospheric icing conditions in the complex orography of western Norway.
Using the Weather Research and Forecasting (WRF) Model we did two simulations of the full 2015-16 winter season covering approximately 18 km^2 of the mountaineous regions of western Norway. The model was forced by ERA-Interim reanalysis data, and applied the Thompson microphysics scheme. The first simulation was used as a control run, where the calculated accumulated ice load on a so-called standard icing object, was compared to observations provided by state-of-the-art instruments. The second simulation was made using modified input data, where temperatures at the boundaries of the model domain were increased by 2°C while the relative humidty was kept the same, allowing higher specific humidity. The results showed significantly smaller accumulative ice loads in the warm run compared to the control. This was found to be mostly due to several episodes where the temperature was above freezing in the warm run and just below freezing in the control run, resulting in fewer icing events as well as more frequent melting episodes in the warm run . The differences seemed to increase with terrain height, and only sporadic events where the icing intensity was higher in the warm run was found. A part of the differences in frequency and intensity of atmospheric icing is explained by a spatial redistribution of high atmospheric water content in the warm run compared to the control run.

O-14.3

Daily and sub-daily extreme rainfall over the Swiss Alps: a climatology

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This study presents a radar-based climatology of daily and sub-daily rainfall over the Swiss Alps and the surrounding regions, thus focusing on extreme events which are likely to cause not only big inundations, but also flash floods, debris flow and landslides.
MeteoSwiss radar rainfall estimates, rain gauge measurements and a merging of the two sources of data (CombiPrecip) for the period 2005-2016 are employed in this study. Despite the relatively short length of the weather radar archives, in fact, their high spatial resolution reveals features of local precipitation extremes that cannot be resolved by standard rain gauge networks.
Precipitation is integrated over temporal periods ranging from 1 hour to 24 hours at each radar pixel of the radar

domain (108000 km^2). Simple statistical analyses reveal huge differences in the spatial distribution of extremes between the Alps, the Pre-Alps, and the nearby flat regions; moreover, the spatial patterns of the heavy rainfall strongly depend on the length of the temporal integration.
An extreme rainfall analysis is also performed, in order to derive the return levels for precipitation measured over different temporal scales for each pixel of the radar domain.
A deep comparison between radar and rain gauge extreme rainfall statistics is also included in the study.

O-14.4

Multi-sensor precipitation estimation in the Alps: challenges and opportunities

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To measure precipitation in a mountainous region is like pitching a tent in a snowstorm: the practical use is obvious and valuable, but problems are abundant. Better knowledge of precipitation fields in the Alpine environment is needed both in weather Nowcasting and climate research: more accurate precipitation measurements, especially in complex-orography catchments, are essential to develop reliable warnings.
In this contribution we will see the complex problem of quantitative precipitation estimation in the Alpine region from four different points of view: 1) a modern network of automatic telemetered rain gages (GAGE); 2) a recently upgraded dual-polarization Doppler ground-based weather radar network (RADAR); 3) a real-time integration of GAGE and RADAR using a co-kriging-with-external-drift technique (CombiPrecip); 4) spaceborne observations acquired by the dual-wavelength precipitation radar onboard the Global Precipitation Measuring (GPM) satellite. Obviously there are large differences in sampling modes, which we have tried to minimize by integrating synchronous observations during the first two years of the GPM mission. The data comprises more than 250 “wet” overpasses over Switzerland since the launch of GPM in February 2014.
By comparing the GPM radar estimates with the other three MeteoSwiss products, we find similar performance in terms of bias. That is, GPM suffers from similar underestimation when compared with GAUGE, RADAR and CombiPrecip. For instance, the underestimation amounts to about -0.4 dB over the Swiss plateau and -1.3 dB in the Alps provided that both GPM and RADAR are able to measure precipitation below the melting layer. Consequently, GPM is not suitable to precisely assess which is the best product in terms of average precipitation over the Alps. However, GPM can be used to evaluate the dispersion of the error around the mean, which is the geographical distribution of the error inside the Country. Using 215 rain-gauge sites, the result is clear both in terms of correlation and scatter, which is a robust, weighted measure of the dispersion of the multiplicative error around the mean. The best agreement is between GPM and CombiPrecip. Second comes RADAR, whereas larger disagreement was found for GPM versus GAGE.
In short, comparison with GPM confirms that for precipitation mapping in the Alpine region the best result is obtained by combining ground-based radar and rain-gauge measurements.

O-14.5

US Army Research Lab's Meteorological Sensor Array

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US Army Research Laboratory’s (ARL) Atmospheric Science Center is developing a reliable, sustained, and world-class high resolution observational Meteorological Sensor Array (MSA) as an atmospheric science community asset for basic research on the dynamics of boundary layer processes in mountainous complex terrain. The array will address a community need for high resolution observational data for developing and verification and validation of high resolution meso-gamma and micro-scale forecast models, exploring new flow physics processes, integrating observations and state-of-the-art assessment tools, and sensor development.
When complete, the MSA will be a complex of 108 towers outfitted with state-of-the-science meteorological and ground sensing instrumentation at grid resolutions below 1km. The proposed location includes a continuous domain of 45 km x 25 km, that encompasses a valley (USDA’s Jornada Experimental Range (JER) near Las Cruces, New Mexico) at an elevation of 1300 m and the San Andres Mountains (White Sands Missile Range (WSMR), New Mexico) which peak at an elevation of 2500 m. This configuration provides the unique opportunity to examine diverse climatological complex terrain meteorological phenomena due to the varying seasonal background

meteorological conditions and continual operation. The scientific objectives including collaboration interests, available instrumentation assets, and ARL's new Atmospheric Science Center, which provides unique opportunities for scientific collaboration, will be discussed.

O-14.6

The causes of foehn warming in the lee of mountains

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The foehn effect is well known as the warming, drying and cloud clearance experienced on the leeside of mountain ranges during 'flow over' conditions. Foehn flows were first described more than a century ago, when two mechanisms for this warming effect were postulated. An isentropic drawdown mechanism where potentially warmer air from aloft is brought down adiabatically; and a latent heating and precipitation mechanism, where air cools less on ascent – due to condensation and latent heat release – than on its dry descent on the leeside. Here, for the first time, the direct quantitative contribution of these and other foehn warming mechanisms are shown. The results suggest a new paradigm is required after it is demonstrated that a third mechanism, mechanical mixing of the foehn flow by turbulence, is significant. In fact depending on the flow dynamics any of the three warming mechanisms can dominate. A novel Lagrangian heat-budget model, back trajectories, high resolution numerical model output and aircraft observations are all employed. The study focuses on a unique natural laboratory – one that allows unambiguous quantification of the leeside warming – the Antarctic Peninsula and Larsen C Ice Shelf. The demonstration that three foehn warming mechanisms are important has ramifications for weather forecasting in mountainous areas and associated hazards such as ice shelf melt and wildfires.

O-14.7

On forecasting snow surface temperature in complex alpine terrain

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Numerical weather prediction (NWP) is the core business of any operational weather service. The horizontal and vertical resolution of numerical weather prediction models strongly increased during the last decades. However, numerical weather prediction in complex terrain is still challenging, because the underlying physics in the majority of subgrid-scale parameterizations have been developed for flat or idealized terrain. Weather prediction in alpine countries – such as Austria or Switzerland – is not only challenged by complex topography, furthermore, for a good part of the year the ground is snow covered influencing boundary layer processes such as turbulence and radiation. Currently, most NWP models predict the formation and evolution of the seasonal mountain snow cover in a simplified way, i.e. often by means of a single layer model. For this study we validated the performance of the currently implemented snow cover scheme of the COSMO model (Consortium for Small-scale Modelling) in terms of the snow surface temperature, a key parameter for the evolution of the snow cover as well as the near-surface air temperature. In a case study snow surface temperature measured at an automated weather station over a 48-hour period was compared to the corresponding COSMO run at 2 km horizontal resolution. Snow surface temperature was found to be overestimated especially during the night. This corresponds to the performance of COSMO when 'climatologically' evaluating 2 m temperature at 120 sites in the Swiss Alps over a year. By implementing a multi-layer snow module, which minimizes the energy balance equation with regard to snow surface temperature and then iteratively solves the heat equation the daily cycle of the snow surface temperature can be predicted accurately. This procedure shows promising potential not only for an accurately modeled snow surface temperature – hence an improved snow cover evolution – it has also the potential to improve the NWP performance in predicting the near surface air temperature during snow covered periods.

O-15.1

Examples of applications of mesoscale meteorology in the complex orography of Norway

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UMERIC

O-15.2

The Cerdanya-2017 field experiment: an overview of the campaign and a few preliminary results

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La Cerdanya is one of the largest valley of the Pyrenees mountain range, spreading across Spain and France (between Occitanie and Catalunya). It is about 10 km wide and 35 km long oriented ENE-WSW (whereas most valley in the Pyrenees are oriented N-S) with a relatively flat bottom at about 1000 m above sea level and mountain ridge around rising above 2900 m.
The field experiment Cerdanya-2017 took place in this valley from October 2016 to April 2017, focusing on three meteorological phenomena in mountainous terrain: cold pool, mountain waves and orographic precipitations.
The Cerdanya-2017 field experiment focuses in particular on the detailed inversion structure and the surface energy budget of cold pool, rotors and boundary layer separation in mountain waves situations, and orographic triggering and intensification of precipitations under stratiform and convective regimes.
An overview of the field experiment, the instruments and the meteorological situations observed will be presented first. Then some preliminary results regarding in particular fine scale circulation within the valley and numerical weather prediction model performance will be shown.
This research is a joint effort of several teams from the Euroregion Pyrenees-Mediterranean, these teams belong to the Universities of the Balearic Islands and of Barcelona, METEO-FRANCE & CNRS and the Meteorological Service of Catalonia.

O-15.3

Downslope windstorms, mountain waves, orographic precipitation and associated processes analysis during 10-17 January 2017 in The Cerdanya-2017 field experiment

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In the framework of the GWOP'17 (Gravity Waves and Orographic Precipitation) project, we use measurements from The Cerdanya-2017 field campaign to analyze episodes of mountain waves, orographic precipitation and their associated processes over the Pyrenees. The Pyrenees is a west to east oriented mountain range located along the border between France and Spain. In its oriental part, between Occitaine and Catalunya, The Cerdanya valley sits around 1000 m above sea level (a.s.l.) with surrounding peaks that reach above 2900 m a.s.l. The instrumentation

deployed during The Cerdanya-2017 field experiment includes: an Ultra High Frequency wind profiler located at the foot of a lee slope and several instruments located at the center of the valley: a radiometer, a lidar, a windrass, a microwave rain radar, a disdrometer, an eddy covariance station and a ceilometer, among others. Some radiosoundings were launched during intensive observation periods and several automatic weather stations were deployed along the valley.
In this study we will present the preliminary results obtained during a selected severe weather period from 10th to 17th January 2017, mainly dominated by northern strong winds and some precipitation events, and we have analyzed the data from the observational network. In the 8-day analyzed period we identify different episodes including: downslope windstorms and possible hydraulic jumps, mountain wave generation with associated rotors near the surface, and heavy precipitation events with large amounts of snow accumulation. In addition, we explore the interaction and connection between these phenomena.

O-15.4

The Cerdanya Cold Pool Experiment 2015 (CCP15): a field campaign study of the cold pool in the largest pyrenean valley

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The Cerdanya Cold Pool Experiment 2015 (CCP15) consisted in a two-week long field campaign that took place in October 2015 in the Cerdanya valley, western Pyrenees. This valley, a graben 35 km long and 15 km wide, has a distinct ENE-WSW orientation that stands out among the rest of the pyrenean valleys, generally oriented in the N-S direction. Its topographical configuration, with a valley floor at 1000 m above sea level (asl) and surrounded by mountain ranges rising above 2900 m asl to the north and up to 2700 m asl to the south, is prone for the development of intense cold-air pooling at its bottom part, even under the presence of significant synoptic pressure gradients. This campaign was designed to study the structure and evolution of the cold-air pool at the bottom part of the valley, together with the slope and valley winds that generate under fair weather conditions. For this purpose, a boundary-layer temperature and wind profiler (Windrass, Scintec) and a fully equipped surface energy budget station operated by the Catalan Met Service (Meteocat) were installed near their operational station at the Das Aerodrome, a facility situated at the valley bottom where the minimal temperature values of Catalonia are recorded under good weather conditions. This instrumentation was supplemented by a 2-m height column of thermistors to analyse the lowest part of the surface thermal inversion. An additional surface weather station was installed at a secondary sub-basin of the Cerdanya valley located few kilometres downstream to evaluate the spatial thermal differences at the surface.
Five Intensive Observational Periods (IOPs) were selected during the field campaign for the continuous operation of a tethered balloon from evening to morning transitions, while a remotely-controlled multicopter was involved at shorter time windows. Both devices provide in-situ data that complement the vertical profiles obtained by the remote sensing device. The selected IOPs represent a variety of cases that allow to study the cold-air pool formation and development of local winds under quiescent conditions, under the presence of a weak general wind channelized along the main valley axis or with increasing cloud cover.
This presentation will provide an overview of the field campaign and summarize the recent research results on the phenomena observed, which will be compared against the corresponding outputs from a high-resolution mesoscale simulation.
A preliminary analysis of these results lead to the design of a second field campaign that took place in January-February 2017 to study the cold-air pool and thermally-driven flows under snow conditions. An overview of this last campaign, which has been finished very recently, will be presented in another communication at this conference.

O-15.5

Lidar observations and high-resolution modelling of a wind jet at the exit of the Isarco Valley (Italy)

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The Isarco Valley is one of the main tributary valleys that feed into the Bolzano basin, in theCentral Italian Alps. The wind field in this area is characterised by a very complex behaviour, due to the interaction between the local thermally-driven circulations, that daily develop in the different valleys joining the basin.
Recently it was observed that the nocturnal drainage flow at the exit of the Isarco Valley behaves like a low-level jet with peak intensities between 5 and 10 m s^{-1}. The topography of the valley is indeed suitable for the development of such a flow, since it is characterised by narrow cross sections up to its outlet in the Bolzano basin. A Doppler wind lidar (WindCube100S, Leosphere) was installed in the period January-March 2017 at the outlet of the Isarco Valley, in order to monitor the wind field at the exit of the valley. The experimental dataset is completed by a sodar and by a thermal profiler installed in the Bolzano basin and by several surface weather stations.
Different scans with the lidar were carried out using different spatial resolutions, to capture the structure and the dynamics of the jet both in the Isarco Valley and in the Bolzano basin. A correlation of the shape of the jet with the influence of synoptic forcing and with the presence of thermal inversions was observed. In particular the presence (absence) of synoptic forcing determines the development of dynamically-driven (thermally-driven) jets. Ground-based and upper thermal inversions modify the vertical profile of the jet from a wall-jet-like profile to a free-jet-like one.
In this contribution results obtained from the experimental dataset are presented. Moreover observations are complemented by high-resolution numerical simulations performed with the WRF model, in order to get a complete three-dimensional picture of the development of the valley exit jet and to evaluate its spreading into the Bolzano basin.

O-15.6

Periodic wind systems in the Dead Sea valley - first comprehensive measurements of their characteristics and evolution

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The Dead Sea is located at the lowest point of the Jordan Rift valley and its water level is currently at -429 m above mean sea level (amsl). To the West the Judean Mountains (up to 1000 m amsl) and to the East the Moab Mountains (up to 1300 m amsl) confine the north-south oriented valley. Previous studies showed that the valley's atmosphere is often governed by periodic wind systems. However, their analysis was based on ground measurements only and could therefore not resolve the three-dimensional structure and evolution of these wind systems.
Therefore, a field campaign with the mobile observatory KITcube was conducted to study the three dimensional structure of these atmospheric processes in 2014. The combination of several in-situ (e.g. energy balance stations, radiosondes) and remote sensing (e.g. lidar, microwave radiometer, radar) instruments allows temporally and spatially high-resolution measurements in an atmospheric volume of about 10x10x10 km^3.
Based on near surface measurements and lidar data, we identified three typical diurnal wind systems, their evolution, as well as the impact of regional scale conditions on the valley's atmosphere. The three diurnal wind systems are (i) nocturnal northerly along-valley flows, (ii) the Dead Sea lake breeze during the day, and (iii) downslope windstorm-type flows (DWFs) in the evening, with wind velocities of over 10 m s^{-1}. The results show that these DWFs occur at nearly 70 % of the days in summer. They are triggered by temperature differences between the air masses at the crest and the valley, caused by prolonged warming of the air in the valley compared to the air masses upstream. Additionally, cooler maritime air masses are frequently advected upstream by the Mediterranean Sea Breeze supporting the development. They can be further classified according to their duration, height, penetration distance into the valley, and wind velocitiy, into three groups. We conclude that in the morning, afternoon, and night, wind conditions in the valley are mainly decoupled from the regional scale, but that in the evening the upstream processes determine the atmospheric conditions in the valley.

O-15.7

Long-range transport to summits north, south and at the Eastern Alpine divide - an outstanding Sahara dust event

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Introduction
Long range transport of mineral dust e.g. from the Sahara desert or of volcanic ash, plumes of forest fires or

transport of anthropogenic pollution to the Alpine ridge may influence the Alpine ecological system (e.g. via changes of the radiation budget or the nutrient input) and is relevant in the context of air quality. Background stations at remote sites are an essential part of air quality networks to differentiate between the impact of local or regional emissions and long-range transport and to quantify contributions of the latter. Aerosols, especially light absorbing particles, furthermore may influence the snow albedo after being deposited on the snow cover via wet or dry deposition. Finally, aerosols plumes of sufficient density may have a significant impact on direct radiative forcing in the atmosphere.

In an ongoing study, air pollution measurements are operated at three meteorological mountain stations in Austria to investigate the impact of long-range transport to the Eastern Alpine divide as well as to the Alpine Forelands north and south with special focus on outstanding Sahara dust events.

Monitoring network

Atmospheric trace gases, particulate matter and meteorological parameters are continuously observed at the Sonnblick Observatory (3109 m asl). Due to the remote position of this site in high Alpine environment these data allow the monitoring of the background pollution level in the Alpine boundary layer unaffected from local sources as well as in free tropospheric air masses. Manned meteorological stations are operated about 105 km north of Sonnblick, at top of the mountain Feuerkogel (1618 m asl) and about 40 km south of Sonnblick, at top of the mountain Dobratsch (2117m asl). These stations were additionally equipped with monitoring instrumentation for gaseous atmospheric constituents (SO_2, NO_2, ozone) and particle matter (PM10 and PM2.5). This line of mountain top observations across the Eastern Alps is accomplished by ceilometer observations of the aerosol structure within and above near-by valleys. These remote sensing measurements support the distinction between boundary layer air and free tropospheric air contributing to the pollution observations at the mountain tops.

Modeling

WRF-Chem (Grell, 2005) is the Weather Research and Forecasting (WRF) model coupled with chemistry. The model simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorology. The model is used for the investigation of regional-scale air quality, field program analysis, and interactions between clouds and chemistry. In the current study, the meteorological fields are based on ECMWF forecasts run twice daily for 72 hours. The horizontal resolution is 12 km for the area of Europe.

The sensitivity of a receptor (e.g. the average PM10 concentration at the grid cell representing the observatory at Hoher Sonnblick) to a source (in this case the dust emissions from the Saharan desert, a volume source acting during a specified time interval) can be described by the source – receptor relationship (Seibert and Frank, 2004). The calculations are done with the Lagrangian particle model FLEXPART (Stohl et al., 2002) in the backward-running, receptor-oriented mode considering the atmosphere up to 2000 m. In this mode, the particle trajectories are integrated backward in time, using a negative time step. The results are so-called source-receptor sensitivity (SRS) fields which describe both the origin and the concentration of PM10 at the receptor.

Results

The largest dust source region in the world is North Africa. About 10% of the desert dust which is entrained into the free atmosphere is transported towards the Mediterranean Sea and Europe depending on the prevailing large-scale pressure fields and flow patterns (Schepanski et al., 2016). Sahara dust fall on the Alpine ridge is documented by the observations at mountain stations several times of the year (Collaud et al.,2004; De Angelis and Gaudichet, 1991; Sodemann et al., 2006).

At the begin of April 2016, a Saharan dust cloud reached the Eastern Alps, leading to enhanced PM10 concentrations and reduced visibility over several consecutive days. Exemplary results from this outstanding Sahara dust event will be shown in this presentation. Particle matter concentrations significantly increased at the Austrian mountain stations. Webcam pictures reveal large differences in visibility before and during the dust episode in a very impressive way. From visible inspection only one cannot solely determine whether the poor visibility is due to the Saharan dust cloud or to fog. Therefore, ceilometer profiles close to the mountains are considered, as this remote sensing technique discerns cloud droplets from other aerosols.

The respective pronounced Sahara dust event is successfully forecasted with the model WRF-Chem. The dust emissions in the Algerian Sahara desert due to stormy winds and the transport across the Mediterranean Sea to Central Europe are well reproduced in the model simulations. The modelled PM10 concentrations are furthermore in good agreement with the increased values measured at the Austrian air quality stations. Finally, the results of the FLEXPART backward model runs integrated over days as well as loops render insight in the most dominant source regions in a demonstrative way. The temporal evolution of the flow patterns north and south of the Alpine ridge, the boundary layer structure and the corresponding transport phenomena are revealed by the synopsis of the available data and material and discussed in detail.

This case study demonstrates that the combination of the meteorological and air quality monitoring network and modelling and analysis tools renders the optimum basis for the interpretation of exceptional air pollution events as for example caused by long-range transport of Sahara dust to the Alps. This application is of particular relevance as these events can be classified as “natural events” in the official reporting of air quality measurements to the European Union and do not add to the number of PM10 daily mean threshold exceedances.

Acknowledgement

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O-15.8

Gap wind and wakes in SE-Iceland on 18 October 2016

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On 18 October 2016 the flow pattern downstream of the topography of SE-Iceland was observed with the Facility for Airborne Atmospheric Measurements (FAAM) of the National Centre for Atmospheric Science (NCAS). The low level flow was weak and from the northwest resulting in a relatively low upstream shallow water Froude number. The operational simulations with the non-hydrostatic model HARMONIE at 2.5 km horizontal resolution showed wakes forming in the lee of both Mýrdalsjökull glacier in S-Iceland and Vatnajökull glacier with weak return flow. Between the glaciers and as the flow descended from the highland toward the coast there was a moderately strong gap wind with indications of a weak vertically propagating gravity wave. The flow was probed downstream of the topography along a line extending from the Mýrdalsjökull glacier wake eastward into the Vatnajökull glacier wake. The measurements confirm the overall simulated flow pattern as well as showing that the gap wind had local maxima close to it’s borders. Furthermore the weak reverse flow in the wakes was observed and the complexity of wake flow highlighted.

O-16.1

Interactions of a mesoscale katabatic flow with a small crater basin to produce cold and warm air intrusions, flow bifurcations and a hydraulic jump

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Observations from the Second Meteor Crater Experiment (METCRAX II) on the night of 19-20 October 2013 are used to investigate the interactions between a regional scale katabatic flow and Arizona’s Meteor Crater. The crater is a 1.2 km wide, 170-m-deep, near-circular basin with a rim that extends 30-50 m above the plain. On clear,

quiescent nights a southwesterly katabatic flow lifts the stable boundary layer (SBL) on the 1° tilted plain over the crater rim to produce a continuous inflow of negatively buoyant air that runs down the crater's inner sidewall. As the SBL deepens and the katabatic flow strengthens, a flow bifurcation forms above the rim with the negatively buoyant lower portion running down the inner sidewall to produce a hydraulic jump and the neutrally buoyant upper portion carried quasi-horizontally over the basin. Unsteady short waves form in this overflow behind the rim. As the stable layer continues to deepen and a mesoscale downslope flow develops above the katabatic flow, a high-amplitude short wave develops in the lee of the rim bringing warm air from the elevated residual layer downward into the basin. Interactions between the continuous cold-air intrusion and the descending lee wave accelerate the flow down the slope to enhance the hydraulic jump, which then reaches vertically to merge with the rising air in the ascending portion of the lee wave. The strong winds penetrate to the basin floor, displacing and stirring the pre-existing, intensely stable, cold pool and creating warm air streaks.

O-16.2

Processes leading to heavy precipitation over north-eastern Adriatic during the HyMeX SOP1

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During SOP1, 16 IOPs were dedicated to heavy precipitation events (HPE) over the western Mediterranean and 8 of these events subsequently affected the eastern Adriatic Sea and Croatia. All of them produced localized heavy precipitation and often were properly forecast by the available operational model ALADIN but prediction of the amount, precise time and the location of maximum intensity was not always exactly represented. The total precipitation for the SOP1 was above the corresponding climatology for the Adriatic. Maximum of precipitation (more than 1.000 mm in 61 days at some locations) was recorded on the northern Adriatic (city of Rijeka) and its mountainous hinterland of Gorski Kotar.
Most the HPEs contain similar ingredients and synoptic setting but of different intensity: a deep upper level through, a cyclone strengthening over the Mediterranean (or developing over Gulf of Genoa, Lyon or Tyrhennian sea), a strong south-westerly low-level jet stream that advects the moist and warm air towards the orographic obstacles along eastern Adriatic coastline and destabilizes the atmosphere and the strong low level winds which pick up the moisture from the sea. As the sea provides a large source of moisture and heat, the steep slopes of the surrounding mountains in the vicinity of urbanized northern Adriatic coastal areas are the key factors in determining the moisture convergence and the rapid uplift of moist and unstable air responsible for triggering condensation and convective instability processes.
Overview of processes leading to heavy precipitation over north-eastern Adriatic during the HyMeX SOP1 will be presented, with special focus on the extraordinarily rare heavy precipitation event IOP2 (12 September 2012) that occurred in wider area of the city of Rijeka.

O-16.3

INCA analysis and nowcasting as part of the international collaborative experiments for the PyeongChang Olympic and Paralympic Games 2018 (ICE-POP 2018)

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After SNOW-V10 (Vancouver 2010) and FROST (Sochi 2014), ICE-POP 2018 is the third major WMO/WWRP supported RDP/FDP project focusing on the observation and forecasting of winter weather at and around Olympic venues. The 23rd Olympic and the 13th Paralympic Winter Games will be held in PyeongChang, Korea in February and March 2018 and offer a unique opportunity to enhance, apply and verify NWP models and nowcasting systems in an extremely user-oriented environment and setting.
One of the goals of ICE-POP 2018 is thus, amongst others, to "advance seamless prediction from nowcasting to short-range forecasting for winter weathers over complex terrains based on intensive observation campaigns". That is supported by an extremely dense observation network, featuring almost all kinds of in-situ and remotely sensed measurements.
The INCA Analysis and Nowcasting System is widely used and also plays an important role in the provision of very short range field- and point-forecasts over the Olympic area. INCA is coupled with and merged into to the Korean VDAPS model and currently provides analyses and forecasts up to +6h of lead time on a 1 km x 1 km regular grid covering the north-eastern part of the Korean peninsula. The time resolution and update frequency is currently set to 1 hour for temperature, relative humidity, snowfall line, zero degree line, wind and gusts and to 10 min for precipitation and precipitation type.

In accordance with the requirements defined in ICE-POP 2018, INCA has been set up in test mode for the PyeongChang Olympic area during the last winter season, and it is now being evaluated, enhanced and prepared for application in the upcoming Olympic winter season.
The presentation will give an introduction into ICE-POP 2018 and it will summarize the current status of the implementation of INCA for PyeongChang, including case studies and first evaluations.