37th International Conference on Alpine Meteorology (ICAM)

CROATIA 2025

ICAM

Book of Abstracts

29 September - 3 October 2025

Poreč, Croatia

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37th INTERNATIONAL CONFERENCE ON ALPINE METEOROLOGY

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Conference Overview

SUNDAY, 28 Sept

- 18:00-20:00 Registration

MONDAY, 29 Sept

- 08:00-09:00 Registration
- 09:00-09:30 Conference opening

Dynamics

09:30-10:00	B. Grisogono ☆
10:00-10:15	N. Krieger
10:15-10:30	V. Wirth

- 10:30-11:00 Coffee break

Dynamics

11:00 - 11:15	F. Lott
11:15 - 11:30	M. Teixeira
11:30 - 11:45	P. Šácha
11:45 - 12:00	H. Houtman ◊
12:00 - 12:15	Y. Asano
12:15 - 12:30	G. Wei ◊

- 12:30-14:00 Lunch break

Fcst. & Ver.

14:00 - 14:30	A. Holzer ☆
14:30 - 14:45	C. Böttcher
14:45 - 15:00	N. Novak
15:00 - 15:15	J. Sepehri ◊

- Posters Dynamics, Interactions, TEAMx and other field campaigns & coffee break

TEAMx & o.f.c.

17:00 - 17:15	P. Sheridan
17:15 - 17:30	D. Corradini ◊
17:30 - 17:45	G. Doglioni
17:45 - 18:00	L. Giovannini
18:00 - 18:15	E. Gutmann
18:15 - 18:30	M. Udina

- 20:00 Ice breaker

TUESDAY, 30 Sept

TEAMx & o.f.c.

08:45 - 09:15	M. Lehner ☆
09:15 - 09:30	M. Rotach
09:30 - 09:45	P. Gasch
09:45 - 10:00	A. Alexa ◊
10:00 - 10:15	M. Kossmann
10:15 - 10:30	C. Brun

- 10:30-11:00 Coffee break

NWP

11:00 - 11:30	C. Kühnlein ☆
11:30 - 11:45	G. Zängl
11:45 - 12:00	L. Jansing
12:00 - 12:15	D.-C. Littmann
12:15 - 12:30	C. Steger

- 12:30-14:00 Group Photo & Lunch break

Interactions

14:00 - 14:30	C. Lebeaupin Brossier ☆
14:30 - 14:45	K. Ruić ◊
14:45 - 15:00	I. Vilibić

- Posters Boundary Layer, Clouds and Precipitation, Forecasting and Verification, NWP & coffee break

Dyn.

17:00 - 17:15	J. Mikkola ◊
17:15 - 17:30	H. Kusaka
17:30 - 17:45	A. Stephens ◊

- 19:15 City excursion to Poreč

WEDNESDAY, 1 Oct

Climate

09:00 - 09:30	D. Belušić ☆
09:30 - 09:45	G. Pistotnik
09:45 - 10:00	P. Jureša ◊
10:00 - 10:15	M. Anić
10:15 - 10:30	J. Minder

- 10:30-11:00 Coffee break

NWP

11:00 - 11:15	K. Flacké Haualand
11:15 - 11:30	M. Vazquez Ballesta ◊
11:30 - 11:45	M. Stefanelli

- 11:45-12:45 Lunch break
- 12:45 Excursion to Brijuni
- 19:30 Conference dinner

THURSDAY, 2 Oct

Boundary Layer

08:45 - 09:15	I. Stiperski ☆
09:15 - 09:30	S. Carpentari ◊
09:30 - 09:45	R. Mott
09:45 - 10:00	P. Asemann ◊
10:00 - 10:15	T. Silva ◊
10:15 - 10:30	J. Jurković

- 10:30-11:00 Coffee break

Boundary Layer

11:00 - 11:15	J. Schmidli
11:15 - 11:30	T. Pletzer
11:30 - 11:45	A. Rauchöcker ◊
11:45 - 12:00	B. Goger
12:00 - 12:15	M. Fritz ◊
12:15 - 12:30	J. Quimbayo-Duarte

- 12:30-14:00 Lunch break

Clouds & Precip.

14:00 - 14:30	D. Kirshbaum ☆
14:30 - 14:45	S. Serafin
14:45 - 15:00	B. Geerts
15:00 - 15:15	F. Polls ◊
15:15 - 15:30	P. Veals

- Posters Applications, Climate & coffee break

Applications

17:00 - 17:30	B. Kosović ☆
17:30 - 17:45	I. Odak
17:45 - 18:00	C. Staquet

- 20:15 Pub quiz

FRIDAY, 3 Oct

Clouds & Precip.

08:45 - 09:00	A. Abbate
09:00 - 09:15	M. Wasserstein ◊
09:15 - 09:30	A. Orr
09:30 - 09:45	S. Smith
09:45 - 10:00	M. Ogrin
10:00 - 10:15	E. M. Samuelsen

- 10:15-11:00 Coffee break

Applications

11:00 - 11:15	N. Aksamit
11:15 - 11:30	P. Maier ◊
11:30 - 11:45	K. Kvist ◊
11:45 - 12:00	K. Pagh Nielsen
12:00 - 12:15	Ó. Rögnvaldsson

- 12:15-12:30 Award and closing ceremony

☆ Invited speaker ◊ Eligible for Young Scientist Award

[Dynamics] Chairs: Guðrún Nína Petersen, Mathias Rotach, Alexander Gohm, Haraldur Ólafsson, Nicolai Krieger, Volkmar Wirth
[Forecasting and Verification] Chairs: Karmen Babić, Ólafur Rögnvaldsson
[TEAMx and other field campaigns] Chairs: Bart Geerts, Manuela Lehner, Chantal Staquet, Ivana Stiperski
[NWP] Chairs: Marco Arpagaus, Brigitta Goger, Julian Quimbayo-Duarte, Endi Keresturi
[Interaction of mountain, coastal and marine processes] Chairs: Maja Telišman Prtenjak, Lorenzo Giovannini
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[Applications] Chairs: Iris Odak, Nikolas Aksamit, Kristian Horvath, Nevio Babić

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Dynamics

Online

NON-SYNOPTIC WINDSTORMS THROUGH THE EYES OF OTHERS

Grisogono Branko[1]

[1]Croatian Meteorological Society, Zagreb, Croatia

A broad spectrum of mesoscale phenomena is associated with convective storms, including squall lines, tornadoes, downbursts, and microbursts. However, several impactful systems can occur independently of convection. These include downslope windstorms - such as Bora, Chinook, Foehn, Santa Ana, Yamaji- kaze, and Zonda as well as bores, gap winds, katabatic flows, sting jets, and low-level jets. Among them, severe Bora along the Adriatic coast stands out as a dynamically driven downslope windstorm, particularly significant in complex mountainous terrain with numerous peaks and passes, and is examined here in greater detail. Bora occurs in various forms. When weak to moderate - locally referred to as 'burin' - it is often thermodynamically driven, resembling katabatic or down-valley flows. When moderate to strong, it may manifest as a gap flow, possibly accompanied by mountain wave steepening; these are typically more localized phenomena. However, when Bora becomes severe -disrupting traffic and other activities - it is associated with overall mountain wave overturning and breaking, affecting (sub)regional scales. From an interdisciplinary perspective, the perception of such windstorms varies among atmospheric scientists, engineers, and other stakeholders. For instance, meteorologists, especially those focused on the atmospheric boundary layer, tend to distinguish classical turbulence spectra from coherent structures such as Kelvin-Helmholtz wave instabilities. In contrast, engineers often include these longer-period components due to their relevance for sub-resonant structural vibrations in bridges, tall buildings, aircraft, and other infrastructure. Further differences in interpretation arise across sectors such as agriculture, renewable energy, education, health, hydrology, tourism, and transportation. These diverse viewpoints underscore the need for stronger communication and integration between meteorological science and applied disciplines, particularly in regions influenced by complex orography.

Key words: downslope windstorms, bora, mountain wave overturning, and breaking

Onsite

A LOCAL WINDSTORM IN A DEEP AND NARROW VALLEY: MEASUREMENTS AND DECAMETRE-SCALE LARGE-EDDY SIMULATIONS

Krieger Nicolai[1], Sprenger Michael[1], Kühnlein Christian[2], Hervo Maxime[3], Bättig Philipp[3], Krieger Ulrich[1], Müller Eugen[4], Wernli Heini[1]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich , Switzerland; [2]ECMWF, Bonn, Germany; [3]MeteoSwiss, Payerne, Switzerland; [4]MeteoSwiss, Zurich, Switzerland

During a winter storm in January 2007, a train derailed due to strong winds in a narrow and deep valley in northeastern Switzerland. The accident was attributed to the Laseyer, a local windstorm characterized by flow reversal that manifests as easterly to southeasterly winds at the valley floor during strong prevailing northwesterly winds above. Using measurements from a sonic anemometer and a Doppler lidar and based on semi-idealized large-eddy simulations (LES) performed with the Portable Model for Multi-Scale Atmospheric Prediction (PMAP), we analyze a case of the local windstorm that occurred in December 2023. The data from both measurements and LES reveal a highly turbulent flow in the narrow valley and extreme wind speeds exceeding 45 m/s during Laseyer conditions. Additionally, the data reveal that the flow in the narrow and deep valley is characterized by flow separation on the upstream ridge (with regard to the ambient wind direction) and that a recirculation region in the valley emerges, leading to the south- easterly winds at the valley floor. Moreover, both measurements and simulations exhibit quasi-periodic oscillations of the winds at the valley floor, consistent with reports from local residents. Accurately simulating the Laseyer and the three-dimensional flow in the narrow and deep valley requires high spatial resolution with horizontal grid spacings of at most 44 m and very accurate topography representation. Under these conditions, the LES, using a height-based terrain-following vertical coordinate, are characterized by extremely steep topographic slopes exceeding 80°. Lower horizontal resolution or a smoothed topography results in considerable differences between the simulated flow and Doppler wind lidar measurements. These findings highlight the crucial role of topography representation for the correct simulation of atmospheric flows in complex terrain in decametre-scale LES, in addition to accurate mesoscale boundary conditions. In conclusion, this is the first work to characterize the three-dimensional flow structure in the narrow and deep valley and immediate surroundings during Laseyer conditions, and the findings underscore the value of real-weather LES in accurately capturing fine-scale atmospheric dynamics and for advancing the understanding of microscale flows in mountainous regions.

Key words: Large-eddy simulations windstorm Doppler wind lidar

Onsite

FLOW REGIMES CONDUCIVE TO BANNER CLOUD FORMATION: COMBINING LARGE EDDY SIMULATIONS WITH OBSERVATIONS FROM THE MATTERHEX FIELD CAMPAIGN

Wirth Volkmar[1], Thomas Marius[1], Hoch Sebastian[2], Lehning Michael [3], Huwald Hendrik[3]

[1]Institute of Atmospheric Physics Johannes Gutenberg University Mainz, Mainz, Germany; [2]Earth Observing Laboratory, Mainz, United States of America; [3]Laboratory of Cryospheric Sciences, Mainz, Switzerland

Banner clouds are clouds which are attached to the leeward side of steep mountains or sharp ridges. This type of cloud can frequently be seen, e.g., at the Matterhorn in the Swiss Alps. In the past there have been quite a few investigations into this phenomenon, but most of them relied on idealized Large Eddy Simulations. Amongst others, these simulations indicated that flow separation and lee-side flow reversal with strong uplift are key ingredients for banner cloud formation. Such features occur preferably for flow past tall and steep mountains in a weakly stratified ambient atmosphere. In this contribution we revisit this topic based on new observations as well as on refined simulations. More specifically, we report on a measurement campaign at the Matterhorn (carried out in fall 2023) as well as extensive Large Eddy Simulations with realistic Matterhorn orography. The campaign allowed us to simultaneously observe banner cloud formation (through webcam footage), to characterize the ambient atmosphere (through radiosondes), and to detect the detailed flow structure in the lee of the mountain (through a Doppler lidar). Using the upwind conditions from radiosonde observations, we can evaluate how well theoretical guidance predicts lee-side flow reversal and uplift and, hence, a good chance for banner cloud formation. Interestingly, the prediction holds for all days for which sufficient lidar data is available to evaluate the lee-side flow regime. Moreover, the key aspects of the observed flow structures are consistent with Large Eddy Simulations of flow past realistic Matterhorn orography.

Key words: Flow past a mountain, Large Eddy Simulation, Measurement Campaign

Online

RATIONALE FOR A SUBGRID SCALE OROGRAPHY PARAMETERIZATION THAT INCLUDES TURBULENT FORM DRAG, GRAVITY WAVE DRAG AND LOW LEVEL FLOW BLOCKING

Lott François[1], Beljaars Anton[2], Deremble Bruno[3]

[1]Laboratoire de Météorologie Dynamique, PSL Research Institute, Ecole Normale Supérieure, PARIS, France; [2]ECMWF, Reading, United Kingdom of Great Britain and Northern Ireland; [3]Institut des Géosciences de l'Environnement, University Grenoble Alpes, GRENOBLE, France

Parameterizations of subgrid scale mountains are commonly used in large scale numerical weather prediction and climate models. They try to represent quite separate processes: the enhancement of the turbulent drag by orography, gravity waves and low level flow blocking. Among the gravity waves some schemes eventually separate between the upward propagating waves and the trapped lee waves. Using a recent theoretical methodology that addresses the interaction of stratified boundary layers with mountains, a theory that handles the transition from neutral to stratified dynamics and trapped waves, we propose a formalism that can include all these effects. As in most parameterizations it separates the flow between a linear part and a blocked part. Here the linear part handles enhanced turbulent drag in the neutral case and gravity waves in the stratified case, trapped lee waves in the transition. In this presentation we evaluate the mountain drag associated to all these processes as well as the fraction of the drag that stays within the boundary layer instead of being radiated in the far field. We also try to evaluate the blocked part by combining the sheltering effects that dominate when stratification is small and the blocking effects that dominate when stratification is large.

Key words: Mountain waves, boundary layer turbulence, parameterization, theory

Onsite

ESTIMATING OROGRAPHIC DRAG BASED ON THE VERTICAL VELOCITY FIELD OF 2D TRAPPED LEE WAVES

Teixeira Miguel[1], Argaín José[2]

[1]University of Porto, Porto, Portugal; [2]University of Algarve, Faro, Portugal

A result originally by Bretherton (1969) states that the gravity wave drag produced by 2D trapped lee waves is related to the integral of the square of the vertical velocity associated with these waves along the (vertical) phase lines at which this quantity is a maximum. This provides a way of estimating the total drag produced by these waves alternative to integrating the surface pressure perturbation multiplied by the terrain slope, or calculating the wave momentum flux at some level above the orography (which equals the drag at the surface in the linear approximation). Using Bretherton's result overcomes two practical difficulties: 1. It is not always easy to pinpoint which orography generated given trapped lee waves when that orography is not isolated; 2. The calculation of the momentum flux from its definition is prone to partial cancellations, as the product of the horizontal and vertical velocity perturbations can be positive or negative. In this study, we evaluate the orographic drag produced by trapped lee waves for different types of atmospheric profiles over isolated orography using Bretherton's method, and compare it with the drag obtained from the more fundamental definitions mentioned above. The advantage of Bretherton's method is that, as in the momentum flux method, the terrain elevation does not enter into the calculation, but since the square of the vertical velocity is a positive definite quantity, there is no risk of cancellations. Since this method uses the wave field, its accuracy is potentially less affected by nonlinearity than the traditional definition based on the surface pressure distribution. Limitations of the method are that the phase lines of the trapped lee waves may not be perfectly vertical, and their oscillations may not be perfectly periodic, potentially adding uncertainty to the drag evaluation.

Key words: Orographic flows, Stratified flows, Gravity waves, Mountain waves, Trapped lee waves, Gravity wave drag, Wave momentum fluxes

Onsite

WHAT IS THE SKILL OF THE CURRENT SUBGRID-SCALE OROGRAPHY PARAMETERIZATION SCHEMES FOR THE FLOW OVER IDEALIZED ISOLATED HILLS?

Šácha Petr[1], Hájková Dominika [1], Bartoň Šimon[1]

[1]*Charles University, Faculty of Mathematics and Physics, Prague, Czechia*

Orographic gravity waves (OGWs) created by the flow - orography interaction are ubiquitous in the atmosphere. Propagating both vertically and horizontally away from their sources, OGWs influence dynamics and transport across atmospheric layers. The horizontal scales of OGWs largely reflect the horizontal scales of orographic variations with typical horizontal wavelengths ranging from a few to thousands of kilometers. This means that much of their spectrum cannot be resolved even in the most advanced current global climate models and the effects of OGWs below the model's effective resolution must be supplemented to the dynamical core of the model by a parameterization scheme. Many OGW parameterization schemes have been developed to date and while they often share basic concepts, they may differ in the treatment of the subgrid-scale orography, in the variety of physical mechanisms considered and in selective tuning of the free parameters included in the scheme. As a result, the differences in parameterized OGW drag between the schemes translate into intermodel differences in dynamics and circulation. Here we use the WRF model to study the flow over isolated hills in an idealistic 2D and 3D set-ups in high-resolution and confront the resolved OGW fields and drag with the coarse resolution simulations and OGW drag estimates from a set of traditional OGW parameterization schemes employed in CMIP6 and applied to WRF in our case. Our results demonstrate the sensitivity of the parameterized OGW drag to the choice of the free parameters and highlight additional aspects of the resolved OGW field that should be considered for future development of the OGW parameterizations.

Key words: Orographic gravity waves, subgrid-scale orography, parameterization scheme, idealized WRF simulations, climate models.

Onsite

INVESTIGATING LEE WAVE TRAPPING MECHANISMS OVER THE UK AND IRELAND

Houtman Hette G.[1], Teixeira Miguel A.C.[2], Gray Suzanne L.[1], Vosper Simon[3], Sheridan Peter[3], van Niekerk Annelize[4]

[1]Department of Meteorology, University of Reading, Reading, United Kingdom of Great Britain and Northern Ireland; [2]CEFT, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal; [3]Met Office, Exeter, United Kingdom of Great Britain and Northern Ireland; [4]European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom of Great Britain and Northern Ireland

Although various lee wave trapping mechanisms have been studied theoretically since Lyra (1940), not much is known about the relative occurrence of these trapping mechanisms in the real world, or of their relative contribution to drag at low levels in the atmosphere. For this purpose, vertical atmospheric profiles are clustered here using self-organising maps. Because in-situ observations of trapped lee waves are scarce, these vertical profiles are extracted from the Met Office's convective-scale UKV model, which has previously been found to reproduce trapped lee wave characteristics accurately. We subsequently use the trapped lee wave identification model developed by Coney et al. (2023) and a linear Taylor-Goldstein equation solver to determine which vertical profiles are associated with trapped lee wave activity. The resulting momentum fluxes are extracted from the UKV model fields. We confirm that high low-level wind speeds are a necessary condition for the generation of trapped lee waves of substantial amplitude. We find that wind speeds increasing with height contribute to wave trapping in most cases. When using decision trees to predict trapped lee wave activity from vertical profiles, the inclusion of static stability as input does not significantly improve accuracy. The implications of these findings for the development of a trapped lee wave drag parametrisation scheme are discussed.
Key words: trapped lee waves, clustering, parametrisation

Online

NON-HYDROSTATIC EFFECTS OF MOUNTAIN WIDTH ON DOWNSLOPE WINDSTORM OCCURRENCE

Asano Yuki[1], Kusaka Hiroyuki[1]

[1]*Center for Computational Sciences, University of Tsukuba, Tsukuba, Japan*

This study investigates the influence of mountain width on the occurrence of downslope windstorms by deriving a theoretical solution for two-dimensional flow over an idealized mountain range, incorporating non-hydrostatic effects. The solution was validated through idealized numerical simulations. The proposed solution offers novel insights into the physical mechanisms governing mountain width effects following wave breaking. As mountain width decreases, the number of wave crests per unit horizontal distance increases, corresponding to a higher horizontal wavenumber. This leads to a lower vertical wavenumber and thus a longer vertical wavelength. The non-dimensional mountain height, defined using this vertical wavelength, is consequently reduced. A lower non-dimensional height suppresses the development of downslope winds after wave breaking. The analytical formulation extends local hydraulic theory into non- hydrostatic regimes, contributing to a deeper understanding of local wind systems. The numerical simulations supported the analytical findings. Narrow mountain ranges were found to require greater heights to induce downslope winds compared to wider ranges. Specifically, no downslope winds occurred after wave breaking in simulations involving narrow mountains of a certain height, whereas downslope winds occurred after the wave broke in the simulation with a wide mountain range of the same height.

Key words: Downslope windstorms, Mountain waves, Mountain width, Non-hydrostatic effects, Theory, Numerical Simulation

Onsite

DYNAMICAL MECHANISMS OF BACKGROUND WIND SHEAR WEAKENING THE SURFACE MOMENTUM FLUX OF OROGRAPHIC GRAVITY WAVES EXCITED IN UNIDIRECTIONAL FLOW OVER THREE- DIMENSIONAL MOUNTAIN

Wei Guorui[1], **Xu Xin**[1,2,3]

[1]Key Laboratory of Mesoscale Severe Weather/Ministry of Education and School of Atmospheric Sciences, Nanjing University, Nanjing 210023, Jiangsu, P. R. China, Nanjing, China; [2]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, P. R. China, Beijing, China; [3]Key Laboratory of Radar Meteorology, China Meteorology Administration, Nanjing 210023, Jiangsu, P. R. China, Nanjing, China

Orographic gravity waves (OGWs) are triggered when stably stratified flows are perturbed by topography. The gravity wave momentum flux (GWMF) at the surface is a key parameter in the parameterization of subgrid-scale OGWs for numerical weather prediction (NWP) and general circulation models (GCMs). For steady, hydrostatic and Earth-rotation-neglecting OGWs excited in horizontally homogeneous, unidirectional and constantly-sheared background flow over an isolated mountain, previous theoretical modeling and numerical simulation studies have shown that, the surface GWMF is aligned with the surface background flow, with its magnitude decreases as the background shear increases (i.e., Richardson number, Ri, decreases). However, the physical mechanism by which the surface GWMF is weakened by background shear remains unclear. Aiming to explore this, in this work the OGWs surface pressure perturbation is decomposed into two components corresponding to the two terms of the divergence equation obtained by combining the horizontal momentum perturbation equation and the mass continuity equation. The first component of surface pressure perturbation is related to the twisting effect. This component, although dominating the OGWs' surface pressure response to background wind shear at small Ri, does not affect the surface drag or GWMF due to its symmetry with respect to the topography. The other component of surface pressure perturbation is related to the advection of surface convergence by the background flow. Due to the asymmetric changes in surface convergence, the response of this component to background shear is biased toward the down-shear side of the mountain, resulting in a change in drag in the direction opposite to the background surface flow, thus weakening the surface GWMF. The interpretation of these results from the Fourier spectral perspective is briefly discussed. This work improves the understanding of the dynamics of OGWs in sheared background flow.
Key words: gravity waves, mountain waves, momentum flux, dynamical mechanism, spectral analysis

Onsite

IMPACT OF BLACK CARBON ON THERMALLY-DRIVEN VALLEY WINDS IN IDEALISED SIMULATIONS

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Thermally-driven valley winds are efficient in transporting pollutants, moisture and trace gases out from the valley atmosphere. Sensitivity of these winds to the shape and surface properties of the valley and synoptic-scale forcing has been studied by numerous measurement campaigns and modelling studies. In this study we investigate how light-absorbing aerosols affect the valley winds and transport in idealised simulations. Theoretically aerosol load can alter the thermally-driven winds by reducing the amount of solar radiation reaching the surface. However, the aerosol load can vary both vertically and horizontally which defines where the absorption and scattering of the incoming solar radiation occurs. This can lead to in-homogeneous heating rates, having simultaneously both cooling and warming effects within the boundary layer (BL). The effect of the aerosol load on these winds has not been studied systematically for mountain valleys in idealised model simulations - a shortcoming that is addressed in this study. As we investigate the direct radiative effect of the aerosols, we focus on black carbon (BC). BC is particulate aerosol which absorbs shortwave radiation efficiently and is mostly concentrated in the BL, as it is emitted to the atmosphere mainly from surface-based anthropogenic sources. For clarity, all the other aerosol compounds are set to zero in our simulations. We perform multiple simulations using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). WRF-Chem is run in LES mode with horizontal grid spacing of 200 meters. Along-valley inclination of the idealised valley topography is varied between the simulations. BC is initialised with a logarithmic vertical profile with highest concentrations near the surface and is not emitted during the simulation but can be removed by dry deposition at the surface. Reference simulations include model runs with the aerosol direct feedback switched off. Our preliminary results based on 12-hour long simulations show that the aerosol load weakens the daytime up-valley and up-slope winds. Although the BL is warmer than in the reference simulation, the temperature contrast between the valley atmosphere and the flat part of the model domain is in fact weaker. The weaker up-slope winds are likely caused by the reduced surface heating due to absorption of the solar radiation in the BL. However, more BC is ventilated out from the valley in the simulation with the aerosol direct feedback. An in-depth analysis of the winds and fluxes of BC are performed for extended simulations and will be presented at the conference.

Key words: Valley winds Mountain venting WRF-Chem Chemical transport model

Online

TEMPORAL AND SPATIAL EVOLUTION OF A LOCAL WIND IN JAPAN, "KIYOKAWA-DASHI": INSIGHTS FROM HIGH-DENSITY OBSERVATIONS AND NUMERICAL SIMULATIONS

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The Kiyokawa-dashi is a distinctive local wind observed over the small Shonai Plain in Japan, reaching its maximum intensity at the exit of the Mogami Gorge—a narrow valley, 1.5 km wide, cutting across a small mountain range approximately 0.4–0.8 km high and 10 km wide. Characterized by very strong winds that occasionally inflict significant damage on rice crops, the Kiyokawa-dashi is regarded as one of Japan's three most notorious local wind phenomena. Because it occurs in a genuinely small-scale topographic setting, it offers an excellent opportunity for unique observational studies and serves as an important natural laboratory for understanding the impact of complex terrain on airflow. This study investigates the spatiotemporal evolution of the Kiyokawa-dashi through high-density surface meteorological observations and numerical simulations. Near-surface observations, conducted with 17 anemometers spaced approximately 1 km apart, revealed that the typical Kiyokawa-dashi transitions from a localized event near the Mogami Gorge to a widespread phenomenon affecting the entire Shonai Plain over time. Numerical simulations using the Weather Research and Forecasting (WRF) Model were performed to explore the three-dimensional structure and dynamics of the transitional-type Kiyokawa-dashi. Both the simulation results and downslope windstorm theory suggest that, during the initial stage, airflow is channeled through the Mogami Gorge, confining strong winds near its exit. In the mature stage, however, airflow traverses both the mountains and the gorge, resulting in widespread strong winds across the plain. Additionally, the spatial characteristics of the Kiyokawa-dashi resemble those of classic foehn events, exhibiting features of a shallow foehn during its initial stage and a deep foehn during its mature stage. Furthermore, the study found that the Mogami Gorge plays a crucial role in accelerating the onset of the Kiyokawa-dashi. These findings offer new insights into the universality of topographic influences on airflow, demonstrating that even small-scale mountain-valley systems can produce dynamic effects similar to those associated with major downslope windstorms elsewhere in the world.

Key words: Kiyokawa-dashi, local wind, downslope windstorm, small-scale mountain range, level gap

Online

THE CHARACTERIZATION AND IMPACT OF EXTREME WINDS IN NARES STRAIT

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Extreme winds in the Arctic can affect sea ice flow, the formation of open-water areas called polynyas, ocean convection, and maritime and aviation activity. This work investigates a severe wind event that demolished a research ice camp in Nares Strait in April 2005. We aim to determine whether the event was extreme or typical for the region and quantify its exceptionality. Nares Strait is a long, narrow body of water between Ellesmere Island (Nunavut, Canada) and northwestern Greenland. There are steep mountains on both sides, significantly impacting meteorological phenomena and making it difficult to model weather events in the area accurately. Therefore, we used the new Copernicus Arctic Regional Re-analysis (CARRA) data with 2.5 km horizontal resolution, covering the period 1991-2022, to characterize the wind climate of the region. Our results indicate that the winds were extreme at specific points in space and time during the April 2005 storm, briefly exceeding the 95th percentile, although most winds did not exceed this mark. The re-analysis generally concurs with the oceanography camp's description of events, although some of the highest observed wind speeds were not captured in the dataset. This result has implications for future research expeditions and the Arctic Climate System because the wind in Nares Strait controls the flow of most old, thick sea ice that exits the Arctic.

Key words: extreme events, extreme wind, low-level jet, reanalysis, climate change, Arctic, sea ice, climate, climatology, extremes, Copernicus Arctic Regional Re-Analysis (CARRA), Canada, Greenland

Onsite

EXTREME WINDS IN EAST-ICELAND CAUSED BY MOUNTAIN WAVE BREAKING?

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On 5 February 2025, an intense cyclone moved north through the Greenland Strait. It was followed by another cyclone on 6 February, moving in its path. The cyclones caused very strong southwesterly and southerly winds over Iceland. Although the wind speed had in most cases a return period of less than five years, it is seldom to see such high wind speeds over the whole country within 24 hours. This windstorm was one of the strongest in the last few years. Wind speed exceeded 24 m/s at 140 weather stations on 5 February and 96 stations on 6 February. Highest wind gust measured was 66.3 m/s. The weather resulted in electrical disturbances, with the number of lightings being the highest ever measured in Iceland during winter, and damages all over the country. The weather was worst in the Eastfjords, especially in the fjord Stöðvarfjörður where a roof was blown of one house in the village and 10 other houses were damaged. The region has complex orography, with narrow fjords surrounded by steep mountains. Stöðvarfjörður is a west-east facing fjord, perpendicular to the wind direction of the event, and the village is on the northern shore. To the south of the fjord are complex mountains with steep peaks at 550 to 850 m a.s.l. In this presentation we will discuss this event in Stöðvarfjörður and if it might have been caused by breaking mountain waves into the fjord.

Key words: extreme winds, windstorm, mountain waves, wave breaking, complex orography, Iceland

Onsite

DEPICTION OF ROTORS OVER THE FALKLAND ISLANDS USING LIDAR AND VERY HIGH RESOLUTION SIMULATIONS

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The Falkland Islands are uniquely placed in the South Atlantic, representing a small area of significant orography of relatievly simple structure, within a flow which when northerly, is prone to very strong low level inversions leading lee waves, downslope windstorms, rotors and hydraulic jump-like features in the lee. The hazards associated with these flows impact the islands' main airport on East Falkland, and flow over the local hills has been the subject of numerous studies. Opportunities to study the flows have been greatly enhanced by the configuration of a 300 m resolution experimental quasi-operational configuration in 2019, running daily since then, and subsequently the installation of a scanning doppler lidar at the airport in 2022. Together with daily radiosonde releases and a surface station these provide a rich wealth of information at high spatial and temporal resolution, capable of revealing rotor flows in detail for scientific research and model verification purposes. Various angles of attack have been pursued to leverage these data for the purposes of improving knowledge and services, from case study comparisons by eye to machine learning, new diagnostic characterisations, etc., and we present the results of some of these, but there is much more to exploit.

Key words: turbulence, foehn, gap wind, wake, aviation, remote sensing

Forecasting and Verification

Onsite

FORECASTING SEVERE CONVECTIVE STORMS CLOSE TO COMPLEX TOPOGRAPHY - THE RELEVANCE OF THE TIM FIELD CAMPAIGN

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Severe thunderstorms are among the most damaging and impactful weather phenomena. In Europe, notable clusters occur in the vicinity of complex terrain. These areas not only experience frequent thunderstorms but also show a strong climate change signal with an increasing storm frequency. Despite the relevance of the subject, our understanding of severe convection in complex terrain remains incomplete. For forecasting, aspects of modification of pre-storm environments, convection initiation, storm-scale interactions with complex terrain, as well as innovative storm observations are of high relevance. Highlighting the gaps in our understanding, a recent white paper underscores the need for a coordinated European field campaign on Thunderstorm Intensification from Mountains to Plains (TIM). Initial plans for the TIM campaign are outlined and their relevance for forecasting discussed. Obtaining coordinated and dense data on orographically driven storms is a key step toward not only improving warnings and forecasts but also future climate projections, and adaptation measures.

Key words: Severe Thunderstorm Forecasting, Warnings, Forecasting Aspects of Field Campaign

Online

IMPROVEMENTS OF THE GERMAN FIRE WEATHER INDEX OF THE GERMAN METEOROLOGICAL SERVICE FOR THE APPLICATION IN MOUNTAINOUS REGIONS

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An increasing amount of evidence suggests that climate change affects fire weather dynamics in alpine and mountainous areas, which have historically seen less fire activity because of low temperatures and high humidity. The observed trends in the Alps - like earlier snowmelt, reduced snow cover, and prolonged dry periods - indicate a possible rise in fire weather conditions, including an increase in days with heightened fire risk. This paper compares the old and the new WBI (WaldBrandgefahrenIndex) of the German Meteorological Service and shows some aspects, developed as part of the project "WBI-Praxis", which can improve the practical application of the model, especially in mountainous and alpine regions. These include the topographically correction of incoming radiation, the change of the angle of incidence and shading effects. The slope inclination increases the spread of fire and changes the fire behavior. In addition, the use of raster data (ICON EU) is being tested in order to move away from station-based calculations. We consider our improvements to the WBI to be particularly relevant for high-altitude regions, where there are growing indications that anthropogenic climate change may influence fire regimes and present new challenges to ecological resilience and forest management.
Key words: fire weather index, fuel moisture, fire behaviour, fire intensity

Onsite

MACHINE LEARNING IN POSTPROCESSING OF NUMERICAL WEATHER PREDICTION AND DATA FUSION FOR HYPERLOCAL SHORT-TERM WEATHER FORECAST – INTERNATIONAL HACKATHON PERSPECTIVE

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It is evident that extreme weather events are becoming increasingly frequent and of increased impact, resulting in a growing need for more accurate real-time updated weather prediction where short term weather forecasting (nowcasting) is gaining critical importance. With availability of real-time open-source data such as Numerical Weather Prediction (NWP) forecasts, satellite and weather radar imagery, and localized weather measurements, new and interdisciplinary possibilities are emerging in the way weather forecasts are generated. Multi-modal real-time data can be paired with machine learning approaches to improve the accuracy and reliability of weather predictions. A new perspective on pairing information and communication technologies (ICT) with meteorology expertise offers significant opportunities in improving or transforming weather forecasts by what is generally referred to as artificial intelligence (AI). A broad overview of the approaches in curation of datasets, machine learning (ML) models and end-use cases is established and compared through organization of an international hackathon “AI in Enhanced Weather Forecasting”, with the next stage now supported by international associations and competition platforms. The results showed the possibility of notable improvements in particular weather variables, such as air temperature or relative humidity, and challenges in others, such as precipitation. The approach is tested on six variables in three biomes as case studies in Europe, Middle East and Africa. These learnings and experiences are the steering premises of the proposed area of research, aimed to enhance international capacity of AI in meteorological services, in the context of international collaboration, initiatives and knowledge exchange. The focus is the downscaling of short-term numerical weather forecasts to hyper- and sub-local areas based and enable utilization of multimodal data. This paper provides a comprehensive analysis and presents findings, results and conclusions of an international hackathon-style competition that gathered 10,000 views and evaluated 16 teams. It elaborates innovative methodologies of best three participating teams from Jordan, Egypt and United Kingdom, together with a Croatian benchmark of two regional clusters with 12 weather stations. State-of-the-art ML algorithms, including gradient boosting and transformer-based models, will be presented. The Paper will elaborate methodology and present validation of 7-day hourly resolution predictions reaching 80-97% accuracy, as significant improvement compared to regular NWP.

Key words: Machine Learning, Data Fusion, Hyper-local forecasting, Hackathon

Onsite

MULTI-STEP MULTIVARIATE WEATHER FORECASTING USING TWO- LAYER NEURAL NETWORKS: A CASE STUDY OF PINCHER CREEK

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Accurate weather forecasting plays a crucial role in various sectors, including agriculture, transportation, and disaster management. This study focuses on multi-step, multivariate weather forecasting by simultaneously predicting three key meteorological parameters—temperature, relative humidity, and wind speed—in the Pincher Creek region. The dataset comprises hourly records from 2011 to 2024, amounting to 110,882 valid samples after preprocessing. To evaluate the model's performance, the data was split into 70% training, 30% testing, and the last 1,000 records were designated for extrapolation. The proposed framework employs 15 two-layer neural networks, each receiving historical values of the three target variables at three consecutive time steps (t–2, t–1, t) and forecasting a single future time step. Five models predict temperature, five predict relative humidity, and five predict wind speed for time steps t+1 through t+5. These outputs are then integrated to generate simultaneous multi-step forecasts. A rigorous training and validation process, including cross-validation techniques, was conducted to enhance model accuracy and reduce overfitting. Experimental results indicate high forecasting accuracy for temperature, with a slight decline in performance for relative humidity and wind speed as the forecasting horizon extends. The framework demonstrates strong short-term prediction capabilities, while long-term forecasts present inherent challenges due to increasing uncertainty. Overall, the study highlights the effectiveness of two-layer neural networks in capturing complex weather patterns and provides valuable insights for improving future forecasting models.

Key words: Weather Forecasting, Simultaneous Prediction, Two-Layer Neural Networks, Multivariate Prediction, Pincher Creek

Onsite

VERIFICATION AND SPATIAL AUTOCORRELATION OF MODEL PRECIPITATION PREDICTIONS IN RELATION TO RAINGRS COMPOSITES: A CASE STUDY OF THE SEPTEMBER 2024 FLOOD IN POLAND

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In September 2024, southern area of Poland experienced an intense flood event, posing a challenge for precipitation forecasting models. This study evaluates the predictive performance of COSMO and ICON models run operationally at IMGW-PIB compared to the RainGRS precipitation composite, with a focus on catchment. The assessment includes an examination of the spatial autocorrelation and the impact of employed weighted RMSE and MAD metrics on evaluated model forecast accuracy. The results reveal significant differences in the spatial accuracy of forecasts and highlight the advantages of using weighted error measures. The findings provide valuable insights for improving precipitation forecasting and flood risk management.

Key words: forecast verification, extreme precipitation, spatial verification, spatial autocorrelation

Onsite

ENHANCING WIND SPEED FORECASTING OVER THE COMPLEX TERRAIN IN CROATIA

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Croatia is characterized by a combination of mountainous landscapes and coastal areas with frequent episodes of strong winds like the bora or jugo. In regions with such high terrain complexity, forecasting challenges are particularly pronounced. Rapid wind changes typical of the bora wind, along with localized wind extremes driven by orographic effects, pose an ongoing challenge for Numerical Weather Prediction (NWP) models. Reliable post-processing techniques are therefore essential to mitigate these limitations. At the Croatian Meteorological and Hydrological Service (DHMZ), post-processing techniques are employed to enhance raw NWP outputs by correcting systematic model biases. The analog method, a statistical technique that searches historical dataset for forecasts similar to the current one, is currently operational and has proven effective at improving wind speed predictions. However, while it reduces systematic NWP errors such as bias of the mean, it tends to underestimate wind variability and thus sometimes underperforms in cases of rare (and extreme) wind speeds. This is partly due to the method's inherent limitation when dealing with rare events: with an insufficient number of similar high-value cases in the historical training dataset, the fixed ensemble size (15 members) leads to averaging with more frequent lower values, effectively smoothing out the extremes and biasing the forecast toward climatological means. As a workaround to this issue, we applied a high wind speed correction method previously proposed in related studies. While it led to improved performance in the highest wind categories, the approach relies on a post-processing adjustment applied only to values exceeding a fixed threshold, rather than resolving the underlying scarcity of extreme events in the training data. Recently, we developed the Adaptive Analog Ensemble Sizing Algorithm (ADANESA) to exploit the ensemble potential of the analog method more effectively. ADANESA dynamically adjusts the number of analogs based on forecasted wind speed, tailoring the ensemble size depending on the severity of the forecasted wind. It has demonstrated strong potential and, when combined with high wind speed correction, often outperforms corrected analog- method-based forecasts with fixed ensemble size, as measured by rigorous skill scores such as the Extremal Dependency Index (EDI). It can be concluded that this adaptive ensemble sizing approach improves the analog method's ability to represent rare, high-impact events, contributing to better early warnings, risk assessment, and decision-making. Such enhancements are particularly valuable for Croatia, where strong coastal and mountain winds regularly impact infrastructure, renewable energy production, and transportation.

Key words: Post-processing, Analog method, Complex terrain, Wind speed, Croatia

Onsite

OPERATIONAL FORECASTING CHALLENGES OF BORA WIND EVENTS FOR EASTERN ADRIATIC AIRPORTS

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Majority of Croatian airports are located at the eastern Adriatic coast and are often affected by well known bora winds. Depending on the large-scale dynamics we differentiate main bora types: anticyclonic, cyclonic and frontal bora, as well as shallow and deep bora. Due to its strong and gusty winds, bora poses significant safety risks especially at the airports where its flow is perpendicular to the runway, i.e. at Rijeka and Dubrovnik. Accurate forecasting of bora flow at these airports presents significant challenges. There are several known factors that make accurate bora forecasting complicated. The complex orography in the lee of the Dinaric Alps, with steep slopes and narrow mountain passes, creates considerable variability in wind patterns, including bora's sudden onset and intense gusts. Additionally, local topographic features induce significant variations in the intensity and direction of bora wind, which is most pronounced at Rijeka and Dubrovnik airports. For example, bora flow with an elevated jet-like profile is the most challenging to forecast since rotors occur frequently. The formation of rotors is also present at both airports during deep bora which makes wind fields very inhomogeneous due to strong directional wind shear which presents significant hazard to aviation. Due to these factors the traditional numerical weather prediction (NWP) models are struggling to accurately simulate fine-scale details of bora flow. In this work, we use wind profiles from ALADIN (Aire Limitée Adaptation dynamique Développement International) NWP model to determine the type of the flow (shallow, deep or elevated jet bora) as well as wind observations at the airports (METAR). Aerodrome wind forecasts (TAF) are verified compared to METAR observations. The results indicate that the model underestimates surface wind speed for all bora types. The accuracy of wind forecasts generally improves for airports located further from complex terrain. The analysis shows that the shallow frontal bora type is the most likely to produce extreme wind records. For shallow bora the maximum wind speed in the modeled wind profile can successfully be used to forecast maximum wind gusts, while the mean wind speed is 1.6 to 2 times less than the wind gusts. For deep or elevated jet types, the relationship is not this straightforward. Verification results show that while the mean wind speed is well forecasted, the wind gust forecasts are more challenging, especially at Rijeka and Dubrovnik airports.

Key words: wind forecasting, bora flow, aviation, verification

Onsite

DYNAMIC AND STATISTICAL ANALYSIS OF GIANT HAIL ENVIRONMENTS IN NORTHEAST ITALY

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On July 24, 2023, the new European record for hail size was set in northeast Italy with a 19-cm wide hailstone recorded during a supercell outbreak. During this event, severe storms were triggered in the Alps, moved eastward, intensified rapidly in the foothills, and generated damaging hailstorms in the plains. A detailed analysis of the available observations and numerical simulations highlights that the atmospheric environment was unusual. A tongue of warm and moist air over the Adriatic Sea was lifted by a southerly flow above the cold pool generated by the thunderstorm outflow associated with an initial supercell. This raised the air associated with the most unstable layer to 1–2 km above mean sea level in the area affected by the hailstorm. The vertical profile was characterized by moderate potential instability and intense southwesterlies in the mid-troposphere. Additionally, there was anomalously high water-vapor transport in the layer 2–5 km above mean sea level. Consequently, high instability seems unnecessary for the occurrence of giant hailstorms in the region. This hypothesis is assessed with a statistical analysis performed for the 2018–2023 period in the region using hail reports and observed soundings. The results show that hail size has a much lower correlation with potential instability compared with mid-troposphere kinematic parameters and water-vapor transport. Furthermore, thermodynamic parameters have better skill in predicting normal-to-large hail, while mid-troposphere kinematic parameters are better predictors for very large-to-giant hail events.

Key words: complex orography, hail, instability indices, severe storms, statistical regression and classification

TEAM and other Field Campaigns

Onsite

HIGH RESOLUTION METUM FORECASTS OVER ALPS DURING TEAMX

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The Multi-scale Transport and Exchange processes in the Atmosphere over Mountains — programme and eXperiment (TEAMx) is a comprehensive multi-national field campaign taking place over the Alps involving many in situ, remote sensing, sounding and aircraft platforms and aimed at characterising the huge impact mountain ranges have on the weather and climate locally and remotely, and driving forward model physical parametrisation development for complex terrain. As part of the forecast provision to guide deployments during the campaign, a 1 km Met Office Unified Model (MetUM) configuration was run quasi-operationally, and its output broadcast, for the duration of the campaign, alongside other centres' equivalent models. This yielded a large dataset of variables for studying atmospheric processes, comparing the model against the TEAMx observations and other models, optimising the configuration, and learning important lessons on generic and model-specific performance in such highly complex, dramatic terrain. The configuration forms a starting point for research configurations at 1 km and finer resolution, to which the lessons learnt can be taken forward, and examples of sub-km output will be presented. These research configurations are being developed in partnership with the TEAMxUK grant consortium and used by Met Office and academic scientists for TEAMx-related work, and some case study results will be presented.
Key words: Foehn, windstorm, cold air pool, stable boundary layer, exchange, lee wave

Onsite

EVALUATING CONVECTIVE CLOUDS AND PRECIPITATION IN ICON USING DEEP LEARNING AND HIGH RESOLUTION OBSERVATIONS

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Due to climate change, the severity of storms, particularly in the Alpine region, is expected to increase. At the same time, the current models' ability to accurately predict extreme rainfall in complex terrains remains limited. Concurrently, the World Climate Research Programme highlights gaps in observing, understanding, and modeling precipitation, particularly over mountainous terrain. To reduce the modeling and observational gaps over orography, the year-long TEAMx measurement campaign took place over the Alps in 2024/2025. In the region around Bolzano, a complete setup of ground-based profiling instruments was located during the summer of 2025 to detect convection onset and precipitation variability with elevation. Beyond the local observations, the new Meteosat Third Generation (MTG) Flexible Combined Imager (FCI) observations with improved temporal and spatial resolution are available over the area. In this contribution, we propose an approach to evaluate numerical weather prediction's ability to produce realistic cloud spatial structures using a self-supervised deep learning framework trained on satellite data. Once trained with 10.8, and 6.2 microns brightness temperatures, the algorithm creates a feature space where cloud classes are clustered based on semantic similarities. We then use the feature space to evaluate the ICON-GLORI model by simulating the satellite channels from the ICON-GLORI runs for significant case studies. In our results, we characterize the obtained cloud classes in terms of cloud properties (cloud optical depth, cloud phase, cloud top height) and precipitation amounts using satellite observations. Then, the simulated satellite channels get classified by the algorithm to verify, also exploiting the additional ground-based datasets, if similar cloud patterns were generated in analogous conditions. We can in this way characterize the evolution of relevant case studies collected during the TEAMx campaign over the Bolzano region in model and observations, highlighting relevant aspects of the spatiotemporal evolution of the observed cloud properties.

Key words: Convection, Infrared Imagery, Model Evaluation, Precipitation, Deep Learning, Self-supervision, Ground-based profiling

Online

DISENTANGLING MECHANISMS CONTROLLING ATMOSPHERIC TRANSPORT AND MIXING PROCESSES OVER MOUNTAIN AREAS AT DIFFERENT SPACE- AND TIMESCALES: PRELIMINARY RESULTS FROM THE FIELD CAMPAIGNS OF THE PROJECT DECIPHER.

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Two major field campaigns were performed in the summer of 2024 at two selected sites in the eastern Italian Alps under the project DECIPHER (Disentangling mechanisms controlling atmospheric transport and mixing processes over mountain areas at different space- and timescales). The project was ancillary and preliminary to the intensive observing period envisaged by the international research initiative TEAMx (Multi-scale transport and exchange processes in the atmosphere over mountains — programme and experiment). The first site was near the peak of Col Margherita, in the area of the eastern Dolomites, where a permanent monitoring station is operated by the Institute of Polar Sciences for monitoring atmospheric pollutants, and in particular particulate matter and mercury, besides a conventional weather station for standard meteorological variables. The second site was the east-facing sidewall of Monte Baldo, a 70-km long north-south oriented mountain range east of Lake Garda in the southern Prealps, on a slope spanning an altitude that ranges from the slope foot at 1400 m ASL to the top at 1670 m ASL. The results of these campaigns were a useful preliminary exercise for the full campaigns to be held under the TEAMx Special Observing Period in the Summer of 2025. For the latter, all instruments were concentrated at the Monte Baldo site at three different levels: a) at the top crest, b) at mid-slope, as for 2024 campaign, and c) at the slope feet. Preliminary results from all the above campaigns will be presented as well.

Key words: Slope winds, turbulence, pollutant transport.

Onsite

INVESTIGATING THE SURFACE ENERGY BALANCE CLOSURE OVER MOUNTAIN AREAS: RESULTS FROM THE INTERFACE PROJECT

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This contribution presents an overview of the activities and results of the INTERFACE project. The project aims to quantify the non-closure of the surface energy balance at different sites in the Alpine environment, where processes related to the lack of closure, i.e., advection due to the development of thermally-driven circulations, are expected to be particularly significant. This objective is addressed by combining flux station and unmanned aerial system (UAS) measurements. The use of the UAS allows spatially distributed measurements around the eddy-covariance sites, which are crucial for the estimation of advection. The analysis of eddy-covariance data from various sites representative of different Alpine contexts (e.g., valley floor, valley slope, mountain top) and climatic settings (North and South of the main Alpine crest) allows a systematic quantification and comparison of the characteristics of the surface energy balance, including the lack of closure. Particular attention is given to the evaluation of the role of thermally-driven circulations in the non-closure of the surface energy balance, selecting, by means of objective criteria, days with well- developed slope and valley circulations. The INTERFACE project contributes to the TEAMx international research programme, which aims to improve our understanding of exchange processes in the atmosphere over mountains.
Key words: surface energy balance, eddy-covariance, unmanned aerial system, TEAMx

Onsite

VALLEY WINDS AND RIDGE SCALE TURBULENCE INFLUENCES ON ALPINE BOUNDARY LAYER AND SURFACE FLUXES

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We have examined two years of field campaign measurements from the Surface Atmosphere Integrated Laboratory (SAIL) and the Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology (SPLASH) field campaigns to evaluate the sensitivity of surface fluxes and boundary layer development to valley scale thermally driven flows and ridge height turbulence in the East River basin in Colorado. We compare a high-resolution LES simulation of eddies downwind of Gothic Mountain with doppler lidar scans of similar turbulent structures in the real atmosphere to better understand how ridge height turbulence erodes the deep valley surface layer setup by katabatic flow. We also evaluate the strength of both katabatic and anabatic flows at multiple stations along the valley axis to understand better understand how snow cover influences the valley wind field and thus surface fluxes. We quantify connections between the ridge height cross-valley turbulence with near surface turbulence. These findings illustrate the importance of considering the three-dimensional valley system as a whole when evaluating even local turbulent flux measurements.

Key words: boundary layer, field campaign, turbulence, katabatic, anabatic

Onsite

LIAISE-2021 CAMPAIGN: IRRIGATION IMPACT ON BOUNDARY LAYER AND PRECIPITATION CHARACTERISTICS IN WRF MODEL SIMULATIONS

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The Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE) campaign examined the impact of anthropization on the water cycle in terms of land-atmosphere-hydrology interactions. The objective of this study is to assess the effects of irrigation on the atmosphere and on precipitation in WRF model simulations during the LIAISE Special Observation Period in July 2021 (LIAISE- 2021 SOP). Comparisons between simulations and observations show better verification scores for air temperature, humidity and wind speed and direction when the model included the irrigation parameterization, improving the model warm and dry bias at 2 m over irrigated areas. Other changes found are the weakening of the sea breeze circulation and a more realistic surface energy partitioning representation. The boundary layer height is lowered in the vicinity of irrigated areas, causing a decrease in the lifting condensation level and the level of free convection, which induce increases in CAPE and CIN. Precipitation differences between simulations become relevant for smaller areas, close to the irrigated land. When convection is parameterized, simulations including irrigation tend to produce a decrease in rainfall (negative feedback) while convection-permitting simulations produce an increase (positive feedback), although the latter underestimates substantially the observed precipitation field. In addition, irrigation activation decreases the areas exceeding moderate hourly precipitation intensities in all simulations. There is a local impact of irrigated land on model-resolved precipitation accumulations and intensities, although including the irrigation parameterization did not improve the representation of the observed precipitation field, as probably the precipitation systems during LIAISE-2021 SOP were mostly driven by larger scale perturbations or mesoscale systems, more than by local processes. Results reported here not only contribute to enhance our understanding of irrigation effects upon precipitation but also demonstrate the need to include irrigation parameterizations in numerical forecasts to overcome the biases found.

Key words: boundary layer, irrigation, convection, WRF

Onsite

THE TEAMX OBSERVATIONAL CAMPAIGN

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TEAMx (Multi-scale transport and exchange processes in the atmosphere over mountains — programme and experiment) is an international research program that focuses on improving our understanding of atmospheric transport and exchange processes over complex terrain and at evaluating and improving the representation of these processes in numerical weather and climate prediction models. One pillar of the TEAMx program is a one-year long observational campaign to collect a unique dataset that can be used to address the research goals. The TEAMx Observational Campaign (TOC) started in September 2024, with observational activities taking place in four target areas arranged in an approximate north-south transect trough the Alps. In addition to long-term monitoring using continuous measurements at multiple locations throughout the entire TOC, two six-week long extensive observational periods (EOPs) were conducted. The two EOPs, one in winter (wEOP) and one in summer (sEOP), were designed to target specific processes, with a high density of observations at individual supersites located in the TEAMx domain. The activities focused on, for example, the mean and turbulence characteristics of katabatic and anabatic winds, the three-dimensional structure of the mountain boundary layer at different spatial scales, the initiation and development of orographic convection, and the structure of gravity waves. To address these research topics, a suite of observational tools was applied, including research flights with three aircraft, radiosonde launches from multiple locations, UAS flights, a range of different remote-sensing instrumentation to capture the vertical wind and temperature profiles throughout the TEAMx domain, and networks of weather and turbulence stations. In addition, the observational activities were supported by dedicated high-resolution forecast runs from several European weather services to provide guidance for daily IOP decisions. The presentation will give an overview of the research goals for the TOC, its design and observational activities, and some first and preliminary results.

Key words: exchange processes, mountain boundary layer, field campaign

Onsite

ON THE MOUNTAIN BOUNDARY LAYER (MOBL) HEIGHT

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Over complex, mountainous terrain, the lowest layer of the atmosphere has to be considered as the 'Mountain Boundary Layer '(MoBL). Different to the 'atmospheric boundary layer' (ABL), its counterpart over flat terrain, the MoBL is characterized by intrinsic horizontal heterogeneity, three-dimensionality and failure of many of the well-known boundary layer parameterizations. Even if horizontally inhomogeneous — or maybe even more so because it is horizontally inhomogeneous - the MoBL height remains a key property to characterize the MoBL. While the ABL height is generally defined on the basis of turbulence — either a Richardson number criterion, the magnitude of, e.g., turbulence kinetic energy, or the effect of turbulent mixing in the potential temperature profile — such a definition needs to be extended over mountainous terrain. For the ABL, the 'mixing property' is taken into account when using turbulence as a defining process, since turbulence is the mixing agent. For the MoBL, mixing also occurs through the interaction with meso-scale flows such as valley/slope winds or downslope windstorms (which originate due to orography themselves). In this contribution, different approaches to define a MoBL height will be presented and discussed. Examples of ABL height diagnostics in complex terrain will be compared to MoBL heights and conditions identified under which differences can be expected to be most important.

Key words: complex terrain, terrain-atmosphere exchange, horizontal inhomogeneity

Onsite

LINKING VALLEY FLOW AND VERTICAL EXCHANGE IN COMPLEX TERRAIN – THE LIVAVERT(EX)² PROJECT

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Quantifying the exchange of mass, momentum and energy between the earth's surface and the atmosphere is pivotal for the understanding and prediction of weather and climate processes. Due to the superposition of horizontal and vertical transport, exchange processes in complex terrain are especially efficient and important. This contribution presents a new project embedded in the international TEAMx campaign. The LIVAVERT(EX)² project - linking valley flow and vertical exchange in complex terrain - focuses on observing exchange processes in the Sarntal Alps region, a local hotspot of convection initiation in the Alps. As part of the project, a novel airborne Doppler lidar (ADL) is deployed for the first extended measurements in complex terrain. Thereby, 3D wind observations are available at 100 m along-track and vertical resolution, providing spatially resolved insight into valley wind systems and vertical exchange. The variability observed across repeated flights enables the differentiation between recurring and transient features. TEAMx also encompasses a KITcube deployment in the Sarntal Alps region, which establishes an extensive meso-scale ground-based Doppler lidar (GDL) network. Through the comparison of ADL and GDL observations of valley flow, the Doppler lidar wind profiling accuracy and representativeness can be validated. Additionally, new ways to validate existing GDL-based volume flux estimation methods are created. Combining volume flux budget and direct vertical exchange observations allows a more quantitative insight into valley flow and its relation to convective initiation over the surrounding mountains than ever before. Overall, the LIVAVERT(EX)² project aims to improve our understanding and the prediction of atmospheric processes in complex terrain.

Key words: TEAMx, airborne research, Doppler lidar, complex terrain, convection initiation, boundary layer meteorology

Onsite

THREE-DIMENSIONAL TURBULENCE CHARACTERISTICS IN A SMALL ALPINE VALLEY MEASURED WITH A FLEET OF UNCREWED AERIAL SYSTEMS DURING TEAMX

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Exchange of energy and momentum in the atmospheric boundary layer (ABL) over horizontally homogeneous and flat terrain happens mainly by turbulence. In complex terrain, especially in the mountain boundary layer (MoBL), further processes contribute to the exchange, and the 3D structure of turbulence can be more complicated. Most model parameterizations do not reflect these processes and the turbulence characteristics of the MoBL correctly which can lead to deficient weather forecast quality in mountainous regions. To improve parameterizations, a deeper understanding of the spatio-temporal structure of turbulence in the MoBL is required, which can be achieved through a combination of observations and simulations. From an observational perspective, it would be ideal to perform measurements with high spatial and temporal resolution at all relevant scales reaching the MoBL height across different mountainous areas. To investigate the scales that appear within a small valley, a fleet of uncrewed aerial systems (UAS) was deployed at the Alpine pasture Nafingalm during multiple campaigns in the framework of TEAMx. The utilized drone fleet, comprising 45 drones from two generations, is part of DLR's so-called SWUF-3D fleet. The first generation includes 34 drones, allowing flight times of up to 25 minutes. The second generation of 11 UAS allows flight times over 60 minutes at slightly reduced wind resistance. Both types allow 3D wind measurements and are equipped with fast temperature sensors and a state-of-the-art capacitive humidity sensor. In autumn 2024, a maximum of ten UAS simultaneously was in operation. In one flight pattern, eight drones hovered at the corners of a cube to derive two-point correlation in three dimensions and at different flight heights. In a different flight pattern, a line of ten drones along the valley axis was set up in linear and logarithmic separation to derive the spatial structure function and visualize the spatial propagation of gusts within the valley. For the TEAMx summer campaign in 2025, flight patterns were refined and up to 30 drones including both generation types were planned to fly synchronously to span a wider area and capture even larger turbulent eddies in the valley. The measurement strategy and first results of the fleet data analysis will be presented in this contribution.

Key words: TEAMx, mountain boundary layer, turbulence, UAS, drone fleet

Online

MOUNTAIN BOUNDARY LAYER OBSERVATIONS IN THE INN VALLEY EXIT AREA DURING THE TEAMX SUMMER EOP

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The Inn valley in the European Alps is well known for its frequently occurring thermally driven winds under clear high-pressure weather conditions. During night time a strong down-valley flow of up to several hundred meters can be observed in the valley exit area, referred to as ‘Inn valley exit-jet’. This contribution describes measurements of the atmospheric boundary layer structure and the Inn valley exit-jet that will be conducted during the TEAMx Extensive Observation Period (EOP) in summer 2025. The measurements include data collection from 5 automatic weather stations, a Doppler wind lidar, mobile radiosonde systems, meteorological drones, and an instrumented car. The presentation of preliminary results will include the diurnal boundary layer development and the along-valley differences of near surface variations of pressure, air temperature, wind speed and wind direction between the Inn valley and the adjacent Bavarian foreland, as well as vertical profiles of these parameters.
Key words: TEAMx, Inn Valley Target Area, measurement campaign, atmospheric boundary layer, mountain winds, valley exit-jet

Onsite

IN SITU OBSERVATION OF TURBULENCE IN KATABATIC AND ANABATIC WINDS ON STEEP SLOPES FROM THE AUSTRIAN TO THE ITALIAN ALPS.

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The present study is part of the international TEAMx project for the observation of mountain meteorology in the European Alps, with a focus on exchange processes on complex topography https://www.teamx- programme.org . The focus here is on two opposing aspects of the atmospheric boundary layer: diurnal (anabatic) and nocturnal (katabatic) slope winds and their contribution to turbulent mixing processes in alpine terrain. This is a multi-scale issue, from surface boundary layer turbulence to the triggering of vertical convection in the diurnal anabatic case, and concerns air mass, momentum and heat transport and exchange processes. There are few observations of these processes in mountainous terrain, particularly within a collaborative integrative framework such as that proposed by the TEAMx 2025 observation campaign, which is spread over two periods, winter and summer. The focus here is on katabatic episodes observed on the alpine slopes of the Innsbruck valley, Austria, from 13 January to 28 February 2025, followed by anabatic episodes observed on the alpine slopes of Monte Baldo in the Adige valley, Italy, from 16 June to 25 July 2025. High frequency resolution pitot probes (1.5 KHz) will be used to reconstruct the 3D turbulent field in the surface layer from z=2mm up to a height of 2m from the ground. These measurements will be used to study the behaviour of the turbulent boundary layer on steep Alpine slopes, in particular its deviation from logarithmic laws on flat ground due to the buoyancy effect. Particular attention will be paid to comparing anabatic and katabatic configurations. Fine-scale field measurements will be compared with results obtained on the same slopes by teams from the University of Innsbruck and the University of Trento, respectively. In addition, meteorological models are particularly sensitive to surface conditions, so we need a better understanding of the processes involved in order to improve parameterisation, particularly in mountainous areas. Finally, the impact of these processes, which initiate phenomena on a larger scale, particularly deep convection, is crucial and needs to be better described in order to improve climate models and better predict the mechanisms of climate change in the long term.

Key words: katabatic winds, anabatic winds, turbulence, atmospheric stable boundary layer

Onsite

PRESSURE SPECTRA AND PRESSURE–TURBULENCE COUPLING IN WINTER SLOPE-FOLLOWING ABL FLOWS: INSIGHTS FROM THE TEAMX CAMPAIGN

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Turbulent pressure fluctuations play a key role in Atmospheric Boundary Layer (ABL) flow dynamics, yet remain poorly characterized compared to their velocity counterparts. In particular, their contribution to the return-to-isotropy process, through the pressure–strain correlation term in the turbulent kinetic energy (TKE) budget, and to the coupling between different turbulent scales is still not fully understood. This gap largely reflects the experimental and practical challenges of capturing high-frequency pressure fluctuations under real atmospheric conditions, which have constrained the development of a comprehensive theoretical framework for pressure. As part of the TEAMx (multi-scale transport and exchange processes in the atmosphere over mountains — programme and experiment) observational campaign, we conducted an intensive field study on a steep alpine slope (average inclination ~26°) during winter. The site (a meadow alternately snow-covered and grassy) was characterised by frequent shallow katabatic flows and intermittent foehn events, providing an ideal natural laboratory to investigate pressure fluctuations in slope-following turbulent flows. We deployed eight high-resolution nanobarometers and eight sonic anemometers on six 3-metre towers arranged in two cross-slope transects of three. All the instruments captured turbulent fluctuations at 20 Hz resolution. This enabled simultaneous measurement of pressure and velocity at multiple vertical and horizontal locations. Our initial analysis comprised one- dimensional pressure spectra, pressure–velocity and pressure–temperature co-spectra, and the corresponding phase shifts. In this work, we place particular emphasis on pressure–turbulence coupling, examining its impact on energy redistribution among the velocity components. Preliminary results reveal that the observed pressure spectra, within the inertial subrange, consistently deviate from the classical Kolmogorov ~$k^{-7/3}$ power-law scaling of isotropic, homogeneous turbulence in a way that the spectral slope is a function of wind speed. This suggests the presence of terrain-induced and stratification-related modifications to the turbulent cascade.

Key words: pressure, nanobarometer, katabatic flows, sonic anemometers, TEAMx, turbulent measurements, spectra, observations

Onsite

OBSERVING MULTISCALE INTERACTIONS IN A SMALL ALPINE VALLEY DURING TEAMX: OVERVIEW AND FIRST RESULTS

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The mountain boundary layer (MoBL) is shaped by a multitude of atmospheric processes spanning a wide spectrum of scales. Temperature and humidity structure within valleys are determined not only by turbulent transport of heat and moisture but also by advective transport caused by local and regional winds, where slope and valley winds play a crucial role. More recently, however, it has been shown that regional winds, such as the mountain-plain wind circulation and foehn, can interact with these local winds and fundamentally alter the MoBL structure within the valley compared to conceptual or idealized models that do not account for these multiscale interactions. Hence, to better understand the multitude of these processes and their interactions — crucial for improving boundary layer parameterizations — a field campaign within the TEAMx programme and experiment was conducted in summer 2025 in a small Alpine valley, the Weer Valley (Austria), at the mountain pasture Nafingalm. This location is frequently affected by scale interactions because regional winds can easily flow over the so-called Geiseljoch saddle and interact with the valley atmosphere. The base instrumentation, operated for approximately six weeks (the summer Extensive Observation Period, sEOP), consisted of three Doppler wind lidars, ten automatic weather stations, and one eddy-covariance station. During selected days, so-called Intensive Observation Periods (IOPs), a fleet of uncrewed aircraft systems (UAS) was deployed to observe the spatial characteristics of turbulence. Flyovers by two research aircraft on IOP days, along with radiosonde ascents and additional TEAMx instrumentation in the Inn Valley, helped place the local measurements into a broader regional context. This presentation will provide an overview of the campaign, focusing on lidar and weather station observations, present initial results, and briefly outline future high-resolution modeling efforts to better understand scale interactions in complex terrain.
Key words: TEAMx, mountain boundary layer, scale interaction, thermally-driven winds, dynamically-driven winds, field campaign

Onsite

INVESTIGATING FLOW CONDITIONS DURING THE TRANSITION FROM PRE-CONVECTIVE TO CONVECTIVE SITUATIONS IN THE SARNTAL ALPS AND THE ADIGE VALLEY USING NOVEL OBSERVATION SYSTEMS

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Long-term investigations of convective initiation (CI) regions in the Alps have identified the Sarntal Alps in South Tyrol as the only inner-Alpine hotspot for convection. In particular, the western part of this north-south oriented mountain range, bounded by the Adige and Passeier valleys to the west, shows a distinct maximum in CI frequency. This study aims to gain a deeper understanding of the transformation of the valley atmosphere in the Adige Valley from pre-convective (stable) to convective (unstable) conditions. To support this, newly developed low-cost sensors designed for very high-frequency (100 Hz) three-dimensional wind measurements are deployed as mobile meteorological stations. These sensors are installed on the Meran 2000 gondola line, which runs from Meran up to the western ridge of the Sarntal Alps, as well as on a vehicle that repeatedly travels along the Adige Valley between Merano and Bolzano. The instruments are operated during the Extended Observing Period (EOP) of TEAMx, from 16 June to 25 July 2025. Continuous, high-resolution wind measurements along the gondola line during operating hours provide detailed insights into the temporal evolution of slope wind profiles throughout the day. Since the sensors also measure temperature, humidity, and pressure, the study includes thermodynamic analyses. Wind data collected from the vehicle enable the identification of valley flow patterns, especially up-valley and down-valley flows associated with convergent or divergent zones, which can then be analysed in the context of CI processes." Initial findings from this experimental setup will be presented.

Key words: Convection initiation, slope winds, valley winds, high-resolution wind measurements

Onsite

DOPPLER LIDAR VOLUME FLUX OBSERVATIONS IN A BROAD ALPINE VALLEY

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This contribution presents a methodology for estimating volume fluxes associated with local winds in an Alpine valley using ground-based Doppler lidar data. A prototype retrieval is applied to data gathered during the TEAMx pre-campaign in the Inn Valley in September 2024. The methodology serves as a precursor to the LIVAVERT(EX)² campaign within TEAMx, refining measurement setups and diagnostics in complex terrain. The valley volume flux quantifies air mass transport through a cross-sectional valley area, a key parameter for airflow studies in mountainous regions. Measuring this flux at multiple valley locations enables the establishment of a flux budget. Through the flux budget, changes in horizontal along-valley flux (i.e., flux divergence) yield an indirect estimate of vertical air mass exchange along the valley. Vertical air mass exchange is difficult to observe directly due to spatial wind variability but has important implications for the vertical exchange of energy, momentum, and trace constituents. Better valley flux observations are crucial for weather prediction, pollution dispersion, and microclimate studies. A key difficulty has been achieving representative volume flux measurements from a single ground-based Doppler lidar. Doppler lidars provide range-resolved radial velocity measurements, but spatial flow variability may introduce errors in volume flux estimation. In particular, it is important to capture cross- valley variation of along-valley flow. Prior studies have addressed this by assuming two-dimensional flow and applying empirical weighting factors to account for this variation. This study refines and validates volume flux estimation techniques using Doppler lidar measurements in the broad Inn Valley. The approach includes quality control of radial velocity data, improved hard-target filtering, and integration of digital elevation model data for valley geometry characterization. Empirical weighting factors established in literature are compared to new estimations for the broad Inn Valley derived from cross-valley scans. The analysis also identifies which scan pattern is best suited for volume flux calculations. Furthermore, the analysis considers flow characteristics and boundary layer properties, providing insight into intra- and inter-day variations over one month. Finally, the measurements are compared to novel airborne Doppler lidar data, which provide 3D wind measurements at 100 m resolution across the valley. Four overflights enable wind and volume flux intercomparison, offering further insight into retrieval properties and accuracy. Overall, the results enhance valley-scale volume flux estimation methodologies, supporting future field campaigns and improving understanding of valley-atmosphere interactions.

Key words: Valley volume flux, TEAMx, Doppler lidar, complex terrain, volume flux budget, boundary layer meteorology

Onsite

THE IMPACT OF SNOW COVER ON THE VALLEY-WIND CIRCULATION IN THE INN VALLEY – A WRF SENSITIVITY STUDY

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Land-cover characteristics and their spatial variations can strongly impact thermally driven circulations, such as slope and valley winds. Snow cover, in particular, can modify local surface properties. The high albedo of fresh snow reduces net radiation and heating of the near-surface atmosphere. Depending on the snow depth and the vegetation type, snow can also reduce the surface roughness length, affecting turbulent exchange between the surface and the atmosphere and the local wind field. Valley winds, which are driven by differential heating of the boundary layer, resulting either from variations in the terrain, for example, between the valley and the surrounding plain, or from variations in the surface-energy balance, are thus strongly affected by the presence or absence of snow. In this presentation we show results from a WRF sensitivity study for a wintertime case with a closed snow cover in the Inn Valley, Austria, and the surrounding Alpine foreland. Three simulations are performed to evaluate the impact of variations in the snow cover: (i) a closed snow cover in the valley and over the surrounding plain, (ii) a closed snow cover in the valley but no snow over the plain, and (iii) snow cover only above a certain altitude. The results highlight the impact of the snow-cover specification on the simulated wind field. If the snow cover does not extend to the Alpine foreland, the weaker heating in the snow-covered valley compared to the snow-free plain counteracts the effect of the smaller air volume in the valley. The result is a reduced forcing for daytime up-valley winds. Restricting snow cover to higher altitudes, on the other hand, can strengthen the exchange between snow-covered tributary valleys and the snow-free main valley.

Key words: surface characteristics, thermally driven winds, numerical modeling

Onsite

DATA-DRIVEN PARAMETERIZATION OF SUBGRID-SCALE OROGRAPHIC GRAVITY WAVES

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Momentum transported by orographic gravity waves (OGWs) significantly influences weather-scale systems and large-scale circulations. However, only a fraction of OGWs can be resolved by numerical weather prediction and general circulation models due to limited resolution. The parameterization of subgrid-scale OGWs can effectively reduce wind biases and improve forecast and prediction skills (e.g., in the polar night jet, Tibetan precipitation, and the summer monsoon). Nevertheless, non-negligible uncertainties still exist in OGW parameterization due to incomplete understanding of their complex mechanisms. In recent years, machine learning (or deep learning) has advanced rapidly, enabling the extraction of high-dimensional features and non-linear relationships of big data. These techniques offer a new approach to develop a data-driven parameterization from high-resolution simulation data. In this research, we conduct a one-month simulation over the Tibetan Plateau by the Weather Research and Forecasting (WRF) model. The horizontal resolution is 4-km and the maximum vertical resolution is approximately 500-m. Using a Gaussian filter, we separate the resolved and un-resolved components of meteorological variables (relative to a low-resolution model) and calculate the OGWs momentum flux (OGWMF). Fourier truncation is then applied to obtain coarse-grained data, including OGWMF, horizontal wind, temperature, pressure, air density and specific humid. The subgrid orography is derived by subtracting the average height within a coarse grid. We develop a CNN-LSTM architecture to map subgrid orography and coarse-grained meteorological variables to subgrid-scale OGWMF. A convolutional neural network (CNN) extracts spatial features from subgrid orography, while a feedforward neural network (FNN) connects these features to the initial state of a long short-term memory (LSTM) network. As the parameterization scheme is in a single-column, meteorological variables are in 1-D from the surface to model top. We therefore use LSTM to capture meteorological features and output OGWMF through a linear mapping. Our network demonstrates strong learning performance, achieving a coefficient of determination (R^2) of 0.93 and a root mean square error (RMSE) of 0.001620 across all levels and samples in the training set. Additionally, it exhibits robust generalization ability, with an R^2 of 0.71 and an RMSE of 0.002226 in the testing set which are derived from four one-week simulations conducted at different times. The horizontal and vertical distributions of gravity wave drag, derived from OGWMF, also show great consistence between WRF and network outputs.
Key words: orographic gravity waves; data-driven parameterization; CNN-LSTM

Onsite

FIRST RESULTS OF THE DATA COLLECTED BY THE METEOROLOGICAL MONITORING NETWORK ON BIOKOVO MOUNTAIN

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Mountain areas are extremely sensitive to climate change, but they are also an indicator of it. As part of the CroClimExtremes project, the first measurements of temperature and relative humidity were taken on Biokovo, a Croatian mountain known for its complex topography and extreme climatic conditions. In February 2024, 22 measuring devices were installed along two transects - on the slope facing the sea and on the one facing inland. In addition, two rain gauges and an automatic weather station were set up to measure precipitation, air temperature, relative humidity, wind direction and speed and total solar radiation. The measurements are carried out to investigate the meteorological conditions on the coastal and inland sides of the mountain and to detect possible extreme weather conditions. The first results of these measurements are presented here with the aim of comparing the vertical profiles of the measured variables, their diurnal and seasonal variations and identifying possible influencing factors.
Key words: meteorological monitoring network, Biokovo, vertical profiles, diurnal and seasonal variations

Onsite

COLD-AIR-POOL DEVELOPMENT IN MOUNTAIN FROST HOLLOWS: A COMPARATIVE STUDY FROM BÜKK PLATEAU (HUNGARY) AND KOMNA ALPINE PLATEAU (SLOVENIA)

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Cold air pools (CAPs) often form in closed karst depressions under certain topographical conditions and they are also called frost hollows. These microclimatic phenomena are responsible for extreme temperature minima and extreme temperature gradients, but are not yet sufficiently accounted for in high- resolution meteorological models. This ongoing research aims to investigate CAP dynamics through a comparative GIS-based analysis of frost hollows in two climatically different Central European regions. The study is based on a detailed microclimatological investigation of a well-studied Hungarian doline on the Bükk mid-mountain karst plateau with a proven history of extreme temperature minima. It is compared with a study area on the Komna plateau in the Julian Alps (Slovenia), with different climatic conditions and at a different altitude. At both sites, temperature is systematically monitored in-situ to determine the spatial extent of cold air formation and accumulation. High-resolution raw digital surface models (DSMs) derived from UAV-based photogrammetry are used to calculate key geomorphometric parameters such as Sky- View Factor, Cold-Air Flow Index, Wind Exposition, and Diurnal Anisotropic Heat. Our multimodel GIS- based approach enables the definition and quantification of cold-air-pool with high spatial resolution. In the selected frost hollows, we show how mono- and multisinkhole systems and the surrounding topography contribute to extended inversion layers. Near-surface temperature data confirm significant minima and temperature gradients between the coldest points in the frost hollows and the nearby saddle ridge areas, even at similar elevation differences. The investigated frost hollows serve as a case study that allows the exploration of CAP development under different depression morphologies and different regional climates. The study also aims to reveal the internal flow conditions of the different autonomous air flow systems. The study highlights the need for spatial, physical-geographic GIS-based interpretations of microclimates in the case of closed and partially closed depressions, with potential applications in detailed research of ecological conditions and processes of such sites in frost risk management research and climate-sensitive spatial planning. The results underline the importance of topographically determined microscale processes for the occurrence of nocturnal temperature minima and provide information on how complex terrain modulates local atmospheric stability.

Key words: microclimate, cold-air-pool, frost hollows, sinkholes, GIS, modeling, Slovenia, Hungary,

Onsite

LAND-ATMOSPHERE INTERACTION, BOUNDARY-LAYER DYNAMICS, VENTING, AND OROGRAPHIC CONVECTION IN AN ARID ENVIRONMENT: A CALL FOR INTEGRATED MULTI-SCALE OBSERVATIONS

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While climate models indicate an increase in water vapor and precipitation in a warming climate in the Southwestern United States as most other places, observations over the last 4 decades indicate otherwise. The likely culprit of this discrepancy is a poor numerical representation of key processes, which in turn relates to inadequate measurements. Precipitation in the Southwest during the North American monsoon (NAM) is highly orographic and results from deep convection. Operational models, including convection-permitting models, are challenged with predicting the timing and spatial distribution of the orographic convection, including its occasional upscale growth and propagation off the terrain. Flash floods are especially poorly predicted. NAM precipitation is an integral part of a complex water cycle which also includes long-range transport, surface evapotranspiration, boundary-layer (BL) venting, and precipitation evaporation. The transition from dry soils to wet soils during the NAM and the overall weak synoptic forcing make the region a suitable natural laboratory to study land-atmosphere interaction, diurnal BL growth and convection. One key process inadequately captured in models is the diurnal venting of moisture and heat over complex terrain, in the form of shallow to deep convection. Therefore an integrated field campaign is needed over the complex terrain of the Southwest to improve our scientific understanding of the multiscale processes governing the diurnal evolution of surface heat fluxes, BL growth, dry venting from the BL, and the initiation, propagation, and upscale growth of deep orographic convection. This presentation describes the science motivation, an uncertainty analysis based on output from regional climate models and NWP models, and a proposed campaign experimental design.

Key words: orographic convection boundary-layer dynamics mountain venting land-atmosphere interaction

Numerical Weather Prediction

Onsite

DEVELOPING A MODEL FRAMEWORK FOR FUTURE WEATHER PREDICTION AND RESEARCH

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Despite decades of progress in resolution and skill of atmospheric models for weather prediction, significant potential exists to enhance their physical fidelity and computational efficiency. Legacy model infrastructures and methods can hinder the adoption of emerging energy-efficient computing technologies, seamless integration of data-driven approaches, and increasing resolution. The models can also lack flexibility needed to support scientific research and collaborative initiatives. This presentation will highlight ECMWF's ongoing model development with member state partners and Destination Earth, towards a future framework for weather prediction and research. Key aspects include a high-level programming model for improved portability and productivity, alongside numerical model advancements for high resolution and complex terrain.

Key words: weather prediction, high resolution, high-performance computing

Onsite

OPERATIONAL 500-M ICON FORECASTS FOR GERMANY AND THE TEAMX OBSERVATIONAL CAMPAIGN

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Motivated by the GLORI Alpine Digital Twin Project and the plan to provide sub-kilometer scale forecasts for the TEAMx campaign, model development activities towards a 500-m configuration of ICON were started at DWD in late 2022. In autumn 2023, when the benefits that can be achieved with such a resolution enhancement became clear, it was decided to prepare in addition operational 500-m forecasts for Germany. Under the internal name ICON-D05, these forecasts became operational on February 27, 2025, following about six month of pre-operational production that started in September 2024 together with our quasi-operational TEAMx forecasts (ICON-A05). Using ICON's two-way nesting capability that allows starting nested domains during runtime, both forecast configurations start from DWD's operational deterministic ICON-D2 forecasts after the end of the latent-heat nudging phase, avoiding the need of an additional ensemble data assimilation that would not be affordable at such a high resolution. ICON-D05 (and ICON-A05) forecasts are provided 8 times per day for a lead time of 48 hours. The presentation will start with an overview of the preparatory model development that was necessary to obtain the desired quality benefit from the enhanced model resolution. This involves tuning changes in the transfer and turbulence schemes, including the coupling between the SSO scheme and the turbulence scheme, using additional 3D elements in the numerical diffusion scheme, and applying slope-corrected solar radiation including topographic shading. Moreover, the gust parameterization had to be revised in order to account for the wind profile occurring in small-scale vertically decaying orographic gravity waves, and for the fact that the model may become large-eddy-permitting at a mesh size of 500 m under summertime conditions with a deep convectively mixed boundary layer. Our standard verification against surface stations indicates that the benefit of the enhanced resolution for the forecast quality is primarily related to the better representation of the orography. Improvements are obtained for a variety of variables, including 10-m wind speed and gusts under stable conditions (at night and generally during the winter months), 2-m temperature and humidity for most of the months, and low visibility (fog) in valleys and basins.

Key words: Weather forecasting High-resolution modelling Model development

Onsite

ADVANCES AND CHALLENGES IN PREDICTING CONVECTIVE PRECIPITATION WITH ICON OVER THE ALPINE REGION

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In May 2024, MeteoSwiss operationalized a new ensemble prediction system based on the ICOsahedral Nonhydrostatic weather and climate model ICON. The ICON model significantly improved the representation of spatio-temporal variability for various meteorological parameters across Switzerland. As a weather service, however, we are also particularly focused on accurately predicting extreme events that hold high societal relevance. In this regard, it is worth highlighting that most of the extreme precipitation events over Switzerland during the summer of 2024 were relatively well forecasted. Nevertheless, the introduction of the new modeling system also revealed several shortcomings in the precipitation prediction. One of the key challenges is the overestimation of localized precipitation peaks during convective events. This overestimation can potentially be attributed to several model simplifications, including the absence of subgrid-scale entrainment of environmental air into buoyant updrafts. To address this, the German Weather Service DWD implemented new calibration options for the one-moment cloud microphysics. These include updraft-dependent supersaturation in convective clouds, a modified size distribution of rain droplets depending on local rainfall intensity, and a reduced graupel fall velocity. Together, these adjustments are shown to reduce the frequency of high-intensity precipitation overestimation in both Switzerland and Germany, leading to an overall improvement in forecast quality. In addition to localized overestimation, MeteoSwiss also faces the challenge of excessive spread in the ensemble predictions of heavy precipitation, which negatively affects hydrological runoff forecasts in Alpine catchments. The Stochastically Perturbed Parametrization Tendencies (SPPT) scheme has been identified as a primary driver of this excessive spread. The last part of the talk will therefore outline and discuss potential solutions to reduce the ensemble spread in precipitation. In summary, several targeted efforts have been made to substantially improve the prediction of convective precipitation within our ensemble prediction system. Looking ahead, further potential developments include increasing the horizontal grid spacing to 500 m, adopting the more physically realistic two-moment cloud microphysics scheme, and assimilating 3D radar reflectivities to enhance the quality of the initial conditions.

Key words: NWP, ICON, heavy precipitation

Onsite

EVALUATING CONVECTION AND THERMALLY DRIVEN FLOWS OVER THE ALPS USING HIGH-RESOLUTION MODELS

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Convection over complex terrain such as the Alps is driven by a variety of thermodynamic and dynamical processes and remains one of the fundamental open problems in operational forecasting. Higher resolution models offer the potential to improve the representation of key exchange processes within the boundary layer. In recent years, sub-kilometre grid spacing has been adopted by several meteorological services for operational forecasting. However, atmospheric models often deviate from observed precipitation patterns and intensities. The timing and intensity are often misplaced because many of these processes interact and reinforce each other. Forecasting in mountainous regions is particularly challenging due to the complex topography and associated multi-scale meteorological processes. Accurate representation of unresolved processes becomes more difficult and may reduce the validity of traditional parameterisations. The GLObal to Regional ICON Digital Twin (GLORI-DT) project aims to improve the quality of high-resolution forecasts in the Alpine region. Simulations are carried out using the ICOsahedral Non-hydrostatic model in its Limited Area Mode (ICON-LAM), which allows a refined representation of the boundary layer of complex terrain. The model configuration uses a one-way nesting approach, covering the entire Alpine region at a horizontal grid spacing of 2 km. Within this domain, two nested grids are embedded, refining the horizontal resolution to 1 km and further to 0.5 km in selected sub-regions. Initial deterministic experiments were conducted for a period characterised by frequent convective activity in June 2024. The performance of the model was assessed by extensive verification against observations from surface meteorological stations. The use of refined reanalysis and sensitivity tests with adjustments to the turbulent kinetic energy (TKE) scheme showed that the bias of near-surface variables such as temperature and wind speed could be reduced. However, the results also revealed a limited sensitivity of certain TKE source terms within the parametrisation. Increasing the horizontal grid spacing did not significantly improve the representation of accumulated precipitation. These results highlight the need for a more sophisticated representation of exchange processes, especially in complex terrain.

Key words: Alps, complex terrain, high-resolution simulation, convection, thermally driven flow, boundary layer, numerical weather prediction

Onsite

EVALUATING A TOPOGRAPHY–SURFACE RADIATION PARAMETERIZATION IN ICON FOR NWP

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In complex terrain, incoming short- and longwave radiation at the surface is strongly influenced by local and surrounding topography. Slope inclination, aspect, and topographic shading can significantly alter direct beam shortwave radiation, typically outweighing effects on diffuse shortwave and longwave radiation components. These terrain-induced modifications to surface radiation impact the surface energy balance and, consequently, near-surface variables such as 2 m air temperature and snow cover. Such changes can further influence mesoscale circulations, including valley wind systems. In numerical weather prediction (NWP) models, like ICON, terrain effects on surface radiation are not inherently captured due to the applied two-stream approximation for atmospheric radiative transfer, which does not capture lateral energy exchange by radiation, and the uniformly horizontally aligned grid cell surfaces. To address this, a dedicated parameterisation is required. Beside local slope angle and aspect, such parameterisations require the terrain horizon for every model grid cell, which we compute with a high-performance ray tracing library in an accurate and efficient way. We assess the impact of this topography–radiation parameterisation on forecast quality in ICON simulations with kilometre-scale resolutions. The evaluation focuses on surface radiation-related variables, such as global radiation and sunshine duration, as well as 2 m air temperature. Additionally, we present results from a newly implemented sub-grid parameterisation that captures terrain effects on direct beam shortwave radiation at a 30 m resolution, corresponding to the native grid spacing of the input digital elevation model.

Key words: radiation, topography, topographic shading, global radiation, sunshine duration

Online

METEOROLOGICAL IMPACT OF GLACIER RETREAT AND PROGLACIAL LAKE TEMPERATURE IN WESTERN NORWAY

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Glaciers are retreating worldwide, yet little is known about the influence of these changes on local weather and climate in glacial landscapes. Changes in glacier extent and proglacial lakes alter the thermodynamic forcing in glacier-lake-valley systems that may be of similar or greater importance for future microclimate than direct effects of global warming. To study the impact of these changes, we combine the first set of high-density spatiotemporal observations of a glacier-lake-valley system at Nigardsbreen in western Norway with high-resolution numerical simulations from the Weather Research and Forecasting (WRF) model. The sensitivity of the thermodynamic circulation to glacier extent and proglacial lakes is tested using glacier outlines from 2006 and 2019 as well as varying lake surface temperature. The model represents the evolution of glacier flow and cold air pools well when thermal forcing dominates over large-scale forcing. During a persistent down-glacier flow regime, the glacier-valley circulation is sensitive to lake temperature and glacier extent, with strong impacts on wind speed, convection in the valley, and interaction with mountain waves. However, when the large-scale forcing dominates and the down-glacier flow is weak and shallower, impacts on atmospheric circulation are smaller, especially those related to lake temperature. This high sensitivity to meteorological conditions is related to whether the flow regime promotes thermal coupling between the glacier and the lake. The findings of this study highlight the need for accurate representation of glacier extent and proglacial lakes when evaluating local effects of past and future climate change in glacierized regions.

Key words: glacier-atmosphere interactions, WRF modelling, observational campaign, glacier retreat, proglacial lakes, glacier wind, mountain waves, cold air pools

Onsite

DOWNSCALING METEOROLOGICAL DATA WITH A DEEP LEARNING ALGORITHM USING A SAMPLING METHOD

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The growing need for high-resolution weather fields, either over a long period of time to investigate climate change adaptation in cities or in real-time to forecast accidental pollutant release, requires efficient tools for generating these fields. Traditional meteorological models, even with massively parallel computing, are unable to produce high-resolution numerical predictions in a timely manner. Statistical downscaling using convolutional neural networks (CNNs) offers a promising alternative, as they can generate high-resolution fields much faster than traditional models. However, training CNNs requires a large database of large-scale (input) and fine-scale (target) meteorological data and, for the reason just discussed, the latter fields cannot be generated at high resolution over a long time period. To overcome this challenge, this study proposes methods to reduce the database size with sampling methods. Techniques such as K-means clustering, Latin Hypercube Sampling, Sobol or Halton sequences, and pseudo-random sampling are explored. For this purpose, daily ERA5 time-series for 15 meteorological variables, spanning 30 years around 2006, are considered. A new challenge arises with these sampling methods due to the discrete nature of the meteorological data. Methodological adaptations are tested to achieve uniform sample coverage and a wide range of meteorological situations including extreme events. Key metrics like recovery rate and Kolmogorov-Smirnov tests (comparing distribution sample with ideal uniform distribution) indicate that adapted approaches using Sobol sequences combined with Principal Component Analysis (PCA) with or without K-means clustering yield superior performance. A preliminary downscaling test using a CNN from Dupuy et al. [2023] for a 2.5-year dataset of wind fields around Cadarache (at 9 km for input and 1 km for target) demonstrated that a training using 100 days sampled with the Sobol+PCA+Kmeans method yields similar statistical results as using the full 2.5-year dataset. The next objective is to perform such a downscaling with target data at 1/9 km for Cadarache and 1/5 km for Grenoble. The input data will consist in ERA5 data over a 30-year period around 2006 for Cadarache and in data from the regional climate model MAR (at 7 km) over a 30-year period around 2050 for Grenoble. Based on the results above, 100 days will be first selected from the Sobol+PCA+Kmeans sampling methodology from each 30- year database and simulated numerically with the WRF (Weather Research and Forecasting) model to create the target databases. Two CNN, one for each location, will then be trained and validated using their respective 100-days database.
Key words: High-resolution Downscaling, neural networks, complex terrain, sampling.

Onsite

A NEURAL NETWORK-BASED OBSERVATION OPERATOR FOR WEATHER RADAR DATA ASSIMILATION

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Forecasting convective storms is a major challenge in Numerical Weather Prediction (NWP). Data Assimilation (DA) improves the initial condition and subsequent forecasts by combining observations and previous model forecasts (background). Weather radar provides a dense source of observations in storm monitoring. Therefore, assimilating radar data should significantly improve storm forecasting skills. However, the short-range precipitation forecast performed by extrapolating rainfall patterns (nowcasting) from radar data is often better than numerical model-based forecasting with DA (Fabry and Meunier, 2020). This is related to the fact that the radar data only provides information on the precipitation pattern and intensity in the area affected by the storm. Furthermore, it does not directly provide information on the environmental conditions of the storm, such as temperature, wind, and humidity, neither within the precipitation region nor in the areas far from the storm. A potential solution involves using machine learning (ML) to construct the DA observation operator to generate a model-equivalent of the radar data. In this approach, NWP model fields (temperature, wind components, relative humidity) would serve as input, and radar observations would be the output of an encoder-decoder neural network. The constructed observation operator describes a non-linear relationship between the NWP model storm-related variables and radar observations, while its Jacobian allows radar information to infer other variables in the data assimilation, potentially enhancing storm forecasting skills.

Key words: data assimilation, observation operator, weather radar, neural networks, Numerical Weather Prediction

Onsite

SEASONAL PREDICTION OF HYDROLOGICAL DROUGHT IN LAKE VICTORIA BASIN IN UGANDA USING THREE PROPOSED FORECASTING SYSTEMS

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Ensemble hydrological predictions are normally obtained by forcing hydrological models with ensembles of atmospheric forecasts produced by numerical weather prediction models. To be of practical value to water users, such forecasts should not only be sufficiently skilful, they should also provide information that is relevant to the decisions end users make. The Lake Victoria Basin in Uganda has experienced severe droughts in the past, resulting in crop failure, economic losses and the need for humanitarian aid. In this paper we address the seasonal prediction of hydrological drought in the Lake Victoria Basin by testing three proposed forecasting systems (FS) that can provide operational guidance to reservoir operators and water managers at the seasonal timescale. All three FS include a distributed hydrological model of the basin, which is forced with either (i) a global atmospheric model forecast (ECMWF seasonal forecast system — S4), (ii) the commonly applied ensemble stream flow prediction approach (ESP) using resampled historical data, or (iii) a conditional ESP approach (ESPcond) that is conditional on the ENSO (El Niño–Southern Oscillation) signal. We determine the skill of the three systems in predicting stream flow and commonly used drought indices. We also assess the skill in predicting indicators that are meaningful to local end users in the basin. FS_S4 shows moderate skill for all lead times (3, 4, and 5 months) and aggregation periods. FS_ESP also performs better than climatology for the shorter lead times, but with lower skill than FS_S4. FS_ESPcond shows intermediate skill compared to the other two FS, though its skill is shown to be more robust. The skill of FS_ESP and FS_ESPcond is found to decrease rapidly with increasing lead time when compared to FS_S4. The results show that both FS_S4 and FS_ESPcond have good potential for seasonal hydrological drought forecasting in the Lake Victoria Basin.

Key words: Hydrological models, Atmospheric forecasts, Weather prediction models, Lake Victoria Basin

Onsite

EARTH OBSERVATION FOR BIODIVERSITY, HYDROLOGY AND INTEGRATED WATER RESOURCE MANAGEMENT (IWRM) MONITORING: A CASE STUDY OF UGANDA.

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Introduction: The lack of water relevant information in many countries hinders the deep knowledge of its water cycle at continental and basin levels. This represents a critical drawback for these governments to completely understand the current status of the water resources, to identify the impacts of climate change in water availability and to set up adaptation and mitigation measurements to cope with future potential threats. The main aim of the study was to assess the use of Earth Observation (EO) for biodiversity, hydrology and Integrated Water Resource Management (IWRM) monitoring. Methods: The study used Water Observation and Information System (WOIS) to monitor and assess water resources using integrated field and satellite remote sensing data in conjunction with Geographic information systems, rainfall monitoring, drought and flood mapping. Results: Uganda has sufficient freshwater resources available for sustainable economic and social development. But there is growing pressure on arable land, forest reserves, and wetlands, and increasing freshwater pollution from urban centers and agriculture, which threaten resource availability. Increased urbanization and population pressure have strained natural resources causing a vegetation decline. Earth Observation data derived eleven products required for IWRM including; precipitation, soil moisture, evapotranspiration, groundwater, surface water level, water quality, land use, topography, open water evaporation, runoff /stream flow and river discharge. Conclusion: Watershed resource management in Uganda is still facing risks exacerbated by increasing population pressures, Climate change impacts, increasing pressure on watershed resources, increased pollution and encroachment into wetlands, riparian land, and forests.
Key words: Earth observation, Biodiversity, Hydrology, Integrated Water Resource Management.

Onsite

EVALUATION OF PRECIPITATION FORECASTS OF SEVERAL NWP MODELLING SYSTEMS IN COMPLEX TERRAIN OF THE SOUTHEASTERN EUROPE

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To improve severe weather warnings in the southeast Europe, five state-of-the-art prediction systems are evaluated for quality of precipitation forecasts: the operational IFS model of the European Centre for Medium-Range Weather Forecasts (ECMWF) and four limited area model (LAM) configurations for South-East Europe (SEE) including: ALADIN-ALARO, COSMO, ICON, and WRF NMM-B. We study strengths and weaknesses of these prediction systems to assess the models' success in simulating precipitation, including extreme events, over a pilot area of wider eastern Adriatic coast. First, our approach uses moment-based and categorical statistical verification, including a decomposition of scores into biases and dispersion (phase) errors. Best results averaged over all stations are not achieved for a single model but vary across several modelling configurations depending on the score analyzed. It is clearly noticeable that models are of lower accuracy near the mountainous coast compared to continental inland due to the generally more intense precipitation, influence of the complex terrain and influence of sea and surface inhomogeneities. Likewise, categorical verification suggests low-medium intensity precipitation forecast accuracy is the lowest where Dinaric Alps are the most complex, but results do improve in higher precipitation categories. Although results are far from perfect for most extreme events, all models show skillful predictions and none of the models shows considerably more strengths than others with extremal dependence index (EDI) ranging from 0.45 up to 0.85 depending on the model and country. To alleviate effects of small errors in time and space on verification measures, in absence of spatially homogenous precipitation data, we apply a neighborhood verification approach, which offers an alternative that rewards closeness by relaxing the requirement for exact matches between forecasts and observations in the spatial domain. The single-observation neighborhood approach (SO-NF) results show an improvement in ETS values with an increase of the spatial scale for the categories of events. At the highest precipitation category (above 30 mm/24h) and common spatial scale of ~45 km, ECMWF and COSMO models seem to perform somewhat more consistently than other models. Nevertheless, the improvement of the results with the forecast neighborhood size noticed for most models and countries shows the benefits of the SO-NF approach in terms of recognizing additional forecasted values present in the proximity of the exact location, even though they were slightly displaced.

Key words: severe waether, heavy precipitation, southeast Europe, evlauation, NWP, complex terrain

Onsite

ESTIMATING PARAMETERS OF OROGRAPHIC DRAG SCHEMES USING HIGH-RESOLUTION SIMULATIONS OVER COMPLEX ALPINE TERRAIN

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Recent studies have used ensemble data assimilation methods, in particular joint state and parameter estimation, to improve the representation of subgrid-scale boundary-layer turbulence in models. Inspired by those studies, we have evaluated the sensitivity of two orographic drag schemes, based on the works of Kim and Doyle (2005) and Lott and Miller (1997), to their empirical parameters. The purpose is to identify candidates for effective parameter estimation experiments. A central component of orographic drag schemes is the parameterization of gravity-wave drag at a reference level, which depends on the variance of the subgrid-scale orography. Thus, we assess the sensitivity of the two schemes to all the empirical parameters that affect the magnitude of the reference-level drag. Parameter estimation is then carried out in an observing system simulation experiment (OSSE), where a high-resolution model simulation serves as virtual truth (nature run). The nature runs are simulations of gravity wave events during the TEAMx winter campaign, conducted with the Weather Research and Forecasting (WRF) model at a resolution of 1 km. We assimilate gravity-wave momentum-flux observations from the nature runs into ensembles of idealized two-dimensional simulations, which are integrated at a coarser resolution (10 km) using an orographic drag parameterization. The 2D domain represents a transect across the orography, therefore limiting the propagation of the gravity waves to the vertical and cross-mountain directions. The observations of gravity wave momentum fluxes are used to constrain the parameterizations in this idealized setup. The assimilation is carried out using the Ensemble Adjustment Kalman Filter (EAKF), which is a deterministic root-mean square filter. The values of empirical parameters differ in each ensemble member: initially, they are randomly drawn from assumed prior distributions; afterwards, they are adjusted iteratively at every analysis time based on nature-run observations. The estimated parameter values are optimal in a statistical sense, as long as the simulated system meets the assumptions of the assimilation filter. We demonstrate that the estimated parameters converge to stable values that depend only marginally on the configuration of the assimilation system. We also compare ensemble runs with and without parameter estimation, discussing the impact of parameter estimation on the accuracy of the analyses and subsequent forecasts. We show that: (1) Optimal parameter values are not uniform across the simulation transect; (2) Analysis accuracy and forecast skill improve in the ensemble runs with parameter estimation.

Key words: parameter estimation, gravity wave drag, parameterization, orographic drag, data assimilation, Kalman filter

Onsite

EVALUATING PRECIPITATION MICROPHYSICS IN THE WRF MODEL OVER COMPLEX TERRAIN: A WINTER CASE STUDY IN THE PYRENEES

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Numerical weather prediction (NWP) models are fundamental for both operational weather forecasting and atmospheric research. Over mountain regions they often exhibit biases or they are not able to resolve local scale circulations, due to complex orographic terrain which may not be adequately resolved by the model grid. Among the various atmospheric variables predicted by NWP models, precipitation is particularly important due to its significant impact on human and environmental systems. Precipitation is simulated through microphysical schemes that parametrize the interaction between different hydrometeor species, such as cloud water, ice crystals, raindrops, snowflakes, and graupel, which are strongly influenced by the assumed particle size distribution (PSD). The Weather Research and Forecasting (WRF) model offers a wide range of microphysical parametrizations, including bulk single-moment (predicting only mixing ratios) and double-moment schemes (predicting both mixing ratios and number concentrations), as well as varying representations of hydrometeor species. This variety makes WRF a flexible modelling tool, but it also requires a careful selection of schemes based on the meteorological conditions and region of interest. This study explores how different microphysical schemes within WRF model simulate a winter precipitation event over the Eastern Pyrenees (Spain). Several simulations using six-species schemes (including rain, snow and graupel precipitating hydrometeors) were compared with surface observations from disdrometers. Although observational and simulated data generally agree, a temporal bias was found in some simulated periods. Additionally, schemes like WRF Double–moment 6– class Scheme tended to simulate higher number concentrations and smaller raindrop diameters. These discrepancies may be attributed to the definition of the PSD via lambda and mu parameters in gamma distributions and can influence the parametrized mass and number concentration fluxes between hydrometeor classes. This study is supported by the Spanish project ARTEMIS (PID2021-124253OB-I00) and the Water Research Insitute of the Univeristy of Barcelona.

Key words: Precipitaiton Microphysics, WRF model, drop size distribution

Onsite

DEVELOPMENTS OF GRAVITY WAVE DRAG REPRESENTATION IN THE UNIFIED MODEL AND IMPACTS ON ARCTIC CIRCULATION

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Nudging of fields around areas of complex orography have indicated an exacerbation of biases in the Met Office's Unified Model's representation of polar regions, particularly in key diagnostics such as Pressure at Mean Sea Level, and so it is worth evaluating the effects of recent or soon to be implemented developments on these biases; these developments include the introduction of a scale-aware scheme to account for differing length-scales of orography within individual grid cells, moving from previous assumptions of elliptical orography, and accounting for reduced gravity wave stress due to flow blocking. Parallel development in the UM has required a new evaluation of the effect of this scheme. This project considers the implementation of this new scheme and testing at multiple resolutions; configurations differing from those associated with the initial development of the scheme are considered to account for new developments made between GAL 8 and GAL 9, due to greater exacerbation of these biases under current configuration and recommended tuning parameters, and causes for this greater exacerbation are evaluated. Multiple resolutions are tested for versatility of the new scheme, with a focus on effects in polar regions.

Key words: Model development, scale-aware, global, polar, UM

Onsite

PHYSICALLY CONSISTENT MODEL EVALUATION IN COMPLEX TERRAIN

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Evaluation of mesoscale models is often based on a comparison of the model output with observational data, in particular from automatic weather stations. A fair comparison between measurements and model is, however, only possible if the terrain and land-cover characteristics at the measurement site match those of the corresponding model grid cell, including, for example, slope angle and orientation, surface albedo, and roughness length. Over complex terrain, these characteristics can vary considerably over small spatial scales that are not resolved by the model terrain and land-cover data, limiting the spatial representativeness of point measurements and affecting model evaluation. In this study we attempt to provide guidelines for a fair model evaluation with data from weather and eddy-covariance stations over complex, mountainous areas. The first step is a correction of systematic biases arising from differences in terrain height between model and measurement site and from differences between the sensor height above ground and the height of the lowest model level or the diagnosed surface variables. As a second step, we propose to use a physically consistent grid cell for the evaluation, which takes topographic parameters into account in addition to the distance from the measurement site. The goal is to select a grid cell that represents the terrain and land-cover characteristics at the measurement site. Using a case study with convective summer conditions and a pronounced valley wind circulation in the Inn Valley, Austria, we compare the model performance for this physically consistent grid cell to that of the nearest grid cell.

Key words: model evaluation, spatial representativeness, surface heterogeneity

Interaction of mountain, costal and marine processes

Onsite

OCEAN-ATMOSPHERE COUPLING AND ITS IMPACTS ON MEDITERRANEAN HEAVY PRECIPITATION

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The North-Western Mediterranean region, which is a semi-enclosed sea surrounded by mountains, is prone to severe events. Heavy precipitation events (HPEs) are characterized by a moist and rapid low- level flow over sea converging and/or encountering mountainous area, triggering and feeding stationary deep convective systems that lead to very localized, large amounts of rainfall in only some hours (typically more than 100 mm in less than 24 hours), generating flash-floods. As highlighted during the HyMeX (Hydrological cycle in Mediterranean Experiment) program, such extreme events imply strong wind and air- sea exchanges in the marine area with a local, rapid and large ocean response, and complex atmospheric circulation and processes in the coastal, mountainous area. To better represent the mesoscale environment and the exchanges in numerical modelling and weather prediction systems, fine horizontal resolution and coupling are key. The AROBASE (AROme-BAsed coupled SystEm) project aims to assemble a kilometer-scale limited-area multi-coupled modelling system of the physico-chemical atmosphere, the ocean (including sea-ice and marine biogeochemistry), waves and land surfaces (soil, vegetation, cities, snow, lakes and rivers). Since late August 2024, a first AROBASE forecast demonstrator is applied daily over the Metropolitan France region. It couples the AROME numerical weather prediction model at 1.3 km resolution and the NEMO ocean model with a 1/36° resolution. The comparison of the ocean-atmosphere AROBASE system results with uncoupled forecast during severe meteorological situations that affected the North-Western Mediterranean region will be presented during the conference, as the pathways of future developments, notably to include waves coupling on one hand and on the other hand to progress towards kilometer-scale coupled regional climate modelling.

Key words: Heavy Precipitation Events ; Ocean-atmosphere coupling ; AROBASE ; Mediterranean Sea;

Onsite

POTENTIAL PREDICTABILITY OF COMPOUND STORM SURGE AND METEOTSUNAMI EXTREMES – TESTED ON 29-30 OCTOBER 2018 EVENT

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An extreme sea level event occurred in the Adriatic Sea on 29–30 October 2018, when two processes, each operating on different timescale, acted jointly to flood coastal areas from the northern to the southern Adriatic. The first process was an intense storm surge, which manifested as intense low-frequency (periods larger than 2 h) sea level rise, while the second was a meteotsunami which manifested as high-frequency (periods shorter than 2 h) sea level oscillations. A deep extratropical cyclone developed over the northwestern Mediterranean and intensified over the Gulf of Genoa before moving into the Adriatic Sea, driving the pronounced storm surge. Embedded withing this synoptic setting, a cold front moved over the Apennine mountains and a train of atmospheric pressure disturbances crossed from the western to the eastern Adriatic coast, triggering high-frequency sea level oscillations and producing a meteotsunami in Vela Luka (Korčula Island) while it traversed the Adriatic. A sea level extreme event during which both storm surge and meteotsunami occur is termed a compound extreme. We evaluated three strategies for forecasting compound events, using the 29–30 October 2018 event as our test case. Using machine learning technique, and a pre acquired knowledge of the general synoptic conditions that favour compound extremes we first (1) used a synoptic-similarity classifier that successfully identified the potential compound extreme three days in advance. Following this, we used Weather Research and Forecasting atmospheric numerical model (WRF) alongside the oceanographic numerical Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) to make (2) a one-way coupled numerical forecast which reproduced the storm surge and the general pattern of atmospheric pressure pulses but misrepresented the spatial distribution of the high-frequency sea level oscillations. Finally (3) we used a hybrid scheme merging real-time pressure observations with rapid SCHISM runs, which delivered the most accurate onset time and amplitude estimates for the high-frequency sea level oscillations, including the observed meteotsunami. These findings imply that an operational warning system that blends machine learning synoptic alerts, targeted field measurements, and fine-scale ocean modelling, and that aims at reproducing and forecasting compound coastal extremes might be feasible.

Key words: Meteotsunami, storm surge, WRF, SCHISM, machine learning, Forecasting extreme events

Onsite

OBSERVING AND MODELLING BORA-DRIVEN DENSE WATER DYNAMICS IN THE ADRIATIC SEA

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Among the many consequences of the wintertime outbursts of the bora—a downslope northeasterly gale that brings dry, cold air masses over the Adriatic—the most oceanographically significant is the generation of dense water in both the northern and southern Adriatic. This process drives the Adriatic-Ionian thermohaline circulation and oxygenates the deep Adriatic waters. The two dense water formation sites differ in their thermohaline characteristics: in the shallow northern Adriatic, rapid surface cooling leads to ocean density anomalies approaching or exceeding 30 kg/m³, producing the densest waters in the entire Mediterranean. In contrast, the deep southern Adriatic undergoes open-ocean convection that can mix the water column to depths of up to 900 meters. The dense waters formed in the north flow downslope as bottom density currents into the middle and southern Adriatic basins, while the southern site serves as a key source of deep waters for the entire Eastern Mediterranean. This presentation provides an overview of the state-of-the-art in observing thermohaline properties, long-term changes in dense water formation, its spreading and accumulation, as well as its numerical modeling—particularly across the complex eastern Adriatic bathymetry and extending to climate-scale variability.

Key words: Adriatic, bora, dense water formation, observations, numerical modelling

Onsite

IMPACT OF BORA WIND EVENTS ON SEA SURFACE TEMPERATURE IN THE KVARNER BAY: INSIGHTS FROM HIGH-RESOLUTION BUOY DATA

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Bora is a cold, downslope (katabatic), and gusty wind that blows from land to sea, most commonly from the northeast. It forms as cold continental air flows over the Dinaric mountains and descends toward the Adriatic coast, often accelerating through mountain passes. Characterized by sudden onset, strong gusts, and intense turbulence, the Bora is primarily driven by synoptic-scale pressure gradients between a continental high and a Mediterranean low. In this study, we investigate how this wind affects sea surface temperature in the Kvarner Bay, using high-resolution data from the DHMZ's meteorological-oceanographic buoy "Kvarner". A two-year time series of wind speed and sea temperature was analyzed to quantify the response of the sea surface to gale-force Bora events. The multi-season dataset enables exploration of interannual variability and provides a solid basis for understanding the broader influence of Bora in the context of mountain meteorology. Results reveal a clear correlation between extreme wind events and rapid surface cooling, confirming the Bora's role as a driver of vertical mixing and upper-layer ventilation. These findings contribute to a deeper understanding of air–sea interaction in the dynamic environment of the mountainous Adriatic coast.

Key words: Bora wind, Adriatic Sea, Sea surface temperature, Air–sea interaction, Vertical mixing, Meteorological-oceanographic buoy

Onsite

QUANTIFYING BORA WIND GUSTINESS ALONG THE EASTERN ADRIATIC: A BUOY-BASED INDEX APPROACH

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Bora wind displays a gusty character, with wind gusts significantly exceeding the mean wind speed. This study proposes a methodology for quantifying Bora gustiness through an index based on the ratio of gust to mean wind speed. Data from a network of meteorological-oceanographic buoys along the eastern Adriatic coast were used, focusing on events where average wind speeds reached gale-force levels. The computed gust factor allows for spatial comparison of Bora intensity across different locations, aiming to identify areas with the highest potential for extreme gusts. Results indicate pronounced spatial variability in gustiness, driven by local orography and coastline configuration. This index may prove useful in early warning systems and in the planning of infrastructure and maritime safety measures.

Key words: Bora wind, Wind gustiness, Gust factor, Adriatic Sea, Coastal meteorology, Orographic effects, Wind variability, Meteorological-oceanographic buoys, Maritime safety

Onsite

STATISTICAL AND NEURAL NETWORK CLIMATOLOGY OF FOG AND MIST AT COASTAL PULA AIRPORT IN CROATIA

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A study was conducted on the climatological characteristics of fog and mist at Pula Airport in the northeastern Adriatic, using statistical and machine learning approaches. The study utilized meteorological data from Pula Airport, along with satellite sea surface temperature (SST) data from two coastal areas west and east of the airport, to gain insights into the influence of sea temperature on fog formation. To identify weather patterns associated with the occurrence of fog and mist, wind and mean sea level pressure (MSLP) data from the fifth generation reanalysis (ERA5) of the European Centre for Medium-Range Weather Forecasts (ECMWF) were analyzed using Growing Neural Gas (GNG), a machine learning algorithm. A notable finding was a declining trend in the frequency of fog and mist at the airport, which can be linked to the results of the GNG analysis of the ERA5 data. This analysis showed a decrease in synoptic patterns favorable for fog and mist. Fog occurs mainly between October and March and is primarily associated with weak westerly and northwesterly winds. Additionally, fog is more likely to occur when the sea surface temperature is higher than the air temperature. Mist has similar characteristics to fog, although it is more likely to occur with easterly winds.

Key words: Coastal fog, neural networks, climatology, SST

Onsite

INVESTIGATING THE ROLE OF OROGRAPHY ON DEEP MIXING AND BOUNDARY LAYER EVOLUTION OVER THE TIBETAN PLATEAU

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Deep atmospheric boundary layers (ABL; depth > 4 km AGL) are observed over the Tibetan Plateau (TP), significantly impacting regional and large-scale atmospheric dynamics during late winter and spring. Such deep mixing profoundly impacts exchanges in the upper troposphere–lower stratosphere (UTLS) region. The primary drivers of these deep ABLs, observed in particular over the western Tibetan Plateau, remain uncertain. However, weak upper-level stability, linked to the circulation of westerly jet streams, has been reported earlier as a causal mechanism for such deep mixing. The high-elevation region of the TP (~4500 m) features small-scale orography which can induce local circulations. The influence of these local circulations on the deep ABLs remains largely unexplored. However, these factors may play a crucial role in regulating ABL structure and mixing processes. We investigate the potential impact of these factors in semi-idealized large-eddy simulations (LES) using the Cloud Model 1 (CM1) with a horizontal grid spacing of 50 m and a vertically stretched grid ranging from 20 to 100 m. To analyze mixing, two passive tracers are injected: one at the surface via a constant surface flux and another in the region above 4 km AGL via initial conditions. A reference simulation without orography (FLAT) produces a deep ABL of about 4.5 km. To assess the impact of small-scale orography, a simulation with realistic 3D terrain (REAL) and REALu10 (REAL terrain plus a upper-level wind of 10 m s^{-1}) are conducted. Small-scale orography substantially accelerates early growth: by midday the CBL in REAL is ∼80 m higher than in FLAT, and locally above the mountain it is ∼500 m deeper. In REALu10, added shear organizes convection into longitudinal roll vortices, contrasting with the isolated terrain-anchored plumes in the no-shear (REAL) case, and
enhances vertical mixing. These results demonstrate that unresolved small-scale orography can increase daytime CBL height by up to 15% and expedite entrainment of free-tropospheric air. Under clear-sky conditions, the plateau's CBL can exceed 9 km within a single day given strong surface heating and weak stability aloft. Our findings highlight the importance of including fine-scale terrain and shear effects in models, as their omission may underestimate CBL growth and vertical exchange over high-altitude regions.

Key words: Atmospheric Boundary Layer, small scale orography, mixing.

Onsite

NUMERICAL SIMULATIONS OF SUPERCELLS IN NORTHEASTERN ITALY WITH WRF-HAILCAST

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In the early morning of 1 August 2021, a supercell developed over the northeastern Italian plains, moving eastward towards Friuli-Venezia Giulia, locally producing hailstones with diameters up to 9 cm. In the present work, this event is studied by means of simulations with the Weather Research and Forecasting (WRF) model at 1 km resolution, coupled with the HAILCAST hail growth parameterization, which provides estimates of the maximum hail size at the ground. Several simulations are performed using different initial and boundary conditions (GFS and IFS forecasts), different initialization times and physics options, to study the predictability of the event. The analysis of the model results highlights a significant sensitivity to the forcing meteorological model and the initialization time. In particular, WRF is not able to properly simulate the development of strong convection over the Veneto and Friuli-Venezia Giulia plain in the early morning of 1 August using GFS forcing, while better results are obtained with IFS initial and boundary conditions, especially when simulations are initialized more than 24 hours before the event. Moreover, results are significantly affected by the microphysics scheme and the land surface model, whereas the planetary boundary layer parameterization seems to have a minor influence. However, the development of the supercell is properly simulated, with hailstone diameters comparable to observations, only when data from radiosoundings of Udine Rivolto are nudged into the model, highlighting the importance, and at the same time the complexity, of correctly reproducing local thermodynamic conditions for the simulation of extreme convection events. Finally, the same modelling setup is applied for simulating another supercell event over the same region, which produced hailstones with a maximum diameter of 19 cm on 24 July 2023. The model was also able to reasonably reproduce this event, shedding light on the dynamics of severe convection over the northeastern Italian plains, often affected by the interaction between air masses with different characteristics, i.e., warm and humid winds blowing from the nearby Adriatic Sea and cooler air flowing from the Alpine chain.

Key words: supercell, Weather Research and Forecasting model, HAILCAST, convection, predictability

Climate

Onsite

BENEFITS OF KILOMETER-SCALE CLIMATE MODELS FOR WIND IN COMPLEX TERRAIN: PRESENT AND FUTURE CLIMATE

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While it is intuitively clear that sufficiently high resolution is required to successfully simulate wind in complex terrain, it is difficult to generally quantify the exact resolution and added value of using it due to the lack of adequate observations and the complexity of interaction between wind and terrain. Here the benefits of kilometer-scale models are reviewed for reproducing different types of wind systems in complex terrain in the present and future climate. General evaluation studies using ensemble of km-scale models in the wider Alpine region show mixed results regarding their added value compared to coarser models. The largest benefits are seen for strong winds and tend to occur for stations at low to medium altitudes. In the Scandinavian mountains, there is a clear added value of km resolution in simulating wind speed in mountainous terrain, especially for strong winds. In particular, strong winds in the present climate depend on the terrain height and model resolution more than on the differences in large-scale forcing. During synoptically weak winds, thermally generated circulations form that also considerably depend on the model resolution. This resolution dependence is mostly pronounced in the warmer part of the year when a convergence zone forms between downslope glacier wind at high altitudes and upslope wind below. The future change of strong winds is mostly governed by the large-scale circulation change provided by the parent model. On the contrary, the future of thermally generated circulations is primarily governed by the temperature change, which is typically estimated with less uncertainty compared to circulation change. Therefore, the future projections of local thermal circulations in synoptically weak wind situations can be deemed more reliable compared to stronger winds.
Key words: Convection permitting model; Climate projections; Weak winds; Strong winds

Onsite

SYNTHESIZING A HIGH-RESOLUTION CLIMATOLOGY OF SEVERE THUNDERSTORMS IN THE GREATER ALPINE REGION

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Thunderstorms and their associated phenomena like heavy rain, hail and damaging winds are among the costliest and most dangerous natural hazards in the Greater Alpine Region (GAR). Their limited spatio-temporal extent and their volatile occurrence impede comprehensive, homogeneous observational databases of their incidence as well as their realistic, credible simulation by climate models. We address the observation gap by integrating real-time data on weather-related fire brigade operations, transmitted directly to GeoSphere Austria, and non-routine weather reports submitted by voluntary observers via the AWOB (Austrian Weather Observer) app. After quality control and a standardized classification into severe weather types and intensities, additive logistic regressions blend these data with optimized predictors for severe thunderstorms from ERA5 reanalyses, thus linking grid-scale meteorological conditions to occurrence probabilities of high-impact, subgrid-scale weather phenomena. The application of this statistical mapping function establishes a "synthetic" climatology of expected severe thunderstorm events per unit area and year, which can be arbitrarily extended from the current training dataset (the period 2016-2024 in Austria) to the past and future, given that suitable reanalyses or climate projections are available. Our presentation illustrates climatological trends and spatio-temporal variabilities of severe thunderstorm phenomena in the GAR based on ERA5 and on EURO-CORDEX regional climate projections and explains the patterns by the behaviour of the "ingredients" for severe convection in the context of climate change. The most striking feature is a pronounced increase of expected severe thunderstorm occurrence over high-Alpine terrain, mostly explainable by enhanced moisture in a warmer atmosphere. Another aim is to close the "last mile" between grid-scale severe weather estimates and the more demanding needs of stakeholders who benefit from the provision of climate services. These stakeholders include political decision makers at municipality level, civil defence organizations, insurances, and companies seeking to achieve compliance with the EU Taxonomy Regulation 2020/852 for environmentally sustainable economic activities. We therefore emphasize the portability of our approach not only to the GAR as a showcase area, but also to other regions in the EU, and the final steps to further downscale estimates of severe weather frequency and intensity to individual municipalities. Additionally, we suggest a comprehensive nomenclature and criteria for severe weather in climatological studies and severe warning operations to facilitate and universalize the interpretation in the dialogue between providers and stakeholders.

Key words: Thunderstorms, severe weather, reanalyses, regional climate projections, climate services, hazard assessment

Onsite

KILOMETER-SCALE CLIMATE PROJECTIONS OF DOWNSLOPE WINDSTORMS IN THE SCANDINAVIAN MOUNTAINS

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Downslope windstorms (DWs) are mesoscale atmospheric phenomena with impacts on everyday life in mountainous regions, characterized by strong descending winds on leeward slopes but also wind acceleration on windward slopes. This study employs the high-resolution regional climate model HARMONIE-Climate (HCLIM) with nested grids of 12 km and 3 km horizontal resolution to investigate DWs in a changing climate over the Scandinavian mountains. A two-step detection algorithm is applied to identify DW events, first by delineating favorable terrain, followed by event identification based on atmospheric stability and horizontal and vertical wind speed. DWs are further classified by synoptic circulation types (CTs) to assess their occurrence under different large-scale conditions. The region is divided into four subregions, with analyses focused on the winter season, when DW frequency is highest. DW frequency is obtained for a historical period (1986–2005), mid-century (2041–2060), and end-century (2081–2100) under the RCP8.5 scenario, using boundary conditions from EC-Earth2 and GFDL-CM3 global climate models. For both forcing models there is a future decline in DW occurrence in the northern Scandinavian mountains. In the south, projected changes vary depending on the forcing model and subarea. To attribute these changes, total DW occurrence change is decomposed into contributions from changes in CT frequency and changes within specific CTs. Results indicate that for EC-Earth2, within-CT changes dominate, while for GFDL-CM3, both components contribute comparably.

Key words: downslope windstorms, regional climate model, CPRCM, HCLIM, Scandinavian mountains

Onsite

IMPACT OF CLIMATE CHANGE ON FORESTRY AND AGRICULTURE IN HIGHLAND CROATIA

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Highland Croatia separates the lowland part of the country from the Mediterranean and makes up approximately 20% of Croatia's total area. The richness of forested areas has directed the region's development toward the wood industry and forestry, with wood processing having a long tradition and an export-oriented focus, holding a significant place in the economy of Highland Croatia. Due to the mountainous terrain and colder climate, agriculture in these regions has specific characteristics. It is practiced by a smaller percentage of the population and is mostly present in karst fields. This work analyzes the impact of climate change on forestry and agriculture in Highland Croatia, with an emphasis on changes in climatic indicators crucial for the management of natural resources. The focus is on trends in growing degree days (GDD), changes in the Fire Weather Index (FWI), and occurrences of drought periods (SPEI). For livestock needs, the temperature-humidity (THI) index was analyzed. The analysis is based on long-term data (1961–2020), which indicates a significant increase in seasonal and annual growing degree days. This directly affects the vegetation cycle, plant phenology, and increases the risk of pests in forestry, as they can produce more generations in warmer climates. The rising trend of the FWI index suggests that in this region, which historically was not heavily threatened by wildfires, conditions are gradually becoming favorable for the emergence and spread of forest fires, especially during the summer months. Additionally, drought index (SPEI) is thoroughly examined, revealing increasingly frequent and prolonged drought episodes, with pronounced negative impacts on agricultural yields and the regeneration and stability of forest ecosystems. Extreme weather events such as ice storms and windthrow, depending on their intensity, can cause significant damage to forests. To mitigate the consequences of these threats, it is necessary to introduce changes in forest management, crop selection, and the application of agrotechnical measures. To improve preparedness, efforts must be made to develop early warning systems for extreme climate conditions. The development of such a system is one of the main goals of the Interreg Central Europe project Clim4Cast. As part of the project, a monitoring and forecasting platform for drought, heatwaves, and wildfire risk has been developed and will be presented at the conference.

Key words: Climate change, agriculture, forestry, drought, wildfires

Onsite

THE CHARACTER AND CAUSES OF ELEVATION-DEPENDENT CLIMATE WARMING OVER THE ANDES MOUNTAINS IN KILOMETER-SCALE SIMULATIONS

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The Andes are the longest mountain range in the world, but compared to some northern hemisphere mountain regions, relatively little is known about the impacts of climate change in the region. Previous simulations with global climate models (GCMs) and regional climate models (RCMs) indicate that the terrain of the Andes strongly modulates the changes in temperature, with warming patterns that vary systematically with elevation (elevation-dependent warming: EDW). However, the relatively coarse grid spacing of these simulations (typically >25-km) fails to resolve important orographic processes, limiting confidence in their predictions. This study analyzes a first-of-its kind suite of km-scale RCM simulations over South America to address the question: What mechanisms shape elevation-dependent warming (EDW) over the Andes? The simulations use the WRF model to simulate the weather of the entire South American continent at 4-km horizontal grid spacing from 2000–2021 with reanalysis boundary conditions for a control simulation (CTR). They also simulate the same periods using a pseudo-global warming (PGW) approach, wherein the control simulation is repeated with boundary conditions perturbed based on monthly mean climate changes (2060–2080 minus 2020–2000) taken from the 100-member Community Earth System Model Large Ensemble version 2 GCM experiment under the SSP3-7.0 emissions scenario. Comparing the PGW and CTR simulations reveals a substantial EDW pattern in annual mean temperature changes throughout the Andes, from the equatorial regions to the mid-latitudes. In all regions studied, the highest elevations are found to warm 1–1.5°C more than the low elevations. However, the elevation- dependent structure of the warming pattern varies between regions. Additional analysis presented will examine the seasonal cycle warming over the Andes and changes in other variables to explore the role of different potential climate feedback mechanisms responsible for the simulated Andean EDW.

Key words: Andes Mountains; Regional climate modeling; Elevation-dependent warming

Onsite

SPIRAL STRIP VISUALIZATION GRAPHIC

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A visual graphic called Spiral strip is presented, consisting of color-coded segments arranged in a spiral. The width and length of each individual segment can be different, which can be used to convey additional information (besides the color-coding). Although the primary motivation for developing the new graphic was related to climate data, it can also be used with other types of data. Several examples based on climate, population size, and historical data are used to show the graphic's visual appearance and main properties. The examples also demonstrate how the meaning of the graphic can be easy to grasp and intuitively understood by a casual observer. An easy-to-use python code package for drawing the Spiral strips was published in a public repository.

Key words: visualization; spiral geometry; climate stripe

Onsite

EXTREME PRECIPITATION MONTHS IN THE HIGH MOUNTAIN REGIONS OF BULGARIA AND LINK TO ATMOSPHERIC CIRCULATION

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Precipitation in high mountain areas is of critical importance as these regions are major sources of freshwater, supporting river basins, ecosystems, and downstream communities. Changes in precipitation regimes at these regions can have cascading impacts on water availability, agriculture, hydropower, and biodiversity. The aim of present study is to give new information about precipitation variability in high mountain regions of Bulgaria and to assess the role of large-scale atmospheric circulation patterns for the occurrence of extreme precipitation months. The study period is 1937-2024 and the classification of extreme precipitation months are based on the 10th and 90th percentiles of precipitation distribution. The temporal distribution of extreme precipitation months was analyzed by comparison of two periods (1937-1980 and 1981-2024). The impact of atmospheric circulation was evaluated by correlation between number of extreme precipitation months and indices for North Atlantic Oscillation (NAO) and Western Mediterranean Oscillation (WeMOI). Based on the analyses was revealed that in the 1981-2024 period, summer precipitation has risen markedly, counteracting previous downward trends (for the period 1937-1980). Spring, however, continues to exhibit intensifying dryness, particularly at Cherni Vrah. While annual precipitation at Musala is now on the rise, it still shows a negative trend at Cherni Vrah—though less so than before. The proportion of extremely wet months significantly decreased after 1980 — for example, from 84% to just 15% at the station Cherni Vrah. Meanwhile, the frequency of extremely dry months increased, especially during winter and spring after 1981, reaching up to 72% of all extremely dry months. The correlation analysis shows that the hight NAO indices tends to be associated with dry conditions while WeMOI is more associated with wet conditions. The results of the study emphasize the need for adaptation strategies in the water management sector and early warning systems for extreme climate events in mountainous regions Acknowledgement: The study was carried out within the framework of the project 1.004-0008-C01 (SUMMIT-Sofia University Marking Momentum for Innovation and Technological Transfer), funded by the European Union—NextGenerationEU through the National Recovery and Resilience Plan of the Republic of Bulgaria.
Key words: seasonal precipitation; extreme dry month; extreme wet months; NAO, WeMOI, Bulgaria

Onsite

THE DYNAMICS OF SNOW COVER AT HIGH-MOUNTAIN STATIONS IN BULGARIA

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Understanding long-term changes in snow cover is essential for evaluating the impacts of climate variability on mountainous ecosystems, water resources, and socio-economic activities. This study analyzes the temporal variations in days with snow cover and snow cover depth across three high-mountain meteorological stations in Bulgaria—Cherni Vrah, Murgash, and Vrah Botev—over the period 1995–2025. Utilizing daily meteorological data, we assess trends in maximum snow depth and the number of days with snow cover to identify potential climate-induced changes in the country's mountainous regions. The results show a slight increase in the number of days with snow cover at the Botev Vrah station and a slight decrease at the Cherni Vrah station, but in both cases, the trend values are close to zero. The trend analysis of the number of days with snow cover at the Murgash station indicates a value of
-6 days per decade. Regarding snow depth, a notable increase is observed at Vrah Botev (22 cm per decade), whereas Cherni Vrah and Murgash exhibit decreasing trends of 9 cm and 4 cm per decade, respectively. These findings contribute to a deeper understanding of snow dynamics in the region and highlight the importance of continued monitoring to inform climate adaptation strategies in sensitive alpine environments. Acknowledgement: The study was carried out within the framework of the project 1.004- 0008-C01 (SUMMIT-Sofia University Marking Momentum for Innovation and Technological Transfer), funded by the European Union—NextGenerationEU through the National Recovery and and Resilience Plan of the Republic of Bulgaria
Key words: snow cover, snow depht, trends, climate changes

Onsite

3D HEAT WAVE TYPES IN EUROPEAN REGIONS

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We evaluate climatological characteristics (temperature anomalies, mean precipitation, and the Climatic Water balance index defined as the difference between potential evapotranspiration and precipitation) and links to atmospheric circulation (characterized by the Jenkinson–Collison classification) for three-dimensional (3D) heat wave types in several European regions (Christensen & Christensen 2007). Heat waves are classified according to their 3D structure of temperature anomalies in ERA5 over 1979–2022 (the satellite period) into near-surface, lower-tropospheric, higher-tropospheric, and omnipresent types (Lhotka & Kyselý 2024, https://www.nature.com/articles/s43247-024-01497-2). We show large differences in surface temperature anomalies, dryness, and links to circulation patterns among the heat wave types, particularly between near-surface and higher-tropospheric heat waves. Special attention is paid to processes important for the heat waves' onset and development, differences between the European regions, and the role of orography. Christensen JH, Christensen OB (2007) A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic Change 81, 7–30. https://doi.org/10.1007/s10584-006-9210-7 Lhotka O, Kyselý J (2024) Three-dimensional analysis reveals diverse heat wave types in Europe. Communications Earth & Environment 5, 323. https://doi.org/10.1038/s43247-024-01497-2

Key words: air temperature;heat waves;vertical structure;climate variability;Europe

Onsite

QUANTIFYING RATES OF CLIMATE CHANGE AND RISKS IN MOUNTAIN REGIONS OF CZECHIA

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This article focuses on climate change in the Czech Republic, with a focus on mountain areas (areas above 800 meters above sea level). Although mountain areas occupy only about 4% of the Czech Republic's territory, they are important for both living and non-living nature, for its protection, recreational use and cultural heritage. Mountains are an important source of drinking water in the Czech Republic, support biodiversity and provide a backdrop for recreational and sporting activities. The highest mountains in the Czech Republic reach altitudes of around 1,100–1,600 m above sea level, and important subalpine and alpine ecosystems can be found here. As there is a relatively dense network of long-term meteorological stations in the Czech Republic, supplemented by a number of remote measurements, climate change trend analyses are significantly more accurate than similar global analyses. From this data, we already know that air temperature is rising in all seasons. In winter, the proportion of precipitation in the form of snow decreases, reducing the ability to form snow cover and thus reducing potential sources of surface and groundwater, for example. Moreover, the current trends have been accelerating in recent years. Mountain areas are very sensitive to the effects of climate change. The PERUN project (TAČR SS02030040 - PERUN, Prediction, Evalua-tion and Research for Understanding National sensitivity and impacts of drought and climate change for Czechia) focuses on research into climate extremes, drought, and the consequences of its intensification in the Czech Republic. The aim of the project is to analyze in detail not only ongoing but also predicted future changes, including the identification of risks to the environment and society. Within the PERUN project, three scenarios of potential climate development in the Czech Republic were created based on the SSP (Shared Socioeconomic Pathways) socio-economic scenarios. Using these scenarios, we can get an idea of the changes in the values of selected meteorological elements and the associated climate indices, which we use to assess the risks of these changes for nature and the landscape in mountain areas.

Key words: Czechia, climate change, climate risk, mountain, climate scenario, PERUN

Onsite

MORE THAN JUST RAIN: SPATIAL AND TEMPORAL VARIATIONS IN PRECIPITATION ACROSS THE VERONA-TYROL ALPINE TRANSECT, 1923-2024

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Historical meteorological data are crucial for understanding a region's climate. This research analyzes spatial patterns and trends of daily precipitation in a transect between the Po Plain near Verona, Italy, and Tyrol. A dataset of daily precipitation was created spanning 1923-2024. Many station's data were manually digitized from historical annual reports. The entire dataset was quality-checked with suitable procedures, and suspicious data were verified. The time series were homogenized using the R library Climatol. Climatological precipitation indices were calculated on the homogenized dataset. Additionally, some indices were spatially interpolated for three normal reference periods (1931-1960, 1961-1990, and 1991-2020). Data normality was first verified. Then, an iterative procedure calculated experimental semivariograms to determine the best interpolation parameters. Finally, the kriging with external drift algorithm was executed. Results confirm established climatic features of pre-alpine precipitation distribution. Notably, however, novel spatial patterns have emerged. The Precipitation Concentration Index suggests that, over the past century, locally the domain has seen an increase in highly irregular precipitation distribution. Furthermore, R95pTOT, R99pTOT, R95p, and R99p indices indicate spatial shifts and significant variations within the domain. The synoptic-scale weather regime variability is currently hypothesized to be the driving force behind this observed pattern. In conclusion, the present study underlines the importance of reliable historical data from meteorological measurements and encourages the systematic digitization and publication of paper-based annual reports.

Key words: Precipitation, Data Rescue, Alps, Digitization of Historical Data, Climatological Indices, Italy, Austria

Onsite

URBAN HEAT ISLAND CHARACTERIZATION IN AN ALPINE VALLEY CITY: INTEGRATING OBSERVATIONS AND MODELS IN BOLZANO'S COMPLEX TERRAIN

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Effectively understanding urban climate patterns and heat distribution is essential for developing climate adaptation strategies and mitigating urban risks related to heat stress. The characterization of Urban Heat Islands (UHI) presents significant challenges in mountainous regions, where complex terrain creates unique microclimate conditions that standard approaches often fail to capture adequately. Our research introduces an integrated methodology to examine the UHI phenomenon in Bolzano, an Alpine city situated in northeastern Italy that experiences particularly intense summer heat episodes. Bolzano's distinctive topography—surrounded by steep mountain slopes within a convergence of three valleys—creates a complex thermal environment where mountain-valley circulations significantly influence temperature distribution patterns. During summer, this topographic configuration can trap heat within the urban core, while winter conditions facilitate persistent cold air drainage and pooling that fundamentally alter the UHI dynamics. The methodological framework combines innovative mobile monitoring with traditional fixed measurements and numerical modeling. The mobile monitoring system will consist of 25 meteorological sensors (MeteoTracker devices) deployed on public transportation vehicles traversing urban-rural areas, collecting continuous temperature, humidity, and pressure data. This mobile system is planned to be deployed after a successful preliminary trial on one bus throughout the entire month of April. This dynamic network is supplemented by fixed weather stations of the official provincial network and quality-filtered observations collected by NetAtmo citizen weather stations. For comprehensive spatial coverage, we used the outputs from two models: the UrbClim urban climate model at 100-m resolution providing historical simulations (2003-2022) and future projections (mid-term and long-term) for a range of indicators, and the Weather Research and Forecasting (WRF) model at 1-km resolution, serving as the state-of-reference model for the region over the very recent past (2020-2024). Together, these models provide complementary insights into the spatiotemporal dynamics of temperature patterns across Bolzano's urban landscape and surrounding terrain. While UrbClim, operating in a simple hydrostatic mode, offers computational efficiency for extended climate simulations, the non-hydrostatic WRF model can resolve the thermally driven flows that characterize Bolzano's valley system, capturing the circulation patterns that influence heat transport and re-distribution that play a crucial role in modulating the urban heat island effect in this complex topography.

Key words: Urban-Climate, Complex-Terrain, local and mobile observations, high resolution modeling, long-term modeling, Urban Heat Island

Onsite

THE INFLUENCE OF CLIMATE CHANGE ON TEMPORAL TRENDS OF AVALANCHE ACTIVITY AND NIVO-METEOROLOGICAL VARIABLES IN THE AOSTA VALLEY, ITALY

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This study investigates the influence of climate change on avalanche activity in the Aosta Valley, an Italian Autonomous Region located in the Western Alps, over the period 2005 to 2023. The research aims to analyse possible temporal trends in meteorological and snow-related variables at different spatial scales, understand their impact on avalanches, and delineate the relationships between temperature, snowfall, and avalanche phenomena. Available data concerns meteorological and snow measurements deriving from automatic weather stations and manual observations collected at snow field sites, and the spontaneous avalanche records described in the Avalanche Cadaster of the Aosta Valley Autonomous Region. Data analysis consists of statistical temporal trends evaluations, also considering non-dimensional variables obtained by using the Standardised Anomaly Index. The results indicate a noteworthy increase in average winter temperatures and a concurrent reduction in snowfall, both of which significantly influence the distribution of avalanche activity both spatially in the region and temporally during the winter season, from December to April. Notably, there is a transformation in the types of avalanches occurring, with a rise in wet avalanche problems and a reduction in those associated with new snow; nevertheless, the overall number of recorded avalanches per season remains mostly unchanged in the analysed period. Finally, this research provides key insights into the relationship between climate change and avalanche activity in the Aosta Valley, laying a foundation for further studies. Among these, it would be beneficial to focus on the questions raised by practitioners during the discussion of the current results, including whether the apparent temporal shift in different patterns of avalanche situations can be rigorously captured in the dataset and how to apply these findings to help manage the risk in anthropised areas.

Key words: Snow avalanches, Italian Alps, Climate Change, Trends

Onsite

THE IMPACT OF OCEAN-ATMOSPHERE COUPLING ON PRECIPITATION CLIMATOLOGY OVER EASTERN ADRIATIC AND DINARIC ALPS

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Regional climate models incorporate multiple components of the climate system to address the need for more reliable information at regional scales, resulting in the regional climate system models (RCSMs). These models are particularly important for regions like the Mediterranean, where complex interactions and feedback processes among different climate components, especially the atmosphere and ocean, significantly impact local climate. In the Adriatic region, for example, air-sea interactions play a critical role during autumn, when strong temperature gradients between the sea surface and the atmosphere are most pronounced. High-frequency coupling resolves these rapid air-sea feedbacks and moisture transport from sea to land, thereby enhancing the extreme precipitation representation. However, uncertainties remain, particularly regarding the impact of coupling over inland areas far from the coupling areas themselves. Furthermore, the coupling effects vary by region and season, highlighting the need for further investigation. To assess these impacts at the climatological scale over the eastern Adriatic and Dinaric Alps, we compare daily precipitation from the atmospheric regional climate model CNRM-ALADIN64 and the fully-coupled CNRM-RCSM6, which includes the atmosphere, aerosols, land surface, ocean and river components of the Mediterranean climate. Both models share an identical atmospheric component to isolate the coupling effects as accurately as possible. The precipitation analysis system MESCAN-SURFEX is used as a reference dataset and a range of basic climatological and extreme precipitation indices is analysed for the 1980 to 2018 period (39 years). Our results show that the coupling has a modest overall effect. The strongest effect is reported during summer months, when it enhances precipitation frequency and intensity of both mean and extreme precipitation, resulting in better agreement with observations. Although the long-term impact of coupling is relatively subtle, our findings suggest that incorporating sub- daily sea surface temperature variations could further enhance the accuracy of specific heavy precipitation events.

Key words: coupled models; precipitation; ocean-atmosphere coupling; Adriatic; Dinaric Alps; regional climate models

Onsite

IDENTIFYING CONVECTIVE HOTSPOTS IN THE EUROPEAN ALPS BY ANALYZING SYNOPTIC ENVIRONMENTS AND REPORT DATA OF THE LAST 30 YEARS

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Convective events are characterized by extreme precipitation, wind, lightning, and hail events and account for a significant portion of insured natural hazard damages, particularly affecting the agricultural, vehicle, and building sectors. In recent years, record-breaking hailstone sizes (up to 19 cm), substantial damage costs (e.g., 2021 in Switzerland), and prolonged, intense convective storms have been observed in Europe. The increase in temperatures due to global warming enhances the air's saturation vapor pressure, thereby intensifying convective processes through moisture supply and increased latent heat release. Recent climatological studies of hail and lightning point towards distinct hotspots regions of convective activity around the Alps. The complex topography of mountain ridges and valleys significantly influences the large-scale atmospheric flow, leading to many of the most intensive convective events in Europe. However, a comprehensive analysis of synoptic- to meso-scale environments of these hotspot regions, their spatio-temporal variability, and the underlying processes has not yet been conducted across multiple Alpine countries and convective hazards types. In a first attempt to link large scale atmospheric patterns to regional convective events, we present synoptic circulation types (CTs) of the last 30 years, classified with the cost733class package (Philipp et al. 2014) and ERA5 reanalysis data (Hersbach et al. 2020), that show heightened convective activity through clusters of reports found in the European Severe Weather Database (ESWD) (Dotzek et al. 2009). Additionally, the ERA5 data at the report-sites was analyzed with regard to anomalies of various environmental parameters. The classification of 18 CTs was completed with ERA5 data products of mean sea level pressure (mslp), convective available potential energy (cape), 700 hPa wind speed (ws700), and 500 hPa geopotential height (z500). Combined with ESWD-report data, first results show differing synoptic conditions for, e.g., large hail events north and south of the Alps. Most distinct differences were found in the z500 data, indicating implications of upstream trough and downstream ridge locations on hail-prone regions. CTs that occur only during the convective season show positive anomalies of specific humidity at 850 hPa (s850) and sea surface temperatures (sst), while mslp anomalies are comparatively weak. Identifying which synoptic environments favor convective events at different regional hotspots could lead to more reliable forecasting abilities and help to reduce the impacts of extreme events on the livelihoods of people around the European Alps.

Key words: European Alps, Convective Events, Convective Hotspots, Synoptic Circulation Types, Convective Environments, Hail,

Onsite

EXTREME WEATHER EVENT DETECTION IN HIGH-RESOLUTION CLIMATE SIMULATIONS

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In order to better understand atmospheric conditions during severe weather events, we will analyse decade-long simulations of high-resolution (less than 4 km) convection-permitting climate models (CPMs). The added value of convection being explicitly resolved in models was evaluated and confirmed in several studies so far in the context of precipitation. This research will focus on the Croatian territory, where the presence of Adriatic Sea causes land-sea interactions near the already orographically complex mountainous areas. Here, for the first time, we evaluate models' ability to reproduce favourable conditions for frost and deep convection (specifically, hail and lightning) in several climate zones that span through this region. Since frost is not explicitly modelled in simulations, different techniques for its detection have been investigated in previous studies. In this research we will adopt a method from a recent study that provided the most satisfactory results in predicting the frost development, and apply it on CPM outputs. We will evaluate this method using frost occurrence data collected from surface meteorological stations. Convective processes are known for their complexity, and modelling products of convection such as hail and lightning is a major challenge. However, specific hail parameters can be simulated using the HAILCAST module combined with NWP models, while the use of Lightning Potential Index (LPI) shows great performance in lightning density prediction. Also, numerous efforts have been made to identify weather patterns associated with hail by using proxies. In this work, we will create a proxy and use LPI values to estimate favourable conditions for development of hail and lightning in CPM outputs. We will verify LPI results against lightning data from the Lightning Detection Network (LINET) and evaluate estimated hail events against the hail occurrences at surface meteorological stations. Our main goal is to contribute to the understanding of how frost and convection can be detected in CPM simulations. As a final result, we aim to create a climatology of frost, hail and lightning density, leading to detailed risk maps of the mentioned extreme weather events for the present and future climate in Croatia.

Key words: convection-permitting climate models, frost, hail, lightning, climatology

Boundary Layer

Onsite

NEAR-SURFACE TURBULENCE OVER MOUNTAINOUS TERRAIN

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Mountainous regions pose a unique challenge for understanding and forecasting atmospheric flows. In particular, the turbulence structure over mountainous terrain remains poorly understood due to a scarcity of systematic observations, the strong dependence on local surface characteristics, as well as the multiscale nature of atmospheric processes and their non-linear interactions that govern turbulence. Nonetheless, the limited studies of idealized topographic flows indicate that turbulence over mountainous terrain differs significantly from that over flat, homogeneous surfaces—the conditions under which most turbulence theories and parameterizations were originally developed. While some theoretical developments that take this difference into account exist for low hills and neutral flows, the mountainous area present additional challenges. Using an extensive collection of datasets from multiple observational campaigns in mountainous terrain we investigate whether systematic patterns in turbulence properties can be identified in stratified flows over mountainous terrain. Our goal is to assess the potential and review the efforts for generalizing turbulence theories to mountainous environments, where the assumptions underlying existing parameterizations are clearly violated.
Key words: Atmospheric Boundary Layer, Turbulence, Mountainous Terrain

Onsite

IMPACT OF PROCESSING TECHNIQUES ON FLUX ESTIMATES AND SURFACE ENERGY BALANCE CLOSURE IN COMPLEX TERRAIN

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The surface energy balance (SEB), i.e., the partitioning of the energy exchange between the Earth's surface and the atmosphere, is crucial for defining atmospheric boundary layer characteristics and evolution. An accurate assessment of its components is essential for a variety of applications. However, measurements of the SEB terms are still affected by uncertainties. In particular, eddy-covariance measurements of turbulent heat fluxes typically do not balance the available energy. Studies suggest this discrepancy primarily results from advection driven by secondary circulations, prevalent over heterogeneous and complex terrain as a consequence of differential heating. This study aims to analyze the first two years of eddy-covariance measurements from a tower located in Mezzolombardo, in the Alpine Adige Valley (Trentino - Italy), to investigate the SEB closure. The analysis focuses on the assessment of the relationship between SEB non-closure, surface heterogeneity, and the resulting development of local and mesoscale thermally-driven circulations. Objective criteria to select days with the development of thermally-driven circulations are used, refining the method proposed by Lehner et al. (2019). The impact of various eddy-covariance data processing techniques, including averaging and rotation approaches, on flux estimates and SEB closure is quantified. Moreover, analyses conducted on other Alpine sites within diverse complex terrains (e.g., valley floor, valley slope, mountain top) will also be presented. The overall results provide a systematic quantification of the non-closure of the SEB in several typical Alpine contexts, highlighting similarities and differences between sites located in various topographic and land cover settings and under different meteorological conditions. The present work is part of the INTERFACE project (INvestigating ThE suRFACe Energy balance over mountain areas), which is performed in the framework of the TEAMx research programme.

Key words: Energy Balance Closure, Eddy-Covariance, Thermally-driven flows, Atmospheric Boundary Layer, Complex Terrain, Data Processing Techniques

Onsite

FINE-SCALE THERMAL DYNAMICS OF GLACIER WINDS

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The glacier boundary layer is primarily governed by katabatic winds, which play a crucial role in turbulent heat exchange. However, when impacted by cross-glacier or synoptic flows, these winds can be disrupted, enhancing turbulent mixing and driving warm air toward the surface—ultimately altering the glacier microclimate. This study uses high-resolution thermal infrared (TIR) imaging combined with turbulence measurements to examine fine-scale near-surface temperature dynamics within the lowest four meters above a glacier. The aim is to evaluate the utility of TIR imaging in capturing temperature variations across glacier wind regimes and document thermal responses under stable katabatic and disturbed conditions. Thermal data were collected using an InfraTec VarioCAM HD (1024 × 768 pixels), operating at 30 Hz, and directed at two vertically positioned synthetic screens (up to 4 m high) aligned with the primary glacier wind direction. The effective spatial resolution was ~6 mm per pixel. Data collection occurred during a three-day Intensive Observation Period (August 22–24, 2023) as part of the HEFEX II campaign. Five representative sequences of approximately one hour were selected to capture both katabatic and disturbed flows during day and night. TIR imagery revealed detailed thermal stratification and high-resolution temperature fluctuations. Comparisons with turbulence sensor data show that while the TIR method slightly underestimates high-frequency temperature variance at lower heights (e.g., 1.2 m) during katabatic conditions, it aligns well above 2.2 m and under disturbed or nighttime flows. This underestimation is likely due to the thermal inertia of the screen material, which dampens the highest-frequency fluctuations. Spectral analysis indicates that turbulent fluctuations up to ~0.1 Hz are resolved, capturing key scales even under stable conditions. Results show strong temperature stratification within the lowest meter under persistent katabatic flow, with stratification breaks typically between 2 and 3 meters. Jet heights, usually 1 to 3 meters, aligned with maximum temperature variance and layering. In disturbed flows, stratification weakened, and temperature variance spread vertically, indicating enhanced mixing. Shallow jets increased near-surface fluctuations via intermittent warm air entrainment, while deeper flows preserved thermal stability. These findings enhance our understanding of fine-scale thermal processes in glacier boundary layers and offer high-resolution validation data for atmospheric models that aim to capture glacier– atmosphere interactions in complex alpine environments.

Key words: glacier winds, thermal infrared imaging, temperature dynamics, glacier microclimate

Onsite

TURBULENCE AND STRATIFICATION NEAR THE JET IN GLACIER WINDS: INSIGHTS FROM INFRARED IMAGING

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Understanding micrometeorological processes at the glacier surface is essential for quantifying surface energy exchange and mass balance. Yet, capturing the spatial and temporal variability of near-surface turbulence dynamics in complex, glacierized terrain remains a challenge. Standard micrometeorological measurements such as point-scale temperature and turbulence sensors provide detailed information in time, but lack the spatial coverage needed to fully resolve the structure of katabatic flows and near-surface stratification. To complement traditional turbulence measurements, we explored the use of thermal infrared (TIR) imaging in recent field campaigns on Silvretta glacier, Switzerland, and Hintereisferner, Austria. Large vertical fabric screens, up to 4 m high, were set up on the glacier surface, aligned with the direction of the glacier wind. By directing an infrared camera at these screens we are able to visualize two- dimensional temperature dynamics within the lowest meters above the glacier surface with ultra-high spatial and temporal resolution. These data offer new perspectives on the thermal dynamics within the glacier boundary layer that would be difficult to capture by other means. A particular focus of this work is the region surrounding the wind speed maximum, a key feature of katabatic flows where notable changes in turbulent quantities are expected. What exactly happens to turbulence statistics at and around this layer? How do the profiles of temperature gradient, temperature variance, heat fluxes, or spectral shape behave in relation to the vertical wind speed profile? Under neutral conditions, temperature spectra follow a height-dependent ordering with spectral energy decreasing with distance from the surface. Under katabatic conditions, however, this ordering is disrupted, and spectra near the wind speed maximum or strongest stratification are shifted upward, suggesting enhanced variability at that level. These patterns hint that the jet height may align with local maxima in temperature gradient and temperature variance. In that case, thermal infrared data could help identify features that are otherwise missed by point-wise measurements. We will share first insights from both field sites, comparing infrared data to simultaneous sonic anemometer data. Although the full analysis is ongoing, this work aims to assess how much information about turbulent exchange and katabatic flow structure is truly accessible from thermal imagery alone — and what remains out of reach.

Key words: Glacier boundary layer, thermal infrared imaging, katabatic flow, turbulence, temperature spectra

Onsite

CLIMATOLOGY, SYNOPTIC AND ATMOSPHERIC BOUNDARY LAYE R CONDITIONS DURING PITERAQS IN SOUTHEAST GREENLAND

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In Greenlandic, “piteraq” refers to a strong, cold, downslope wind that originates from the Greenland Ice Sheet, known for commonly causing damage to infrastructure in the Tasiilaq area of Southeast Greenland. From a network of weather observations, we identified piteraq events dating back to 1958 based on the predominant direction of extreme winds. On average, four piteraq events occur each year, typically lasting around 18 hours, with maximum wind speeds reaching 23 m/s. The less frequent summer piteraqs are often associated with a sharper drop in relative humidity and warming near peak wind intensity, in contrast to the cooling seen during winter events. To examine the spatiotemporal variability of these winds, we used a high-resolution, polar-adapted reanalysis dataset. We also consulted local media reports to extend the observational records, particularly during periods of sparse weather data. While piteraqs are generally classified as storm-force winds in Tasiilaq, they can reach hurricane-force category 1 over the steep slopes of the ice sheet. We found that piteraq near-surface winds follow a preferential pathway across the ice sheet before reaching Tasiilaq. To better understand the synoptic and the atmospheric boundary layer conditions preceding and during piteraq events, we examined along these flowlines the flow regime, the dynamic stability, the low-level jet features, and the wind shear. We also analyzed near-surface temperature, humidity, and pressure differences between the ice sheet ridge and Tasiilaq. Our findings enhance our understanding of the local and large-scale weather evolution before and during the piteraq events, potentially leading to an improved early warning system.

Key words: piteraq; downlope windstorm; Greenland; synoptic conditions; atmospheric boundary layer

Onsite

IDENTIFYING BORA WIND PULSATIONS IN CEILOMETER BACKSCATTER

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For decades, the primary purpose of operational ceilometers has been detecting clouds. In aviation, reliable cloud measurements are essential for defining procedures during reduced visibility and low ceiling events. Observation and nowcasting of these events are crucial for aviation users. In Croatia Control, we have developed a tailored visualisation of raw vertical profile data together with automatically extracted information from the state-of-the-art Vaisala and Lufft ceilometers. For several years, we thoroughly selected cases from ceilometers in Croatia. As expected, we found a large range of meteorological phenomena with different operational significance - from fog and low ceiling episodes to the ones with lower operational impact but very interesting, for instance growth of the convection boundary layer, evaporation precipitation, Kelvin-Helmholtz waves etc. For the first time, from detected temporal changes of the backscatter vertical profile during bora episodes, we try to confirm the well-known bora pulsation with periods 4-12 minutes. Operational ceilometers are located at airports on the eastern Adriatic coast: Pula, Rijeka, Zadar, Split and Dubrovnik. The measured frequency is 15 seconds, and depending on the ceilometer type, the vertical range is 7000 - 15 000 m while the resolution is 5-15 m. Backscatter time series from different heights (70-400m) are transformed and submitted to spectral analysis. Preliminary results of the spectral analysis and wavelet analysis are promising. As backscatter attenuated vertical profiles are standardised vertically to the strongest signal, better results are obtained when the period taken in spectrum calculation is for the same conditions, e.g. without change of clouds and the best in cloud-free conditions. The spectrum of backscatter is compared to the wind speed. Several examples of different bora episodes ranging from weak bora episodes to severe ones for different locations will be shown. Pulsations are more pronounced at locations near the base and slopes of the mountains compared to more distant ones (20-70 km). Further analysis of this method will show whether it could be developed into a viable detection tool to be used in operational products for aviation at the airports.

Key words: ceilometers, bora, pulsation

Onsite

ON THE STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER OVER HIGHLY COMPLEX TERRAIN

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The atmospheric boundary layer (ABL) over mountainous regions plays a key role in the exchange processes between the surface and the free atmosphere, influencing weather, climate, and air quality. In contrast to the relatively uniform ABL over flat terrain, the structure of the mountain boundary layer (MoBL) is highly complex due to the wide spectrum of scales of motion induced by multi-scale orography. These range from small-scale turbulence and coherent structures to slope and valley winds, encompassing both thermally and dynamically forced flows. This intricate interplay of processes leads to a highly heterogeneous and variable boundary layer that challenges traditional modeling approaches and necessitates detailed investigation. This study aims to enhance our understanding of the convective boundary layer (CBL) over highly complex terrain by addressing the following questions: What are the characteristics of coherent structures (e.g., thermals) in the CBL and how stationary are they? What is their diurnal cycle, and how do their statistics, such as preferred locations, vary from day to day? To answer these questions, we utilize the ICON model to perform large-domain, real-world large-eddy simulations (LES) at a resolution of 65 m, encompassing 1.5 million grid points. The simulations employ a nesting strategy with four domains at resolutions of 520 m, 260 m, 130 m, and 65 m to progressively refine the model and capture fine-scale dynamics. Conducted over the Swiss Alps for seven days in August 2022, the simulations reveal a highly heterogeneous boundary layer with persistent thermal "hot spots" exhibiting a consistent diurnal cycle and surprisingly small day-to-day variability. Preliminary results show that different modeling approaches, including comparisons with Alptherm, a Lagrangian model developed for forecasting gliding conditions, agree rather well in terms of the spatial organization of thermals and their temporal variation. Moreover, strong thermals, while covering only a small fraction of the area, contribute disproportionately to the total mass flux. These findings emphasize the need for comprehensive sampling of all active thermal regions ("hot spots") to accurately measure regional fluxes. Insights from this study contribute to a deeper understanding of the mountain ABL and provide guidance for improving mesoscale and forecasting models over complex terrain.

Key words: complex terrain, convective boundary layer, coherent structures, thermals, LES, ICON, Alptherm, TEAMx

Onsite

REVEALING HIDDEN COHERENT STRUCTURES IN PLUME- ATMOSPHERIC DYNAMICS

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Wildfire-atmosphere interactions are characterized by complex, non-linear dynamics that span a hierarchy of spatial and temporal scales, all the way from integral scale (depth of the boundary layer) to microscale (in the surface layer). Traditional approaches to understanding plume dynamics have been constrained by the inherent difficulties in analyzing coherent turbulent structures within a Eulerian framework, where the rapidly evolving and transient nature of these features often obscures their role in governing energy transport processes. This research introduces a novel application of Lagrangian Coherent Structure (LCS) analysis to fire plume simulations within convective and near-neutral atmospheric boundary layers, adapting techniques more commonly employed in two-dimensional flows such as surface ocean currents to identify transport barriers in atmospheric flows. By applying LCS methods to high-resolution large eddy simulations of fire plumes, we identify and characterize persistent coherent structures that govern the flow dynamics and dispersal patterns of the fire plume. Advanced visualization techniques further enable the identification and tracking of these structures in ways that conventional approaches cannot. Our results demonstrate how LCS methods reveal the transport barriers between coherent turbulence structures that organize the seemingly chaotic flow within and around fire plumes. This approach not only enhances our fundamental understanding of atmospheric transport processes within the boundary layers of wildfires, but also establishes a new methodological framework that more accurately reflects the three-dimensional reality of atmospheric flows as experienced in nature.

Key words: coherent structures, turbulence, fire plumes, visualization

Onsite

TURBULENCE ANISOTROPY IN LARGE EDDY SIMULATIONS OF CONVECTIVE BOUNDARY LAYER FLOWS OVER IDEALIZED RIDGES

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Convective Boundary Layer (CBL) flows are associated with daytime conditions, when the sun heats up the surface and buoyancy is a source of turbulence kinetic energy and contributes to the growth of the boundary layer. CBL flows have been studied extensively through measurement campaigns as well as numerical simulations both over flat and complex terrain. Their very near surface structure remains insufficiently resolved, though. Recently, turbulence anisotropy was proposed to explain observed deviations of fluxes from Monin-Obukhov Similarity Theory in complex terrain. However, the effect of characteristic length scales associated with complex terrain on turbulence anisotropy are still not quantified. While different research groups performed Large Eddy Simulations (LES) of flows over idealized ridges in the past, none analyzed turbulence anisotropy for such flows so far. In this talk, we want to close this gap and discuss how turbulence anisotropy evolves in a CBL flow across idealized mountain ridges through LES data generated with the Cloud Model 1 (CM1). To this end, LES were performed for idealized, two-dimensional ridges that are immersed within a CBL for two different ridge heights. The initial profile features a capping inversion on top of the CBL and large-scale forcing only above the ridge top. The boundary conditions are chosen to represent different flow regimes based on the shallow water Froude number and the ratio between ridge height and boundary layer height. Turbulence anisotropy and turbulent moments of the different simulations are analyzed at various locations across the ridge and compared to otherwise identical simulations over flat terrain. Preliminary results show that turbulence is more anisotropic where shear is stronger. For the same ridge height, turbulence in the surface layer is more isotropic if Froude number is small. Turbulence is more anisotropic in the low Froude number case, however, in the area of a hydraulic jump on the lee slope and in the mixed layer above the ridge top, where the stagnant layer below crest height interacts with the flow above. For the same Froude number, turbulence is more anisotropic in the upper mixed layer for a higher ridge, but more isotropic below crest height when compared to a simulation with a lower ridge. Therefore, both ridge height and Froude number have an impact on turbulence anisotropy.

Key words: Numerical Modeling, Turbulence Structure

Onsite

EXPLORING THE POTENTIAL OF A LARGE-EDDY SIMULATION OVER ENTIRE SWITZERLAND TO SIMULATE MOUNTAIN BOUNDARY LAYER PROCESSES AND SEVERE MOIST CONVECTION

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Together with the rise of computational power and the GPU-accelerated code of the ICON model, the horizontal grid spacing of real-case, full-physics simulations can be reduced to dx=100m. In this study, we present a large-eddy simulation (LES) domain with a horizontal grid spacing of 100m covering the country of Switzerland and surroundings. One of the major advantages of a large domain is to avoid common problems of LES in small limited-area setups (e.g., unwanted effects of domain boundaries, or the general limitation in size, or turbulence spin-up). Furthermore, we hope to gain accuracy by reducing discretization errors and by reducing implicit empiricism in physical parametrizations, by allowing for an explicit representation of scale interactions as much as possible. We select two case studies to present: First, we show the results of a day with weak synoptic forcing, where boundary layer processes dominate (September 13, 2019). We show the interaction of the mountain boundary layer with the ambient flow at very high resolution on the mountain-to-plain scale, while the major mountain boundary layer processes, e.g., the thermally-induced circulation such as valley winds and slope flows, are already resolved on the grid. Furthermore, we explore the differences in turbulence structure between 'complex terrain' and the surrounding 'plain' and give suggestions for potential parameterization development. As a second case study, we show a day with thermally-forced thunderstorm evolution over the Swiss Alps (July 31, 2024). Under comparably weak synoptic forcing, thunderstorms developed over the Alps before noon and led to high wind gusts and hail over the Swiss plateau, while the operational kilometric ICON model failed to simulate realistic precipitation patterns. Given the high horizontal resolution of our LES, we can expect that the thermally-induced flows leading to updrafts - and henceforth moist, deep convection - lead to more realistic precipitation patterns. We validate the simulation results with stations and radar composites and discuss the physical mechanisms leading to severe convection over the Alps.

Key words: large-eddy simulations, boundary layer, convection, numerical modelling

Onsite

PARAMETER ESTIMATION FOR THE YSU BOUNDARY-LAYER TURBULENCE SCHEME OVER HETEROGENEOUS TERRAIN

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Planetary boundary layer (PBL) parameterizations depend on spatially and temporally invariant empirical parameters. These are commonly set by comparing parameterization output with large-eddy simulations (LES), and seeking for the parameter values that minimize the differences. Typically, the reference LES assumes a flat and horizontally homogeneous environment. As a consequence, PBL parameterizations generally do not account for the impact of terrain geometry on turbulent transport in the overlying atmosphere. A straightforward way to extend single-column PBL parameterizations to orographically complex terrain is to make some empirical parameters dependent on the terrain geometry. Here, we demonstrate that ensemble-based idealized data assimilation experiments can be used for this purpose. Parameter estimation (PE) within a data assimilation framework provides a method to reduce model errors by adjusting model parameters based on atmospheric observations. To achieve this, we utilize an idealized modelling environment implemented with WRF and DART. We conduct Observing System Simulation Experiments (OSSEs), which involve a LES serving as the virtual truth and an ensemble of single-column models (SCM), where the only model error source is the PBL parameterization. Based on previously published parameter identifiability studies, we focus on global parameters influencing the parameterized vertical turbulent mixing. We assimilate vertical profiles from the LES simulations using the Ensemble Adjustment Kalman Filter (EAKF), in order to objectively adjust the mixing parameter. Specifically, we focus on the YSU PBL scheme. The empirical parameters in this scheme were originally determined through subjective comparison with a set of dry LES simulations, which represent various atmospheric regimes characterized by wind speed and sensible heat flux over flat and homogeneous terrain. We extend the original set of LES simulations by considering different geometric properties of the surface, such as elevation, slope aspect, and angle. We feed synthetic observations from these LES simulations into the PE algorithm and demonstrate that the optimal parameters do not converge to a single value across our experiments. With these results, we want to understand if optimal parameter values depend in any systematic way on the geometric properties of the surface.

Key words: Boundary Layer, Complex Terrain, Parameter Estimation, Data Assimilation, DART, WRF

Onsite

ASSESSING THE REPRESENTATION OF FLOW SEPARATION IN FOEHN DESCENT WITH HIGH-RESOLUTION NUMERICAL SIMULATIONS

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Foehn winds are warm, dry downslope flows that occur on the leeward side of mountain ranges. They result from air being forced to ascend, cool, and shed moisture on the windward slopes, followed by adiabatic warming during descent on the leeward side. This process produces characteristic temperature and humidity profiles. In the Alps, the descent of foehn winds is often restricted to specific hotspots, where the interaction between complex terrain, mountain-induced gravity waves, and flow separation concentrates the descending air. These hotspots are associated with localized warming and drying, significantly affecting weather conditions, forecast uncertainty, and have implications for ecosystems and human activities in the region. Previous studies using the COSMO model—run at 1 km resolution—have visualized these hotspots and linked them to gravity wave dynamics. However, whether a 1 km resolution is sufficient to accurately resolve near-surface flow separation—a key factor in foehn dynamics and their predictability—remains an open question. To investigate this question, we conducted high-resolution simulations for two case studies: one in the Rhine Valley (February 2017) and another in Meiringen, Switzerland (March 2022). Simulations were performed with the Icosahedral Nonhydrostatic (ICON) model
—a unified framework for both numerical weather prediction and climate research—using three nested domains with horizontal grid spacings of 520 m, 260 m, and 130 m, respectively. Turbulence was represented using large-eddy simulation (LES) techniques in all three domains. In the first stage, the model was successfully validated for the Meiringen case using data from the 2021–2022 Meiringen field campaign, which included wind lidar and microwave radiometer observations, providing detailed wind and temperature profiles. For the Rhine Valley case, previously analyzed at 1 km resolution, we re-examined the event at higher resolution to assess improvements in capturing flow separation dynamics. Additionally, we used offline backward trajectories to identify the descent pathways of foehn air parcels, enabling a detailed evaluation of how model resolution affects the spatial distribution of descent hotspots in the Swiss Alps. This study is the first to combine backward trajectory analysis with LES in the context of foehn research, allowing for a detailed visualization of the descent pathways of foehn air parcels. By integrating these approaches, we aim to enhance our understanding of how model resolution influences the representation of foehn dynamics. Ultimately, the study seeks to provide guidance on selecting suitable model resolutions for accurately capturing foehn events and their associated impacts.

Key words: Numerical modelling, foehn, LES, Lagrangian trajectories

Onsite

STRUCTURE OF THE CONVECTIVE BOUNDARY LAYER OVER COMPLEX TERRAIN: ICON-LES AND HIGH RESOLUTION 3D WIND OBSERVATIONS DURING A TEAMX TEST FLIGHT

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The atmospheric boundary layer (ABL) over mountainous terrain plays an important role in modulating the exchange of momentum, heat, and moisture between the surface and the free atmosphere. Unlike flat terrain, where boundary layer dynamics are relatively homogeneous, the mountain boundary layer (MoBL) exhibits pronounced heterogeneity driven by the complex interplay of multiscale orographic features. These interactions generate a broad spectrum of atmospheric motions, from turbulent eddies and coherent thermals to thermally and dynamically induced slope and valley flows. Understanding this complexity is essential for improving weather prediction, climate modeling, and air quality assessment in mountainous regions. This study investigates the structure and dynamics of the convective boundary layer (CBL) over highly complex terrain during a TEAMx test flight on 18 September 2024. Specifically, we address the following questions: What are the dominant characteristics of coherent structures in the CBL? How stationary are these features in space and time? What is their diurnal cycle? How does the model compare to observations? To address these questions, we employ the ICON model in large-eddy simulation (LES) mode at a horizontal resolution of 65 m, using a nested domain configuration (520 m to 65 m) to capture processes across scales. The simulation domain encompasses a region around the Sarntal Alps, one of the TEAMx target areas. The ICON-LES results are compared with novel airborne wind measurements obtained during a test flight of the AIRflows system aboard the TU Braunschweig Cessna F406 research aircraft. AIRflows delivers high-resolution, three-dimensional wind profile measurements along the aircraft track, providing a unique opportunity to validate and evaluate the LES output in real atmospheric conditions. Preliminary results reveal a complex, spatially variable CBL structure with persistent thermal features and localized regions of enhanced turbulence. The comparison with AIRflows data confirms the presence and spatial organization of key dynamical structures captured by the model, while also highlighting discrepancies that inform model improvement. This work contributes to a deeper understanding of the CBL in mountainous regions and demonstrates the value of combining advanced numerical simulations with targeted airborne observations for model validation and process studies.

Key words: complex terrain, convective boundary layer, coherent structures, thermals, TEAMx, LES, 3D wind observations

Onsite

ON THE SENSITIVITY AND RELIABILITY OF TURBULENT INFLOW GENERATION BY EDDY RECYCLING IN LARGE-EDDY SIMULATIONS

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Large-eddy simulations (LES) are an important tool to study turbulent flows on the local scale. When studying turbulence over horizontally homogeneous and flat surfaces, periodic boundaries emulate an infinitely long domain, where turbulence develops over time when random perturbations are introduced to the flow field at the initialization of the simulation. When performing simulations with open boundaries, introducing random perturbations at model initiation is not sufficient to produce realistic turbulence. Still, open boundaries might be needed to analyze undisturbed flow over isolated topographic features. To generate and maintain turbulence in simulations with such boundaries, more elaborate techniques are necessary. In the Cloud Model 1 (CM1), eddy recycling is used to generate turbulence at the inflow. The eddy recycling method captures the turbulent perturbations a certain distance downstream of the inflow and injects the captured turbulent field in the inflow region. The capture region has to be far enough from the inflow to prevent artificial periodicity in the turbulent moments. In addition, a filter is used to scale the captured perturbations and to recycle them only within the boundary layer, which is necessary to maintain numerical stability. To determine the fetch necessary to develop realistic turbulence and investigate the sensitivity of the fetch size to the specification of the spatial filter, a set of idealized LES were conducted for a shear and buoyancy driven atmospheric boundary layer with CM1. These tested the sensitivity of the method towards different spatial filters, damping factors and capture strategies. The analysis revealed a strong sensitivity of first and second-order moments to all parameters tested, and the response to changes in multiple parameters was non-linear. The agreement with the periodic reference simulation for flows with strong advection improved significantly by linearly decreasing the amplitude of the recycled perturbations with height The optimal filter and parameter choice varied for different flow speeds and boundary layer structures, however, highlighting the need to tune the parameters for each case and casting doubts on the suitability of the method for parameter tests of complex terrain flows.

Key words: Numerical modeling, Boundary condition, Boundary Layer Turbulence

Onsite

NEUTRAL AND CONVECTIVE BOUNDARY LAYER OVER GENTLE HILLS: INVESTIGATING THE SOURCES OF ANISOTROPY

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Gentle hills constitute a noticeable fraction of the Earth's surface and impose an important modification on the atmospheric flow above them. Interaction between gentle hills and the overlying atmosphere is relatively well understood for the neutral boundary layer. However, even for this simple case the near-surface turbulence structure remains a challenge. For stratified flow, existing parameterizations of surface fluxes are based on the Monin-Obukhov similarity theory (MOST) that is not valid over complex terrain. Recently, the degree of turbulence anisotropy was shown to improve near-surface scaling over complex terrain, especially under convective stratification. Here we perform very high-resolution large eddy simulations (LES) of neutral, forced-, and free-convective turbulent flows over idealized two-dimensional hills using the NCAR pseudo-spectral model. The simulations are designed to resolve the inner layer. The simulations are used to explore systematically the dependence of turbulence anisotropy on flow regime and relation relative to topography, with a special focus on the influence of streamline curvature.
Key words: Flow over hills, idealized LES, turbulence anisotropy

Onsite

TURBULENCE STRUCTURE AND SCALING IN STABLE BOUNDARY LAYERS

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Stable boundary layer (SBL) turbulence is notoriously difficult to describe due to the strong stratification that suppresses vertical turbulent motions, resulting in intermittent and highly anisotropic turbulence, especially during nocturnal wintertime conditions in Alpine valleys and depressions. Traditional turbulence scaling approaches, which often assume isotropy or rely solely on averaged flux parameters, are inadequate for capturing the complex topology and directional structure of turbulence in very stable regimes, and Monin–Obukhov Similarity Theory (MOST), commonly used to parameterize surface fluxes, shows significant limitations under very stable conditions. This study aims to evaluate a novel turbulence scaling framework that explicitly incorporates turbulence anisotropy as a key parameter, moving beyond traditional flux-based MOST. We analyze high-resolution Large Eddy Simulation (LES) data from the psNCAR LES code simulating the GABLS1 case, a canonical high-Reynolds-number stably stratified boundary layer driven by constant geostrophic winds over a horizontally homogeneous surface. The domain size is 400 m × 400 m × 400 m with a fine grid resolution of approximately 20 cm, enabling detailed capture of turbulent structures. Two datasets with different surface cooling rates correspond to weakly and strongly stratified turbulence, thus allowing testing the scaling framework under varying stability conditions. Our analysis focuses on quantifying turbulence anisotropy using metrics derived from the Reynolds stress tensor. We examine how the different anisotropic states—ranging from near-isotropic to highly anisotropic one-component turbulence — appear in the SBL. Further, we relate the anisotropic states to turbulence scaling and coherent turbulent structures. The results highlighting the importance of anisotropy-aware scaling.

Key words: stable boundary layer, turbulence, scaling, LES, anisotropy

Onsite

FLOW REGIMES, THEIR DRIVERS AND TURBULENCE CHARACTERISTICS ON A MID-LATITUDE GLACIER

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Mountain glaciers are a perfect laboratory to study the interaction between the mountain atmosphere, and the stably stratified glacier boundary layer driven by the glacier ice surfaces. Due to their setting within mountain valleys, the structure of the glacier boundary layers is a result of a complex interplay between the surface thermal forcing, the thermally and dynamically driven multiscale mountain flows and the larger scale flow aloft. This complex flow structure plays an important role in glacier microclimates with implications for surface energy and mass balance of glaciers. However, few datasets of atmospheric measurements over the whole surface of a glacier are available to probe this complex interaction and its spatio-temporal variability. In August and September 2023, the Second Hintereisferner Experiment (HEFEX II), a three-week measurement campaign took place on the Hintereisferner glacier in the Austrian Alps to address these challenges. The glacier was instrumented with 18 surface weather stations, of which 10 were equipped with two or three levels of turbulence measurements distributed in along and across glacier transects. The data from this extensive dataset is used to characterize the spatio-temporal structure of the near-surface flow over the glacier and investigate its turbulent properties. Using a clustering method on the vertical profiles from one tower at the upper part of the glacier tongue, we show that glacier boundary layer is characterized by different classes of katabatic flows, as well as perturbed flows related to the impact of larger scale forcing. We also show that these different types of flow show characteristic horizontal wind and temperature structure across the glacier tongue. The surface measurements are then used to explore the turbulence structure during the different flow regimes, the evolution of the different types of katabatic flow with down-glacier distance, and estimate the surface energy balance over the glacier.

Key words: Glacier boundary layer, turbulence

Onsite

EXPLORING THE IMPORTANCE OF HORIZONTAL TRANSPORT TERMS IN KATABATIC FLOW OVER A GLACIER

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Common turbulence parametrizations in numerical weather prediction models and traditional boundary layer theory are predominantly designed for horizontally homogeneous flat terrain and only consider vertical transport processes. However, these assumptions fail in valleys, where the horizontal constrictions to the flow as well as prevalent surface heterogeneity mean that horizontal terms in the budget equations (e.g. advection) become important. Over a mountain glacier, in addition, the acceleration of the katabatic wind downslope, a decrease in wind speed from the centerline towards the margin due to lateral variation in the forcing (glacier ice vs. rocky sides), and horizontal temperature gradients necessitate consideration of horizontal terms in the budgets of mean and turbulent quantities. We investigate the importance of horizontal terms in the budgets of momentum, heat and TKE for deep katabatic flows over the Hintereisferner glacier in Austria. The analysis is based on data collected during the three-week-long Hintereisferner Experiment (HEFEX) in summer 2018, where four turbulence towers with two observational levels were installed in an along- and across-glacier transect, allowing the estimation of not only vertical but also horizontal terms in the down-glacier and cross-glacier direction. Towers were equipped with two levels of turbulence sensors at 1 m and 2 m, an additional level of mean wind at 3 m and temperature sensor at 1 m. The focus of the study is on deep flows where both turbulence observational heights were below the potential jet maximum height, so that all the estimated budget terms are located within the same layer. In addition, the results are qualitatively compared to the budget results of the large eddy simulations (LES) case study for one of the days. For selected deep-flow periods, results show that horizontal terms significantly contribute to the budget equations. The largest contributions arise from horizontal advection, improving heat budget closure by 3–40 % (observations) and 365% (LES) relative to the heat flux divergence in the mean over the entire glacier. Additionally, the momentum budget demonstrates an improvement of 37–123% (observations) and 1034% (LES) over the entire glacier, relative to momentum flux divergence. While the observations show negligible horizontal shear contributions, the model results indicate a better budget closure when accounting for horizontal shear contributions. The TKE budget residual decreases by 1–4% (observations) and 15% (LES) over the whole glacier relative to dissipation. These findings highlight the need of considering horizontal processes when representing boundary layer dynamics in complex terrain.

Key words: TKE budget, momentum budget, heat budget, katabatic layer, boundary layer, glacier, glacier flow, glacier wind, katabatic wind, turbulence budget, complex terrain, glacier boundary layer, horizontal advection, large eddy simulation (LES), surface heterogeneity, horizontal shear, mountain meteorology, turbulence observations, numerical weather prediction (NWP), Hintereisferner glacier, HEFEX, stable boundary layer

Onsite

ANALYSIS OF TURBULENCE MEASUREMENTS FROM SEVERAL EDDY COVARIANCE STATIONS ON AN ALPINE GLACIER: HINTEREISFERNER, AUSTRIA.

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On glaciers, wind regimes largely control turbulent fluxes of sensible and latent heat. Turbulent fluxes represent the heat input from the atmosphere, directly related to atmospheric warming and may be the main melt energy flux before solar radiation but they remain poorly understood, especially in katabatic wind regimes leading to a wind maximum close to the surface and strongly reducing the surface layer of constant fluxes. The high variability of turbulent fluxes in time and space is an important component of glacial melt variability. In the mountains, the relief may generate low-frequency disturbances in the wind field. Linked to interactions between local wind (katabatic and valley winds) and orographic perturbations of atmospheric flows, the variability of turbulent fluxes at the surface of mountain terrain remains poorly understood. HinterEisFerner EXperiment (HEFEX II) deployed extensive instrumentation on an Austrian glacier in summer 2023 to investigate glacier microclimate, turbulence properties, and multi-scale atmosphere-glacier exchanges. Here, we analyze measurements from eddy covariance stations to better document spatial variations in turbulent fluxes at the glacier surface according to wind regimes. Providing access to turbulence intensity variables, the eddy covariance method remains rarely used in mountain environments. Such turbulence measurements in complex mountain environments also make it possible to test and generalize the Monin-Obukhov similarity theory developed for flat, homogeneous terrain. Analysis of Fourier spectra and co-spectra of 20Hz turbulence data show significant differences between eddy covariance stations located along the flow line of the glacier. However, low frequency disturbances, most likely due to large-scale outer-layer turbulent structures, are observed in most spectra. Katabatic wind conditions prevailed during the measurement campaign. A wind speed maximum was frequently recorded at heights close to 2 m, significantly reducing the surface layer. Thus, aerodynamic profile methods based on Monin-Obukhov Similarity theory tend to underestimate the turbulent heat fluxes.

Key words: Turbulence; atmospheric boundary layer; eddy-covariance measurements; mountain glacier

Onsite

REFINING VALLEY WIND DAYS DETECTION FROM IN SITU OBSERVATIONS AND ERA5 REANALYSIS

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Numerous studies proposed algorithms to identify days with well-developed valley wind circulations, commonly applying thresholds based on measurements from surface weather stations and/or reanalysis datasets. In the present study, the method suggested by Lehner et al. (2019) was selected as a starting point to detect valley wind days in the Alpine Adige Valley (Italy), based on a year-long dataset collected at an eddy covariance flux station. The method employs three fixed thresholds: two on geopotential height gradients at 700 hPa in the North-South and West-East directions (synoptic forcing), and one on longwave radiation (Clear Sky Index, local forcing), following Marty and Philipona (2000). In order to refine the procedure, four geopotential pressure levels (850, 700, 500, and 300 hPa) were considered in this study, utilizing the ERA5 reanalysis dataset spanning the period 1991-2020. Geopotential height gradients were calculated for both the North-South and West-East directions over a domain across the entire Alpine region. Furthermore, thresholds were assessed through the application of an n-day moving window. The Clear Sky Index was calculated based on more than 10 emissivity parameterizations. The latter were evaluated both in their original formulations and with parameters optimized for the region of interest. The minimization problem was addressed using the Levenberg–Marquardt algorithm. Finally, the most suitable emissivity parameterization for the Adige Valley and the most significant geopotential level were selected.
Key words: Clear-sky Index, ERA5 Reanalysis, Weak Synoptic Forcing, Valley Wind Days, Thermally- driven flows, Emissivity Parameterization

Onsite

CHARACTERISTICS OF LAND-ATMOSPHERE INTERACTIONS IN THE COMPLEX MOUNTAINOUS TERRAIN OF THE SOUTHEASTERN MARGIN OF THE TIBETAN PLATEAU

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Abstract: The Hengduan mountain situated in the southeast area of the Tibetan Plateau is in the conjunction area of the south Asia monsoon and southeast Asia monsoon, and it is also the heating sensitive area of the atmospheric heating source. It is of great importance for the understanding of the key processes of the atmospheric water resource in the Tibetan Plateau to investigate the effects and its parameterization schemes of the interaction between the land surface and the atmosphere on the water and energy exchange processes in this region. Based on the continuous eddy covariance measurements from the Erhai lake, Lijiang alpine grassland and Tengchong Beihai wetland land surface process observation sites, the characteristics of the interaction between the wetland/ lake/ grassland surfaces and the atmosphere will be analyzed. Combined with remote sensing datasets, the effect of the interaction between the land and the atmosphere on regional water and energy budgets and its theoretical model will be investigated in this region. The applicability of planetary boundary layer parameterizations schemes over this region in the mesoscale models will be validated. New parameterization schemes for the water and heat process in the planetary boundary layer over complex regions in mesoscale models will be developed. We try to find the mechanism of the effects of the exchange processes between the land surface and the atmosphere on energy and water cycles at regional scales (10-30 km) over complex terrain in the southeast part of the Tibetan Plateau.
Key words: the land surface-atmospheric interaction; the water and heat flux exchange process; the parameterization scheme; the complex mountain terrain; the southeastern area of the Tibetan Plateau

Onsite

CHARACTERISTICS OF TOPOGRAPHIC SHELTERING IN ICELAND

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Mean winds over the waters around Iceland are typically 8-10 m/s, while over land, there are many locations with much less mean wind speed. A number of such locations, with mean wind speed below 3.5 m/s, are identified by the help of an extensive network of automatic weather stations, run by different bodies and for different purposes. At all these low-wind locations, the topographic sheltering from winds from the most frequent directions can be identified. In about half of the cases, the sheltering is reproduced in a dynamic downscaling of winds with a horizontal resolution of 2.5 km , while at the other half of the locations, the relevant topography is poorly resolved and the shelter is not reproduced. The best shelter location, with mean winds of 1.9 m/s is found to be inside a narrow valley in NW-Iceland, Tungudalur, where several mesoscale mountain ranges run perpendicular to all prevailing wind directions.

Key words: Iceland, topographic shelter

Onsite

TRENDS IN LAND SURFACE TEMPERATURES IN ICELAND

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Data from remote sensing is retrieved to map the evolution of land surface temperatures (LST) in the complex topography of Iceland 2001-2023. There is very large regional and local variability in the trends of LST. This variability may be linked to rising air temperatures, leading to changes in snow cover and vegetation. In certain regions, the change in snow cover appears to dominates the change in LST, while in other regions, changes in LST may be attributed to changes in vegetation. The reduction of major ice caps, changes in volcanic and geothermal activity give a clear signal in the dataset.
Key words: Land Surface Temperature, Iceland, snow cover, vegetation changes

Clouds and precipitation

Onsite

CONVECTION INITIATION MECHANISMS OVER COMPLEX TERRAIN

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Moist orographic convection is often conceptualized as a simple process: conditionally unstable (or potentially unstable) air is lifted by orography to its nominal level of free convection (or saturation), whereupon deep convection initiates. Although this notion is not without merit, it grossly underestimates the complexity of the problem and thus cannot explain many real-world convection events. In particular, as airflow traverses the terrain, the degree of moist instability, and the necessary lifting to realize it, is strongly modified and becomes as spatially heterogeneous as the terrain itself. Achieving a complete understanding of orographic deep convection requires a joint understanding of two different problems: deep-convection initiation (CI) and orographic flow dynamics, including multiscale circulations and turbulence. To encompass this broad scope, this presentation first reviews the modern understanding of CI, including adiabatic parcel theory and impacts of critical processes neglected by the theory (cloud- environmental mixing and vertical perturbation pressure gradients). Focus then shifts to the orographic CI problem, broken down according to orographic flow regimes. For each regime, the effects of the orography on multiscale flow kinematics and thermodynamics are considered, with attention focused on processes leading to the coincidence of strong updrafts and sufficient local moisture/moist instability to support CI.

Key words: Moist convection, orography, turbulence

Onsite

THERMALLY-DRIVEN OROGRAPHIC CONVECTION INITIATION IS SENSITIVE TO TERRAIN STEEPNESS

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Diurnal mountain winds favor the onset of deep moist convection, both because they transport heat and moisture horizontally and vertically, making the environment more supportive, and because they may lift air parcels above their level of free convection. We study the effect of cross-valley circulations on convection initiation under synoptically undisturbed and convectively inhibited conditions, using idealized large-eddy simulations with the Weather Research and Forecasting (WRF) model. We consider quasi-2D mountain ranges of different heights and widths and we contrast convection initiation over relatively steep mountains (20% average slope) and less steep ones (10%). Under identical environmental conditions, steeper mountains cause stronger thermal updrafts at ridgetops, but lead to a delayed onset and lower intensity of deep moist convection. Analysis of the ridgetop moisture budget reveals the competing effects of moisture advection by the mean thermally driven circulation and of turbulent moisture transport. At mountaintops, the divergence of the turbulent moisture flux offsets the convergence of the advective moisture flux almost entirely. Considering in-cloud vertical profiles of equivalent potential temperature, we demonstrate that buoyant updrafts over steeper mountains are more strongly affected by the turbulent entrainment of relatively dry environmental air. This depletes their moisture and cloud water content and makes them less effective at initiating deep convection. The weaker convection over steeper mountains is a robust finding, valid over a range of background environmental stability and mountain sizes.
Key words: Orographic convection; Convection initiation; Large-eddy simulation; Moisture budget

Onsite

A CASE STUDY OF COLD-SEASON EMERGENT OROGRAPHIC CONVECTION AND ITS IMPACT ON PRECIPITATION

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It is not uncommon for layers within the warm conveyor belt in a frontal system to become potentially unstable, releasing elevated convection. The present study examines this destabilization process over complex terrain, and resulting precipitation, with a focus on the surface coupling, orographic ascent, and the initiation and evolution of convective cells. This study uses detailed observations combined with numerical modeling of a baroclinic system passing over the Idaho Central Mountains in the United States on 7 February 2017. The data were collected as part of the Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment (SNOWIE). Specifically, observations from a ground-based scanning X-band radar and an airborne profiling Doppler W-band radar along ~100 km long flight tracks aligned with the wind describe the development and evolution of convective cells above shallow stratiform orographic clouds. Convection-permitting numerical simulations of this event, with an inner domain grid resolution of
0.9 km, and Large Eddy Simulations at 100 m resolution, capture the emergence and vertical structure of the convective cells. Therefore, they are used to describe the advection of warm, moist air over a retreating warm front, cold air pooling within the Snake River Basin and adjacent valleys, destabilization in a moist layer above this shallow stable layer, and instability release in orographic gravity wave updrafts. In this case, the convective cells topped out near 6 km ASL, and the resulting precipitation fell mostly leeward of the ridge where convection was triggered, on account of strong cross-barrier flow. Sequential convection initiation over terrain ridges and rapid downwind transport led to banded precipitation structures

Key words: cold-season orographic convection embedded in stratiform cloud observations and LES modelling

Onsite

COMPARATIVE ANALYSIS OF PRECIPITATION PHASE CLASSIFICATION USING MRR, X-BAND POLARIMETRIC DATA, AND DISDROMETER OBSERVATIONS IN COMPLEX TERRAIN

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This study aims to verify a simplified hydrometeor classification methodology applied to single-polarisation K-band vertically pointing Doppler radar (Micro Rain Radar, MRR) observations. The methodology is implemented for both MRR2 or MRR-Pro models processing raw spectral data (Garcia-Benadí et al., 2020, 2021). The MRR classification is compared here with two different classifications obtained from an X-Band Polarimetric Radar (Mont Moucherotte operational X-band dual polarisation radar operated by Météo-France) and a ground-level disdrometer. Despite the three hydrometeor classifications compared here have a number of different precipitation types, for the sake of simplicity, we remap them in only three types, considering their phase: liquid, solid and mixed. The comparison is carried out in Grenoble, a complex terrain region in the French Alps, at different altitudes to assess the accuracy and consistency of the MRR classification. The MRR data, providing high-resolution measurements (10 seconds), are compared with lower temporal resolution (5 minutes) common volumes of X-RAD data at 1802 m high above the MRR. Additionally, two disdrometers providing surface-level data with a 1-minute temporal resolution are used: one collocated side by side with the MRR, and the other located 1500 meters above the MRR and at a horizontal distance of 12 kilometres from it, for further comparison. The results show an overall good agreement between the MRR, X-RAD, and disdrometer measurements, confirming the reliability and accuracy of the MRR methodology in classifying the precipitation phase different altitudes. This supports the use of the MRR classification as a precise tool for understanding the vertical structure of precipitation and accurately identifying hydrometeor types. These findings demonstrate the potential of the MRR methodology for improving precipitation phase monitoring in complex terrain regions and contribute to their complementary use with polarimetric radar systems for operational applications.

Key words: Micro Rain Radar, X-Band Radar, Hydrometeor Classification, Disdrometer,

Online

PREDICTING SNOW-TO-LIQUID RATIO IN THE MOUNTAINS OF THE WESTERN UNITED STATES

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The snow-to-liquid-ratio (SLR) and its inverse, snow density, are crucial for forecasting snowfall in numerical weather prediction models and for estimating snow-water-equivalent (SWE) on the ground using remote sensing. SLR also varies widely in space and time, making it challenging to forecast accurately, particularly in the heterogenous terrain and climate of the mountains of the western United States. This study utilizes high quality, manually-collected measurements of new snowfall and new SWE from 14 mountainous sites across the region to build multiple linear regression (MLR) and random forecast (RF) algorithms to predict SLR as a function of atmospheric variables. When an MLR algorithm is trained on a simple combination of wind speed and temperature from either the ERA5 reanalysis, the Global Forecast System (GFS), or the High Resolution Rapid Refresh (HRRR), it predicts SLR with considerably more skill than existing SLR prediction methods. When a more extensive set of variables is considered, the skill improves further. The variables used to achieve the most skillful prediction of SLR are temperature, wind speed, relative humidity, specific humidity, maximum solar altitude angle during the observing period, CAPE, and HRRR QPF (Quantitative Precipitation Forecast). When an RF algorithm is trained using these variables, it can predict SLR with R2=0.43 and MAE=2.94. For the existing SLR prediction techniques currently used in operations, R2 ranges from 0.04 to 0.23 and MAE ranges from to 4.01 to 9.45. Therefore the algorithms built in this paper can drastically improve SLR prediction over the mountains of the western US. When the observed new SWE is used as a predictive variable, instead of QPF, the skill improves further. New SWE is the single most skillful variable in predicting SLR, which means that errors in model QPF strongly translate to errors in SLR prediction.

Key words: Snow, Precipitation, Machine Learning, Forecasting

Online

ON THE APPLICABILITY OF THE LUME MODEL TESTING CONVECTIVE OROGRAPHIC RAINFALLS: CASE STUDIES IN THE ALPINE MOUNTAIN RANGE

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In the field of geo-hydrological hazard, rainfalls represent the most important triggering factor for superficial terrain failures such as shallow landslides, soil slips and debris flows (Guzzetti et al., 2008). These phenomena are triggered over mountain regions where the density of the ground-based meteorological network is sometimes poor. Moreover, the local effects caused by mountain topography can change dramatically the spatial-temporal distribution of rainfalls (Abbate et al., 2021; Abbate et al., 2022) especially when convective rains are expected. Trying to reconstruct a representative rainfall field across mountain areas is a challenge due to the complex interaction between terrain elevation and cloud microphysics. We present here an evolution of the Linear Upslope Model Extension (LUME) developed in recent years by (Abbate et al., 2021; Smith and Barstad, 2004). This model has been designed to describe the mechanism of orographic precipitation considering vertically integrated quantities. The precipitation mechanism is driven by the incoming water vapour flux that hits the mountain upslope region. It is a didactical numerical routine that aims to understand better the mechanism of the rainfall generation under different initial and boundary conditions, linking the characteristic of the rain event with the expected or the reported geo-hydrological effects on the ground. We aimed to increase the accuracy of LUME including some correlation within the meteorological indexes retrieved from radiosonde parameters and the empirical estimation of the precipitation efficiency. We have extended the LUME model to work automatically within a 2D domain including also the 2D representation of the convective triggering functions that depend on the convergence/divergence of the incoming atmospheric fluxes. A simplified representation of the warm-rain and cold-rain bulk schemes implemented within the COSMO model (COSMO Consortium for Small-scale Modeling, 2025) has been included considering two possible scenarios that take into account the activation/non-activation of the moist convection. The latter has been resolved using implicit/empirical convection schemes able to predict the expected rainfall rates. The results obtained applying the new "LUME 2D Conv" release that includes moist convection were tested for a couple of case studies that happened in Northern Italy. Results were then compared with the local rain gauge amounts recorded on the ground. They have shown a satisfactory reproduction of the amounts, rates and locations of the rainfall maxima, giving a realistic reconstruction of the precipitation that occurred for the critical event studied.

Key words: #convection, #heavyrain, #hydrogeologicalhazard, #python, #2D, #upslopemodel

Onsite

OROGRAPHIC INFLUENCES ON PRECIPITATION IN A CONTINENTAL MOUNTAIN ENVIRONMENT AS OBSERVED BY MOUNTAIN AND VALLEY PROFILING RADARS

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Orography has a dramatic influence on cool-season precipitation over the western continental United States, building an upper-elevation snowpack for regional water resources and winter tourism and modulating winter storms that impact transportation and public safety. Using K-band profiling Micro Rain Radar (MRR) and PARSIVEL disdrometer observations from the Wasatch Mountains (2676 m MSL) and the adjoining Salt Lake Valley (1365 m MSL) during the 2022/23 and 2023/24 cool seasons, which produced well-above average mountain snowfall, this presentation examines the characteristics of cool-season storms in the continental mountain environment of the eastern Great Basin of North America. Observations reveal important differences between mountain and valley radar profiles. At the mountain site, a higher frequency of 0–20 dBZe reflectivities occurred, consistent with increased precipitation occurrence due to orographic enhancement. Echoes were deepest during southerly or southwesterly flow with high integrated vapor transport and the passage of cold fronts or baroclinic troughs and shallowest during post-cold-frontal precipitation periods when median -10 dBZe echo tops were only 1260 m AGL. Reflectivities increased with decreasing height near the ground at the mountain site, consistent with shallow orographic precipitation growth, especially during post-cold-frontal precipitation periods. In contrast, at the valley site, reflectivity frequencies declined with decreasing height near the ground, presumably due to sub-cloud sublimation and evaporation. These results illustrate important contrasts in precipitation growth and loss processes between mountain and lowland sites, with sub-cloud sublimation and evaporation underappreciated mechanisms for reducing lowland precipitation and enhancing the orographic precipitation gradient. Operational radars and space-borne sensors likely inadequately sample or account for these near-surface processes in continental mountain environments.

Key words: Orographic Precipitation, Snow, Radar

Onsite

USING NOVEL LAKE-BASED SNOWFALL MEASUREMENTS IN THE ROCKIES, ALPS, AND HIMALAYAS TO OPTIMISE THE REPRESENTATION OF SNOWFALL IN THE METUM REGIONAL ATMOSPHERIC MODEL AT KILOMETRE GRID-SCALES

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Complex mountain orography induces sharp gradients in precipitation accumulation locally, which makes snowfall observation and prediction by regional atmospheric models a major challenge and susceptible to bias. This study addresses these challenges by using a unique repository of snowfall measurements with little bias at a range of ‘super sites’ in the Rockies, European Alps and Himalayas, which are used to produce a snowfall-optimised version of the atmosphere-only UK Met Office Unified Model (MetUM) at a spatial resolution of 1.5 km. The snowfall measurements involve using the winter time-series of water pressure in frozen lakes to measure the mass of falling snow during extreme precipitation events directly over the lake area, which are comparable in size to the model’s grid cells. Development of the snowfall-optimised version of the MetUM involves undertaking a series of model sensitivity experiments focused on testing and understanding the influence of the double moment cloud microphysical scheme (CASIM) used by the MetUM, with the aim of better capturing the onset and end periods, and amounts received during observed snowfall events. The results presented here will show that the snwfall-optimised MetUM is able to accurately simulate both the timing and amounts of snowfall observed, i.e., its snowfall output is essentially considered as pseudo-observations. We subsequently present results showing detailed climatological maps of snowfall for the Alps and western-central Himalayas based on running the snowfall-optimised MetUM over these regions from 2000 to present.

Key words: Snowfall, observations, optimised-model, high-resolution, production runs, Alps, Himalayas, Rockies

Onsite

REPRESENTING SUB-GRID OROGRAPHIC FORCING IN A NEW CONVECTION SCHEME.

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It is well known that flow over orography produces ascent which can initiate or enhance convection, but the importance of small-scale orography is uncertain. Comparison of high resolution simulations of the 2018 Kerala Floods case with full and degraded orography have demonstrated that small-scale orography is able to significantly enhance convective precipitation over the Western Ghats. This demonstrates the need to represent the effects of sub-grid orography within convection schemes, which currently assume a flat, horizontally homogenous underlying surface. The high resolution Kerala Floods simulation was also used to show that orographic ascent depends simply on the grid-box mean wind speed and the sub-grid orographic slope. This simple representation of sub-grid orographic forcing has been coded into a new convection scheme currently being developed at the Met office. Initial results of standard tests are promising, with a significant reduction in the long-standing dry precipitation bias over India in N96 climate simulations. High resolution case study simulations will be verified against TEAMx observations, hopefully to demonstrate that they can treated as "truth". They can then be used in combination with observations to aid understanding of the underlying processes involved in orographic convective initiation. They can also be used to verify low resolution simulations using the convection scheme. There are also plans to utilize the Met Office model in idealized mode, to both improve and validate the sub-grid orographic forcing in the convection scheme.

Key words: Orographic convective initiation; TEAMx

Onsite

THE INFLUENCE OF TOPOGRAPHY ON LOWERED SNOW LINE IN ALPINE VALLEYS

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This research examines the lowered snow line during the precipitation event in the case of two alpine valleys close to one another (Koritnica valley and Zadnjica valley) located in the eastern part of the Julian Alps. Based on a set of 2 year measurements and study of topographic amplification factor (TAF), we investigated the influence of the valley topography on the occurrence of a lowered snow line and intensity of latent cooling. In order to determine whether the snow line in the valleys drops at the same time and with the same intensity of latent cooling, in the first part we compared the temperature conditions during precipitation events with a lowered snow line. In the higher parts of the valleys, the phenomenon was more pronounced in Koritnica, and in the lower parts of the valleys in Zadnjica. In some cases we found out that the lower parts of the valley can cool down more than the upper. As the findings in the second part of the study indicate, the dynamics of a lowered snow line depend on the intensity of the precipitation and the topography of the valley (TAF). The research confirmed the influence of the shape of the valley on the dynamics of a lowered snow line and in open parts of the valley, latent cooling is weaker than in closed ones. In such cases differences in elevation play a smaller role in the occurrence of a lowered snow line than does the topographic openness of the valley itself.

Key words: lowered snow line, latent cooling, TAF, Julian Alps, zero isotherm

Onsite

ICING SENSITIVITY TO HORIZONTAL RESOLUTION OF THE HARMONIE-AROME MODEL DURING OROGRAPHICALLY-FORCED FLOW IN NORWAY.

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In February and March 2025, Airbus helicopters conducted a flight campaign in Northern Norway based in Brønnøysund. During this campaign, the H145 helicopter was instrumented with a Cloud Droplet Probe (CDP) and temperature sensors to measure liquid water content, droplet sizes, and temperature during icing conditions. The goal was also to get a better understanding of the response of the helicopter in such conditions. Two days in particular stood out as interesting, in which the helicopter flew into orographically-forced flow over a mountain north of Brønnøysund. In the operational weather model with 2.5 km horizontal resolution, these two days looked quite similar with respect to liquid water content, temperature, and the calculated icing conditions. However, measurements from the CDP and reports from the pilots describe a different story, with the first day showing quite high water contents and considerable icing, while the second day shows considerably less water and icing. On the other hand, retrospective analysis with experimental HARMONIE-AROME with 300 m grid spacing and cubic grid reproduces the observed differences more accurately. The high-resolution model not only accurately reproduces the greater liquid water content lifted higher into the atmosphere on the first day, but also more distinctly captures the markedly reduced water content on the second day, despite quite similar flow conditions. This illuminates the importance of running physical models with high resolution over terrain in order to capture complex flows with high spatial and temporal variations in water contents.

Key words: Mountain waves, flight campaign, observations, numerical weather prediction, atmospheric icing

Onsite

IMPACT OF SOUTHWESTERLY UPPER-LEVEL FLOW ON PRECIPITATION IN THE KVARNER REGION – FIRST APPROACH

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The Kvarner region frequently stands out in weather forecasts due to precipitation that is either absent or more abundant compared to other areas in Croatia. Meteorological observations and analyses indicate that forecasts of cloudy conditions and rain provided by various meteorological models for the Kvarner region only occasionally prove to be accurate. In some cases, precipitation appears only in traces or is entirely absent. This phenomenon is particularly observed during synoptic situations characterized by a deep trough at the 500 hPa level with humid and relatively cooler air mass descending from northwestern Europe towards the Mediterranean, and at the same time the absence of direct cyclonic activity or frontal system passage at mean sea level pressure over the Adriatic. In such synoptic situations, southwesterly flow at the 500 hPa level is established over the northern Adriatic, while surface flow is predominantly from the southeast. The interaction of the moist airflow with the rapidly rising orography in the hinterland of Rijeka results in forced ascent which leads to cooling and cloud formation. To systematically investigate these patterns, geopotential height data at the 500 hPa level from ERA5 reanalysis were analyzed using the EOF method. Synoptic patterns characterized by southwesterly airflow over the Adriatic and Croatia were selected for further analysis. Here, a representative case study was chosen for numerical simulation using the Weather Research and Forecasting (WRF) model. A comprehensive analysis of temperature, relative humidity, and wind speed and direction at various pressure levels was conducted. The model outputs were validated against surface observations from the Croatian Meteorological and Hydrological Service (DHMZ), and the analysis was supplemented by radar and satellite imagery, as well as lightning data obtained from the LINET system.

Key words: 500 hPa level southwesterly flow, orographic precipitation, synoptic analysis

Onsite

THE ROLE OF OROGRAPHY ON CONVECTION INITIATION OVER HAINAN ISLAND

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High-resolution quasi-idealized simulations are conducted to investigate orographic impacts on deep-convection initiation (CI) over China's tropical Hainan Island, particularly early CI that occurs prior to sea-breeze convergence. A control simulation and sensitivity tests are conducted to reproduce Hainan's characteristic diurnal cycle and quantify CI-related processes. In these experiments, diurnal heating is essential for CI despite large convective available potential energy (CAPE) and minimal convective inhibition (CIN), highlighting the critical importance of thermal (rather than mechanical) forcing. To interpret this finding, a series of Gaussian-mountain (GM) simulations are conducted, which greatly simplify the island terrain but reasonably reproduce the CI from the full-terrain simulations. The heated GM case develops a much stronger updraft, and more favorable thermodynamic conditions for CI, in the mountain lee than corresponding unheated cases. This difference stems primarily from up-mountain-directed buoyancy forcing, which opposes the decelerative pressure gradient force (PGF) and friction over the windward slope, allowing the humid low-level flow to ascend the mountain. Due to increased windward adiabatic ascent, the PGF strengthens over the crest to drive strong cross-barrier flow. On the lee slope, the buoyancy and PGF act in concert to force a strong flow reversal, bringing a deep layer of moist, humid air up the lee slope. This reversed flow collides with the strong cross-barrier flow across the crest, creating an intense leeside updraft that causes CI. In contrast, the unheated GM case exhibits flow blocking and major drying over the crest and into the lee, with a weaker leeside PGF that only induces a shallow layer of reversed flow. Even if the initial morning sounding is replaced by a destabilized midday sounding with larger CAPE, the absence of diurnal heating still prevents CI. The insights from the GM simulations help to explain the CI sensitivities found in experiments using the full Hainan terrain.

Key words: Moist convection, orography

Onsite

MULTI-RIDGE EFFECTS ON COOL-SEASON OROGRAPHIC PRECIPITATION IN THE WASATCH RANGE, UTAH, USA

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At the eastern periphery of the Great Basin Provence in the interior western United States, the meridionally oriented Stansbury, Oquirrh, and Wasatch Ranges and their adjacent broad basins make up the basin-and-range orography of northern Utah. Distances between ridge crests in these ranges are roughly 40 km, and the terrain of the Wasatch Range reaches peak elevations of 3500 m MSL. This region features remarkable climatological precipitation gradients, with mean cool-season (Nov-Apr) liquid precipitation equivalent (LPE) increasing from 238 mm in Salt Lake City, UT (1288 m MSL) to 813 mm at Alta (2655 m MSL) in the Wasatch Range. The heavy cool-season orographic precipitation in the Wasatch Range can cause high avalanche danger and intense precipitation rates which impact transportation and commerce but builds a wintertime snowpack which supports tourism and provides water resources for over
1.1 million people in the Salt Lake City metropolitan area. In this research, we use high-resolution (Δx= 300 m) Weather Research and Forecasting (WRF) simulations of a trough passage across the serially arranged Stansbury, Oquirrh, and Wasatch Ranges on 22 March 2019 during the "Terrain Effect on Clouds and Precipitation — An Educational Campaign" (TECPEC) field program to examine how the region's basin-and-range orography impacts precipitation. The event featured a gradual shift from southwesterly flow to west-northwesterly flow with the trough passage. While precipitation totals were modest, we have high-quality aircraft data which we can use to validate results. We conduct sensitivity studies by reducing the elevation of Stansbury and Oquirrh ranges upstream of the Wasatch. Compared to simulations with reduced upstream terrain, real terrain simulations feature higher relative humidity with more area at saturation and lee waves generated by upstream terrain which propagate downstream to the Wasatch. These mechanisms combine to increase precipitation in the Wasatch in simulations with real terrain. This suggests the upstream basin-and-range topography of the region led to an aggregate effect that increased precipitation in the downstream Wasatch Range during this event rather than a decline in precipitation as one might expect due to vapor depletion.

Key words: Orographic precipitation, multi-ridge orography

Onsite

CHARACTERISTICS OF COOL-SEASON PRECIPITATION IN THE PARK RANGE OF NORTHWEST COLORADO

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Mountain regions are critical for global freshwater supply, a resource at risk due to the high sensitivity of these regions to climate change. Climate change can alter precipitation processes, increasing the risk of droughts and extreme precipitation that adversely affect communities. The Colorado Park Range is an important water source for the driest regions of North America and home to Storm Peak Laboratory (SPL). SPL has been a focal point for atmospheric research for decades. Despite the need to climatologically situate ongoing research and contextualize precipitation hazards that are amplified by global warming, no comprehensive precipitation climatology of this region exists to date. This study fills the gap by developing a cool-season precipitation climatology and investigating relevant precipitation mechanisms in mountainous terrain from the microscale to climate, by emphasizing extreme events. The study employs statistical and machine learning techniques using various types of precipitation observations, cloud measurements, and reanalysis data. Preliminary results indicate a bimodal precipitation seasonality (maxima in January and April), with no correlation to the El Niño Southern Oscillation (ENSO) and the Pacific North American (PNA) index. Snow extremes occur at significantly colder temperatures, more northerly flow, and higher wind speeds than extremes of liquid precipitation equivalent (LPE). Initial synoptic classification suggests snow extremes are linked to fronts and closed lows, while LPE extremes are driven by integrated water vapor transport (IVT). Further research will refine these results and investigate the relationship of large-scale conditions with mesoscale and microscale processes.

Key words: Orographic Precipitation, Extreme Cool-Season Precipitation, Synoptic Classification, Climatology, Cloud Physics

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OBSERVATION OF MICROPHYSICAL CLOUD PROPERTIES WITH HOLOGRAPHIC IMAGER ON SONNBLICK OBSERVATORY

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The understanding of microphysical cloud processes is key to improve precipitation forecasts and estimates of the cloud optical properties in climate projections. In-line holography is a well-established technique for in-situ measurements of microphysical cloud parameters such as the hydrometeor size distribution, phase, shape and clustering of cloud droplets and ice crystals down to a single particle level. During the ECCINT-INT02 and ACI0-SBO campaigns, two holographic imagers were placed on the Sonnblick Observatory in the Austrian alps (3106m a.s.l.). These instruments differ in resolution and measurement volume, complementing each other. smHolimo is oriented towards liquid-phase clouds with a resolution down to 3.7um while Holimo has a larger observational volume to capture more ice crystals. Over a two-month period, they captured various cloud types — predominantly liquid-phase clouds — alongside a suite of other meteorological, cloud, and aerosol instruments. To investigate the effect of wind-instrument misalignment on the performance of the holographic imagers, a targeted study was conducted. The imagers were deliberately oriented at different angles relative to the prevailing wind direction, and the resulting variations in droplet concentration within the measurement volume were analysed. Observed performance was compared with theoretical predictions based on computational fluid dynamics (CFD) simulations of the airflow around the instrument. This analysis quantified the dependency of errors in cloud hydrometeor size distribution and liquid water content (LWC) on the misalignment angle, informing recommendations for optimized instrument housing design. Additionally, LWC measurements from both holographic imagers were compared to other campaign instruments. This intercomparison served to validate the holographic instruments and to establish a consistent methodology for cloud hydrometeor size distribution and LWC measurement in future studies. Beyond stationary measurements at the observatory, cloud profiles were obtained by mounting one holographic imager on the Sonnblick Observatory cable car running between 1600 m a.s.l. and 3100 m a.s.l. The in-situ cloud microphysical observations were contextualized with aerosol measurements and meteorological data recorded on the cable car, enabling analysis of the vertical evolution of cloud microphysical properties from cloud base to cloud top.

Key words: clouds, microphysics, holography, in-situ, intercomparison, profiles, size distribution, cable car, Sonnblick

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THE INDIAN SUMMER MONSOON: AEROSOL-CLOUD INTERACTIONS AND THEIR IMPACT ON EXTREME RAINFALL EVENTS

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The Indian summer monsoon (ISM), occurring during June–September, is characterized by intense rainfall events that frequently trigger severe natural hazards, such as floods, with profound societal and economic consequences. Accurate prediction of heavy rainfall remains crucial for effective risk mitigation. While the influences of large-scale circulation patterns, water vapor availability, and orography on monsoon convection are well-documented, the role of aerosol-cloud interactions in modulating extreme precipitation remains insufficiently understood. Aerosols, serving as cloud condensation nuclei (CCN) and ice nuclei (IN), play a pivotal role in cloud microphysics and precipitation processes, thereby influencing the hydrological cycle and contributing to weather and climate variability. Mixed-phase clouds, particularly sensitive to aerosol perturbations, significantly impact the Earth's radiation budget. However, accurately representing their complex microphysical processes, including ice nucleation and hydrometeor growth, remains a persistent challenge in numerical models. In this study, the Weather Research and Forecasting (WRF) model coupled with a triple-moment cloud microphysics scheme is employed to investigate the influence of aerosol-cloud interactions on ISM precipitation. High-resolution simulations of monsoon depression events are conducted under contrasting aerosol regimes—clean continental and urban (polluted) conditions. Model outputs are rigorously evaluated against observational datasets to assess the accuracy and robustness of the simulations. Sensitivity experiments reveal that polluted conditions enhance extreme precipitation and intensify updraft velocities. This is attributed to enhanced ice-phase processes, which promote the formation of larger snow and graupel hydrometeors, thereby increasing latent heat release and further invigorating convection. The results underscore the critical role of aerosol loading in modulating extreme rainfall through intricate microphysical, thermodynamic, and dynamical feedbacks. Furthermore, the study highlights how uncertainties in aerosol representation contribute to biases in quantitative precipitation forecasts (QPF), underscoring the need for improved aerosol parameterizations in numerical weather prediction models. By elucidating the microphysical mechanisms driving aerosol-induced precipitation variability, this research provides new insights into ISM dynamics and offers actionable knowledge to enhance the predictability of extreme rainfall events.

Key words: Extreme rainfall, WRF, CCN, IN

Applications

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MULTISCALE SIMULATIONS OF ATMOSPHERIC BOUNDARY LAYER FLOWS FOR WIND ENERGY APPLICATIONS

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Most of human activity, including wind energy harvesting, happens in the atmospheric boundary layer (ABL). The ABL frequently evolves under unsteady, complex forcing, and over heterogeneous surfaces including variable topography. An accurate characterization of the complexity of ABL structure and evolution is needed for wind energy applications, but also for wildland fire prediction, urban climate studies, operation of uncrewed aerial vehicles, wind engineering applications, among others. Until recently, numerical studies of ABLs have been focused on idealized conditions based on simplifying assumptions such as homogeneity and steady geostrophic forcing. In recent years, these studies were expanded to account for heterogeneous terrain and variable forcing. However, the study of evolving, heterogeneous ABLs requires accounting for a range of complex interactions between the ABL and both the surface and large-scale atmospheric motions. High-performance computing capabilities and advanced numerical weather prediction models now facilitate coupled mesoscale to microscale simulations which can represent such interactions and enable numerical studies of realistic boundary layers. The coupling of large-scale simulations with microscale simulations presents several challenges which we have addressed developing methodologies for effective multiscale simulations of realistic atmospheric flows. First, we have developed a cell perturbation method to facilitate turbulence development in a microscale domain nested within a mesoscale domain. Second, we have implemented a three-dimensional planetary boundary layer (3D PBL) parameterization, to better represent turbulence in the so called “gray zone” at scales between 100 m and a couple kilometers. Finally, we have also developed a graphical processing unit based large-eddy simulation model, FastEddy, that enables exploring simulation sensitivity to input parameters and uncertainty quantification with an ensemble large-eddy simulation approach. These developments enable multiscale simulations of evolving heterogeneous boundary layers in complex terrain. The presentation will demonstrate multiscale simulations based on recent field studies in complex terrain.

Key words: multiscale simulations, wind energy applications, complex terrain

Onsite

DETECTION OF ADVERSE AND COMPOUND WEATHER EVENTS IMPACTING POWER INFRASTRUCTURE IN MOUNTAINOUS REGIONS

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Mountain regions are particularly vulnerable to extreme and compound weather events, which can have severe consequences for renewable energy production and critical infrastructure. But what constitutes an extreme event? What meteorological drivers and scenarios are most relevant? And how can this knowledge be applied in the context of energy meteorology? In this contribution, we aim to explore these questions through case-based examples, combining perspectives from both meteorologists and renewable energy stakeholders. H A suite of trheshold-based and AI detection methods, including causality-trigger algorithms, to identify and characterize such events, with a special focus on mountainous and complex terrain. These methods include deterministic and probabilisitic threshold-based detection, pattern recognition algorithms (e.g., SOM, HDBSCAN, Granger causalit). We address single, consecutive, and compound events such as high-impact windstorms, ramping in wind and solar production, and meteorological triggers that cause dynamic line rating (DLR) reductions, infrastructure vibrations, or overloading. Use cases such as storm "Petra" (2020) and the August 2022 derecho illustrate the application of these methods using ERA5, regional reanalyses (ARA), and forecast data cross the horizontal scales down to the hectometric scale. We assess power production cases and infrastructure vulnerability using spatial overlays of power lines, substations, and renewable sites, and evaluate historical and future exposure through scenario simulations. Recent advances incorporate probabilistic risk scores and trigger logic based on causal modeling concepts, enabling scalable detection from local to continental scales. This work supports decision-making for resilient energy system operations in complex terrain and contributes to a better understanding of how extreme weather under climate change can impact infrastructure in alpine regions. Our methods are being integrated into early warning systems and climate services for power system operators.

Key words: adverse weather; extreme events; definitions; detection; prediction; renewable energy; machine learning

Onsite

IMPACT OF HEATWAVE VARIABILITY ON NEAR-SURFACE TEMPERATURE OF AN ALPINE VALLEY

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Concerns about climate change are growing as extreme weather events such as heatwaves, droughts and storms become more frequent and severe. Addressing these issues requires both reducing greenhouse gas emissions and developing suitable adaptation strategies, especially in urban areas that are more vulnerable to climate change. Adaptation to heatwaves requires the knowledge or prediction of near-surface temperature distribution. Yet this distribution may depend upon the heatwave episode. The objective of the present paper is to address this link, for the alpine Grenoble metropolis. The analysis covers three 30-year periods: a historical period centered around 2005 and two future periods centered around 2050 and 2070. For the historical period, ERA5 reanalysis data are used, while future projections rely upon data from the Regional Atmospheric Model MAR forced by the global climate model MPI for the SSP2-4.5 pathway. Horizontal resolution is about 25 km for ERA data and 7 km for MAR data. Downscaling to the Grenoble metropolis at hectometric resolution is also performed during selected past and future heatwaves with the WRF model so as to compute the temperature (and wind) distribution at the valley bottom. Heatwaves are identified using daily maximal and minimal temperatures. Comparison with past heat waves shows that, for the Grenoble metropolis, the 92th percentile should be considered to reproduce the frequency and duration of these episodes. The same percentile is used to define heatwaves in the future. We found that the heatwave variability over the Grenoble metropolis is well characterized by the large-scale wind at 700 hPa -about 3000 m, which is just above the highest summits surrounding the valley. This wind blows either from the Northwest or the Southwest within an Omega pattern. When the speed of this wind is below 10 m/s, which is the most commonly encountered situation, the bottom-valley flow decouples from the large-scale wind and is thermally driven. The temperature field close to the valley bottom is then controlled by the land cover, whatever the heatwave episode. By contrast, when the wind speed exceeds 10-15 m/s, the bottom-valley flow is influenced by the large-scale wind through downward momentum transfer from the latter wind. Daytime temperatures remain land cover- dependent, but nighttime temperatures are influenced by the large-scale wind. However, this wind consistently blows from the Southwest in this case, resulting in similar temperature fields across the episodes.

Key words: Heatwaves, atmospheric boundary layer, urbanized alpine valley, near-surface temperature fields

Onsite

SIMPLIFYING SNOW TRANSPORT DYNAMICS: REDUCED ORDER MODELS AND ACCUMULATION DIAGNOSTICS

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Deriving a set of physical equations for snow particle motion in turbulent winds from first principles remains elusive. Even in a known wind field, snow particle trajectories exhibit significant nonlinear inertial effects due to a density several orders of magnitude larger than the surrounding air. Additionally, snow forms (and evolves) in complex geometries that have unknown drag functions. Despite these complications, scientists and engineers in a wide range of fields must still account for wind-snow coupling processes, such as blowing/drifting snow and preferential deposition. These approximations typically rely on empirical relationships developed from decades of snow and sand transport research. In the present research, we start with the Maxey-Riley equation, the governing equation of small inertial particles in a turbulent fluid, to define the acceleration of individual snow particles. Using tools from applied mathematics, we rigorously derive an approximation of the solution of these equations as a perturbation to the underlying wind field. This simple approach provides spatially and temporally resolved snow particle velocity fields, without numerical instabilities, that are directly parameterized by physical variables such as particle size, shape factors, and density. We combine this snow velocity field with new flow-physics based accumulation diagnostics to predict accumulation and ablation zones at an Arctic-Alpine study site in Northern Norway. Given the accelerated pace of wind simulation developments, a snow particle motion model that can match the fidelity of our wind models is a timely advance. Our snow particle motion equations allow snow scientists, hydrologists, and meteorologists, to study time-varying snow accumulation patterns in complex alpine terrain and provide scalable solutions that can match a range of spatial and temporal resolutions.

Key words: snow, blowing snow, preferential deposition, Lagrangian coherent structures, nonlinear dynamics, slow manifolds, reduced order modeling, terrestrial laser scanning, snow depth

Onsite

UNDERCATCH-CORRECTED GRIDDED PRECIPITATION DATA TO IMPROVE HYDROLOGICAL MODELLING IN HIGH-ALPINE COMPLEX OROGRAPHY

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Hydrological and snowpack models - such as the conceptual rainfall-runoff model COSERO and the physically-based snow and land surface process model Alpine3D - are highly dependent on the quality of meteorological input data. Gridded observational precipitation data sets, which are commonly used as model forcing, are typically derived from spatially interpolated station measurements. However, such data usually lacks correction for precipitation undercatch - i.e., the difference between actual precipitation and what is recorded by rain gauges. This discrepancy arises from factors like instrument design, splash effects, evaporation and wind. As solid precipitation is more susceptible to wind drag, undercatch errors are specifically present in mountainous regions with high elevation. As a result, station-based and gridded meteorological datasets in these areas tend to underestimate the actual amount of precipitation. Consequently, models applied in such areas often struggle to simulate the observed water balance - consisting of discharge, reservoir inflows, evapotranspiration, snowpack evolution and glacier mass balances - unless precipitation inputs are artificially increased to compensate for the missing volumes. Since lower-elevated stations with comparatively small undercatch errors are typically overrepresented in gridded data sets, directly correcting gridded precipitation fields is not feasible. To supply hydrological models with more realistic precipitation inputs in mountainous meteorological conditions necessary to capture the observed water balances, we present a novel set of monthly gridded undercatch correction factors for Austria. These corrections are derived from undercatch-adjusted station data using Generalized Additive Models trained on orographic features like elevation and terrain exposure. The resulting correction factors exhibit their highest values during the winter months and in alpine regions, achieving cross-validation R^2 scores exceeding 0.8. Precipitation adjusted with the derived correction factors is combined with additional meteorological inputs to drive a coupled snow–glacier–discharge modeling framework using a coupled chain of the models COSERO and Alpine3D. This setup is applied to three snow-dominated and glacierized catchments in Austria - Maltatal, Zillertal and Vernagtferner. Model outputs are validated against observed reservoir inflows, glacier mass balances and satellite-derived snow depth maps. Incorporating undercatch-corrected precipitation significantly improves the models' ability to reproduce observed glacier mass balances, snow and reservoir inflow dynamics, and in general, to improve the simulated water balance of mountain catchments.

Key words: precipitation, undercatch, data correction, gridded meteorological data, alpine hydrology, generalized additive models

Onsite

DETECTING MOUNTAIN WAVES FROM MODIS SATELLITE IMAGERY USING A HYBRID SPECTRAL AND MACHINE LEARNING APPROACH

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Mountain waves (MTWs) are an important mesoscale atmospheric phenomenon common to alpine regions, where their influence can be seen in cloud formation, turbulence, and vertical transport of energy and moisture. Accurate detection and monitoring of mountain waves is important for aviation safety, weather forecasting, and understanding atmospheric processes over complex terrain. While traditional detection methods have relied on model diagnostics or in situ observations, satellite-based approaches offer wide-area coverage with high spatial resolution. In this study, we present a new methodology for detecting mountain waves in satellite imagery, focusing on the use of column water vapor (CWV) as a tracer for atmospheric wave activity. The MODIS Terra and Aqua combined Multi-angle Implementation of Atmospheric Correction (MAIAC) Land Aerosol Optical Depth (AOD) Level 2 product is used to provide multiple daily images of CWV data at 1 km pixel resolution. Our current analysis area is restricted to mainland Norway, covering the period from February to May 2021, thus focusing on a region with frequent mountain wave activity and complex orography. In order to enhance detection, the CWV data are combined with 700 hPa wind fields from the AROME-MetCoOp mesoscale numerical weather prediction system. By sampling CWV along wind-parallel transects, we can extract one-dimensional signals in which mountain wave signatures are often clearly expressed. Our detection algorithm employs a hybrid approach that combines spectral analysis with machine learning. The wind-aligned CWV transects are Fourier transformed to obtain spectral density profiles, which are then interpolated to a uniform set of wavenumbers and log-transformed. These processed spectra serve as input to a one-dimensional convolutional neural network (CNN), trained to recognize the spectral features characteristic of mountain waves and to identify the dominant wavenumber bands where these features occur. The training dataset consists of 1000 manually labeled spectra, supplemented by 200 validation spectra. Only spectra with unambiguous mountain wave signatures are labeled as positive, resulting in a conservative training regime designed to minimize false detections. When applied to the validation set, 93 \% of the positives were true. While still under development, this method offers a scalable way to automate mountain wave detection in satellite-based CWV datasets. The approach has the potential to support research into the climatology of mountain waves and to establish a ground truth in validation studies focusing on MTW, as it quantifies MTW frequency bands from observations.

Key words: Mountain Waves, Sattelite image analysis

Onsite

THE DESTINATION EARTH ON-DEMAND DIGTIAL TWIN

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The Destination Earth On-Demand digtial twin is a flexible atmospheric model workflow run at sub-km resolution over any domain of choice in Europe. It includes an event detection and triggering framework for different types of extreme weather. We focus specifically on output for the impacting sectors: Hydrology, air quality, wildfire, storms, wind energy, solar energy, heat waves, and agriculture (frost). Running what-if scenarios is an important aspect of the project. For instance, to evaluate the benefits of switching to electric cars on air quality or the benefit of green areas with respect to heat waves in urban areas. We will show results for running historical pilot cases and cases run in 2024 and 205. We will discuss the scientific challenges of running at sub-km resolution as well.

Key words: Destination Earth; sub-km NWP; hydrology; air quality; renewable energy; what-if scenarios

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THE WEATHER ON-DEMAND FRAMEWORK

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Here we describe the Weather On-Demand (WOD) forecasting framework which is a software stack used to run operational and on-demand weather forecasts. The WOD framework is a distributed system for the following: (1) running the Weather Research and Forecast (WRF) model for data assimilation and forecasts by triggering either scheduled or on-demand jobs; (2) gathering upstream weather forecasts and observations from a wide variety of sources; (3) reducing output data file sizes for permanent storage; (4) making results available through Application Programming Interfaces (APIs); (5) making data files available to custom post-processors. Much effort is put into starting processing as soon as the required data become available, and in parallel where possible. In addition to being able to create short- to medium- range weather forecasts for any location on the globe, users are granted access to a plethora of both global and regional weather forecasts and observations, as well as seasonal outlooks from the National Oceanic and Atmospheric Administration (NOAA) in the USA through WOD integrated-APIs. All this information can be integrated with third-party software solutions via WOD APIs. The software is maintained in the Git distributed version control system and can be installed on suitable hardware, bringing the full flexibility and power of the WRF modelling system to the user in a matter of hours.

Key words: API, data assimilation, NWP framework, WRF

Onsite

UNDERSTANDING LOCAL AIR POLLUTION DYNAMICS IN BOGOTÁ: ATMOSPHERIC MODELLING AND OBSERVATIONS

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The city of Bogotá, situated on a high plateau in the heart of the Andes Cordillera (south America), is a metropolitan area with over 10 million inhabitants. The city frequently faces severe air pollution episodes that exceed both local and international health standards. Measurements of PM_{10}—particulate matter with an aerodynamic diameter smaller than 10 microns—consistently reveal a persistent hotspot in the southwestern part of the city, where concentrations pose serious health risks for the population. Despite increasing public concern, pinpointing the exact sources of particulate pollution remains a challenge. Although various studies have aimed to develop reliable emission inventories, the influence of atmospheric dynamics on extreme pollution events is still not fully understood. This study explores the relationship between observed pollution patterns and key atmospheric processes, including temperature inversions, stagnation, recirculation, and ventilation patterns. The overarching goal of this study is to uncover the atmospheric dynamics driving severe air pollution episodes in Bogotá. Using high-resolution numerical simulations with the Icosahedral Nonhydrostatic (ICON) model—a unified modeling framework for both numerical weather prediction and climate research—the analysis focuses on three pollution events primarily influenced by local emissions. The simulations employ a nested domain setup, with the innermost domain achieving a horizontal resolution of 1 km. Model performance has been successfully evaluated using surface meteorological data from a network of automatic weather stations across the city (19 monitoring stations), as well as daily radiosonde profiles launched from the local airport. Initial findings reveal the presence of stagnation zones within the urban landscape, which appear to correspond with the persistent PM10 pollution hotspots in the southwestern part of the city. These stagnation zones are associated with localized temperature inversions that suppress turbulent mixing and inhibit ventilation, thereby facilitating the accumulation of pollutants near the surface. The results highlight the complex interplay between cold air pool formation and thermally driven flows, which—when coinciding with elevated local emissions—can lead to hazardous concentrations of particulate matter.

Key words: Air pollution, numerical modelling, cold-air-pools

Onsite

SOLAR RESOURCE ASSESSMENT IN ICELAND BY A SYNERGY OF WRF MODELLING, SATELLITE DATA, SURFACE OBSERVATIONS AND A DEEP LEARNING MODEL

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High-resolution (2km) hourly downward irradiance at the surface for Iceland from 1990 to 2023 is estimated through the synergy of dynamical downscaling of the ERA5 re-analysis data using the WRF model, the CM SAF cloud, albedo, and surface radiation dataset based on AVHRR data (CLARA-A3), and surface observations of downward short wave fluxes. The methodology comprises of two main steps. First, daily average irradiance from CLARA-A3 is downscaled using the hourly temporal structure from the WRF dataset to generate an initial estimate of hourly irradiances. Second, errors in the derived hourly data (WRF-CLARA) are reduced using surface observations and a simple two-layer Multilayer Perceptron (MLP) model. This model incorporates input features such as surface albedo, solar zenith and azimuth angles, and elevation above sea level. The MLP is trained using data from 2002 to 2020, while the remaining years are used for independent validation. Comparisons with station observations outside the training period demonstrates the suitability of the generated time series. For all 23 analyzed stations, this methodology is shown to reduced the average hourly root mean square error (RMSE) from 101 W/m² (WRF), to 92 W/m² (WRF-CLARA), and finally to 81 W/m² in the MLP model corrected dataset. After the validation, Typical Meteorological Years (TMYs) are generated for each gridded point of the dataset to support solar resource assessment, taking into account customized solar panel configurations.

Key words: Solar prospecting, dynamical downscaling, remote sensing data, in-situ observations, machine learning

Onsite

A WARNING SYSTEM FOR THE LASEYER WINDSTORM IN A NARROW AND DEEP VALLEY OF NORTHEASTERN SWITZERLAND

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The Laseyer is a very local and uncommon windstorm in a narrow and steep valley in northeastern Switzerland. Whereas the ambient wind is from west to northwest, the strong surface wind in the valley is from the east, leading to gust speeds that become dangerous for the local train running into the valley to the Wasserauen station. To minimize the risk of derailment and to improve passenger comfort, the train service provider Appenzeller Bahnen (AB) has developed a new warning algorithm in close collaboration with academia (ETH Zurich) and the Swiss national weather service (MeteoSwiss). The aim is not only to accurately predict the Laseyer windstorm several hours in advance but also to reduce the number of false alarms. The new warning system is based on the MeteoSwiss operational ensemble prediction system at 1.1-km horizontal mesh size, which is then used in combination with an observation-based machine learning approach to probabilistically forecast Laseyer events up to 30 h in advance. A particular challenge in developing the new system was to introduce the customer, AB, to the modern concept of probabilistic numerical weather prediction, which requires a careful risk assessment by the customer. The operation of the new warning system during the 2021/22 Laseyer season shows that it is working successfully and also indicates that the warning thresholds in the warning algorithm can be adjusted in the future to minimize false alarms without increasing the number of missed events. In addition to the typical Laseyer conditions with westerly to northwesterly ambient winds, it will also be assessed if ambient southerly to southwesterly winds during foehn conditions could also lead to strong wind gusts normal to the railway track in the valley, and if thus these foehn conditions must also be considered in a warning system.

Key words: Forecasting; Forecasting techniques; Operational forecasting; Probability forecasts/models/distribution; Mountain meteorology; Wind gusts

Onsite

TOWARDS REVISION OF EXTREME WIND ESTIMATION OVER THE WIDER ADRIATIC REGION

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The Adriatic sea area is one of the few areas in mid-latitudes worldwide characterized by hurricane 5 scale wind gusts. In particular, severe bora downslope windstorms are frequent phenomena over the complex terrain of the eastern Adriatic coast. Such events are a major threat to human safety, especially at sea and near the coasts, and may cause large economic damage. Due to changes in wind regimes in recent years, maximal measured wind speeds over the Croatia area show significant trends at certain locations. Therefore, estimation of extreme winds, in particular for a 50-year return period, serves as a standardized design value for construction of infrastructure which is incorporated in Croatian Standards Institute normative documents. In our work we study wind speed and wind gust extremes along the wider Adriatic area using both observations and high-resolution ALADIN-HR model data. We first analyse long-term records of 60 measurement stations over Croatia and estimate extreme winds using several methods derived from generalized extreme value theory. Then, we utilize ALADIN-HR model setup at 2 km grid spacing, using both full-physics non-hydrostatic and cost-effective simplified-physics hydrostatic model simulations to study the spatial properties of maximal simulated wind speed and maximal simulated wind speed gusts in a 10-year period. Moment-based and spectral verification of wind speed, performed on a number of surface stations in different climate regions of Croatia, suggests numerical simulations were successful. We further estimate extreme winds for return periods of 10-100 years and perform a comparison of simulated and observed estimated wind extremes. To discuss the spatial representativeness of extreme wind estimations from both measurements and mesoscale numerical models, we utilize multiscale model simulations.

Key words: extreme winds, bora, return periods, impacts on infrastructure

Onsite

INFLUENCE OF THE DINARIC ALPS ON THE ISSUANCE OF SIGMET WARNINGS WITHIN FIR ZAGREB

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SIGMET (Significant Meteorological Information) represents one of the most important types of aviation warnings for weather phenomena which pose hazardous impact to flight safety. This type of warning is issued for turbulence, mountain waves, icing, thunderstorms, sand storms, dust storms, tropical cyclones, volcanic ash clouds as well as radioactive clouds. For each country's FIR (Flight Information Region) the authorized Meteorological Watch Office (MWO) issues such warnings to provide useful information to all aviation users and especially to Air Traffic Control (ATC) regarding the planning necessary staff and imposing flight sector regulations. Timely issuance of SIGMET warnings is therefore paramount to reduce flight delays and enhance flight safety. FIR Zagreb spans a multitude of distinct geographical features, from the Adriatic Sea to the west, the flat Pannonian Basin to the east, and the fairly narrow but steep Dinaric Alps mountain range separating the two. This range, on the one hand, is known to trigger mountain meteorological phenomena such as atmospheric rotors, hydraulic jumps and wave breaking. On the other hand, by splitting the moist maritime environment from the inland relatively drier flatlands, the Dinaric Alps often aid the initiation of deep moist convection. The aim of this study is to explore the influence of the NW-SE oriented Dinaric Alps on most common hotspots for SIGMET issuance pertaining to turbulence (due to rotors and breaking vertically propagating waves), mountain waves (significant vertical velocities but not necessarily turbulent), thunderstorms (embedded, frequent and squall types) and icing due to freezing rain. Specifically, we will determine which environmental conditions (e.g. location of jet stream, stratification, wind shear) potentially favor certain types of conditions, thus fulfilling the criteria to issue a SIGMET. The analysis will focus on all such SIGMET warnings issued by MWO Zagreb between 1 January 2016 and 31 December 2024. Finally, we will supplement the main SIGMET database with the use of the ERA5 reanalysis data set as well as MeteoSat satellite imagery to examine specific case studies. Throughout the year, SIGMET warnings are issued most frequently in the western part of FIR Zagreb, while frequency is lowest in the easternmost part. While the SIGMET for turbulence being the most commonly issued type during winter months can be explained by more frequent southward intrusions of the jet stream over Croatia, the prevalence of SIGMET for frequent thunderstorms during summer reflects the larger CAPE and bulk shear environments driving deep moist convection.

Key words: aviation; SIGMET; thunderstorm; turbulence; mountain wave; rotor; freezing rain

Onsite

OZONE POLLUTION IN THE PYRENEES: INFLUENCE OF HEATWAVE EVENTS

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As a secondary atmospheric pollutant, tropospheric ozone (O_3) is formed through complex photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) with sufficient solar radiation. Ozone formation and accumulation are particularly relevant during summer when high temperatures intensify photochemical reactions and can be advected by recirculation, regional transport or formed in the presence of precursors during heat wave episodes. In the Pyrenees, the biogenic emissions of VOCs from vegetation and forested areas contribute to the formation of this ozone but also ozone generated far away from precursors in urban and industrial areas or formed in nearby rural zones can be transported to mountainous areas, through local, mesoscale or regional circulations. Pollutant concentration data from 20 monitoring air quality stations located in the cross-border area of the Pyrenees are analyzed for the 5-year period from 2019 to 2023. Results show that the legal hourly information threshold (180 µg m-3) is exceeded occasionally in locations in Bellver, Berga, Montsec, Torrelisa and Lourdes. We also found that urban locations such as Escaldes-Engordany (Andorra) and Itrurrama (Basque Country) have lower annual mean ozone levels, while rural places such as Montsec (Catalonia) and Torrelisa (Aragon) register the highest annual mean ozone levels. Heatwave events were identified using ERA5 data and a selected criterion, finding a total of 17 heat wave periods selected during 5 years, including a total of 105 days. The highest ozone concentrations occurred in summer months and during these heat wave periods but some spatial differences are observed along the Pyrenees. Some of these events are analyzed in detail using numerical modeling in order to give an insight of the regional transport influence on local ozone increased concentrations. This study was performed in the framework of the project "Towards a climate resilient cross-border mountain community in the Pyrenees (LIFE22-IPC-ES-LIFE PYRENEES4CLIMA)".
Key words: Ozone, heat wave, regional circulation, Pyrenees

Onsite

IMPROVING THE OPERATIONAL FORECASTS OF OUTDOOR UNIVERSAL THERMAL CLIMATE INDEX WITH POST-PROCESSING

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The Universal Thermal Climate Index (UTCI) is a thermal comfort index that describes how the human body experiences ambient conditions. It has units of temperature and considers physiological aspects of the human body. It takes into account the effect of air temperature, humidity, wind, radiation, and clothes. It is increasingly used in many countries as a measure of thermal comfort for outdoor conditions, and its value is calculated as part of the operational meteorological forecast. At the same time, forecasts of outdoor UTCI tend to have a relatively large error caused by the error of meteorological forecasts. In Slovenia, there is a relatively dense network of meteorological stations. Crucially, at these stations, global solar radiation measurements are performed continuously, which makes estimating the actual value of the UTCI more accurate compared to the situation where no radiation measurements are available. We used seven years of measurements in hourly resolution from 42 stations to first verify the operational UTCI forecast for the first forecast day and, secondly, to try to improve the forecast via post-processing. We used two machine-learning methods, linear regression, and neural networks. Both methods have successfully reduced the error in the operational UTCI forecasts. Both methods reduced the daily mean error from about 2.6°C to almost zero, while the daily mean absolute error decreased from 5°C to 3°C for the neural network and 3.5°C for linear regression. Both methods, especially the neural network, also substantially reduced the dependence of the error on the time of the day
Key words: UTCI forecasting, thermal comfort, verification, post-processing

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BRIDGING SCIENCE AND SKY: THE MET PANEL AS A HUB FOR ATMOSPHERIC RESEARCH AND FREE FLIGHT

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The Meteorological Panel at OSTIV (Organisation Scientifique et Technique Internationale du Vol à Voile) serves as a bridge between the atmospheric science community and the world of soaring and paragliding. While many researchers investigate mesoscale and microscale atmospheric processes—such as valley winds, slope flows, thermals, and lee waves—there remains a valuable opportunity to engage directly with the communities that experience these phenomena daily in flight. The MET Panel has two primary goals:
(1) to communicate scientifically robust results relevant to flight meteorology to the gliding and paragliding community, and (2) to serve as a point of contact and reference for researchers with questions related to air sports. This includes fostering collaborations for the use of flight track data in atmospheric research, equipping aircraft with onboard sensors, exchanging best practices in boundary layer modelling, developing research questions related to soaring meteorology and exchange knowledge with soaring weather experts and experienced local pilots featuring a deep understanding of many understudied atmospheric processes. Additionally, researchers can publish their work relevant to the soaring community in OSTIV's journal "Technical Soaring". We invite scientists working on relevant atmospheric processes— or those who are passionate about flight themselves—to join the MET Panel network and help shape an interdisciplinary exchange. Links: OSTIV: https://ostiv.org/ OSTIV MET Panel: https://ostiv.org/sections/scientific-section/meteorological-panel.html OSTIV-publications since 1950: https://journals.sfu.ca/ts/index.php/op/issue/archive

Key words: community, science communication, interdisciplinary studies, application, soaring weather prediction, airborne observations