Education and research of atmospheric dynamics, climate, atmospheric chemistry across scales: from street level modelling to global phenomena

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GAČR CZECH SCIENCE FOUNDATION

FOCI Project GEORISKS

Co-funded by the European Union

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Department of atmospheric physics

As the **only university department in the Czech Republic**, we provide comprehensive education in the field of **meteorology and climatology, including mathematical-physical description**.

Part of the Faculty of Mathematics and Physics, Charles University.

Research areas / groups:

- **Modeling Atmospheric Chemistry and Air Quality**: interactions between weather/climate and atmospheric chemistry, specifics of urban areas
- **Modeling of Flow in the Atmospheric Boundary Layer, Micro-scale Modeling**: Modeling atmospheric turbulence, modeling small-scale flows and urban environments, modeling transport, dispersion, and transformation of pollutants in the atmosphere
- **Study of Climate System Dynamics and Development:** Numerical modeling of climatic processes, climate models, climate change issues and future projections, urban climate, geoengineering.
- **Middle Atmosphere Processes and Atmospheric Waves**: Stratosphere, stratospheric ozone, mesosphere, the role of atmospheric waves (mainly gravity waves), large-scale circulation.
- **Nonlinear Dynamic Systems in the Atmosphere**: Deterministic chaos and predictability of atmospheric processes.

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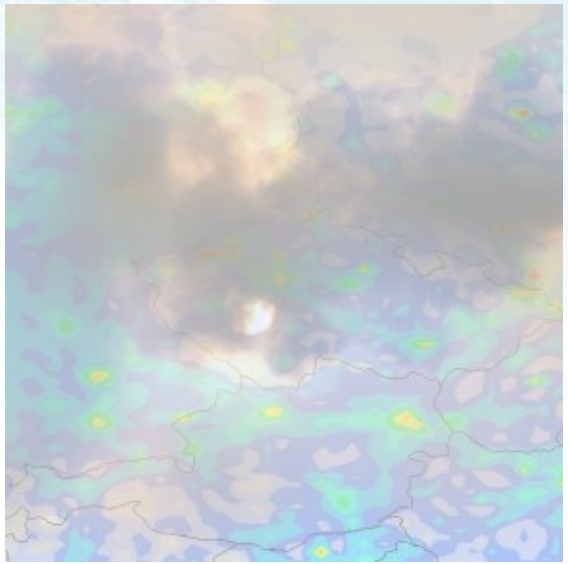
Atmospheric chemistry modeling group

The atmospheric chemistry modeling group focuses in particular on **chemical-transport modeling of chemical processes in the troposphere** with a strong emphasis on **interactions** between the chemical **composition** of the atmosphere (including aerosols) and **meteorological processes** and **climate**.



Numerical models capable of calculating transport, chemical transformations and removal of pollutants are therefore the basic experimental tool of the group.

Modeling of **anthropogenic and natural emissions** is also an integral part of the group everyday research.

Research topics

- modeling the influence of **urban emissions** on local and regional air pollution and **urban-climate-chemistry interactions**
- research and modeling of the **formation of secondary atmospheric aerosol**, especially organic aerosol
- modeling of **biogenic emissions** and their influence on photochemical processes in the troposphere
- modeling of e**missions of wind-blow dust** and their effect on aerosol pollution
- **validation** of chemical-transport models and **bias correction**.

Team: Peter Huszár (group leader), Jan Karlický, Kateřina Šindelářová, Alvaro Patricio Prieto Perez, Lukáš Bartík, Jana Marková

Modeling atmospheric chemistry

Urban-climate-chemistry interactions

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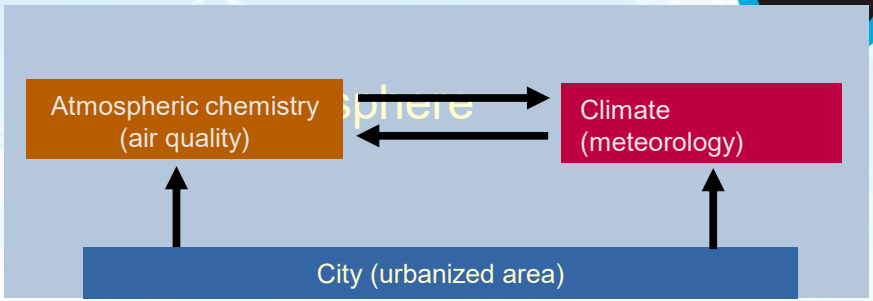
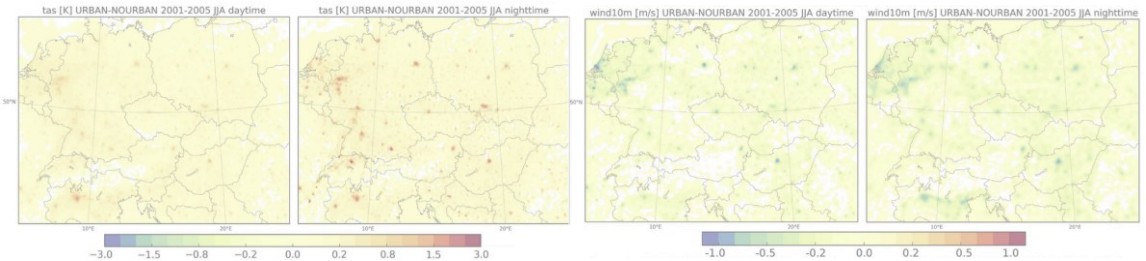
Motivation

- Urban areas are intense emissions hotspots
- More then 60% of Earth's population live in cities
- Urban climate issues – urban heat island (UHI)
- Interaction of urban pollution with urban climate is complex with many feedbacks

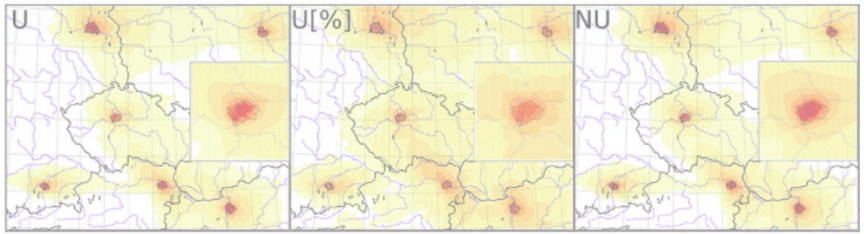


Tools

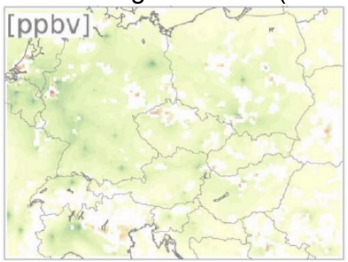
- Regional CTMs or coupled chemistry-climate models : **CAMx, WRF-Chem, RegCM-Chem**
- Emission models: **FUME, MEGAN**



Impact of urban landsurface on temperaure and wind-speed (Huszar et al., 2018b)



Impact of urban emissions on DJF NO2 with and without urban meteorological effects (Huszar et al., 2021)



Impact of urban meteorological effects on NO2 (Huszar et al., 2018a) – acting of increased temperature, decreased winspeeds and enhanced vertical eddy diffusion

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Modeling atmospheric chemistry

Impact of natural emissions

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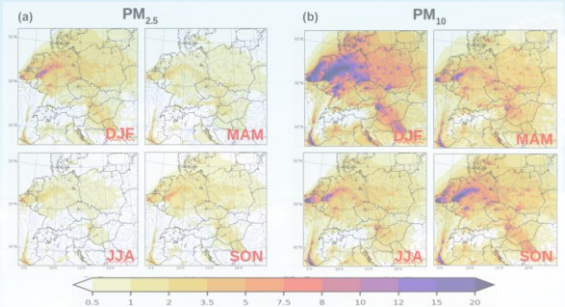
Motivation

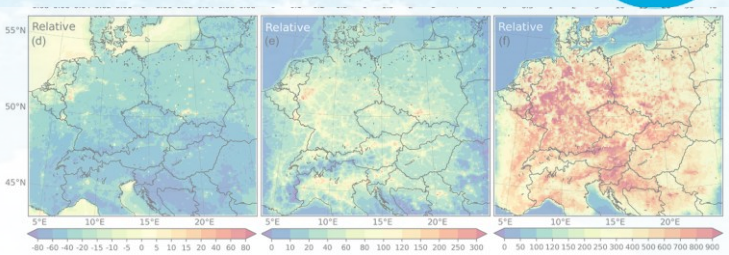
- Natural emissions are closely tight to meteorological conditions and landuse
- These, in general, will change in the future
- They can contribute to the overall air-pollution in a significant way

Wind-blow dust emissions



Seasonally averaged impact of WBD emissions on PM2.5 (a) and PM10 (b) concentrations in micrograms per cubic metre for 2007–2016. (Liaskoni et al., 2023).

Biogenic VOC emissions



The relative impact of all BVOC emissions on the near-surface concentrations of OH, HO2 and RO2) averaged over 2007–2016 JJA (Liaskoni et al., 2024).

Projects and collaborations

- National: TAČR Project ARAMIS (Air Quality Research Assessment and Monitoring Integrated System)
- International
  - Project EU Horizont FOCI (Non-CO2 Forcers And Their Climate, Weather, Air Quality And Health Impacts – a large consortium of many EU research institutes
  - Project CAMS61 and CAMEO – in cooperation with
  - Copernicus Atmosphere Monitoring System

Potential research collaboration with NTNU

- High resolution urban air quality modelling (urban vegetation and their impacts on ozone)
- AQ and climate impact of urban development (e.g. urban greening)
- Assessing sea salt spray aerosol's role in inland areas
- Lightning NOx emissions and their role in ozone chemistry

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Microscale modeling and urban applications

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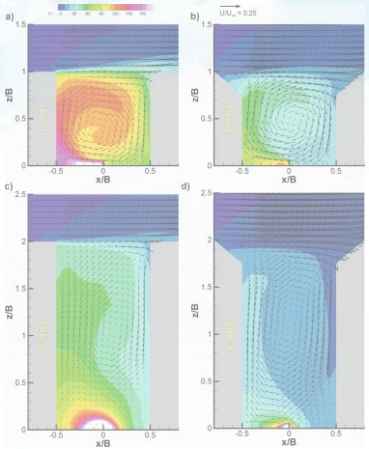
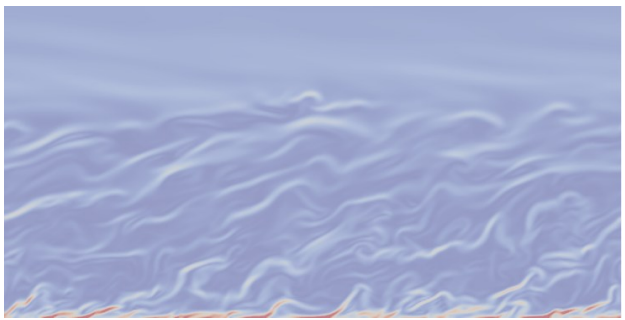
Team

- Senior scientists: Dr. Michal Belda, Dr. Vladimír Fuka
- Doctoral students: Jelena Radović



Topics

- Atmospheric boundary layer
- Urban boundary layer
- Air pollution dispersion in urban areas
- Urban micro-climate
- Large eddy simulation (LES) of urban flows



Microscale modeling and urban applications

Current research activities at KFA

Long-time cooperation with Czech Hydrometeorological Institute and Czech Academy of Sciences, development and application of an open-source LES model **PALM** (Parallelized Large-eddy Simulation Model), an in-house LES model **CLMM** (Charles University Large-Eddy Microscale Model), emission processor FUME

On-going and past projects

- ARAMIS (Air Quality Research Assessment and Monitoring Integrated System)
- MICROBUS (Microscale-based Urban Scenarios, national project started in 2025)
- TURBAN (Turbulent-resolving urban modeling of air quality and thermal comfort) https://www.project-turban.eu/
- GAČR "The role of coherent structures' dynamics on scalar transport and dispersion in the urban canopy layer" (recently finished)
- Urbi Pragensi (Urban Development of weather forecast, air quality, and climate scenario for Prague, 2018-2020)

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Microscale modeling and urban applications

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Future research and potential collaboration ideas

- **Scientific branch**
  - Evaluation of the **sources of errors and uncertainty** in model simulations
  - Further **development of the models** and supporting tools
  - Role of **initial and boundary conditions** in LES
- **Applied branch**
  - **Scenarios of urban development**, adaptation and mitigation measures
  - Simulations of **heat stress and other biometeorological indicators** in the cities
  - **Scenarios of urban greenery** introduction to alleviate the effects of the **urban heat island**
  - Air quality on the street level, links and potential **trade-offs between thermal comfort and air pollution**
  - Real-world applications and collaboration with municipalities

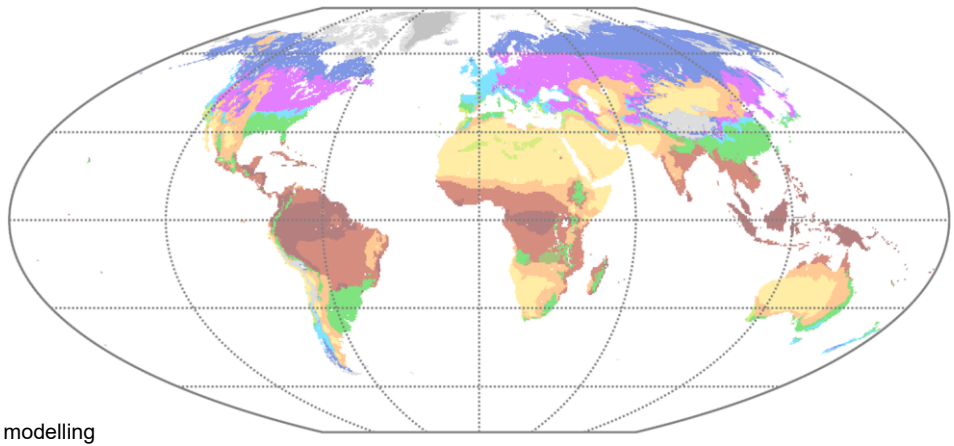
Regional climate change and modeling

KFA

Team: Prof. Tomáš Halenka (lead), 4 senior scientists, 4 post-docs, 3 PhD students

Activities

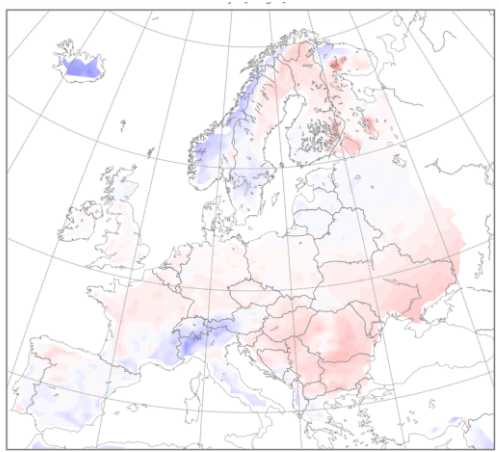
- Statistical analysis of observed climate data (emphasis on non-linear processes and attribution of possible causes of observed changes)
- Regional climate change scenarios and analysis of related uncertainties
- Numerical climate modeling
- Environmental impacts of climate change

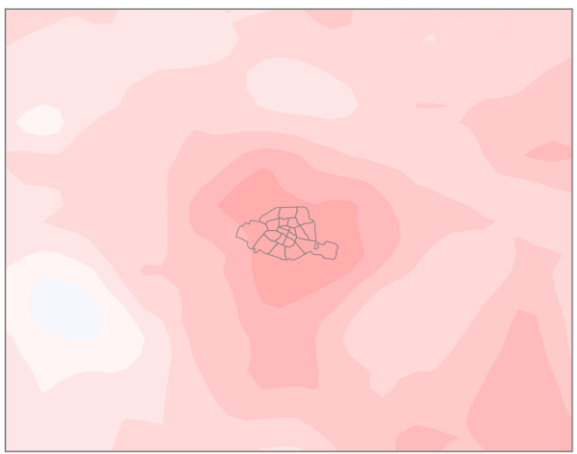


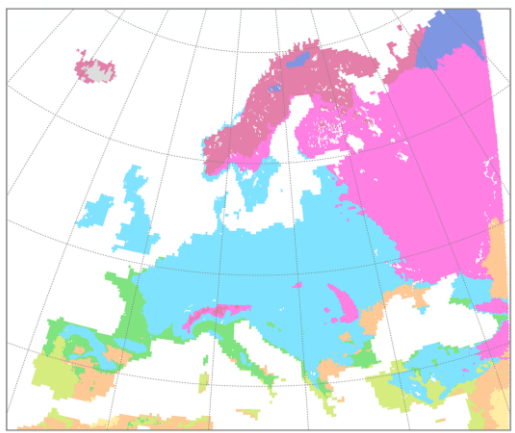
Regional climate change and modeling

Future research and potential collaboration ideas

- Dynamical **downscaling and regional climate modelling over different regions**
- **Urban climate** and representation of cities in the RCMs
- Climate **model evaluation** – potentially specific features relevant to East Asia
- **Extreme events** occurrence – similar methods applicable over different regions, including both Europe and East Asia – including Global Warming Levels approach







Regional climate change and modeling

Selected research projects/activities at the department, international collaboration

- **EURO-CORDEX**
  - Pan-European initiative based in the WCRP activity CORDEX
  - High resolution regional climate models, including post-processing, evaluation of uncertainty with regard to driving global climate models and different SSPs
  - Climate classifications scheme – traditional Köppen based, and more universal Feddema classification scheme
- **Project FOCI** (Evaluation of the climate impact of non-CO2 emissions) – European consortium
- **Project Geohazards**
  - Evaluation of climate models with regard to extreme events, including drought, temperature extremes, extreme precipitation indices
- **Project PERUN**
  - Climate scenarios for the Czech Republic (in collaboration with the Czech Hydrometeorological Institute)
- **Impetus4Change (I4C)**

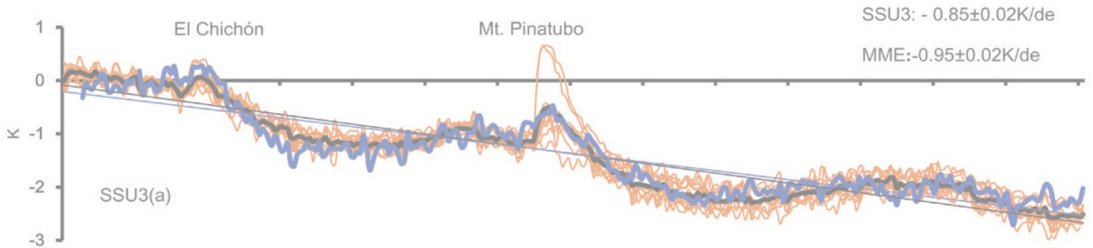
Middle atmospheric research

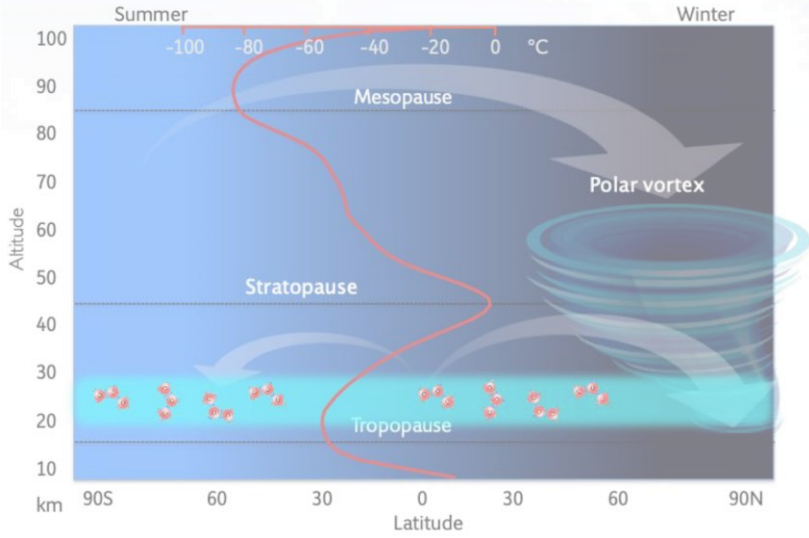
Motivation

- The middle atmosphere plays a crucial role in the vertical coupling of Earth's atmospheric layers.
- Investigating this region helps to understand the transport mechanisms of chemical constituents, energy, and momentum between these layers, which is vital for accurate climate modeling and prediction.
- Research on the middle atmosphere is essential for geophysical engineering, including climate intervention strategies.

Team

- Senior scientists: Prof. Petr Pišoft, Dr. Petr Šácha
- Students: Zuzana Procházková, Dominika Hájková, Massimo Martina, Radek Zajíček, Jakub Žáček

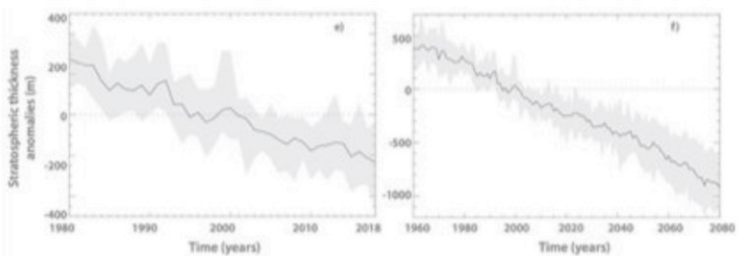




Middle atmospheric research

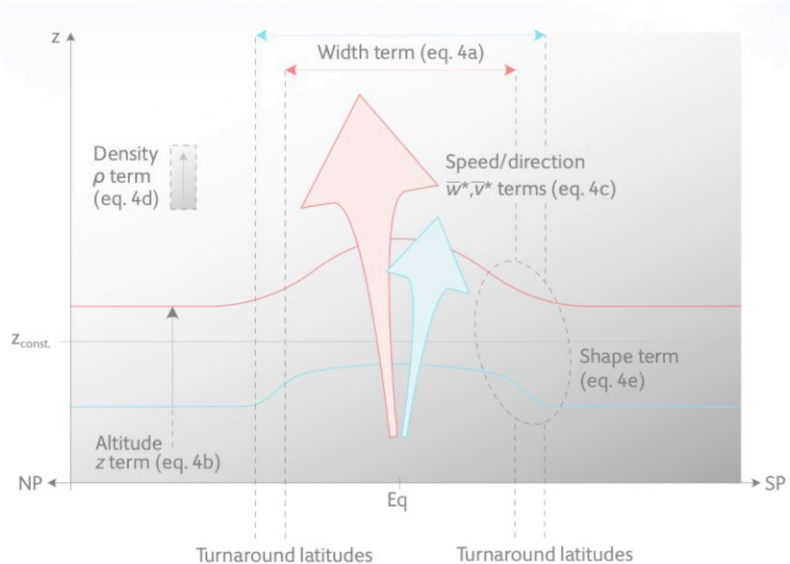
Since 2015 our department includes the **only research group in the Czech Republic systematically studying the stratosphere and mesosphere**. This group significantly overlaps with the research team focused on gravity waves. Our main research areas include:

- Long-term **trends and the manifestations of climate change** in the middle atmosphere
- **Changes in large-scale circulation and transport i**n the middle atmosphere
- **Sudden stratospheric warmings** (SSW), their detection, and impacts
- The **influence of atmospheric waves**, particularly the impact of localized gravity waves forcing
- Implementation and **impacts of geoengineering in the stratosphere**



Pisoft et al., 2021 – Anomalies the stratosphere thickness

Šácha et al., 2024 - Schematic illustration of the contributions to the change of the net upwelling



Middle atmospheric research

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Current collaboration and projects:

- Environmental Physics Laboratory, Faculty of Sciences of Ourense, University of Vigo, Spain, research collaboration focused on the middle atmospheric processes and geoengineering
- Institute of Meteorology, University of Natural Resources and Life Sciences, Vienna, Austria - collaboration focused on the middle atmospheric processes
- Project Natural and Anthropogenic Georisks – WP Analysis and evaluation of the benefits and risks of sulphur aerosol-based geoengineering impact of stratospheric aerosol injection (SAI) on wind and photovoltaic energy sources
- Project Unravelling climate impacts of atmospheric internal gravity waves
- The influence of orographic gravity wave drag (OGWD) in CMIP6 models on resolved waves and sudden stratospheric warmings (SSWs)

Potential collaboration topics:

- Model experiments focused on **Stratospheric Aerosol Injection (SAI)** and analysis of their outputs with regard to regional impacts and **impacts on sectors such as renewable energy sources**.
- **Stratosphere-troposphere exchange** in connection with the Gravity wave research group
- General research directions related to research focuses such as wave interactions, large-scale transport, and long-term changes of the middle atmosphere

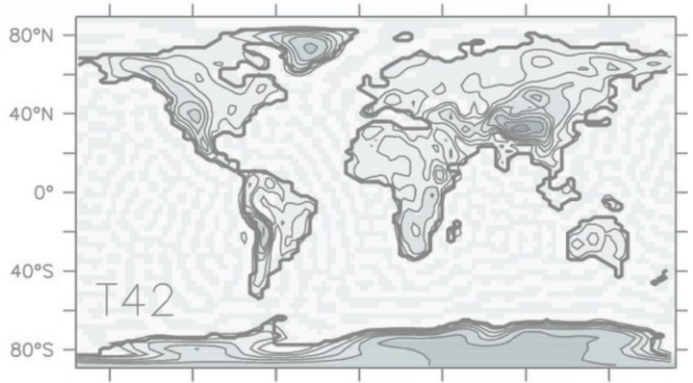
Gravity Wave Research Group

Motivation

- Gravity waves (GWs) play an important role for the energy and momentum transport in the atmosphere.
- GW effects are unresolved in climate models but also partly in global numerical weather prediction models.
- Orographic GW parameterizations were flagged as a major source of uncertainty for future circulation projections.

Team

- Senior scientists: Dr. Anahí Villalba Pradas, Dr. Petr Šácha.
- Students: Zuzana Procházková, Dominika Hájková, Massimo Martina, Radek Zajíček, Šimon Bartoň.



Orography at the traditional climate model resolution T42 (around 2.4°) adapted from Schmittner et al. (2011, Jclim)

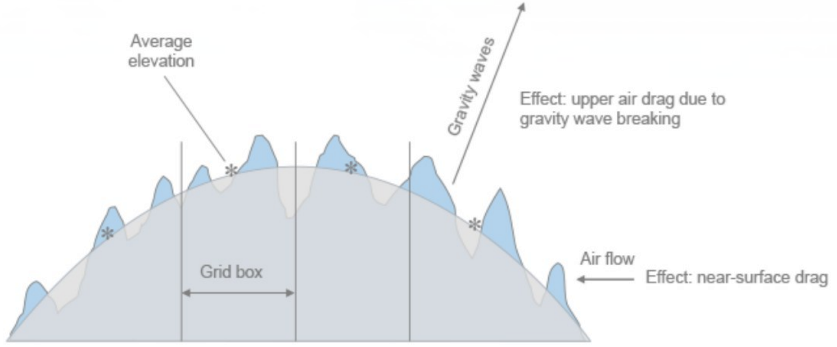
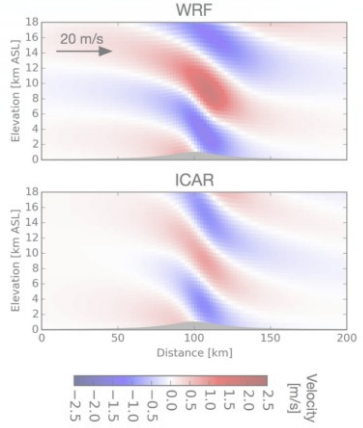


Illustration of the unresolved orography (i.e. the subgrid-scale orography and its missing effects in the models. Courtesy ECMWF)



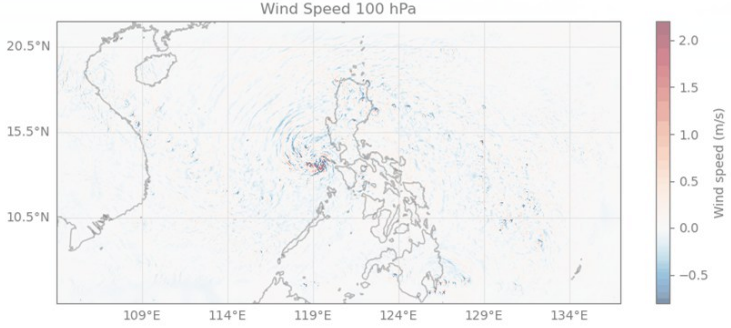
Linear gravity waves created by an idealized hill in a steady flow – idealized 2D simulations.

Gravity Wave Research Group

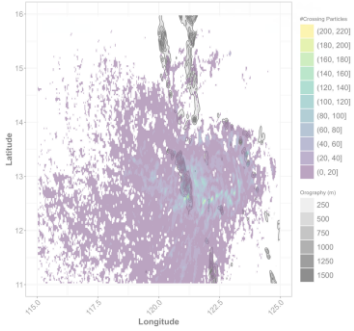
- Basic theoretical research of the interaction between GWs and Rossby waves (synoptic to planetary scales).
- Validation of parameterized GW impacts on the circulation (Sudden Stratospheric Warmings, Brewer-Dobson circulation) using high-resolution datasets.
- Research of orographic influences on transport across scales and atmospheric layers (particularly the stratosphere-troposphere exchange).
- Formulation and application of a novel subgrid-scale orography parameterization scheme.

Tools

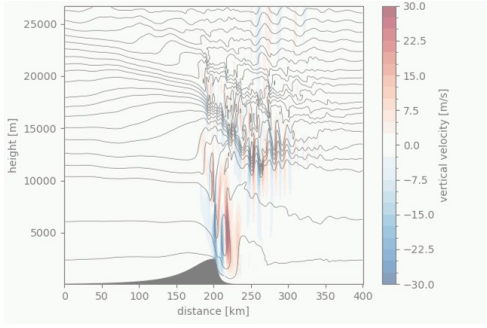
- Various complexity WRF simulations – 2D and 3D with idealistic orography, high-resolution on regional domains, LES.
- Analysis of GW effects in high-resolution global datasets with cutting edge methodologies – ERA5, Dyamond Winter.
- Climate modeling and orography GW parameterization development within the MESSy Consortium – EMAC, ICON.



WRF simulation of the typhoon Molave passing over the Phillipiness. Gravity waves and convection dominate the vertical wind field at the tropopause level.



Flux of parcels that are rapidly transported(in a few hours) from the polluted boundary layer to the stratosphere during typhoon Molave passing over the Philippines (potential implications for dispersion of microplastics).



Idealized 2D WRF simulation of the flow induced by an isolated hill. Note the foehn winds on lee ward side and vigorous turbulence from GW breaking near the surface and around the tropopause.

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Gravity Wave Research Group

Involvement in international research

- We are involved in several APARC (Atmospheric Processes And their Role in Climate; a WCRP core project) activities and projects – GW activity, DynVar (atmospheric dynamics and variability), A-RIP (reanalysis intercomparison project)
- Active members of the TEAMx (Multi-scale transport and exchange processes in the atmosphere over mountains) programme and observational campaign (currently ongoing).
- Organizers of the GW workshop in Prague, getting together each summer around 20 international experts on GWs to discuss latest developments (in 2025 the workshop will take place in July along the ESA meeting in Prague).

GW workshop

Potential collaboration topics

- Study of **orographically induced flows and circulation effects** connected with the pronounced orography of Taiwan.
- Dynamical **interaction of the orography with typhoons** and induced transport anomalies.
- **Stratosphere-troposphere exchange in connection with the Asian Summer Monsoon**, typhoons, orography,...
- We are also open to all possible collaborations in the general research directions that we pursue – theory, high-resolution and climate modelling, reanalyses,...

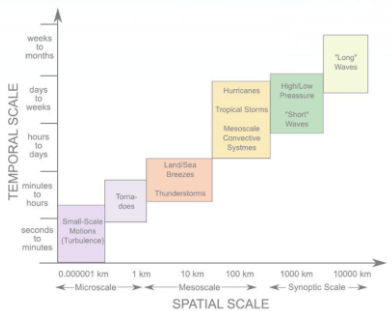
Chaos, Predictability, and Non-linearities Research Group

Motivation

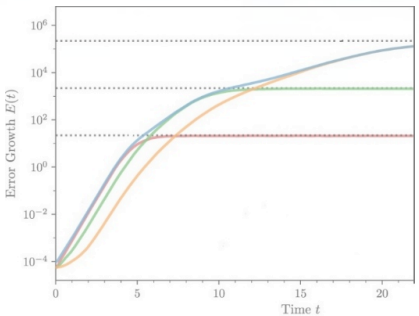
- Knowing the accuracy of weather forecasts and climate projections is one of the fundamental questions of atm. science.
- The “Sub-seasonal to seasonal” (S2S) time scale, which is the area of current research interest, is where the weather (initial conditions error problem) and climate (boundary conditions error problem) scales meet.
- Another recent issue of non-linearity and chaos is the medium-term and long-term variability of the climate system, especially in relation to long-range links of modes of internal climate variability to local meteorological conditions.

Team

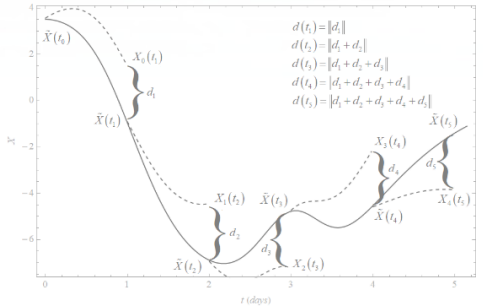
- Dr. Hynek Bednář, Doc. Jíří Mikšovský, Dr. Aleš Raidl.



Typical meteorological graph about time and length scales in the atmosphere adapted from Brisch and Kantz (2019, New J. Phys.).



Description of scale-dependent error growth. After the saturation of the small scale error, the medium scale error continues to grow, but at a lower rate, and will saturate at a larger scale.



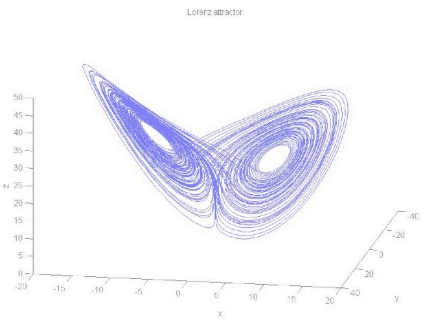
Schematic description of drift d, which describes the difference between the model and reality after a given time.

Chaos, Predictability, and Non-linearities Research Group

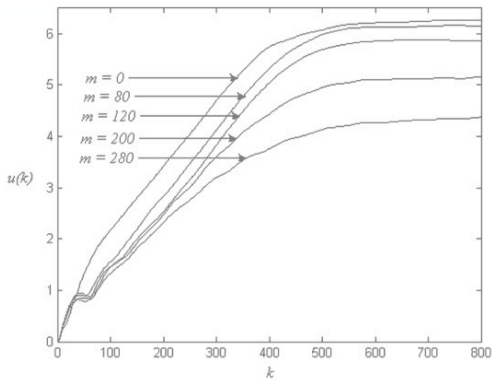
- Investigating the growth of initial condition error in systems with space-time scales.
- Analysis of the growth mechanism of the systematic error of models.
- Determining the influence of the error of the boundary conditions.
- Exploring the possibilities of extending predictability beyond the generally accepted limit for prediction.
- Analysis of nonlinearity of spatial links and mutual interactions of internal climate oscillations.
- Implementation of nonlinear coupling models to refine downscaling techniques and bias correction of model outputs.

Tools

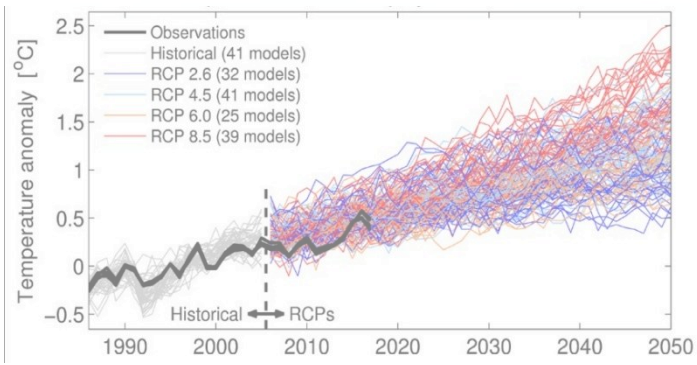
- Lorenz-type low-dimensional models, Global numerical forecast models (ECMWF).
- Numerical forecast models from the Sub-seasonal to seasonal (S2S) prediction systems database.
- Linear and non-linear regression models combined with surrogate data generators.
- Techniques for quantifying nonlinear correlations.



The Lorenz chaotic Attractor.



Initial conditions error growth for the average value over m variables.



An ensemble with various climate models and for each RCP adapted from IPCC (AR5, 2013).

Chaos, Predictability, and Non-linearities Research Group

Involvement in international and national research

- Max Planck Institute for the Physics of Complex Systems, Dresden – Prof. Holger Kantz
- Institute of Informatics, Czech Academy of Sciences, Prague – Dr. Milan Paluš

Potential collaboration topics

- Study the hypothesis of cascading growth of the initial error.
- Description of the model (systematic) error growth in coupled systems.
- Effect of boundary condition error arising from coupling the atmosphere with other subsystems and investigating and describing its evolution in a multi-scale atmosphere.
- Analysis of nonlinearity of spatial links and mutual interactions of NAO, ENSO, PDO, AMO.