## Description of the main research directions investigated by the institute

The results are given in order by teams.

**Whistler mode chorus: space weather effects in the Earth's radiation belts (DSP)**
Electromagnetic emissions propagating in the whistler mode have substantial impact on the dynamics of the Earth's radiation belts through the wave-particle interactions. These space weather effects are especially linked to an important class of whistler mode waves, chorus, which is characterized by discrete elements in the time-frequency spectrum. It is known to be generated by nonlinear wave-electron interactions in the vicinity of the geomagnetic equator, as was shown by numerous theoretical studies, simulations, and satellite observations. We investigated chorus in terms of spectral and polarization characteristics, with special emphasis on wave normal angles, which are important for wave-particle interactions. The latter follow a definite pattern, which enables an unambiguous classification of chorus bursts. Chorus bursts frequently split into a lower and an upper band around one half of the local electron cyclotron frequency. We concentrated on chorus frequencies close to the gap and investigated wave planarities. Another main research direction aimed at wave vectors and Poynting vectors of chorus rising and falling tones. We also investigated chorus elements in the source region, propagating to the spacecraft from two antiparallel directions at different frequencies. We interpreted these features in the frame of the backward-wave oscillator theory by means of two exemplary events, yielding insight into the nonlinear generation mechanism. Previously published statistics based on Cluster spacecraft measurements surprisingly showed that in the outer radiation belt, lower band whistler mode waves predominantly propagate unattenuated parallel to the magnetic field lines up to midlatitudes, where ray tracing simulations indicated highly attenuated waves with oblique wave vectors. We investigated this behaviour by considering a large fraction of ducted waves.

**Equatorial noise (DSP)**
Equatorial noise (often phenomenologically described as magnetosonic waves in the literature) is a natural electromagnetic emission, which is generated by instability of ion distributions and which can interact with electrons in the Van Allen radiation belts. These emissions occur in the vicinity of the geomagnetic equator at frequencies between the local proton cyclotron frequency and the lower hybrid frequency. We investigated observations of equatorial noise propagating inward down to the Earth as a superposition of spectral lines from different distant sources observed at frequencies both below and above the local proton cyclotron frequency. Changes in the local ion composition encountered by the waves during their inward propagation disconnect the identified wave mode from the low-frequency magnetosonic mode. We also aimed at systematic analysis of the data collected by the four Cluster spacecraft. We developed selection criteria for the visual identification of these emissions, and we have compiled a list of more than 2000 events. The evolution of the Cluster orbit enabled us to investigate a large range of McIlwain's parameters outside of the plasmasphere and inside the plasmasphere as a function of MLT.

**Effects of electromagnetic ion cyclotron waves in the Earth's radiation belts (DSP)**
In recent years, experimental results have consistently shown evidence of electromagnetic ion cyclotron (EMIC) wave-driven electron precipitation down to

energies as low as hundreds of keV. However, this is at odds with the limits expected from quasi-linear theory. Recent analysis using nonlinear theory suggested energy limits as low as hundreds of keV, consistent with the experimental results, although to date this has not been experimentally verified. We investigated concurrent observations from spacecraft and ground-based instruments, showing concurrent EMIC waves and sub–MeV electron precipitation, and a global dropout in electron flux and relevant test particle simulation, consistent with the experimentally observed electron precipitation caused by nonlinear trapping. We have also investigated an EMIC rising tone on the nightside of the plasmasphere in terms of the Poynting vector and propagation angle. We also studied the occurrence of broadband, narrowband, and rising tone emissions in the vicinity of magnetospheric plumes, below the local proton gyrofrequency.

**Quasiperiodic emissions (DSP)**
Quasiperiodic (QP) electromagnetic emissions are whistler mode waves at typical frequencies of a few kHz characterized by a peculiar periodic time modulation of their intensity, with modulation periods from a few seconds up to 10 min. We investigated cases where the QP emissions exhibit a sudden change in the wave vector and Poynting vector directions. The change happens in a short interval of latitudes. We also attempted to locate the source region of these emissions and concentrated on the inner boundary of the plasmapause, which also acts as a guide during the propagation of the QP emissions. We investigated the possibility of their downward propagation through the ionosphere.

**Lightning initiation (DSP)**
In connection with our participation on the spacecraft project TARANIS we investigated ground/based observations of electromagnetic signals emitted by lightning processes. There is a lack of understanding of how a lightning flash initiates, as this process usually takes place deep inside thunderclouds. Electromagnetic pulses emitted during lightning initiation, which can be measured from a safe distance, help us to understand lightning better. We investigated if the larger pulses detected during lightning initiation in low-frequency records were systematically accompanied by pulses detected in the very high frequency records. In this case the initial lightning extension process occurs very fast and at multiple length scales and emitted electromagnetic radiation covers a very large range of frequencies. Both unipolar and bipolar magnetic or electric field pulses have been observed during preparatory stages of a lightning flash. We introduced a new simple analytical model to describe both kinds of pulses. We investigated how the polarity overshoot depends on the parameters of the model, including the propagation velocity of the current pulse, the step length, and the injected current waveshape. We also analysed broadband electromagnetic measurements of pulse sequences occurring prior to the first return strokes of negative cloud-to-ground lightning flashes, and we investigated if they can be comparable or higher than the corresponding return stroke peak currents, what are magnitudes of the charge centres, and if such energetic current pulses might be capable to produce elves or terrestrial gamma-ray flashes.

**Effects of electromagnetic radiation from lightning return strokes (DSP)**
We investigated daytime atmospherics with dispersion signatures originating from strong thunderstorms in the North Atlantic region. We newly developed analysis techniques for 3-component electromagnetic measurements to determine the source

azimuth and to attribute these atmospherics to both positive and negative lightning strokes. We investigated the influence of heights of the reflective ionospheric layer, linked to low fluxes of solar X rays, on the dayside subionospheric propagation. We also focused on the polarization of the atmospherics and their dispersed parts, related to the anticipated continuous escape of the right-hand polarized power to the outer space in the form of whistlers. We analysed contribution of thunderstorms to the intensity of electromagnetic radiation at audible frequencies observed at altitudes where these waves can influence the Van Allen radiation belts. We investigated if the radio waves originating in strong lightning storms can significantly overpower all other natural waves in a wide range of frequencies and L-shells, and if the strength of this effect agrees with the local time dependence of both lightning occurrence and the wave attenuation in the ionosphere. We also analysed optical recordings of transient luminous events (obtained by our observer in station Nydek) for a study of an influence of thunderstorm activity on the ionospheric sporadic E-layer and for an analysis of orbital fragmentation of a larger meteorite from Perseid cluster.

**Solar wind and magnetospheric boundaries (DSP)**
The Sun is continuously emitting a stream of charged particles—called the solar wind—from its upper atmosphere. The terrestrial magnetosphere forms the obstacle to its flow. Due to supersonic speed of the solar wind, the bow shock is created ahead of the magnetosphere. This abrupt transition region between supersonic and subsonic flows has been frequently observed by the four Cluster spacecraft. Using a timing analysis, we have retrieved speed and directions of the bow shock motion for a large number of crossings. We have correlated the bow shock speed with the solar wind speed and predictions of the bow shock locations by the empirical model. A better understanding of the bow shock kinematics may bring new insights to wave-particle interactions with applications in laboratory plasmas. We also investigated the distribution of mirror and Alfvén-ion cyclotron (AIC) waves in the magnetosheath together with plasma parameters important for the stability of ULF waves, specifically ion temperature anisotropy and ion beta. We analyzed dependence of both plasma parameters and mirror/AIC wave occurrence on upstream solar wind parameters and different characters of nonlinear saturation of the two modes. Electrostatic plasma waves above and below the local electron plasma frequency represent a characteristic feature of the foreshock region. These waves are generated by electron beams originating from the bow shock and their spectrum varies from narrowband intense waves close to foreshock edge to weaker broadband emissions further downstream. We investigated statistical properties of electron beams observed in the terrestrial foreshock in relation to the broadband and narrowband emissions, and we analysed if the observed combination of beam energy, density, and temperature typically corresponds to a stable situation.

**Interplanetary solar radio emissions associated with coronal mass injections (DSP)**
Coronal mass ejections (CMEs) are large-scale eruptions of magnetized plasma that are responsible for most severe space weather events, such as solar energetic particle events and geomagnetic storms at Earth. Type II radio bursts are slow drifting emissions produced by beams of suprathermal electrons accelerated at CME-driven shock waves propagating through the corona and interplanetary medium while the type III bursts are generated by fast electron beams originated from magnetic reconnection sites of solar flares. For the first time, we have successfully applied a radio direction-finding technique to an interplanetary type II burst detected by two identical widely separated radio receivers. Our work demonstrates the complementarity between radio

triangulation and 3D reconstruction techniques for space weather applications. We have also performed a statistical study of interplanetary type II radio bursts Type III bursts provide us with a unique diagnostic tool for solar wind remote plasma measurements. We performed a statistical survey of simple and isolated type III bursts observed by STEREO and Monte Carlo simulations to study the role of scattering due to random electron density fluctuations.

**Electromagnetic waves originating from lightning at Jupiter (DSP)**
Electrical currents in atmospheric lightning strokes generate impulsive radio waves in a broad range of frequencies, called atmospherics. These waves can be modified by their passage through the plasma environment of a planet into the form of dispersed whistlers. In the Io plasma torus around Jupiter, Voyager 1 detected whistlers as several-seconds-long slowly falling tones at audible frequencies. These measurements were the first evidence of lightning at Jupiter. Subsequently, Jovian lightning was observed by optical cameras on board several spacecraft in the form of localized flashes of light. We investigated measurements by the Waves instrument on board the Juno spacecraft that indicate observations of Jovian rapid whistlers: a form of dispersed atmospherics at extremely short timescales of several milliseconds to several tens of milliseconds. On the basis of these measurements, we compared the observations with thunderstorms on Earth. Intense electromagnetic impulses induced by Jupiter's lightning have been recognized to produce both low-frequency dispersed whistler emissions and non-dispersed radio pulses. We have collaborated on a discovery and analysis of electromagnetic pulses associated with Jovian lightning. Detected by the Juno Waves instrument during its polar perijove passes, the dispersed millisecond pulses called Jupiter dispersed pulses (JDPs) provide evidence of low density holes in Jupiter's ionosphere. We have estimated the characteristic plasma densities and lengths of plasma irregularities represented by density holes in the nightside ionosphere.

**Electromagnetic waves at Saturn (DSP)**
We investigated Langmuir wave amplitudes in Saturn's foreshock using the Cassini Radio and Plasma Wave Science/Wideband Receiver measurements. We focused on the probability density function of amplitudes, the distribution of amplitudes as a function of the depth in the foreshock and on comparison with the generally accepted stochastic growth theory mechanism for the foreshock region. We have reported the first observations of lion roar emissions in Saturn's magnetosheath, representing the first evidence such emission outside the terrestrial environment. We have investigated their new parameter regime characterized by a higher plasma beta (owing to the substantially higher Mach number bow shock) compared to Earth.

**Numerical simulations (DSP)**
In the field of numerical simulations the work of the team is mainly focused (i) on the large scale interactions of the solar wind and magnetospheric plasmas with magnetized and unmagnetised bodies, i.e., planets and moons, and (ii) local kinetic processes in various heliospheric plasma environments. The work is based on numerical models using either full particle-in-cell or hybrid code techniques, which are capable to implement the kinetic aspects of the individual plasma species on the electron and ion scales respectively. Investigation methods further employ data comparison and cross analysis with respect to real space in situ observations. For the need of high demanding computational resources the team maintains a high

performance computational facility Amálka (parallel cluster based on OS Linux currently with 1024 CPU cores).

**Instrument development for space research (DSP)**
We developed the Time Domain Sampler module for the Radio and Plasma Waves instrument (lead by Paris Observatory) on the Solar Orbiter mission to inner heliosphere, devoted to the study of higher frequency plasma waves and dust in the solar wind. This instrument started operations in shortly after the launch of Solar Orbiter in February 2020 and is now routinely providing scientific measurements. As a Co-Principal Investigator institute, we continued in the development of the low frequency wave analyser, a part of the Radio and Plasma Wave Instrument lead by the Swedish institute of Space Physics, for the European JUICE mission to the moons of Jupiter. We developed and delivered an electronic wave analyser module (WAM), including an electromagnetic sensor, as a European contribution to the Russia-lead landing platform of the ESA Exomars 2022 mission. We finalized the development and tests of the IME-HF instrument for the CNES Taranis spacecraft, to be launched in late 2020. In preparation of the mission, the network of ground-based observatories of lightning associated electromagnetic waves is maintained in Czechia, France, Slovakia, and in the Netherlands.

**Atmospheric waves and the influence of the lower atmosphere on the ionosphere – vertical coupling in the atmosphere-ionosphere system (DIA)**
We have been studying effects of gravity waves, acoustic waves (infrasound) and planetary waves of different origin with particular focus paid on waves predominantly coming to the ionosphere from the lower atmosphere.
3-D analysis of medium-scale gravity waves with periods 10-40 min was performed based on three-frequency Doppler shift measurements aimed on 3-D phase and energy propagation of gravity waves, and on their attenuation with height. In the horizontal plane the dominant propagation of gravity waves was against direction of neutral wind as expected by theory.
Large-scale traveling ionospheric disturbances (LSTIDs), which are ionospheric counterparts of large-scale gravity waves, have been investigated using among others the ionosonde at Pruhonice. The investigation was focused on efficiency of the coronal interacting regions (CIRs) and coronal mass ejections (CMEs) in exciting LSTIDs and on differences between LSTIDs excited by CIRs and those excited by CMEs.
Different sources of excitation of gravity waves were examined. During solar eclipse, gravity waves are excited in shadow in relation to upper atmosphere cooling. The main source region of such waves is near altitude of 200 km. Also motion of large meteorological systems excites gravity wave activity, which has well been observed even at ionospheric heights by both the ionosonde and Doppler sounder.
We observe infrasound on ground at Panska Ves and in Cheb region (seismic area) – four microbarograph at each station as a part of the Central and Eastern European Infrasound Network. In winter we detect predominantly infrasound coming from from the North Atlantic Ocean (microbaroms). Their characteristics have been investigated. The large-scale array at Cheb is able to observe also gravity waves in the troposphere. The infrasound of meteorological origin has often been observed for several hours with varying intensity and spectral content in the ionosphere in the frequency range of 3.5-20 mHz. Its dominant periods are longer than periods of coseismic signals. The coseismic infrasound from distant strong earthquakes corresponded to the local seismic vertical motion of ground surface, which generates the vertically upward

propagating infrasound. For strong and less distant earthquakes the situation is more complex due to large amplitudes and consequent nonlinear phenomena. The numerical simulation was in a good agreement with the observation of ionospheric fluctuations by continuous Doppler sounding.
Planetary waves affect significantly the atmosphere and ionosphere. We investigated the impact of planetary wave activity on the activity and characteristics of sporadic-E layer (foEs and hEs), including variability of their spectral content and intensity.

**Impact of space weather on the ionosphere (DIA)**
We have been strongly engaged in the investigations of space weather effect on ionosphere for several decades. We have been focusing particularly on the ionospheric response to ICME (Interplanetary Coronal Mass Ejection) and CIR (Co-rotating Interaction Region)-related magnetic storm-induced disturbances over middle latitudes of both hemispheres. Data from national and international ionosondes, GPS receivers and Continuous Doppler sounders have been used. The results were compared with the relevant outputs of international ionospheric models (e.g. IRI STORM model validation). We obtained interesting new results on ionospheric F1 layer storm time behaviour and on differences in ionospheric effects caused by ICME- and CIR/HSSWS-related storms. For example, the analysis of 45 CIR/CH HSSWS-related events showed that their ionospheric effects (mostly positive) under very low solar activity conditions (2007-2009) could be comparable with the effects of strong ICME-induced magnetic storms under higher solar activity conditions. The similar of ionospheric effects at conjugated locations of both hemispheres were examined, either. Since 2017 we have been investigating ionospheric effects of LSTIDs (large-scale TIDs) triggered by geomagnetic storms driven by CMEs and CIR/HSSWSs; here we focused on efficiency of these storm effect drivers and on possible interhemispheric propagation of triggered LSTIDs. As concerns effects of solar flares, we dealt with the evolution of the Doppler shift of radio signal during flares and with the attenuation of Doppler signal, which was found to correlate with the X-ray flux measured by GOES satellites.

**Long-term trends (climate change) in the mesosphere-thermosphere-ionosphere system (DIA)**
The increasing concentration of greenhouse gases, particularly of $CO_2$, results in heating of the lower atmosphere but cooling of the upper atmosphere. This cooling and resulted atmospheric shrinking resulted in a change atmospheric composition with consequent changes of the ionosphere. International team lead by J. Lastovicka created the first scenario of climate change in the upper atmosphere and ionosphere in 2006 and since we have been adding new information and new phenomena to the scenario and we removed several contradictions in the scenario. The upper atmosphere and ionosphere are affected also by other trend drivers like stratospheric ozone depletion or the secular change of the Earth's magnetic field. Recently we found that the long-term trend in the total electron content is slightly negative contrary to the original opposite result, which was caused by data problem.

**Development of the International Reference Ionosphere, IRI (DIA)**
We participate in development of IRI both by validating models by new data and by the development of global models in the topside ionosphere and plasmasphere, particularly models of plasma temperature and ion composition. V. Truhlik is main author of some submodels/options of IRI. New global model of electron temperature

with high resolution is developed based on measurements onboard CHAMP and Swarm satellites. Also new model of ion temperature is under development based on all available satellite observations. The model of ion composition has been substantially improved for very low solar activity conditions. We also contributed to validation of the IRI 2016 model using measurements of SWARM satellites on the one hand and ionosondes on the other hand.

**Stratosphere – dynamics and ozone (DIA)**
Focus of investigations of stratospheric dynamics was in various aspects of behaviour of winds including reliability of wind data, long-term changes of winds, and impact of the North Atlantic Oscillation in the troposphere on wintertime stratospheric winds from long-term point of view. Stratospheric temperature and wind trends in the last 50 years were affected by evolution of ozone concentration; all their trends changed in the second half of the 1990s. The other focus of our stratospheric investigations was to find two cells of oppositely enhanced meridional circulation from the middle stratosphere to mesosphere at higher latitudes in winter and their temporal stability and physical origin.
We also dealt with Investigations of ozone laminae (narrow layers of substantially enhanced ozone concentration), particularly with the role of planetary and gravity waves in forming the laminae and in their seasonal variation.

**Atmospheric circulation and its links to surface climate (DC)**
Atmospheric circulation fundamentally affects the surface climate and is therefore a key factor in connection with the ongoing changes in the Earth's climate system, including the occurrence of extreme and dangerous phenomena (such as heat waves, droughts, floods, etc.). Our research focuses on the study of atmospheric circulation (teleconnections, modes of low-frequency variability, circulation types), its long-term changes, and influence on surface climatic elements. We test various methods for describing the structure of circulation data, especially with respect to capturing variability associated with less significant modes. An important topic of our research is the links between circulation and the surface climate in current climate models, which reveals models' deficiencies in reproducing physical processes associated with advection of air masses, radiation, or land surface properties. The latest available climate model simulations, especially from the CORDEX activity, are examined for this purpose. We also compare individual atmospheric reanalyses in terms of their ability to reproduce modes of variability/circulation types and their relationships to surface climatic elements, and study the extent to which the trends in surface variables are related to long-term changes in atmospheric circulation.

**Climate variability and change (DC)**
Ongoing and future climate change is one of the main environmental issues of the present, attracting attention in the decision-making and political spheres, as evidenced by the Paris agreement concluded in 2016. We deal with climate change detection, development of methods for the testing of presence and significance of trends, especially in spatial data, and relationships between trends in various variables (e.g. temperature, cloud cover, sunshine). We develop and evaluate statistical downscaling methods as well as methods for constructing climate change scenarios used in assessing climate change impacts on agricultural production and hydrological regime, among others; the main tool for the latter is the multidimensional stochastic spatial weather generator SPAGETTA. We contributed to the formulation of the framework for

validation of downscaling approaches for climate change studies and the intercomparison of a large number of statistical downscaling methods in a wide international cooperation within the COST 1102 Action VALUE. Methodologies for applying tests of the significance of trends in areas with geographically irregularly distributed data are developed, as well as methods to display a full annual cycle of trends in climate elements. Furthermore, we systematically evaluate the outputs of climate models both in terms of capturing the observed climate variability and in terms of projected future changes and their uncertainties.

**Extreme events and their simulation in climate models (DC)**
Extreme climate and weather events have pronounced impacts on the natural environment and human society, and they are receiving increasing attention in connection with the ongoing changes in the climate system. We evaluate outputs of climate models by comparing them to the observed data/reanalyses, study spatial and temporal characteristics of extremes, and examine the role of atmospheric circulation and other meteorological factors in their initiation and development. For precipitation extremes, we develop extreme value models to improve estimates of growth curves and design values for high return levels, with focus on different processes leading to heavy precipitation. We analyse past changes in heat waves' and cold spells' characteristics and evaluate climate change scenarios of extremes and associated uncertainties. We also study compound extremes, e.g. relationships between heat waves and droughts or high-impact winter weather.

**Biometeorology (DC)**
Research in the field of biometeorology is of great importance for society – for example, the development of early warning systems has contributed to reducing the health effects of temperature extremes in many parts of the world. There has been an increasing demand for biometeorological information among professionals and in general public, related also to the fact that climate change may increase frequency and intensity of many dangerous phenomena. We study weather-related morbidity and mortality and differences in vulnerable populations in relation to changing levels of socio-economic and environmental deprivation as well as urbanization, and analyse spatial and temporal patterns of relationships between temperature extremes and mortality. A significant part of the research is related to comparison of methodological approaches in biometeorology. Our activities in this field have been broadened recently also by involvement within the Multi-Country Multi-City (MCC) collaborative research network, which allows the application of methodological procedures to data from different parts of the world and evaluation of regional and global patterns of the weather-to-health links.

**Quantitative forecast of precipitation and other dangerous meteorological phenomena (DM)**
Timely weather forecast and the forecast of dangerous meteorological phenomena in the first place, is an essential prerequisite for the reduction of damages caused by extreme weather every year, including the threat to population. As we devote our effort to this research topic on a long-term basis, we continued the development of numerical weather prediction (NWP) models focused on the very short-range precipitation forecast and the nowcasting of convective storms. The latter topic also includes studies on uncertainty of prediction and general questions on temporal variability and uncertainty of precipitation in the warm part of the year. Further, we concentrated on

the development and testing of the cloud microphysics description in a NWP model in combination with suitable methods of the satellite and radar data assimilation.

**Cloud microphysics and electrification of clouds (DM)**
This is our novel orientation started several years ago. It focuses on research of the electric field in clouds and of the lightning initiation. The research consists in mathematical modelling (cloud electrification model) and analyses of data. The focus on electricity in the atmosphere is related to our participation in the CRREAT project and the installation of a cloud profiler (Ka-band) at the Milešovka observatory. In addition to the development of an explicit mathematical model of cloud electrification, we analyse data from the cloud profiler in relation to the occurrence of lightning in the vicinity of the radar. Part of this research aims at developing of methods for the classification of hydrometeors based on cloud profiler data and we analyse interactions between the characteristics of hydrometeors and the electric field in the cloud. This activity is carried out in collaboration with other research teams in IAP.

**Analysis of hydrometeorological extremes (DM)**
Intensification of the atmospheric water transfer and of the precipitation activity brings about hydrometeorological threats. We work on substantial improvement of the analysis of these processes over Central Europe by an assessing the areal extremity of recent as well as historical extreme events. Relationships between the precipitation extremity and the spatial anomalies in selected meteorological fields are ascertained on both the synoptic and the mesosynoptic scale. Finding the correlation between the quantitative characteristics of the causal conditions of atmospheric circulation and the forecast skill leads to more precise estimates of the precipitation predictability by NWP models. Variants of short-lived precipitation are distinguished according to the distribution of precipitation intensity in time and their frequency in dependence on the extremity of precipitation amount is estimated. Spatial variability in the frequency is evaluated in relation to topography with the high spatial resolution. We focus also on mutual conditionality and co-existence of heavy precipitation and other natural threats, particularly from the point of view of their relations to the occurrence of extratropical cyclones and their characteristic trajectories.

**Road meteorology (DM)**
Successful road weather forecasting makes optimization of winter maintenance possible, which has positive impacts such as an increase of traffic safety and smoothness or a lower consumption of fuel and anti-icing agents. We continue working on improvement of our road weather prediction model. With the aim to provide a probabilistic forecast, we proposed an original ensemble method for estimation of the prediction uncertainty of the road weather model. Methods of a continuous line forecast were elaborated with inclusion of the sky view factor in computation of radiative fluxes, and applied in the operational prognostic line for the road network in the capital city of Prague. Since the road surface temperature forecast is very sensitive to the cloudiness prediction, we started with further novelties, namely utilization of satellite data as one of the model inputs. Research focused on quantitative expression of uncertainty of the forecast mainly by using ensembles and looking for the most efficient usage of the sky factor and the cloudiness nowcasting to improve calculation of radiative fluxes. This research is ongoing. It should be emphasized that our two variants of developed models are used in the Czech Hydrometeorological Institute for operational forecasts for Prague and the whole CR.

## Research activity and characterisation of the main scientific results

The activities of the Department of Climatology fall primarily into the following 4 main areas of research:

### A. Atmospheric circulation and its links to surface climate

Atmospheric circulation fundamentally affects the surface climate and is therefore a key factor in connection with the ongoing changes in the Earth's climate system, including the occurrence of extreme and dangerous phenomena (such as heat waves, droughts, floods, etc.). Our research focuses on the study of atmospheric circulation (teleconnections, modes of low-frequency variability, circulation types), its long-term changes, and influence on surface climatic elements. We test various methods for describing the structure of circulation data, especially with respect to capturing variability associated with less significant modes. An important topic of our research is the links between circulation and the surface climate in current climate models, which reveals models' deficiencies in reproducing physical processes associated with advection of air masses, radiation, or land surface properties. The latest available climate model simulations, especially from the CORDEX activity, are examined for this purpose. We also compare individual atmospheric reanalyses in terms of their ability to reproduce modes of variability/circulation types and their relationships to surface climatic elements, and study the extent to which the trends in surface variables are related to long-term changes in atmospheric circulation.

Key publications (team members underlined):

[A1] Stryhal, J., Huth, R., 2019: Classifications of winter atmospheric circulation patterns: validation of CMIP5 GCMs over Europe and the North Atlantic. Climate Dynamics, 52, 3575–3598

[A2] Stryhal, J., Huth, R., 2019: Trends in winter circulation over the British Isles and central Europe in twenty-first century projections by 25 CMIP5 GCMs. Climate Dynamics, 52, 1063–1075

[A3] Lhotka, O., Kyselý, J., 2018: Circulation-Conditioned Wintertime Temperature Bias in EURO-CORDEX Regional Climate Models Over Central Europe. Journal of Geophysical Research: Atmospheres, 123, 8661–8673

[A4] Beranová, R., Kyselý, J., 2018: Trends of precipitation characteristics in the Czech Republic over 1961–2012, their spatial patterns and links to temperature and the North Atlantic Oscillation. International Journal of Climatology, 38, E596–E606

[A5] Stryhal, J., Huth, R., 2017: Classifications of Winter Euro-Atlantic Circulation Patterns: An Intercomparison of Five Atmospheric Reanalyses. Journal of Climate, 30, 7847–7861

[A6] Kučerová, M., Beck, Ch., Philipp, A., Huth, R., 2017: Trends in frequency and persistence of atmospheric circulation types over Europe derived from a multitude of classifications. International Journal of Climatology, 37, 2502–2521

[A7] Huth, R., Beck, Ch., Kučerová, M., 2016: Synoptic-climatological evaluation of the classifications of atmospheric circulation patterns over Europe. International Journal of Climatology, 36, 2710–2726

[A8] Beranová, R., Kyselý, J., 2016: Links between circulation indices and precipitation in the Mediterranean in an ensemble of regional climate models. Theoretical and Applied Climatology, 123, 693–701

[A9] Philipp, A., Beck, Ch., Huth, R., Jacobeit, J., 2016: Development and comparison of circulation type classifications using the COST 733 dataset and software. International Journal of Climatology, 36, 2673–2691

[A10] Cahynová, M., Huth, R., 2016: Atmospheric circulation influence on climatic trends in Europe: an analysis of circulation type classifications from the COST733 catalogue. International Journal of Climatology, 36, 2743–2760

[A11] Sfica, L., Voiculescu, M., Huth, R., 2015: The influence of solar activity on action centres of atmospheric circulation in North Atlantic. Annales Geophysicae, 33, 207–215

[A12] Pokorná, L., Huth, R., 2015: Climate impacts of the NAO are sensitive to how the NAO is defined. Theoretical and Applied Climatology, 119, 639–652

## B. Climate variability and change

Ongoing and future climate change is one of the main environmental issues of the present, attracting attention in the decision-making and political spheres, as evidenced by the Paris agreement concluded in 2016. We deal with climate change detection, development of methods for the testing of presence and significance of trends, especially in spatial data, and relationships between trends in various variables (e.g. temperature, cloud cover, sunshine). We develop and evaluate statistical downscaling methods as well as methods for constructing climate change scenarios used in assessing climate change impacts on agricultural production and hydrological regime, among others; the main tool for the latter is the multidimensional stochastic spatial weather generator SPAGETTA. We contributed to the formulation of the framework for validation of downscaling approaches for climate change studies and the intercomparison of a large number of statistical downscaling methods in a wide international cooperation within the COST 1102 Action VALUE. Methodologies for applying tests of the significance of trends in areas with geographically irregularly distributed data are developed, as well as methods to display a full annual cycle of trends in climate elements. Furthermore, we systematically evaluate the outputs of climate models both in terms of capturing the observed climate variability and in terms of projected future changes and their uncertainties.

Key publications:

[B1] Dubrovský, M., Huth, R., Dabhi, H., Rotach, M.W., 2020: Parametric gridded weather generator for use in present and future climates: focus on spatial temperature characteristics. Theoretical and Applied Climatology, 139, 1031–1044

[B2] Soares, P.M.M., Maraun, D., Brands, S., Jury, M.W., Gutiérrez, J. M., San-Martin, D., Hertig, E., Huth, R., Vozila, A.B., Cardoso, R. M., Kotlarski, S., Drobinski, P., Obermann-Hellhund, A., 2019: Process-based evaluation of the VALUE perfect predictor experiment of statistical downscaling methods. International Journal of Climatology, 39, 3868–3893

[B3] Krauskopf, T., Huth, R., 2020: Temperature trends in Europe: Comparison of different data sources. Theoretical and Applied Climatology, 139, 1305–1316

[B4] Hynčica, M., Huth, R., 2019: Long-term changes in precipitation phase in Europe in cold half year. Atmospheric Research, 227, 79–88

[B5] Jones, M.E., Bromwich, D.H., Nicolas, J.P., Carrasco, J., Plavcová, E., Zou, X., Wang, S.-W., 2019: Sixty Years of Widespread Warming in the Southern Mid- and High-Latitudes (1957–2016). Journal of Climate, 32, 6875–6898

[B6] Maraun, D., Huth, R., Gutiérrez, J. M., Martín, D. S., Dubrovský, M., (...), 2019: The VALUE perfect predictor experiment: evaluation of temporal variability. International Journal of Climatology, 39, 3786–3818

[B7] Gutiérrez, J. M., Maraun, D., Widmann, M., Huth, R., (...), Dubrovský, M., 2019: An intercomparison of a large ensemble of statistical downscaling methods over Europe: Results from the VALUE perfect predictor cross-validation experiment. International Journal of Climatology, 39, 3750–3785

[B8] Pokorná, L., Kučerová, M., Huth, R., 2018: Annual cycle of temperature trends in Europe, 1961–2000. Global and Planetary Change, 170, 146–162

[B9] Markonis, Y., Hanel, M., Máca, P., Kyselý, J., Cook, E., 2018: Persistent multi-scale fluctuations shift European hydroclimate to its millennial boundaries. Nature Communications, 9, Article 1767

[B10] Rulfová, Z., Beranová, R., Kyselý, J., 2017: Climate change scenarios of convective and large-scale precipitation in the Czech Republic based on EURO-CORDEX data. International Journal of Climatology, 37, 2451–2465

[B11] Dubrovský, M., Trnka, M., Holman, I. P., Svobodová, E., Harrison, P. A., 2015: Developing a reduced-form ensemble of climate change scenarios for Europe and its application to selected impact indicators. Climatic Change, 128, 169–186

[B12] Hlavinka, P., Kersebaum, K.S., Dubrovský, M., Fischer, M., Pohanková, E., Bálek, J., Žalud, Z., Trnka, M., 2015: Water balance, drought stress and yields for rainfed field crop rotations under present and future conditions in the Czech Republic. Climate Research, 65, 175–192

## C. Extreme events and their simulation in climate models

Extreme climate and weather events have pronounced impacts on the natural environment and human society, and they are receiving increasing attention in connection with the ongoing changes in the climate system. We evaluate outputs of climate models by comparing them to the observed data/reanalyses, study spatial and temporal characteristics of extremes, and examine the role of atmospheric circulation and other meteorological factors in their initiation and development. For precipitation extremes, we develop extreme value models to improve estimates of growth curves and design values for high return levels, with focus on different processes leading to heavy precipitation. We analyse past changes in heat waves' and cold spells' characteristics and evaluate climate change scenarios of extremes and associated uncertainties. We also study compound extremes, e.g. relationships between heat waves and droughts or high-impact winter weather.

Key publications:

[C1] Lhotka, O., Kyselý, J., Plavcová, E., 2018: Evaluation of major heat waves' mechanisms in EURO-CORDEX RCMs over Central Europe. Climate Dynamics, 50, 4249–4262

[C2] Beranová, R., Kyselý, J., Hanel, M., 2018: Characteristics of sub-daily precipitation extremes in observed data and regional climate model simulations. Theoretical and Applied Climatology, 132, 515–527

[C3] Lhotka, O., Kyselý, J., Farda, A., 2018: Climate change scenarios of heat waves in Central Europe and their uncertainties. Theoretical and Applied Climatology, 131, 1043–1054

[C4] Rulfová, Z., Buishand, A., Roth, M., Kyselý, J., 2016: A two-component generalized extreme value distribution for precipitation frequency analysis. Journal of Hydrology, 534, 659–668

[C5] Plavcová, E., Kyselý, J., 2016: Overly persistent circulation in climate models contributes to overestimated frequency and duration of heat waves and cold spells. Climate Dynamics, 46, 2805–2820

[C6] Kyselý, J., Rulfová, Z., Farda, A., Hanel, M., 2016: Convective and stratiform precipitation characteristics in an ensemble of regional climate model simulations. Climate Dynamics, 46, 227–243

[C7] Rusticucci, M., Kyselý, J., Almeira, G., Lhotka, O., 2016: Long-term variability of heat waves in Argentina and recurrence probability of the severe 2008 heat wave in Buenos Aires. Theoretical and Applied Climatology, 124, 679–689

[C8] Lhotka, O., Kyselý, J., 2015: Hot Central-European summer of 2013 in a long-term context. International Journal of Climatology, 35, 4399–4407

[C9] Lhotka, O., Kyselý, J., 2015: Spatial and temporal characteristics of heat waves over Central Europe in an ensemble of regional climate model simulations. Climate Dynamics, 45, 2351–2366

[C10] Lhotka, O., Kyselý, J., 2015: Characterizing joint effects of spatial extent, temperature magnitude and duration of heat waves and cold spells over Central Europe. International Journal of Climatology, 35, 1232–1244

[C11] Hanel, M., Pavlásková, A., Kyselý, J., 2016: Trends in characteristics of sub-daily heavy precipitation and rainfall erosivity in the Czech Republic. International Journal of Climatology, 36, 1833–1845

[C12] Collazo S., Lhotka O., Rusticucci M., Kyselý J., 2018: Capability of the SMHI-RCA4 RCM driven by the ERA-Interim reanalysis to simulate heat waves in Argentina. International Journal of Climatology, 38, 483–496

## D. Biometeorology

Research in the field of biometeorology is of great importance for society – for example, the development of early warning systems has contributed to reducing the health effects of temperature extremes in many parts of the world. There has been an increasing demand for biometeorological information among professionals and in general public, related also to the fact that climate change may increase frequency and intensity of many dangerous phenomena. We study weather-related morbidity and mortality and differences in vulnerable populations in relation to changing levels of socio-economic and environmental deprivation as well as urbanization, and analyse spatial and temporal patterns of relationships between temperature extremes and mortality. A significant part of the research is related to comparison of methodological approaches in biometeorology. Our activities in this field have been broadened recently also by involvement within the Multi-Country Multi-City (MCC) collaborative research network, which allows the application of methodological procedures to data from different parts of the world and evaluation of regional and global patterns of the weather-to-health links.

Key publications:

[D1] Urban, A., Kyselý, J., Plavcová, E., Hanzlíková, H., Štěpánek, P., 2020: Temporal changes in years of life lost associated with heat waves in the Czech Republic. Science of the Total Environment, 716, Article 137093

[D2] Armstrong, B., Sera, F. (...) Kyselý, J., Urban, A., (...), 2019: The Role of Humidity in Associations of High Temperature with Mortality: A Multicountry, Multicity Study. Environmental Health Perspectives, 127, Article 097007

[D3] Urban, A., Hondula, D.M., Hanzlíková, H., Kyselý, J., 2019: The predictability of heat-related mortality in Prague, Czech Republic, during summer 2015 – a comparison of selected thermal indices. International Journal of Biometeorology, 63, 535–548

[D4] Liu, C., Chen, R., (...). Kyselý, J., Urban, A., (...), 2019: Ambient Particulate Air Pollution and Daily Mortality in 652 Cities. New England Journal of Medicine, 381, 705–715

[D5] Putnam, H., Hondula, D.M., Urban, A., Berisha, V., Iniguez, P., Roach, M., 2018: It's not the heat, it's the vulnerability: attribution of the 2016 spike in heat-associated deaths in Maricopa County, Arizona. Environmental Research Letters, 13, Article 094022

[D6] Urban, A., Kyselý, J., 2018: Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic. International Journal of Biometeorology, 62, 85–96

[D7] Vicedo-Cabrera, A.M., Guo, Y., (...), Kyselý, J., Urban, A., (...), 2018: Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. Climatic Change, 15, 391–402

[D8] Urban, A., Hanzlíková, H., Kyselý, J., Plavcová, E., 2017: Impacts of the 2015 Heat Waves on Mortality in the Czech Republic – A Comparison with Previous Heat Waves. Environmental Research and Public Health, 14, Article 1562

[D9] Urban, A., Burkart, K., Kyselý, J., Schuster, Ch., Plavcová, E., Hanzlíková, H., Štěpánek, P., Lakes, T., 2016: Spatial patterns of heat-related cardiovascular mortality in the Czech Republic. International Journal of Environmental Research and Public Health, 13, Article 284

[D10] Hanzlíková, H., Plavcová, E., Kynčl, J., Kříž, B., Kyselý, J., 2015: Contrasting patterns of hot spell effects on morbidity and mortality for cardiovascular diseases in the Czech Republic, 1994–2009. International Journal of Biometeorology, 59, 1673–1684

The individual research areas are interlinked in several ways; for example, the study of extreme events (point C) is closely related to atmospheric circulation (A), which is among the main drivers of their occurrence, as well as to biometeorology (D) since impacts of weather on human health are manifested primarily through extremes; climate change scenarios (B) and associated uncertainties are relevant for atmospheric circulation (A) as well as extremes (C) and projections of their impacts (D), etc. Furthermore, the results from studies of atmospheric circulation (A) and extremes (C) are employed in developing the circulation-conditioned weather generator (B), which helps to improve its performance and applicability in various climate change impact studies.

The key publications listed above do not form an exhaustive list of the team's IF journal papers; altogether we published 64 papers in IF journals in 2015–2019, and a number of papers in other publication outlets, including those intended for the national scientific community (Meteorologické zprávy) or a general audience (Vesmír). The papers listed above with the publication year 2020 were submitted or prepared for publication within the evaluation period.

Particular results achieved in 2015–2019 include the following:

*Atmospheric circulation vs. surface climate*

A large database of circulation types over 11 European domains was developed and compiled within the international project COST733 "Harmonisation and Applications of Weather Types Classifications for European Regions," of which R. Huth was vice-chair. Several hundreds of classifications, which were based on more than 20 different classification methods, were developed for every domain [A9]. This database was utilized in the assessment of long-term trends of the occurrence and persistence of circulation types. One of its results was the finding that the trends exhibited by the widely used subjective catalogue of synoptic types of Hess and Brezowsky, reported in several earlier studies, are unrealistic [A6]. The long-term trends in temperature and precipitation in Europe were found to be caused by long-term changes in atmospheric circulation (trends in the frequency and occurrence of circulation types) rather marginally; the only significant effect is observed for temperature in winter [A10]. Individual classifications were also evaluated for their ability to stratify distributions of surface temperature and precipitation [A7]. One of major general findings of these studies is that the simultaneous use of multiple classifications is necessary for the analysis to be valid and to avoid misinterpretation of artifacts of particular classification methods as real features; this finding was further elaborated and applied in comparisons of circulation types in reanalyses [A5].

*Circulation type classifications in reanalyses and climate models*

We used multiple circulation typing methods to assess winter atmospheric circulation over the Euro-Atlantic region in outputs of atmospheric reanalyses and global climate models. A comparison of reanalyses showed that even in regions with dense observation networks there were non-negligible differences between the datasets. In particular, some centennial reanalyses that assimilate only a very limited set of variables provided a very different image of historical circulation compared to their more complex counterparts. This finding questions the usability of such products in climate research. We recommended using several reanalysis products to increase robustness of results [A5]. Furthermore, we validated historical simulations by a large ensemble of GCMs against the reanalyses, which showed marked biases in most models as well as in the ensemble median in the frequency of occurrence and persistence of circulation types over several European regions [A1]. Last, an analysis of model projections for the end of 21st century suggested that westerly circulation over central Europe might become more frequent and easterly flow considerably weaker. However, no changes in persistence of circulation were identified [A2]. Multiple classification methods were used in the studies [A1, A2, A5], and we clearly documented that comparing circulation types between datasets is very sensitive to methodology and one must not rely on a single method.

*Evaluation of downscaling methods*

More than fifty downscaling methods of all types were evaluated in a wide international cooperation within the COST Action ES1102 VALUE (Validating and Integrating Downscaling Methods for Climate Change Research). A general validation framework, listing criteria that should be evaluated when performing a validation of any downscaling method, was formulated. A suite of downscaling methods was compiled [B7] and was subject to a detailed validation of various aspects of behaviour of temperature and precipitation, including mean values [B7], temporal variability from interdiurnal to long-term trends [B6], and various processes related to atmospheric circulation, such as effects of local winds and large-scale circulation modes [B2]. The validation was conducted on a European-wide station network. We contributed to VALUE by developing and implementing several downscaling methods (various modifications of multiple linear regression and stochastic weather generator) [B7], validation of short-term variability [B6], validation of the spatial structure of downscaled fields by cluster analysis and principal component analysis, and validation of effects of the North Atlantic Oscillation and large-scale circulation types on downscaled temperature and precipitation [B2]. Major results of VALUE were published in a special issue of the International Journal of Climatology.

*Weather generator and climate change scenarios*

Two single-site stochastic weather generators developed by the team earlier (parametric M&Rfi and non-parametric GOMEZ) participated in an experiment within the frame of the VALUE project aiming at detailed comparison of downscaling approaches (see previous paragraph for more details). The generators achieved good results with respect to other downscaling approaches [B6, B7]. Single-variate weather generator SPAGETTA was used to produce synthetic multi-site weather series for studying the collective significance of local trends at multiple sites and developing a new test for examining this significance by analysis of data from multiple mutually correlated sites. A more complex version of the generator was designed for producing multi-variate weather series representing both present and future climates for use in hydrological modelling [B1]. Using GCM and RCM simulations, we developed climate change scenarios consisting of changes in averages and variability of multiple weather variables. These scenarios were used to modify parameters of generators (M&Rfi and

SPAGETTA), which thereafter produced synthetic weather series representing future climate for use in climate change impact studies (e.g. [B12]), and in assessing possible changes in spatial temperature characteristics [B1].

*Heat waves and their driving mechanisms*

We developed a methodology for analysing spatial characteristics of heat waves [C10], an approach applicable also into evaluation of climate models. Major Central European heat waves (1994, 2006, and 2015) were studied in detail, and we found the recent increased frequency and intensity of heat waves exceptional since the late 19th century [C8]. The capability of climate models to simulate spatial and temporal characteristics and driving mechanisms of heat waves was examined in large ensembles of RCMs from the ENSEMBLES and EURO-CORDEX projects [C1, C5]. We found drawbacks in the majority of RCMs in simulating precipitation and surface energy fluxes during heat waves, as well as in characteristics of atmospheric circulation (including persistence of circulation types), which resulted in biases in severity and duration of temperature extremes [C1, C5, C9]. The tendency to more severe heat waves was quantified for the next decades, with large uncertainties related to emission scenario [C3] but also to the aforementioned climate models' biases. In the 'worst case' scenario, the recent major heat waves are projected to become regular phenomena in the Central European climate of the late 21st century.

*Precipitation extremes – modelling, trends, and links to circulation*

Possibilities of improving statistical models for short-term precipitation extremes using two-component GEV distribution were examined in collaboration with KNMI (A. Buishand, M. Roth) [C4]. We found that in regions where convective precipitation dominates, this distribution leads to higher return value estimates than a standard GEV distribution for maxima of precipitation amounts. Evaluation of biases in characteristics of parameterized convective (subgrid) and stratiform (large-scale) precipitation in an ensemble of RCMs showed substantial deficiencies in simulating processes leading to precipitation [C6]. In climate change scenarios, mean convective and large-scale precipitation amounts were found to increase in all seasons except summer when large-scale precipitation decreases [B10]. Characteristics of observed sub-daily precipitation extremes were compared with those simulated by RCMs also in terms of the diurnal cycle of precipitation and dependence on intensity and temperature [C2]. We found that the RCMs are not able to capture the range of the shape parameter estimates of the GEV distribution of short-duration precipitation maxima realistically. Trends in mean and extreme precipitation were analysed in connection with changes in precipitation intensity and the North Atlantic Oscillation index [A4]. In an analysis for the Mediterranean area, most RCMs were found to capture links between circulation indices and precipitation reasonably well [A8].

*Spatial and temporal patterns of weather-to-health links*

Spatial and temporal variability of heat stress effects on mortality and morbidity was investigated, with respect to regional and epidemiological aspects [D8, D9, D10]. A study investigating regional differences in heat-related cardiovascular (CVD) mortality across the Czech Republic revealed that climatic conditions, altitude, and urbanization considerably affect the spatial distribution of districts with the highest excess cardiovascular mortality, while socioeconomic status did not show a significant effect

[D9]. As opposed to CVD mortality, below-expected-levels of CVD hospital admissions prevailed during hot spells [D10], suggesting that out-of-hospital deaths represent a major part of excess CVD mortality during heat. Temporal changes in the impacts of heat waves on mortality in the Czech Republic were examined in a couple of studies [D1, D8]. The application of the years-of-life-lost approach helped to understand that although the heat vulnerability of the general population has been decreasing, the total death burden of heat waves remains significant due to a shift of the major heat-vulnerable population group towards older age [D1]. Increasing frequency and intensity of heat waves in Central Europe represent major atmospheric health risks for the Czech population. An international MCC study provided evidence that limiting global warming below the Paris Agreement targets (1.5–2 °C) could prevent large increases in temperature-related mortality in most regions worldwide, including Central Europe [D7].

*Predictability of heat-related mortality*

A suite of statistical models and methodological approaches were applied to investigate the predictability of heat-related mortality [D3, D5, D6, D8]. Spatial Synoptic Classification was applied to assess the links between weather patterns and heat-related mortality [D6]. The impact of the extraordinary heat waves in the summer of 2015 on mortality in the Czech Republic was compared with previous major heat waves using a traditional epidemiological approach [D8]. The ability of selected thermal indices to predict heat-related mortality during the 2015 summer was also investigated [D3]. A collaborative study with the Arizona State University assessed the record setting heat and heat-related deaths in Maricopa County, AZ, US [D5]. Results of all these studies provided evidence that increasing complexity of a model and/or a thermal predictor used for predicting temperature-related mortality does not necessarily improve the model’s accuracy. This hypothesis was confirmed also by an international MCC study that showed little evidence for improved prediction of heat-related mortality when relative humidity was taken into account [D2]. These findings are important for development and revising methodological aspects of heat warning systems.

## Research activity and characterisation of the main scientific results

**1. Atmospheric waves and the influence of the lower atmosphere on the ionosphere – vertical coupling in the atmosphere-ionosphere system.**

We have been studying effects of gravity waves, acoustic waves (infrasound) and planetary waves of different origin with particular focus paid on waves predominantly coming to the ionosphere from the lower atmosphere.

We developed a method for a unique 3-D propagation analysis of medium-scale gravity waves (GWs) in the ionosphere with periods 10-40 min based on multi – point three-frequency Doppler shift measurements and performed analysis of selected distinct events. We found the oblique downward propagation of phase velocities in all analyzed cases, i.e. the oblique upward propagation of energy of gravity waves. The observed attenuation of gravity waves with height was usually 0.05-0.2 dB/km. The dominant horizontal propagation of gravity waves was against direction of neutral wind as expected. A systematic statistical 3-D analysis to obtain distribution of elevation angles and attenuation of medium - scale GWs is the ionosphere is under work. In addition, a 2-D statistical investigation of GW propagation in Taiwan was also performed using our HF Doppler network. A diurnal and seasonal dependence of propagation azimuths was identified at all locations of the HF Doppler network. The GWs usually propagated roughly poleward in summer nights and roughly equatorward in winter days. Using horizontal wind model HWM14, it was shown that the predominant direction of propagation of gravity waves was against direction of neutral winds at altitudes of observations as expected by theory.

Large-scale traveling ionospheric disturbances (LSTIDs), which are ionospheric counterparts of large-scale gravity waves, have been investigated (HORIZON2020 TechTIDE project) using among others our ionosonde at Pruhonice. LSTIDs are usually caused by waves propagating quasi-horizontally from the auroral zone. It was found that LSTIDs of CIR/HSSWS-induced geomagnetic storms are very effective source of LSTIDs; such LSTID activity is of longer duration than that caused by storms of coronal mass ejection origin.

During solar eclipse, gravity waves are excited in shadow in relation to upper atmosphere cooling. The main source region of waves is near altitude of 200 km; waves then propagate with non-zero vertical component up and down. Also motion of large meteorological systems excites gravity wave activity, which has well been observed even at ionospheric heights by both the ionosonde and Doppler sounder.

We observe infrasound on ground at Panska Ves and in Cheb region (Czech seismic area) – four microbarograph at each station. Both stations belong to the Central and Eastern European Infrasound Network. In winter we detect predominantly infrasound coming from the northwest, from the North Atlantic Ocean (microbaroms). Speeds and directions of well-pronounced waves depend on their frequency. The large-scale array in the Cheb region is also able to investigate gravity waves in the troposphere.

The infrasound generated by seismic events or by large convective systems was observed in the ionosphere by our continuous Doppler sounding network. The infrasound of meteorological origin has often been observed for several hours with varying intensity and spectral content in the ionosphere. Such infrasound was observed in the frequency range of 3.5-20 mHz with maximum near 5 mHz, i.e. dominant periods are 3-4 minutes, longer than periods of coseismic signals. The coseismic infrasound from distant strong earthquakes has usually been observed for several minutes and the shape of signals and periods of oscillations corresponded to the seismic vertical motion of ground surface, which generated the vertically upward

propagating infrasound. For strong and less distant earthquakes the situation is more complex due to large amplitudes and consequent nonlinear phenomena; the waveforms in the ionosphere have significantly different spectral content than above the ground. The nonlinear numerical simulation of infrasound propagation that took in to account the viscosity and thermal conductivity of the air was in a good agreement with the observation of ionospheric fluctuations by continuous Doppler sounding. Our results are mainly based on the analysis ionospheric response to 11 March 2011 $M$=9 Tohoku, 24 April 2015 $M$=7.8 Nepal, and 16 September 2015 $M$=8.3 Chile earthquakes.
I addition, we have analyzed atmospheric wave activity with respect to occurrence and propagation of large tropospheric mesoscale systems. Frontal borders are known to be an effective sources of atmospheric waves that have potential to propagate upward up to the ionospheric heights and significantly alter processes in the upper laying atmospheric layers. We identified a threshold in the correlation between long time series of ionospheric parameters above Europe. Extremely high correlation between ionospheric measurements exists up to the “break point” at 10 degrees in longitude and/or horizontal distance of 1000 km (of the order of size of tropospheric mesoscale systems). Further, we found that severe cyclone Fabienne (September 2018) that rapidly moved across Europe significantly affected all upper laying regions. Significant changes in the stratospheric circulation were found on continental scale. The general circulation pattern above Europe at 0.1 hPa before the storm Fabienne event can be classified/characterized as part of the stratosphere in normal conditions in September. Based on that, we attribute the overall change in the stratospheric circulation/dynamics to the strong wave field that was launched upward from the fast-moving mesoscale system. Wave activity abruptly increased during the day of storm frontal border crossing the observation points. We have found significant departures from typical values of ionospheric parameters shortly after the transition of the cold front across the observation point. We have detected a sudden strong increase in wave-like activity on the digisonde directograms and Doppler sounder records. The detected strong echo on directograms shows strong and rapid changes in the horizontal plasma motion. In the strong echo in directograms attributed to the storm, there is no characteristic prevailing motion, but sudden changes in direction are observed through the event. Time-limited increase in plasma drift in the northerly and easterly directions has been detected together with a decrease in velocity of the vertical plasma flow. Wave-like oscillations are present within ionospheric plasma all the time. In the WPS spectra of foF2 we have detected a change in the spectral content during the day of the Fabienne event compared to the preceding day. We have noticed a decrease in the F-layer thickness during the day of the event. Irregular stratification of the ionosphere was seen on ionograms. It is supported by a spread echo recorded by Digisonde during the afternoon and night on 23 September till the morning of 24 September. Doppler sounder data show a significant change in the spectral content, shape and power of the registered signal, corresponding to modulation by waves propagating from the convective system.
Planetary waves affect significantly the atmosphere and ionosphere. The spectral content and intensity of planetary waves in the lower ionosphere were found to be rather variable.
Special summer high-rate sampling campaigns of ionospheric vertical sounding were organized in order to get detail information about atmospheric wave activity reflected into particular ionospheric parameter. The planetary wave activity was detected in the modulation of characteristics of sporadic-E layer (foEs and hEs). The spectral content

within parameters of foEs and hEs was further analyzed with respect to the behavior of wind and temperature within the stratosphere. Coherence analyses revealed persistent structures that seem to propagate through the atmosphere and are detectable within ionospheric summer sporadic E parameters.
P. Koucká Knížová chaired the IAGA working group II-C on meteorological effects on the ionosphere. She organized (Chair of Scientific Organizing Committee) the 6$^{th}$ Workshop on Vertical Coupling in the Atmosphere-Ionosphere System in Taipei in 2016 and the 7$^{th}$ Workshop in Potsdam in 2018. In 2017 she organized and chaired IAGA/SCOSTEP Workshop “Solar variability and coupling effects in the Earth's atmosphere“ in Prague. In 2019 she organized (convenor) joint symposium Coupling Processes in the Atmosphere-Ionosphere at IUGG Assembly in Montreal.

**2. Impact of space weather on the ionosphere.**
The department is strongly engaged in the investigations of space weather effect on ionosphere for several decades. We have recently been focusing particularly on the ionospheric response to ICME and CIR-related magnetic storm-induced disturbances over middle latitudes of both the Northern and Southern Hemispheres. We are analysing changes in the regular course of main ionospheric parameters and plasma drifts using data from the national and international ionosondes, GPS receivers and Continuous Doppler sounders. The results are compared with the relevant outputs of international ionospheric models (e.g. IRI STORM model validation). We obtained interesting new results of ionospheric F1 layer storm time behaviour and of differences in ionospheric effects caused by ICME- and CIR/HSS-related storms. For example, we studied ionospheric behaviour above Northern and Southern Hemispheres during CME- and CIR-related magnetic storms, which occurred through the 23rd and 24th solar cycles with special focus on unusually low solar activity period at 2007– 2009. The analysis of 45 CIR/CH HSSWS-related events showed that, as for changes in the electron density, their ionospheric effects (mostly positive) could be comparable with the effects of strong ICME-induced magnetic storms under higher solar activity conditions. They are in most cases similar at conjugated locations of both the Northern and Southern Hemispheres. We also showed that CIR/CH HSSWS can have a significant effect on the ionosphere and thermosphere also during the period when the CIR/HSSWS influence is diminishing.
Since 2017 we are investigating ionospheric effects of LSTIDs triggered by magnetic storms driven by CMEs and CIR/HSSWSs. Here our analysis indicated that CIR/HSSWS is an efficient source of LSTIDs, which occur at both hemispheres. Some of the analysed CIR/HSSWS events showed an interhemispheric propagation of triggered LSTIDs. During geomagnetic storms, even if of moderate magnitude (SYM-H between 50 and 100 nT), the probability that LSTID are launched is very high. LSTIDs should be expected to be launched at both auroral and equatorial latitudes and propagate equatorward and poleward, respectively. Among all LSTID observed to be conjugate in both hemispheres we found that only 23% propagates into the opposite hemisphere. We did not detect any case of TID launched concurrently in both hemispheres, propagating equatorward, and eventually experiencing constructive interference and amplitude enhancement when crossing each other. We conclude that interhemispheric circulation exists but is not a significant threat to operators otherwise affected by TID.
We focussed on unique aspects of the ionospheric response at the conjugate locations over Europe and South Africa during CME-induced geomagnetic storms including the role of the bottomside and/or topside/plasmasphere in influencing electron density

changes. During the intense geomagnetic storm main phase on 08 September 2017, we have found an ionosonde maximum electron density in the F2 layer and TEC derived from GNSS observations showing different ionospheric responses over the same northern midlatitude location. In situ electron density measurements from SWARM satellite aided by bottomside ionosonde derived TEC up to the maximum height of the F2 layer (hmF2) revealed that the bottomside ionosphere and topside as well as plasmasphere electron content contributions to overall GNSS derived TEC were different in both hemispheres for the 8 September 2017 storm main phase. The differences in hemispheric response at conjugate locations and on regional scale have been explained in terms of seasonal influence on the background electron density coupled with the presence of large scale TIDs and low latitude associated processes.
In collaboration with the European Geostationary Navigation Overlay Service (EGNOS) team we analysed a large number of events when availability of EGNOS was degraded. For 23 CIR/CH HSSWS-related events occurred in 2017 (from 25 analysed) the EGNOS indicated moderate degradation, mostly due to enhanced TID activity.
In collaboration with our colleagues from European and African ionospheric stations we worked on the method for real-time identification and tracking of traveling ionospheric disturbances. A method combining spectral analysis and cross-correlation was applied to time series of ionospheric characteristics (i.e., MUF(3000)F2 or foF2) using data of the networks of ionosondes in Europe and South Africa to estimate the period, amplitude, velocity and direction of propagation of TIDs. The method was verified using synthetic data and was validated through comparison of TID detection results made with independent observational techniques. The method provides near real time capability of detection and tracking of Large-Scale TIDs (LSTIDs), usually associated with auroral activity and will be a part of the European network for identification and tracking of LSTIDs.
As concerns effects of solar flares, we have found that the Doppler shift of radio signal is maximal in the moment of the highest rate of change of solar EUV radiation, whereas it is close to zero at the EUV flux maximum. The attenuation of HF Doppler signal correlates with the X-ray flux measured on GOES satellites and with attenuation observed by riometer as we showed in collaboration with Argentinian colleagues.

**3. Long-term trends (climate change) in the stratosphere-mesosphere-thermosphere-ionosphere system.**

The increasing concentration of greenhouse gases, particularly of $CO_2$, results in heating of the lower atmosphere but cooling of the upper atmosphere. This cooling and resulted atmospheric shrinking result change atmospheric composition with consequent changes of the ionosphere. International team lead by J. Lastovicka created the first scenario of climate change in the upper atmosphere and ionosphere in 2006 and since we have been adding new information and new phenomena to the scenario and we removed several contradictions in the scenario, for example recently the hypothesis on the increasing concentration of atomic oxygen near 120 km (base of the thermosphere) due to the decreasing turbopause height as a main driver of ionospheric trends. The upper atmosphere and ionosphere are affected also by other trend drivers like stratospheric ozone depletion or the secular change of the Earth’s magnetic field.
Recently we found that the long-term trend in the total electron content (TEC) is slightly negative contrary to the original opposite result, which was caused by data problems, mainly by an artificial change of CODE TEC by 3 TECU in 2001. We published an

analysis of origin of differences between some ionospheric trend results; the main problem appears to be quality and homogeneity of data. Another important finding is that the dependence of ionospheric parameters (foF2 and foE) on solar proxies changed around the turn of the century (a few years earlier for foF2), which has not been taken into account in trend investigations and it might affect the results of some ionospheric trend investigations (and also climatological studies and modeling). The origin of this change could be solar, since for example the change of relationships between various solar proxies happens in the same time. Another result is that the optimum solar proxy for correcting impact of solar cycle on trend analysis differs for foF2 and foE; the optimum proxies are Mg II and F10.7, respectively. Our results concerning stratospheric trends are described in item (5) below.
J. Lastovicka to a substantial extent coordinates this research internationally as co-chairman of the respective IAGA working group and as chairman/co-chairman of the SOC of the 9th (Kuehlungsborn, Germany, 2016) and 10th (Hefei, China, 2018) IAGA/ICMA workshops “Long-term changes and trends in the atmosphere”. He is author of the most recent review article and presented a couple of invited talks about long-term trends.

**4. Development of the International Reference Ionosphere (IRI).**
We participate in development of IRI both by validating models by new data and by the development of global models in the topside ionosphere and plasmasphere, particularly models of plasma temperature and ion composition. V. Truhlik is main author of some submodels/options of IRI. New global model of electron temperature with high resolution is developed based on measurements onboard CHAMP and SWARM satellites. Also new model of ion temperature (Ti) is under development based on all available satellite observations. The model incorporates features not described by current version of IRI Ti model especially so called morning enhancement and dependence on solar activity. The model of ion composition has been substantially improved for very low solar activity conditions, particularly large decrease of the boundary between dominant $O^+$ ions and $H^+$ ions (i.e., the bottom height of the plasmasphere or so called upper transition height). The improved model was included into the latest version of the International Reference Ionosphere (IRI). A new version of ion composition model with possible adjustment using actual measured or derived information (especially the upper transition height) is under development. For it as an intermediate step and for further improvement of the ion composition model we developed first versions of empirical models of the upper transition height for solar minimum derived from large amount of available vertical electron density profiles. These models are used to adjust the ion composition model on climatological scale. We also contributed to validation of the IRI 2016 model using SWARM satellites data. Large data sets of the topside sounder data and newly available techniques for estimation of the electron density are used for possible improvement of the IRI electron density in the topside ionosphere. We also tested signals of natural origin like whistlers emitted by lightning and detected by the Absolute Scaler Magnetometer onboard the SWARM satellites to obtain information on the electron density close to F2 maximum for possible improvement of the IRI NmF2 model especially above oceans.
The team developed a large database comprising almost all available satellite thermal plasma parameters and in part also data from Incoherent Scatter Radars. The database contains parameters on densities and temperatures of thermal plasma particles in a uniform format. It has been *continuously* extended by new data. This database is our primary source for building the above empirical models. We checked

consistency of individual datasets included in the database and eventually introduced a calibration or correction factors if necessary.

Important activities related to the presented modeling works is study of processes in the ionospheric environment, which have impact on thermal plasma distribution. For this we use physics based numerical models, especially the FLIP model, which can be also adjusted to measured data (e.g. hmF2, NmF2) to avoid uncertainties in studies of other parameters. One of the important results obtained is that the NRLMSISE-00 model underestimates density of neutral hydrogen in the upper and topside ionosphere by several times. This can explain why models depended on current MSIS model encounter difficulties in describing of light ion fraction in the topside ionosphere.

We compared modeled and observed monthly medians of the foF2 and hmF2 for year 2012 over seven ionospheric locations distributed worldwide in the Northern Hemisphere. Modeling formulations considered here include two empirical models IRI and MIT Empirical model, as well as two physics-based, coupled ionosphere-thermosphere models, CTIPe and TIE-GCM. Although significant errors are occasionally obtained from all modeling approaches, empirical models tend to provide systematically better correlation with the observed medians and follow the observed distributions more successfully, offering smaller prediction errors than the physics-based ones. The prediction accuracy presents seasonal and local time dependence; it is strong for physics-based models, weaker for IRI, and very weak for MIT empirical model.

V. Truhlík (vice-chairman until 2018), D. Burešová and L. Třísková are members of COSPAR/URSI WG “International Reference Ionosphere”.

**5. Stratosphere – dynamics and ozone.**

Some results: (a) Stratospheric winds from reanalysis ERA-40 are wrong in its most recent 3-4 years, particularly in winter, as shown by comparison with other reanalyses and radiosonde soundings at Prague-Libus. (b) Long-term changes of yearly average winds in the stratosphere and mesosphere are similar, which points to unified long-term behavior of the stratosphere-mesosphere system. (c) Winds at 100 hPa in winter and the North Atlantic Oscillation in the troposphere reveal similar long-term changes. (d) Some influence of solar activity on long-term changes in stratospheric winds. Stratospheric temperature and wind trends in the last 50 years were affected by evolution of ozone concentration; when its trend changed in second half of the 1990s, temperature and wind trends also changed. Two cells of oppositely enhanced meridional circulation were found to extend from the middle stratosphere to mesosphere at higher latitudes in winter. They are rather stable from year to year. They are attributed to a stationary planetary wave.

Stratospheric dynamics is analyzed using reanalysis datasets. We have to use these datasets because observations in stratosphere are rare and many gaps occur in time series. That is why mutual comparison with available observations of key parameters (temperature, wind, etc.) has been done as well as tests of homogeneity and data quality. We have used GPS RO, MLS and AMSU (SSU) dataset for temperature. This comparison showed that reanalyses are suitable for climatology studies of temperature. Homogeneity test showed that there are several inhomogeneities during period 1979-2019 which should be taken into account for trend studies. Moreover, these jumps are not the same for all reanalyses (only jump in 1998 occurs in all reanalyses). On the other hand, comparison with available observations (but only for period from 1998) showed that difference at least in the middle stratosphere are not significant and temperature data can be used for long-term trend studies or analysis of stratospheric dynamics.

Reanalyses can be used for studying of various stratospheric phenomena. We have analyzed stratospheric conditions during several sudden stratospheric warmings (SSWs) on the Southern (SH) or Northern (NH) Hemisphere. A different behavior of SSWs on the SH and NH was found.

Investigations of ozone laminae (narrow layers of substantially enhanced ozone concentration) showed that laminae induced by planetary waves have strong seasonal variation and occur much more often than laminae induced by gravity waves. Large laminae are generated mostly by planetary waves, whereas weaker laminae are partly induced by gravity waves.

We analyzed the MERRA-2 reanalysis ozone concentration data series by applying the Pettitt homogeneity test to search for discontinuities. We showed the data above 4 hPa are not suitable for trend analyses due to the unrealistic patterns in an average ozone concentration and due to the frequent occurrence of significant discontinuities in individual grid points. Below 4 hPa in the stratosphere the number of discontinuities is much smaller, and mostly, they are insignificant, and the patterns of the average ozone concentration are explainable. We concluded that the MERRA 2 ozone concentration data may be used in trend analysis with caution and only below 4 hPa.

**6. Monitoring of the state of the ionosphere and receiving satellite signals.**

Digisonde DPS4D at Pruhonice station near Prague continuously monitors the state of the ionosphere. Ionosonde sounding at Pruhonice continues since 1957. Data has been sent online to several international databases as GIRO, DIAS and SWACI. Data of GPS receiver have been sent online to the Czech geodetic network.

The Czech multi-point ionospheric Doppler sounder (2x5 measuring paths at 2 frequencies, 3 measuring paths at three frequencies) continuously monitors the travelling ionospheric disturbance (TID) activity over Czechia; the relevant information has been continuously submitted to the ESA SWE I-ESC web site (ionospheric weather center) for users. For research we use also data of our Doppler sounders in the southernmost South Africa, northwestern Argentina and northern Taiwan.

Observatory Panska Ves (~60 km northward of Prague) has been receiving satellite telemetry from CLUSTER II project since 2007 until present. The station performs in collaboration with J.S. Picket from The University of Iowa scheduling of measuring of Wideband Plasma Wave Receivers on each individual satellite. The received data are processed by the Department of Space Physics. There are also ground-based ionospheric and atmospheric measurements at Panska Ves (ionospheric Doppler transmitters, microbarographs, atmospheric electricity meter, VLF receiver, all sky camera), and hosted measurements for the Geophysical Institute (Seismometer) and for the German Aerospace Center (Infrared camera).

The Czech microbarograph network (small tringle of differential microbarographs at Panska Ves, four microbarographs in western Czechia) run by DIA was originally introduced as support to ionospheric Doppler measurements/investigations. Now it is used mainly independently for middle atmosphere investigations within the European project ARISE.

**7. Study of ionospheric drifts.**

Modern digisondes provide routine ionospheric drift measurements in addition to classical vertical ionospheric sounding. However, up to now complex information showing various aspects of the drift characteristics is still missing.

We identified problems in automatic drift data processing and possible subsequent problems in data interpretation when no correction has been applied. We developed and introduced methodology for selection of the correct source points to calculate the right drift velocity vector. Our analyses of basic plasma drift data characteristics revealed diurnal and annual dependencies of the vertical component of plasma motion for F region over Pruhonice. For instance, we identified pronounced peaks around sunrise and sunset for F region data. Our results show peculiarities in behavior of E region drifts, which is subject of further analyses.

We have been continuing investigations of E/Es layer drifts. We prepare regional/global study of ionospheric drifts in F region. We have started and will continue studies of synchronized multiple-station drift measurements. We already successfully realized a special campaign with the nearest digisonde in Sopron (Hungary). Potentially we can collaborate also with stations Dourbes (Belgium) and Juliusruh (Germany).

Using our multi-point continuous Doppler sounders operated in collaboration with our partners in Taiwan and Northern Argentina and radio occultation scintillation data from FORMOSAT-3/COSMIC satellite, we investigated the low-latitude eastward drift velocities and occurrence rate of equatorial spread-F (ESF) that is often associated with plasma bubbles and significantly influence phase of the signals from GNSS satellites. Significant longitudinal differences of the ESF occurrence rate were found. For instance, the ESF was observed more often over the South America than in the East-Asian sector. The measured ESF drift velocities were higher in Argentina than in Taiwan.

**8. Investigations of atmospheric electricity and of its influence on the secondary cosmic rays in collaboration with the Institute of Experimental Physics of Slovak Academy of Sciences.**

Measurements of atmospheric electrostatic field at Panska Ves and Studenec are part of the international network created under GLOCAEM project which aims to study phenomena in the Global Electric Circuit (GEC) that is formed between the electrically conductive ionosphere and Earth’s surface and that connects electrically disturbed regions with fair weather regions across the planets. Relations between weather and atmospheric electricity, long term changes in GEC related to climate, coupling between space weather and GEC etc. are of interest. Currently, also investigations related to localization of thunderstorm sources of infrasound that are based on simultaneous and collocated measurements of electrostatic field and infrasound detections by large scale infrasound sensor around Studenec are under work. In addition, we operate, in collaboration with Slovak partners, measurements at Slovak mountain stations, on Lomnicky Stit (2634 m a.s.l.) and at its slope at Skalnate Pleso. These measurements serve to investigations of thunderstorm ground enhancements (TGEs) of secondary cosmic rays that are sometimes observed during occurrence of large electric fields in thunderstorms. The measured electric fields exceeded 100 kV/m during thunderstorms at Lomnicky Stit, which are much larger values than those measured at Panska Ves and Studenec, where the values did not exceed several kV/m. Significant enhancements of secondary cosmic rays (gamma or electrons) lasting several minutes were observed at Lomnicky Stit by detector system SEVAN, mainly for large electric fields with orientation that accelerates electrons downward. A likely explanation of the observed enhancements is runaway relativistic electron avalanche (RREA) mechanism. During the most extreme and rare event recorded on 10 June 2017, the enhancement exceeded the background values more than 200 times in the upper channel of SEVAN; moreover, a significant (more than 100%) enhancement was also detected by neutron monitor, indicating possible photonuclear reactions in the atmosphere or in a material surrounding the detector.

**9. Magnetospheric and Earth's foreshock studies in collaboration with the Faculty of Mathematics and Physics of Charles University.**

The topic of the collaboration is the influence of solar activity on the Earth environment, particularly the interaction of solar wind with Earth magnetosphere. It is based on data from THEMIS, supplemented with data from CLUSTER II and MMS. We have analyzed these data during more than one solar cycle and get over 40,000 of magnetopause crossings and 10,000 of bow shock crossings. We found that the magnetic barrier in front of the magnetopause occurres for both polarities of IMF Bz and it is observed nearly exceptionally on the flanks; the occurrence rate strongly rises with the departure of the local time from noon. The barrier is observed preferentially during an enhanced geomagnetic activity.

Our case studies as well as statistics show that the excess of the magnetosheath magnetic pressure is not compensated by the pressure of observable ion plasma component in the magnetosphere. We suggest that the pressure imbalance is only apparent and that the magnetospheric plasma contains a low-energy component that is not observed by the onboard spectrometers. A source of such low-energy component can be plasmasphere, because plasmaspheric plumes were observed in the magnetopause region. This is supported by the fact that majority of events was observed during enhanced geomagnetic activity.

Solar wind modification in the Earth foreshock was confirmed using not only case studies but also statistical studies of the solar wind deceleration and deflection in the foreshock. We have found a systematic deceleration of the solar wind due to its proton component with a decreasing distance to the bow shock. Having wave-particle interactions as its mechanism, the deceleration is controlled by the magnetic compressibility and the level of magnetic field fluctuations in the ULF wave range associated with the flux of reflected and accelerated particles. It was concluded that the reflected particles excite waves of large amplitudes that decelerate the solar wind protons throughout the foreshock.

**10. Influence of external factors (including solar) on humans in collaboration with the Faculty of Natural Sciences of Charles University.**

We investigated the impact of solar activity changes on mortality from cardiovascular causes of death in the solar cycle 23 in the Czech Republic. We used long-period daily time series of numbers of deaths by cause, solar activity indices (R, F10.7), geomagnetic indices (Kp, Dst), and physical parameters describing the ionospheric effects (foF2 and TEC). The results confirm the hypothesis that there is no direct correlation between Kp and the number of deaths from acute myocardial infarction or brain stroke the solar cycle maxima. On the contrary, the ionospheric parameters foF2 and TEC explain more of variability in the number of deaths - for acute myocardial infarction 24.8% of the variability, and 20.5% for brain stroke. These results support the hypothesis that the cardiovascular diseases respond to solar activity indirectly through a concentration of electrical charges in the environment.

We investigated the impact of cosmic radiation and cosmogenic radionuclides concentration on human health. We evaluated lifetime attributable risks induced from solid neoplasms by increasing concentration of cosmic radiation and cosmogenic radionuclides during periods of low solar activity for the Czech Republic. Models are provided for estimating risk as a function of age at exposure, age at risk, sex, and cancer site focusing on the risk from low-LET radiation. Three different scenarios based on dose radiation level were explored.

## Research activity and characterisation of the main scientific results

Research activity and characterisation of the main scientific results (2015-2019)

Basic research

Classification of hydrometeors using cloud profiler data
In 2018, a new Ka-band cloud profiler (KCP) was installed at Milešovka observatory, which together with participation in research project CRREAT has started a new direction of our research - cloud investigation using KCP data with respect to lightning discharges and development of a mathematical model describing the process of cloud electrification explicitly, the cloud electrification model (CEM).
We designed and published a new technique calculating the vertical air velocity (VAV) for the vertically oriented KCP. Using the calculated VAV, we also developed a new algorithm classifying six hydrometeor species. This algorithm enables us to recognize the areas where cloud droplets, rain, ice, snow, graupel or hail occur. The classification algorithm is crucial for our investigation focused on relationships between lightning occurrence and hydrometeors in clouds. Both the new technique for AV and the new algorithm for hydrometeor classification have already been published (Sokol et al., 2018). In the study, we also presented results that confirm that strong electric field develops in thunderclouds in regions where a mixture of hydrometeor species can be found. Moreover, the follow-up study showed that the values of Linear Depolarization Ratio increase in areas where increasing electrification is expected (Sokol et al., 2020).

References:
Sokol, Z., Minářová, J., Novák, P., 2018. Classification of Hydrometeors Using Measurements of the Ka-Band Cloud Radar Installed at the Milešovka Mountain (Central Europe). Remote Sensing, 10, 1674.
Sokol, Z., Minářová, J., Fišer, O., 2020. Hydrometeor Distribution and Linear Depolarization Ratio in Thunderstorms. Remote Sensing, 12, 2144.

Precipitation nowcasting
We dealt with nowcasting of meteorological variables with a special attention paid to precipitation. Specifically, we focused on studying the uncertainty of precipitation forecasts based on extrapolation methods of the current state of the atmosphere described by meteorological variables (Mejsnar et al., 2018). We obtained original results for Central Europe, which confirmed the empirical experience of operational forecasters that there are several meteorological situations such as severe convection that can be predicted by extrapolation methods for up to 10 to 20 minutes only. By default, however, it is possible to predict precipitation up to 1 hour in summer and only exceptionally up to 2 hours and more. These results are in contradiction to several works, where the predictability was given much higher, in the order of hours. Thus in this context, we then focused on developing other prediction methods based on artificial intelligence such as decision tree method, which provide predictions of the probability of exceeding arbitrary precipitation thresholds as the output (Pop et al., 2019). Our motivation for developing such methods is that we believe, based on our research and experience, that the extrapolation methods cannot be significantly improved further, instead one can improve the estimation of their accuracy and thus generally characterize their uncertainty.

References:
Mejsnar, J., Sokol, Z., Minářová, J., 2018. Limits of precipitation nowcasting by extrapolation of radar reflectivity for warm season in Central Europe. Atmos. Res., 213, 288–301.
Pop, L., Sokol, Z., Minářová, J., 2019. Nowcasting of the probability of accumulated precipitation based on the radar echo extrapolation. Atmos. Res., 216, 1–10.

Hail detection and prediction

One of the topics studied at our department was also the detection and prediction of hail, which belongs to natural hazards. For instance, we presented a method for hail detection based on data from a weather radar without polarization. The purpose of it was to be able to determine the occurrence of hail using data from old databases, obtained by weather radars with a single polarization in order to deepen the knowledge on historical hail events. Our analysis showed that suitable statistical models applied on database of derived hail occurrence can provide results comparable to standard applications of dual-polarization radars (Skripniková and Řezáčová, 2019).

Further, we dealt with the explicit prediction of hail using the NWP model COSMO including 2-moment microphysics. The NWP model COSMO was integrated with a horizontal resolution of 1.1 km and the model integrations included assimilation of weather radar reflectivity. The analysis of five hail events showed that the hail forecast is possible for a lead time up to 60 to 90 min.. As far as we know, this was for the first time that quantitative results of a hail prediction by a NWP model were published (Sokol et al., 2016).

References:
Skripniková, K., Řezáčová, D., 2019: Comparison of Radar-Based Hail Detection Using Single- and Dual-Polarization. Remote Sensing, 11, 1436.
Sokol, Z., Bližňák, V., Zacharov, P., Skripniková, K., 2016: Nowcasting of hailstorms simulated by the NWP model COSMO for the area of the Czech Republic. Atmos. Res., 171, 66-76.

Characteristics of hydrometeorological extremes at various spatial scales within central Europe

Precipitation extremes and floods are commonly evaluated by maxima of precipitation totals and peak discharges only, recorded at individual stations. However, impacts of hydrometeorological extremes can be enhanced by their rarity in a given location, size of the affected area, and duration of the event. To reflect these aspects, we developed three indices designed in a way that they enable to evaluate and to analyse relations between extreme precipitation events and floods. A study over the Czech territory showed that precipitation extremes concentrate from May to September mostly but their hydrological response gradually decreases during the warm part of the year (Müller et al., 2015). Maximum floods were detected in the warm half-year, which corresponds to the increasing representation of warm half-year floods from the northwest to the southeast in Central Europe (Gvoždíková and Müller, 2017). Regarding extreme precipitation events in Central Europe, significantly negative correlations were found in their occurrence between the western and the eastern part of Central Europe, which is the reason why such events have never affected half of the studied area (Gvoždíková and Müller, 2019). The study of Minářová et al. (2017) proved the applicability of our approach at smaller scale by analysing the differences of extreme precipitation characteristics between the western and the eastern part of

Central Europe, namely comparing the Ore Mountains with the Vosges Mountains, which are quite similar from the viewpoint of their morphology but are very different from the viewpoint of their hydrometeorology (Minářová et al., 2018).

References:

Müller, M., Kašpar, M., Valeriánová, A., Crhová, L., Holtanová, E., Gvoždíková, B., 2015: Novel indices for the comparison of precipitation extremes and floods: an example from the Czech territory. Hydrol. Earth Syst. Sci., 19, 4641–4652.
Gvoždíková, B., Müller, M., 2017: Evaluation of extensive floods in western/central Europe. Hydrol. Earth Syst. Sci., 21, 3715–3725.
Gvoždíková, B., Müller, M., Kašpar, M., 2019: Spatial patterns and time distribution of central European extreme precipitation events between 1961 and 2013. Int. J. Climatol., 39, 3282–3297.
Minářová, J., Clappier, A., Müller, M., Kašpar, M., 2017: Characteristics of Extreme Precipitation in the Vosges Mountains region (North-Eastern France). Int. J. Climatol., 37, 4529–4542.
Minářová, J., Müller, M., Clappier, A., Kašpar, M., 2018: Comparison of extreme precipitation characteristics between the Ore Mountains and the Vosges Mountains (Europe). Theor. Appl. Climatol., 133, 1249–1268.

Evaluation of heat waves and windstorms in Czechia and their relations

Types of weather extremes are usually studied individually. Therefore, we decided to apply methods analogous to the methods of evaluation of hydrometeorological extremes to evaluate high temperature episodes and windstorms in Czechia, both regarding and regardless their seasonality. This enabled us to analyse relations between the two hazards (heat waves and windstorms) whose rarity, spatial extent, and duration were considered altogether. Synoptic conditions producing the two hazards were analysed using a progressive method of circulation anomalies that quantifies the rarity of current thermodynamic conditions. High temperature episodes were most frequently associated with westerly flows at the 700 hPa level, while the most extreme events occurred during eastern flow with a high pressure area at the northeast of Czechia (Valeriánová et al., 2017). Regarding windstorms, events from late October to early March associated with high pressure gradients were generally more extreme than those from mid-May to mid-September associated with convective storms and with weak flow in the lower troposphere (Kašpar et al., 2017). Thus, the horizontal temperature gradient seems to be a more typical feature for windstorms than the pressure gradient. In high summer, the windstorms usually occurred after extra high temperature episodes. The link between windstorms and high-temperature episodes occurred in the cold part of the year as well, although to a lesser extent.

References:

Kašpar, M., Müller, M., Crhová, L., Holtanová, E., Polášek, J. F., Pop, L., Valeriánová, A., 2017: Relationship between Czech windstorms and air temperature. Int. J. Climatol., 37, 11–24.
Valeriánová, A., Crhová, L., Holtanová, E., Kašpar, M., Müller, M., Pecho, J., 2017: High temperature extremes in the Czech Republic 1961–2010 and their synoptic variants. Theor. Appl. Climatol., 127, 17–29.

Improvements of precipitation intensity estimates from weather radar data and numerical model outputs

Accurate information on precipitation intensities is necessary for meteorological interpretation of individual disasters (flash floods, landslides) but also for the estimation of intense rain probability. Standard estimates of precipitation intensity deal with data from hyetographs and automatic rain gauges which have been rather sparse. Therefore, we employed data from weather radars and numerical weather prediction (NWP) models and combined them with rain-gauge data to improve the estimates. Using ten years of radar precipitation intensity estimates which we derived and adjusted by daily precipitation totals from rain gauges, we analysed mean and maxima precipitation distribution in space and time for various lengths of sub-daily precipitation accumulations (Bližňák et al., 2018). While the highest 24-hour totals usually occurred in mountain regions, maxima of short-term precipitation totals were observed at altitudes of 300-600 m above sea level. Regarding NWP model outputs, we have proposed a method that allows us to reconstruct historical extreme precipitation events more precisely both in space and time by disaggregating daily precipitation measurements using the quantitative precipitation re-forecasts (Bližňák et al., 2019).

References:
Bližňák, V., Kašpar, M., Müller, M., 2018: Radar-based summer precipitation climatology of the Czech Republic. Int. J. Climatol., 38, 677–691.
Bližňák, V., Kašpar, M., Müller, M., Zacharov, P., 2019: Sub-daily temporal reconstruction of extreme precipitation events using NWP model simulations. Atmos. Res., 224, 65–80.

Methods developed for road weather forecast
We continued to develop the model that forecasts road surface conditions for a lead time up to 24 h with a special attention paid to the first 6 hours. The model boundary conditions (temperature, humidity, wind speed, pressure, cloud cover, and radiation flux) are given by forecasts of the NWP model Aladin (operated by the CHMI) and observed temperatures (air, surface and underground temperatures at various levels). During 2015-2019, we made technical improvements related to, e.g., flexible data entry. We significantly improved forecasting by applying ensemble prediction. We were the first who developed a method of generating an ensemble that is based on properties of the model instead of NWP model outputs. The results clearly showed (Sokol et al., 2017) that our proposed ensemble approach gives better prediction because it better considers the errors of the road model than when the ensemble is generated from NWP outputs, as usually.
Further, we prepared and tested various models of implementation of radiation fluxes into the model as it is the radiation fluxes that fundamentally affect the heating / cooling of the road surface. We found out that the most suitable model for the shortwave fluxes is the one that is adjusted to the data from our National Radiation Network, which has significantly refined the temperature forecast at some stations. On the contrary, the sky-view factor did not have the effect we expected on the forecast.
Moreover, we started looking for a suitable way how to use satellite data from MSG to predict radiation fluxes in order to obtain a forecast for 2 to 6 hours. For that, we applied an extrapolation technique which uses time sequences of satellite data (IR10.8) to find the motion field and SAF outputs to estimate cloud cover. The preliminary results seem promising.

References:
Sokol, Z., Bližňák, V., Sedlák, P., Zacharov, P., Pešice, P., Škuthan, M., 2017: Atmos. Res. 187, 33-41.

Investigation of the potential of artificial intelligence in postprocessing of NWP outputs
Recently, artificial intelligence (AI) has started to appear again in meteorological applications; in nowcasting and postprocessing of NWP forecasts. Therefore, we experimentally tried, in cooperation with experts in AI, to test the possibilities of using AI in postprocessing of the prediction of relative humidity using the NWP model (Zjavka and Sokol, 2018). The results showed that it is possible to use AI and that AI provides outputs at least comparable to those given by standard statistical models. This is an important information for us since we had been using AI in postprocessing of meteorological outputs 20 years ago but were unsatisfied with the results. AI techniques has developed since that time and it seems that new AI techniques are more suitable for meteorological applications.

References:
Zjavka, L., Sokol, Z., 2018: Local Improvements in Numerical Forecasts of Relative Humidity Using Polynomial Solutions of General Differential Equations. QJRMS, 144, part A, 780-791.

New methods for constructing maps of wind resources and extreme winds
We have proposed an original method for constructing a high-resolution wind map and published it in Hanslian and Hošek (2015). The proposed method performs a realistic analysis of favorable conditions for wind energy utilization over the Czech Republic. Further, we prepared a clear and understandable overview of various existing methods creating wind maps (Hanslian and Hošek, 2015) since this have been missing before, with an intention to clarify the applicability of the methods including the one we proposed.
Moreover, we also designed another method, which was published by Pop et al. (2016). This method enables to construct maps of extreme wind gust velocity by using observed wind data together with maps of general wind climate (GWC). An example of the application of the method was presented in the study on the area of the Czech Republic. Although the method stems from a technique described and recommended by International Electrotechnical Commission, it uses much more sophisticated relations between the wind gust speeds and the GWC leading to significantly more accurate estimates, verified on observed data.

References:
Hanslian, D., Hošek, J., 2015: Combining the VAS 3D interpolation method and Wind Atlas methodology to produce a high-resolution wind resource map for the Czech Republic. Renewable Energy, 77, 291-299.
Pop, L., Sokol Z., Hanslian, D., 2016: A new method for estimating maximum wind gust speed with a given return period and a high areal resolution. Journal of Wind Engineering and Industrial Aerodynamics, 158, 51-60.

Investigation of the atmospheric attenuation of electromagnetic signal on two different distances
Our study by Dev et al. (2017) enabled to discover conditions for various type of relief that cause signal attenuation of Free Space Optics (FSO), Among such conditions, we

found moderate radiation fogs and rain in the city of Milan situated in lowlands, Italy, and inhomogeneous distribution of fog at the Milešovka Mountain situated in the Czech Republic. In addition, a comparison of the optical attenuation measured by a laser link with that estimated by a visibility sensor using a propagation model showed that the model can help in designing the FSO links. We contributed by 50 % to the comparative study.
In another paper (Ventouras et al., 2019), we contributed to a lesser extent (12 %). However, even this lower contribution resulted in our participation in the interpretation of the outputs of a large-scale European coordinated campaign funded and held by European Space Agency. Among the most valuable outcomes that we participated in actively, we can cite the experimental characterization of the spatial and temporal properties of the earth-space radio channels at Ka- and Q-band for future modelling activities over Europe, and the collection of atmospheric propagation data for development and testing of fading mitigation techniques.

References:
Dev, K., Nebuloni, R., Capsoni, C., Fišer, O., Brázda, V., 2017: Estimation of optical attenuation in reduced visibility conditions in different environments across free space optics link. IET Microwaves Antennas and Propagation, 11, 1708-1713.
Ventouras, S., Martellucci, A., Reeves, R., Rumi, E., Fontan, F.P., Machado, F., Pastoriza, V., Rocha, A., Mota, S., Jorge, F., Panagopoulos, A.D., Papafragkakis, A.Z., Kourogiorgas, C.I. ,Fišer, O., Pek, V., Pešice, P., Grabner, M., Vilhar, A.., Kelmendi, A., Hrovat, A., Vanhoenacker-Janvier, D., Quibus, L., Goussetis, G., Costouri, A., Nessel, J., 2019: Assessment of spatial and temporal properties of Ka/Q band earth-space radio channel across Europe using Alphasat Aldo Paraboni payload. International Journal of Satellite Communications and Networking, 37, 477-501.

## Applied research

Basic research carried out in DM usually solves problems which often have a specific practical application. If we find that there is an interest in the application of our results, we continue to develop techniques to make our results obtained in the basic research usable in practice. This is usually not straightforward. It takes time to go from our published knowledge obtained in the basic research (e.g. a developed model or a developed methodology) to real application, yet the application leads to enriching the theoretical knowledge as well. This additional knowledge is very important from the point of view of its practicability, though is usually not sufficient to be accepted for publication. Therefore, the references mentioned in this section can be similar to those given above.

### Applications of the road weather forecast model

The DM acts as one of the application laboratories of the Czech Academy of Sciences. We develop forecasting methods of the road surface temperature and road atmospheric conditions, in a close collaboration with the national weather service CHMI. Since the CHMI is the road weather forecast provider, our road weather activity has started with the application target directly. In the evaluated period 2015-2019, we focused on line forecasts for roads in the city of Prague (project ICEWARN supported by the Operational Programme Prague – Growth Pole of the Czech Republic; the sustainability phase of ICEWARN starting in 2019). Further, we continued in the operational phase of our previous project focused on the point forecast for Czech highways and supported by the Czech Technology Agency. Integral part of all these road weather application projects is that the road weather prognostic lines developed by DM have been implemented into continuous operation of CHMI during winter periods. The CHMI then distributes the resulting forecast outputs to users, namely the Road and Motorway Directorate of the Czech Republic and the Technical Administration of Roadways of the Capital City Prague, based on bilateral contracts.

Interactive wind maps and wind energy assessment

We created two interactive wind maps for the territory of the Czech Republic and made it permanently available to public on the IAP web page (http://vitr.ufa.cas.cz).

First map “Extreme gusts at 10 m height” is based on the method published by Pop et al. (2016) and its details can be found above in the subsection Basic research. Second map “Wind conditions and wind power production at 10 m height” is suitable for users of small wind turbines at home. We created this map in response to the public demand for such an information.

In the wind energy assessment, we concentrated our activities on performing requested studies and expert services on the demand of private companies.

Applications of the cooling tower plume model

We developed a mathematical model for the propagation of plumes from cooling towers. It is a 1D model, which separately models rising of the plume taking into account mixing of the plume with the surrounding air, microphysics of the warm cloud, information about environment, and propagation of the plume in the open atmosphere. The model enables calculations with a resolution of 10 m and an integration step of 1 s. We gradually extended this 1D model by the possibility of calculating not only plumes with natural traction, but also plumes mechanically forced. Furthermore, we developed the model to make it calculate the advection and the fall of droplets emitted by cooling towers. Currently, the model contains a superstructure which calculates statistical characteristics of plumes and their effect on surrounding microclimate, such as average or maximum increase in temperature and humidity at a given location around the cooling tower, shading size (number of hours per given period), and amount of water droplets emitted by cooling towers. This model is unique in the Czech Republic and Slovakia, therefore several studies have been done on the basis of a contract for clients of both countries.

Examples of research reports:

Study of the impact of the modernization of Jaslovske Bohunice nuclear power station on environment. For Amec, s.r.o., Brno (2015).

A study on the influence of Dukovany power station on microclimate for the EIA documentation. For ČEZ, a.s., Praha (2016).

The spread of moisture from sources of Mondi SCP, Inc. and its influence on the formation of rime and temperature inversion. For Mondi SCP, a.s., Ružomberok, Slovakia (2015).

The spread of moisture from sources of Mondi SCP and their impact on the microclimate after the project ECO PLUS - Installation of a new paper machine PM19. For EKOS PLUS, s.r.o., Bratislava, Slovakia (2017).

NJZ EDU - droplet drift distribution from the cooling towers and evaluation of the influence of cooling towers on local ice formation. For ČEZ, a.s., Praha (2017).

Identification of six types of the rainfall course for water management purposes

When designing small water management structures in the landscape, it is necessary to take into account the so-called design precipitation, not only their magnitude, but also their course. The standard solution uses a single synthetic hyetogram, which obviously does not represent the variability of the actual course of heavy precipitation. Thus, we solved this problem by designing general hyetograms, which were derived from heavy precipitation events in the Czech Republic (Müller et al., 2018). For these purposes, we proposed an original methodology, based on three “half-time concentration” indices, which express normalized proportion of precipitation totals fell during various lengths of time nested in a six-hour time window. The method distinguishes variants that differ one from another regarding the rainfall concentration in time with two of them having; two significant precipitation maxima during the six-hour time window. This approach makes it possible to refine the modeling of design runoff and thus to more accurately design water management structures in the landscape (Kavka, Müller et al., 2018).

References:

Müller, M., Bližňák, V., Kašpar, M., 2018: Analysis of rainfall time structures on a scale of hours. Atmos. Res., 211, 38–51.

Kavka, P., Müller, M., Strouhal, L., Kašpar, M., Bližňák, V., Landa, M., Weyskrabová, L., Pavel, M., Dostál, T., 2018: Short-term rainfall for hydrological modeling and design of small water management structures in the landscape. Certified methodology. Czech Technical University in Prague, Institute of Atmospheric Physics AS CR, Sweco Hydroprojekt, Praha, 80 pp.

New equipment at observatories, their operation and related research

Observatory Milešovka

The observatory is located at the top of the Milešovka mountain (837 m a.s.l.) in the České středohoří Uplands. It is the oldest meteorological mountain station in the Czech Republic, with the measurements being performed continuously since 1905. Due to its unique position with almost a 360° unobstructed view and long series of observations, the station was included in the international network of GCOS (Global Climate Observing System) as the first station in the Czech Republic. The station is operated by five observers who ensure continuous operation in pairs, alternating in weekly turns. The standard meteorological data (SYNOP) are transmitted via our national weather service CHMI to the world meteorological network and all the data are available at request.

The observatory was recently equipped by several remote sensing devices, particularly by a Ka-band vertically pointing cloud profiler MIRA35c (METEK) in 2018, a Doppler dual polarimetric X-band weather radar WR2120 (Furuno) in late 2020, and a ceilometer CL51 (Vaisälä). A new disdrometer (Laser Precipitation Monitor, Thies) and the currently re-deployed Particulate Volume Monitor PVM-100 (Gerber Scientific) also belong to the in-situ measuring devices.

It has to be mentioned that as part of a research institution, we enable external users to perform experimental campaigns at the Milešovka observatory. For instance, the Institute of Chemical Process Fundamentals of the CAS has been investigating the atmospheric aerosol in low clouds at the Milešovka observatory starting from 2018. The results of such campaigns are published in international journals with our contribution (Zíková et al., 2020).

Further, we have been invited to join the pan-European research infrastructure ACTRIS by the representatives of a newly forming task (Cloud In-Situ, CIS) within the ACTRIS. Currently, we take first steps to join this international community with the purpose of making the Milešovka observatory a CIS observational platform. Our vision is to make Milešovka a multidisciplinary observatory significantly involved in international research.

References:
Zíková, N., Pokorná, P., Makeš, O., Sedlák, P., Pešice, P., Ždímal, V., 2020: Activation of atmospheric aerosol in fog and low clouds. Atmos.Environ., 230, https://doi.org/10.1016/j.atmosenv.2020.117490

Observatory Kopisty
The observatory Kopisty is located in the industrially exposed area near the town Most. Its meteorological measurements started in 1969. The observatory is equipped with an 80-meter high mast where temperature, humidity and air flow characteristics (currently by 3D ultrasonic anemometers) are measured at four levels. The station is operated by three observers with weekly turns. The standard meteorological data are transmitted to the national weather service CHMI and all the data are available at request. Recently, the Institute of Thermomechanics of the CAS asked us for the mast data because of its utilization in the COST Action 18235 - PROfiling the atmospheric Boundary layer at European scale (PROBE). We were also asked for and provided the data to the Institute of Theoretical and Applied Mechanics of the CAS for the purpose of computing the effects of atmospheric turbulence on structures. In both cases, DM will participate in the interpretation of the results.

## Research activity and characterisation of the main scientific results

Research activity of the Team of Space Weather and Planetary Environment during 2015-2019 concentrated on all main directions in the focus of the team. Yearly lists of results with illustrations and references for a major part of the team are shown on https://okf.ufa.cas.cz/en/

### 1a. Lightning initiation

In connection with our participation on the spacecraft project TARANIS we investigated ground/based observations of electromagnetic signals emitted by lightning processes. There is a lack of understanding of how a lightning flash initiates, as this process usually takes place deep inside thunderclouds. Electromagnetic pulses emitted during lightning initiation can be measured from a safe distance. We analyzed broadband electromagnetic measurements of pulse sequences occurring prior to first return strokes of negative cloud-to-ground lightning flashes. Preliminary breakdown pulses and the corresponding return stroke pulses were attenuated approximately by 2 dB/100km when propagating in the Earth-ionosphere waveguide. Simulations showed that there is a significant contribution of the sky waves in the waveforms observed beyond 500 km from their source. [Kolmašová et al., 2016]. We demonstrated that the electric field amplitudes of preliminary breakdown pulses were approximately proportional to their peak currents which can reach 200 kA, and can be comparable or higher than the corresponding return stroke peak currents. Bipolar overshoot depends primarily on the characteristic time of the line conductivity increase. The magnitude of the charge centers was demonstrated to be very large in order to model the observed amplitudes up to 32 V/m at 100 km. Such energetic current pulses might be capable to produce elves or terrestrial gamma-ray flashes [Kaspar et al. 2017]. We showed that the expression for the radiation part of the magnetic field decomposed into two time-shifted terms with opposite polarities. The model explained observations of the bipolar preliminary breakdown pulses at time scales of tens of microseconds but also both unipolar and bipolar dart-stepped leader pulses at submicrosecond time scales [Kašpar et al., 2015]. We compared broadband magnetic field waveforms of preliminary breakdown pulses with sources of narrow-band very high frequency (VHF) radiation at 60–66 MHz recorded by two separate Lightning Mapping Arrays (LMAs). We found that almost none of the observed pulses corresponded to geo-located VHF radiation sources, in agreement with previous results and with the hypothesis that processes generating VHF radiation and pulses are only weakly related. However, our detailed analysis discovered that individual peaks of strong VHF radiation seen by separate LMA stations corresponded surprisingly well to the pulses. This result showed that electromagnetic radiation generated during fast stepwise extension of developing lightning channels was spread over a large interval of frequencies. [Kolmašová et al., 2018]. We have used arrays of low-frequency (~0–2.5 MHz) and very high frequency (186–192 MHz) receivers and compared their data during initiation of 20 cloud-to-ground lightning flashes. We have found that the larger pulses detected during lightning initiation in low-frequency records were accompanied by pulses in the very high frequency records. This confirms that the initial lightning extension process occurs very fast and at multiple length scales [Kolmašová et al., 2019].

## 1b. Effects of electromagnetic radiation from lightning return strokes

We detected for the first time unusual daytime atmospherics with dispersion signatures originating from strong thunderstorms which occurred during winter months 2015 in the North Atlantic region. Using newly developed analysis techniques for 3-component electromagnetic measurements, we were able to determine the source azimuth and to attribute these rare atmospherics to both positive and negative lightning strokes in northern Europe. We consistently found unusually large heights of the reflective ionospheric layer which were probably linked to low fluxes of solar X rays and which made the dayside subionospheric propagation possible. Although the atmospherics were linearly polarized, their dispersed parts exhibited left handed polarization, consistent with the anticipated continuous escape of the right-hand polarized power to the outer space in the form of whistlers [Santolík and Kolmašová, 2017]. We have analyzed contribution of thunderstorms to the intensity of electromagnetic radiation at audible frequencies observed at altitudes between 600 and 32,000 km, where these waves can influence the Van Allen radiation belts. We have used the World Wide Lightning Location Network to obtain information about lightning locations and times. Based on that, a lightning activity level has been assigned to individual electromagnetic wave measurements of two spacecraft missions: DEMETER and Van Allen Probes. Subsequently, we compare median wave intensities obtained at the times of high and low lightning activity. Their ratio reveals that the radio waves originating in strong lightning storms can significantly overpower all other natural waves in a wide range of frequencies and L-shells. The strength of this effect substantially depends on the local time. Specifically, it is the best pronounced in the afternoon/evening/night sector and nearly absent in the morning/noon sector. This agrees with the local time dependence of both, lightning occurrence and the wave attenuation in the ionosphere. The observed lightning contribution mainly occurs at frequencies over 500 Hz and with a bandwidth decreasing from 12 to 4 kHz for L between 1.5 and 5 [Záhlava et al. 2019]. We also analyzed optical recordings of transient luminous events (obtained by our observer in station Nydek) for a study of an influence of thunderstorm activity on the ionospheric sporadic E-layer and for an analysis of orbital fragmentation of a larger meteorite from Perseid cluster [Barta et al. 2017].

## 1c. Whistler mode chorus: space weather effects in the Earth’s radiation belts

Electromagnetic emissions propagating in the whistler mode have substantial impact on the dynamics of the Earth's radiation belts through the wave-particle interactions. These space weather effects are especially linked to an important class of the whistler mode waves, chorus, which is characterized by discrete elements in the time-frequency spectrum. It is known to be generated by nonlinear wave-electron interactions in the vicinity of the geomagnetic equator, as was shown by numerous theoretical studies, simulations, and satellite observations. We investigated chorus in terms of spectral and polarization characteristics, with special emphasis on wave normal angles which are important for wave-particle interactions. The THEMIS-D spacecraft crossed an active equatorial source region of whistler mode chorus rising tones on 23 October 2008. The wave normal angles of chorus rising tones exhibited large variations from quasi-parallel to oblique, even within single bursts, but followed a definite pattern. At chorus frequencies close to the gap around one half of the local electron cyclotron frequency we found significantly lowered wave planarities and a tendency of wave normal angles to approach the Gendrin angle [Taubenschuss et al., 2015, Macúšová et al., 2015]. We also presented new results on wave vectors and Poynting vectors of chorus rising and falling tones on the basis of 6 years of THEMIS spacecraft observations. The majority of wave vectors was closely aligned with the direction of the ambient magnetic field. We showed, for the first time, that slightly oblique Poynting vectors were directed away from Earth for rising tones and toward Earth for falling tones. The latitudinal extension of the equatorial source region was limited to ±6° around the magnetic field minimum along magnetic field lines. We found increasing Poynting flux and focusing of Poynting vectors with increasing latitude. Also, wave vectors became most often more field aligned. A smaller group of chorus generated with very oblique wave normals tended to stay close to the whistler mode resonance cone [Taubenschuss et al., 2016; Santolík, 2016]. Data of the THEMIS spacecraft showed two groups of simultaneously visible chorus elements, which are approaching the spacecraft from two different directions: either along or against the direction of the ambient magnetic field. Furthermore, both groups are slightly shifted in frequency with respect to each other and elements are of different intensities. We interpreted these features in the frame of the backward-wave oscillator theory, yielding insight into the nonlinear generation mechanism and the specific source-observer geometry during the observations [Taubenschuss et al., 2017]. We examined the singular value decomposition technique, revisited the interpretation of singular values, and showed to what extent the singular values were able to contribute to a separation between polarized signal and noise. We verified our theoretical findings with synthetic data as well as with whistler-mode chorus wave observations from the THEMIS spacecraft [Taubenschuss and Santolík, 2019]. Previously published statistics based on Cluster spacecraft measurements surprisingly showed that in the outer radiation belt, lower band whistler mode waves predominantly propagate unattenuated parallel to the magnetic field lines up to midlatitudes, where ray tracing simulations indicated highly attenuated waves with oblique wave vectors. We explained this behavior by considering a large fraction of ducted waves. We argue that these ducts can be weak and thin enough to be difficult to detect by spacecraft instrumentation while being strong enough to guide whistler mode waves in a cold plasma ray tracing simulation. After adding a tenuous hot electron population, we have obtained a strong effect of Landau damping on unducted waves, while the ducted waves experience less damping or even growth. Consequently, the weighted average of amplitudes and wave normal angles of a mixture of ducted and unducted waves has provided us with strong quasi-parallel waves, consistent with the observations [Hanzelka and Santolik, 2019].

### 1d. Equatorial noise

Equatorial noise (often phenomenologically described as magnetosonic waves in the literature) is a natural electromagnetic emission, which is generated by instability of ion distributions and which can interact with electrons in the Van Allen radiation belts. These emissions occur in the vicinity of the geomagnetic equator at frequencies between the local proton cyclotron frequency and the lower hybrid frequency. We reported results of a systematic analysis based on the data collected by the STAFF-SA instruments on board the four Cluster spacecraft. The analyzed data set covered the period from January 2001 to December 2010. We developed selection criteria for the visual identification of these emissions, and compiled a list of more than 2000 events. The evolution of the Cluster orbit enabled us to investigate a large range of McIlwain's parameter from about L∼1.1 to L∼10. We demonstrated that EN can occur at almost all analyzed L shells. However, the occurrence rate was very low (<6%) at L shells below L=2.5 and above L=8.5. EN mostly occurred between L=3 and L=5.5, and within 7° of the geomagnetic equator, reaching 40% occurrence rate. This rate further increased to more than 60% under geomagnetically disturbed conditions. Analysis of occurrence rates as a function of magnetic local time (MLT) showed strong variations outside of the plasmasphere (with a peak around 15 MLT), while the occurrence rate inside the plasmasphere was almost independent on MLT. This is consistent with the hypothesis that EN is generated in the afternoon sector of the plasmapause region and propagates both inward and outward [Hrbáčková et al., 2015]. We used multicomponent electromagnetic measurements of the DEMETER spacecraft to investigate if equatorial noise propagates inward down to the Earth. Analysis of a selected event recorded under disturbed geomagnetic conditions showed that equatorial noise can be observed at an altitude of 700 km, while propagating radially downward as a superposition of spectral lines from different distant sources observed at frequencies both below and above the local proton cyclotron frequency. Changes in the local ion composition encountered by the waves during their inward propagation disconnect the identified wave mode from the low-frequency magnetosonic mode. The local ion composition also induces a cutoff which prevents the waves from propagating down to the ground [Santolík et al., 2016].

**1e. Effects of electromagnetic ion cyclotron waves in the Earth's radiation belts**

Electromagnetic ion cyclotron (EMIC) influence the Earth's radiation belts by wave-driven electron precipitation. We presented an analysis of EMIC waves observed by the low-altitude satellite DEMETER during the magnetic storm of November 2004. This is the first time that they were observed for such extensive time periods and at such high frequencies. The analysis of wave propagation pointed to the possible source region placed in the inner magnetosphere (L~2–3). Observed wave frequencies indicated that waves were generated much farther from the Earth compared to the satellite orbit. Exceptionally high frequencies of about 10 Hz were explained by the source region placed in the deep inner magnetosphere at L ~2.5. We hypothesized that these waves were generated below the local helium gyrofrequency and propagated over a large range of wave normal angles to reach low altitudes at L~1.11 [Píša et al., 2015]. On 19 March 2001, the Cluster fleet recorded an electromagnetic rising tone on the nightside of the plasmasphere. The emission was found to propagate toward the Earth and toward the magnetic equator at a group velocity of about 200 km/s. The Poynting vector was mainly oblique to the background magnetic field and directed toward the Earth. The propagation angle became more oblique with increasing magnetic latitude. Comparing our results to previous ray tracing analysis we concluded that this emission was a triggered EMIC wave generated at the nightside plasmapause. This process can contribute to the formation of pearl pulsations [Grison et al. 2016]. Based on a database of 935 Cluster plumes crossings, reduced to 189 unique plumes, we found that broadband activity was the most common case. We confirmed result from a previous study showing that plume vicinity is not a preferred place for observing narrowband emissions. EMIC rising tones were seen in six of 30 plume events (20%) when narrowband emissions were observed. Rising tones were observed at absolute magnetic latitudes larger than 17° and up to 35°. Results of a ray tracing analysis agreed with a tone triggering process taking place above 15° of magnetic latitude [Grison et al. 2018]. In recent years, experimental results have consistently shown evidence of EMIC wave-driven electron precipitation down to energies as low as hundreds of keV. However, this is at odds with the limits expected from quasi-linear theory. Recent analysis using nonlinear theory has suggested energy limits as low as hundreds of keV, consistent with the experimental results, although to date this has not been experimentally verified. In this study, we have presented concurrent observations from POES, Van Allen Probes, GPS, and ground-based instruments, showing concurrent EMIC waves and sub–MeV electron precipitation, and a global dropout in electron flux. We have shown through test particle simulation that the observed waves are capable of scattering electrons as low as hundreds of keV into the loss cone through nonlinear trapping, consistent with the experimentally observed electron precipitation [Hendry et al., 2019].

### 1f. Quasiperiodic emissions

Quasiperiodic (QP) electromagnetic emissions are whistler mode waves at typical frequencies of a few kHz characterized by a peculiar periodic time modulation of their intensity, with modulation periods from a few seconds up to 10 min. We presented results of a detailed wave analysis of nearly 200 events measured by the low-altitude Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) spacecraft. Upper frequency range of studied emissions was limited to 1 kHz due to the sampling rate of the analyzed data. We found that QP emissions propagated nearly field aligned at larger geomagnetic latitudes; they became more oblique at midlatitudes and eventually perpendicular to the ambient magnetic field at the geomagnetic equator and thus perpendicular to the Earth's surface, allowing their downward propagation through the ionosphere. The observed propagation pattern was consistent with the source of emissions located in the equatorial region at larger radial distances [Hayosh et al., 2016]. The DEMETER spacecraft observed events where the QP emissions exhibited a sudden change in the wave vector and Poynting vector directions. The change happened in a short interval of latitudes. We explained this behavior by ionospheric reflection and present a ray-tracing simulation which matched resulting wave vector directions. We also attempted to locate the source region of these emissions and concluded that they are most probably generated at the inner boundary of the plasmapause which also acted as a guide during the propagation of the QP emissions [Hanzelka et al., 2017].

### 1g. Solar wind and magnetospheric boundaries

The Sun is continuously emitting a stream of charged particles—called the solar wind—from its upper atmosphere. The terrestrial magnetosphere forms the obstacle to its flow. Due to supersonic speed of the solar wind, the bow shock is created ahead of the magnetosphere. This abrupt transition region between supersonic and subsonic flows has been frequently observed by the four Cluster spacecraft. Magnetosheath crossings registered by Cluster spacecraft over the course of 2 years served as a basis for the statistics. A strong dependence of occurrence of mirror mode waves and Alfvèn ion cyclotron (AIC) waves on upstream parameters was identified. The occurrence of mirror and AIC modes was compared against the respective instability thresholds. We noted that AIC waves occurred nearly exclusively under mirror stable conditions. This was interpreted in terms of different characters of nonlinear saturation of the two modes [Souček et al., 2015]. Using a timing analysis, we have retrieved speed and directions of the bow shock motion for a large number of crossings. We have correlated the bow shock speed with the solar wind speed and predictions of the bow shock locations by the empirical model. A better understanding of the bow shock kinematics may bring new insights to wave-particle interactions with applications in laboratory plasmas [Kruparova et al. 2015, 2019]. Electrostatic plasma waves above and below the local electron plasma frequency represent a characteristic feature of the foreshock region. These waves are generated by electron beams originating from the bow shock and their spectrum varies from narrowband intense waves close to foreshock edge to weaker broadband emissions further downstream. We have presented a statistical analysis of electron beams observed in the terrestrial foreshock by the Cluster spacecraft. We established a clear correspondence between beam energy and spectrum of the waves. The broadband emissions are correlated with low-energy beams, while high-energy electron beams are associated with narrowband Langmuir waves. We discovered that while the observed electron distributions often exhibit a “bump on tail” feature necessary for an instability, the observed combination of beam energy, density, and temperature typically corresponds to a stable situation. This indicates that strongly unstable electron beams are quickly dissipated by the quasi-linear processes and only stable or marginally stable beams persist long enough to be observed by the instrument [Soucek et al. 2019].

**1h. Interplanetary solar radio emissions associated with coronal mass injections**

Coronal mass ejections (CMEs) are large-scale eruptions of magnetized plasma that are responsible for most severe space weather events, such as solar energetic particle events and geomagnetic storms at Earth. Type II radio bursts are slow drifting emissions produced by beams of suprathermal electrons accelerated at CME-driven shock waves propagating through the corona and interplanetary medium while the type III bursts are generated by fast electron beams originated from magnetic reconnection sites of solar flares. We reported a rare instance with comprehensive in situ and remote sensing observations of a CME combining white-light, radio, and plasma measurements from four different vantage points. For the first time, we have successfully applied a radio direction-finding technique to an interplanetary type II burst detected by two identical widely separated radio receivers. The derived locations of the type II and type III bursts were in general agreement with the white-light CME reconstruction. We found that the radio emission arose from the flanks of the CME and that it was most likely associated with the CME-driven shock. We demonstrated the complementarity between radio triangulation and 3D reconstruction techniques for space weather applications [Krupař et al. 2015, 2016]. We also performed a statistical survey of 152 simple and isolated type III bursts observed by the STEREO spacecraft. We investigated their time–frequency profiles in order to retrieve decay times as a function of frequency and we performed Monte Carlo simulations to study the role of scattering due to random electron density fluctuations on time–frequency profiles of radio emissions generated in the interplanetary medium. Our results suggest that relative electron density fluctuations in the solar wind are 0.06–0.07 over wide range of heliospheric distances [Krupař et al. 2018]. We also reported a statistical study of 153 interplanetary type II radio bursts observed by the two STEREO spacecraft between 2008 March and 2014 August. The shock associated radio emission was compared with CME parameters included in the Heliospheric Cataloguing, Analysis and Techniques Service catalog. We found that faster CMEs are statistically more likely to be associated with the interplanetary type II radio bursts. We have correlated frequency drifts of interplanetary type II bursts with white-light observations to localize radio sources with respect to CMEs. Our results suggest that interplanetary type II bursts are more likely to have a source region situated closer to CME flanks than CME leading edge regions [Krupař et al. 2019].

## 1i. Electromagnetic waves originating from lightning at Jupiter

Electrical currents in atmospheric lightning strokes generate impulsive radio waves in a broad range of frequencies, called atmospherics. These waves can be modified by their passage through the plasma environment of a planet into the form of dispersed whistlers. In the Io plasma torus around Jupiter, Voyager 1 detected whistlers as several-seconds-long slowly falling tones at audible frequencies. These measurements were the first evidence of lightning at Jupiter. Subsequently, Jovian lightning was observed by optical cameras on board several spacecraft in the form of localized flashes of light. We analyzed measurements by the Waves instrument on board the Juno spacecraft that indicate observations of Jovian rapid whistlers: a form of dispersed atmospherics at extremely short timescales of several milliseconds to several tens of milliseconds. On the basis of these measurements, we reported over 1,600 lightning detections, the largest set obtained to date. The data were acquired during close approaches to Jupiter between August 2016 and September 2017, at radial distances below 5 Jovian radii. We detected up to four lightning strokes per second, similar to rates in thunderstorms on Earth and six times the peak rates from the Voyager 1 observations [Kolmašová et al., 2018; Brown et al. 2018]. Intense electromagnetic impulses induced by Jupiter's lightning have been recognized to produce both low-frequency dispersed whistler emissions and non-dispersed radio pulses. We have collaborated on a discovery of electromagnetic pulses associated with Jovian lightning. Detected by the Juno Waves instrument during its polar perijove passes, the dispersed millisecond pulses called Jupiter dispersed pulses (JDPs) provide evidence of low density holes in Jupiter's ionosphere. 445 of these JDP emissions have been observed in snapshots of electric field waveforms. Assuming that the maximum delay occurs in the vicinity of the free space ordinary mode cutoff frequency, we have estimated the characteristic plasma densities and lengths of plasma irregularities along the line of propagation from lightning to Juno. These irregularities show a direct link to low plasma density holes with less than 250 particles in one cubic centimeter in the nightside ionosphere [Imai et al., 2019].

## 1j. Electromagnetic waves at Saturn

We presented the first systematic study of Langmuir wave amplitudes in Saturn's foreshock. We analyzed all foreshock crossings by Cassini from June 2004 to December 2009 using an automatic method to identify Langmuir waves. Using this method, almost $3 \times 10^5$ waveform intervals of typical duration of about a minute were selected. We determined the wave amplitudes for all waveform intervals, and we found that the probability density function amplitudes follow a lognormal distribution with a power law tail. A nonlinear fit for this tail gave us a power law exponent of $-1.37 \pm 0.01$. The distribution of amplitudes as a function of the depth in the foreshock showed the onset of the waves near the upstream boundary with its maximum slightly shifted inside the foreshock ($\sim$1 $R_S$). The amplitudes then fell off with increasing depth in the downstream region. The estimated energy density ratio for largest amplitudes did not exceed $10^{-2}$, suggesting that modulational instability was not relevant for a large majority of waves. The decay instability can be important for the stronger electrostatic waves in Saturn's foreshock, as was previously reported for multiple solar system planets [Píša et al., 2015]. We presented the spatial distribution and spectral properties of Langmuir waves observed upstream of Saturn's bow shock by the Cassini spacecraft. The entire 10 kHz wideband data set obtained between June 2004 and December 2014 was analyzed using an automated procedure. Almost 106 waveform snapshots with intense narrowband emissions in the frequency range of 1–10 kHz were detected. The plasma wave occurrence increased steeply behind the tangent magnetic field line, i.e., the sunward foreshock boundary, and rose with increasing distance from the tangential line into the downstream region. We confirmed that the most intense waves occurred close to the tangent point and that their intensity decreased both deeper in the foreshock and along the tangential line [Píša et al., 2016]. We also presented first observations of intense "lion roars" emissions in Saturn's magnetosheath by the Cassini spacecraft in the dawn sector (magnetic local time ~06:45) over a time period of 11 h before the spacecraft crossed the bow shock and entered the unshocked solar wind. The waves were narrow-banded with a peak frequency of about 0.16 electron gyrofrequency, right hand circularly polarized in the spacecraft frame and propagating at small wave normal angles (<10°) with respect to the ambient magnetic field. We showed the first evidence that such emissions exist outside the terrestrial environment, with 1 order of magnitude difference in frequencies. Our result provided new insights into a parameter regime characterized by a higher plasma beta [Píša et al., 2018].

## 2. Numerical simulations

In the field of numerical simulations, the work of the team is mainly focused (i) on the large scale interactions of the solar wind and magnetospheric plasmas with magnetized and unmagnetised bodies, i.e., planets and moons, and (ii) local kinetic processes in various heliospheric plasma environments. The work is based on numerical models using either full particle-in-cell or hybrid code techniques which are capable to implement the kinetic aspects of the individual plasma species on the electron and ion scales respectively. Investigation methods further employ data comparison and cross analysis with respect to real space in situ observations. For the need of high demanding computational resources the team maintains a high performance computational facility Amálka (parallel cluster based on OS Linux currently with 1024 CPU cores). Using numerical simulations we have continued in the reported period with investigations of the global structure of the Mercury's magnetosphere with applications to NASA Messenger mission and also studied the magnetospheric plasma environment of Jovian moons (with focus on Io, and preparatory model for Europa and Ganymede) in preparation for the future ESA JUICE mission. The local kinetic process were investigated in relation to the study of the turbulent solar wind expansion where analysed namely the possible effects and roles of and evolution of kinetic plasma instabilities.

The use of a sophisticated model of Hermean magnetosphere based on global three-dimensional hybrid code, first described in [Trávníček et al. 2010] and later adopted as a key tool for the analysis and interpretation of MESSENGER observations [Slavin et al. 2010; Shriver et al. 2011], was extended to a detailed description of properties of Hermean plasma belt. The nature of the Hermean plasma belt was examined using a global numerical model under different orientations of the interplanetary magnetic field. The plasma belt region was found to be constantly supplied from solar wind via magnetospheric flanks and tail current sheet regions. Protons in the plasma belt are quasi-trapped in the planetary magnetic field and drift westward along the planet. The simulation results well correspond with real observations of MESSENGER spacecraft [Herčík et al., 2016]. In line with our research plan this model was consequently successfully modified to study the dynamic interaction at Io with the multi-species plasma in the magnetosphere of Jupiter. Using full 3-dimensional global hybrid simulations, we have analyzed the interaction of Io with Jovian magnetospheric plasma under different conditions of plasma sources and compositions. Our results indicate that increased ionization on the downstream side of Io plays an important role in forming the global interaction. The results further strongly support existence of dipole field induced in Io's interior, probably in its highly conductive core [Šebek et al., 2019]. We have also examined the possible effects of ion cyclotron instability at Io. The work deals mainly with analysis of ion cyclotron waves observed in local plasma. Obtained results suggest that the growth of ion cyclotron waves is governed by rate of charge exchanges between plasma ions and atmospheric neutrals. Comparison between simulated results and in situ measurements from NASA Galileo mission indicates asymmetries in spatial distribution of Io's neutral atmosphere [Šebek et al., 2016].

For the study of local ion kinetic processes in the expanding solar wind we have used previously implemented two-dimensional model of expanding box based on the hybrid approach. We have further extended our analysis of the role and behaviour of the kinetic plasma instabilities due to perpendicular/parallel temperature anisotropies. We found the parallel fire hose instability to be generally unable to counteract the anisotropization and the system becomes unstable to the oblique fire hose later on. This instability reduces the anisotropy and the system rapidly stabilizes while the generated electromagnetic fluctuations are damped to protons [Hellinger 2017a]. Consequently, we examined possible coexistence of magnetic structures generated by mirror instability in the turbulent solar wind. We imposed an initial spectrum of Alfvénic fluctuations which rapidly developed a turbulent cascade while the expansion leads to generation of a perpendicular temperature anisotropy that drives the mirror instability. This instability generates large-amplitude non-propagating magnetic structures that reduce the anisotropy [Hellinger et al., 2017b]. On electron scales with use of full particle-in-cell code we provided a study of electron mirror instability effects on nonlinear level. We have analyzed the competition between the electron mirror and whistler instabilities generated by the perpendicular temperature anisotropy in a collisionless plasma. The simulation results show that the linearly subdominant electron mirror instability may dominate on the nonlinear level the whistler instability and generates non-propagating coherent structures in the form of magnetic peaks [Hellinger and Štverák, 2018].

As a preparation for future numerical simulations we have extensively analysed the in-situ electron measurements from the Helios missions. Electrons in the expanding solar wind permanently exhibit non-adiabatic temperature gradients which may indicate presence of external heating. Analysis of observed electron velocity distributions have shown that no external heating is required and the temperature gradients can be explained by internal energy transfer mechanisms provided by Coulomb collisions and electron heat flux. These energy transfer mechanisms are found more efficient in the slower solar wind streams [Štverák et al., 2015]. Our previous findings from Helios observations were also verified and further extended using very recent observations of the Parker Solar Probe (NASA). A clear anti-correlation between the electron temperature and solar wind bulk speed is observed closer to the Sun, as a remnant of different slow and fast wind sources, but disappears as the wind evolves and mixes along the radial expansion [Maksimovic et al. 2019].

## 3. Instrument development for space research

The team developed the Time Domain Sampler module for the Radio and Plasma Waves instrument (lead by Paris Observatory) on the Solar Orbiter mission to the inner heliosphere, devoted to the study of higher frequency plasma waves and dust in the solar wind. In the recent years, the team completed the testing and calibration of the instrument and developed ground software for processing and calibration of the obtained data. This instrument started operations shortly after the launch of Solar Orbiter in February 2020 and is now routinely providing scientific measurements, first public data were released in September. As a Co-Principal Investigator team, we continued the development of the low frequency wave analyzer, a part of the Radio and Plasma Wave Instrument lead by the Swedish institute of Space Physics, for the European JUICE mission to the moons of Jupiter. The main objective of our hardware is to measure and analyze Jovian VLF electromagnetic waves analogous to terrestrial whistlers and chorus waves. The development of the flight model and firmware has been concluded by the delivery of the hardware to the PI institute and in turn to ESA in 2020. We developed and delivered an electronic wave analyzer module (WAM), including an electromagnetic sensor, as a European contribution to the Russia-lead landing platform of the ESA ExoMars mission, now scheduled to be launched to Mars in 2022. The objective of this experiment is to perform the first comprehensive measurement of natural electromagnetic waves on the surface of Mars, investigating the interaction of Mars with space environment and looking for Martian lighting. The team has also finalized the development and tests of the IME-HF instrument for the CNES Taranis spacecraft, to be launched in late 2020. This instrument will investigate radio waves accompanying lighting flashes and transient luminous event above the thunderclouds. In preparation of the mission, a network of ground observatories of lighting associated waves ground-based observatories of lighting associated electromagnetic waves is maintained in Czechia, France, Slovakia, and in The Netherlands, to obtain wider coverage and multi-point measurement capability.