Research strategy of the Institute of Atmospheric Physics of the Czech Academy of Sciences for the period 2025-2029

In 2024, the Institute of Atmospheric Physics of the Czech Academy of Sciences celebrated 60 years of its existence. Since its establishment, the Institute has been one of the key Czech, and later on international, players in advancing knowledge of weather, climate, atmosphere, and interplanetary space. Building on this strong foundation, we continue to tackle challenges of today's changing world.

Our Research Strategy for 2025–2029 is targeted on upholding the excellence and reliability of our scientific work while expanding its relevance to address pressing societal challenges. Collaboration with international partners is a key part of our vision. By collaborating with researchers and institutions around the world, we will share ideas and strengthen our role in the global scientific community. We will also extend our collaboration at the national level with research institutions, both within the Czech Academy of Sciences and outside it, and with universities.

The ultimate notion of our research is excellence. A key element in achieving the excellence is internationalization of research, which will be approached by increasing the share of foreign researchers in our Institute's staff, particularly on the postdoctoral level, by expanding and strengthening of bilateral collaborations, and by ample participation in international projects, especially those with a European dimension.

Based on the latest knowledge and internationally recognized research directions, we will explore the research questions and topics outlined below using our continuously improved and expanded multi-instrumental measurement facilities and experimental infrastructures of European and world-renowned scientific institutions with which we fruitfully cooperate, as well as modern methods of data acquisition, processing and analysis.

Funding is critical to our success. In order to advance knowledge in the priority research directions and topics, we will seek financial support through national and international grants. Specifically, the major sources of national funding for national and bilateral projects will be the Czech Science Foundation, Technology Agency of the Czech Republic, the Czech Academy of Sciences, and the Ministry of Education, Youth, and Sports of the Czech Republic. International funding will be sought mainly in funding schemes of the European Union and through the European Space Agency.

The key research directions we plan to further develop are listed below in the ascending order through the atmosphere, that is, from meteorology through climatology, ionosphere and aeronomy, space physics, up to heliospheric plasmas. While the research teams and topics are compact and clearly defined by the location within the atmosphere and/or interplanetary space and by temporal and spatial scales of the investigated processes, several crosscutting research topics join research efforts of more teams. Crosscutting research is strongly present particularly in topics 2, 4, 7, and 8.

This research strategy will guide our efforts over the next five years as we build on our past achievements and experience and work towards a future where science helps to cope with real-world problems.

1. Processes in clouds and precipitation

We will study processes of evolution of clouds and precipitation at various spatial and temporal scales to improve our understanding of these processes and their representation in numerical models. Microphysical processes in clouds and the role of aerosols in their formation and further evolution will be analysed especially with respect to the liquid and solid phase distribution in space and time. We will also study and simulate cloud electrification; our goal will be to explicitly model distribution of electric charge in clouds.

An ensemble of data from specialized instruments will be employed for our research. Most of the measurements are performed at the Milešovka Observatory, namely in situ cloud and aerosol measurements, which are conducted within the frame of the European ACTRIS infrastructure, disdrometer measurements of precipitation particles, and cloud remote sensing by the Ka-band polarimetric Doppler vertical profiler and the X-band polarimetric Doppler weather radar. In addition to the monitoring performed from the ground, we will also use data from meteorological satellites, mainly from the new Meteosat Third Generation satellite.

2. Phenomena in convective storms

Among weather extremes, convective storms deserve special attention. We will analyse factors influencing the formation and development of convective storms, mainly the influence of orography. We will also study dynamics of the storms and hazardous phenomena produced by them, namely lightning activity, hail, various types of strong winds, and torrential rainfall. The aim will be to specify the characteristics of atmospheric conditions that amplify or attenuate the intensity of the individual phenomena. A wide range of meteorological data from ground stations, aerological soundings and remote sensing will be used for this purpose. Different detection methods will be compared with each other to estimate their uncertainty (e.g., satellite and ground lightning detection). In addition to analyses of measured data, numerical model simulations will also be employed.

Our research on lightning initiation and other lightning processes will be focused on analysis and interpretation of their electromagnetic manifestations. We will also investigate transient luminous events and terrestrial gamma-ray flashes. We will use our Shielded Loop Antenna with Versatile Integrated Amplifier (SLAVIA) sensors installed at the Lomnický Štít observatory in Slovakia, at the Ter Wish measurement site of the Low Frequency Array (LOFAR) radiotelescope in The Netherlands, at the Cap Corse site at Corsica in France, and at the external measurement site of the Laboratoire Souterrain a Bas Bruit at La Grande Montagne close to Rustrel, France, where we operate an interferometer of SLAVIA sensors and very low frequency antennas. We will pay special attention to measurements of the recently installed interferometric system of SLAVIA sensors at the Dlouhá Louka observatory, which are supported by Broadband Lightning Evolution Survey Cluster sites with SLAVIA sensors at Milešovka, Kopisty and Bohosudov. We will also conduct measurements on stratospheric balloons of the Strateole program of the French Space Agency and other balloon projects.

3. Applied meteorology

Because meteorological information is needed in a wide range of practical applications, we will explore ways to further develop selected meteorological applications in order to bring these innovations into practice.

We will further develop the existing system for forecasting road surface conditions and temperature. The aim is to improve the accuracy of short-term forecasts using new types of operationally available data, mainly satellite data. The integration of advanced artificial intelligence methods into road weather forecasting is another aspect we will focus on. The forecasting system will include a quantitative estimate of forecast uncertainty.

We will also focus on applications in wind energy. Methods of wind analysis and wind resource assessment will be further developed and optimized, including improved calibration of existing wind models, and the use and calibration of new ones. For water management purposes, we will further refine estimates of design rainfall characteristics (intensity, temporal and spatial distribution) by combining station and radar data and taking into account topographic characteristics of landscape. We will also apply our expertise in assessing the impact of cooling towers and other industrial sources of heat and water on the microclimate of their surroundings.

4. Weather and climate extremes

Building on our previous research, we will deal with weather and climate extremes in terms of understanding their causes, predicting their occurrence and estimating their impacts on communities and ecosystems. Our research will focus on evaluating extreme events and specifying their characteristics such as areal extent, duration and time course. Particularly heatwaves, extreme precipitation, and droughts are of our interest, including compound events such as hot-dry spells or wind-precipitation events. Using methods to the development of which we substantially contributed within the COST (European Cooperation in Science and Technology) Action DAMOCLES, we will analyse temporal and spatial changes in hot-dry events and their associated environmental impacts. The question of possible future changes in the frequency and characteristics of extreme events due to ongoing climate change will also be addressed. For these purposes, we will use established station and gridded datasets, atmospheric reanalyses, and outputs from both the global and regional climate models.

Special attention will be paid to processes producing heavy precipitation (both heavy rainfall and heavy snowfall events). We will study how precipitation events are influenced by anomalies in selected variables quantifying dynamic and thermodynamic conditions, including integrated water vapour transport through atmospheric rivers. We will mainly focus on local precipitation enhancement induced by embedded convection or interaction with relief resulting in orographic precipitation enhancement. Radar and disdrometer data will be used to distinguish between primarily convective and primarily stratiform precipitation. This distinction will allow for a detailed examination of climatological characteristics of extreme precipitation events.

5. Atmospheric circulation

Atmospheric circulation is a key driver of surface climate and a major factor in observed and projected climate variability and change. As such, it is a central focus of our research. Our work aims to develop innovative methods for studying atmospheric circulation, with methodological advancements concentrated in two key areas: (1) non-linear dimension reduction and neural network-based techniques, such as Sammon mapping and self-organizing maps, and (2) sliding classifications of atmospheric circulation patterns.

This novel approach will provide insights into both traditional and emerging challenges. We will explore selecting the optimal classification method for tasks like analysing solar forcing of atmospheric variability and understanding the links between atmospheric circulation and surface climate. In addition, we will address emerging issues, including changes in extreme events and short-term variability in temperature and precipitation under the ongoing climate change.

An integral part of our work is also the comparison of data sets. We will evaluate how individual atmospheric reanalyses differ in their representation of historical atmospheric circulation and its links to surface weather and climate. Furthermore, we will study the reproduction of atmospheric circulation by current climate models and projected changes in future climate. We will assess how model biases and projected trends influence the simulation of the frequency and severity of extreme weather events.

6. Climate and health

Our research will focus on the analysis of impacts of climate change and variability on the seasonal patterns in human mortality and morbidity. One important aspect of our activities will involve assessing the effectiveness of heat-adaptation measures to prevent heat-related mortality at various scales.

Using the most up-to-date datasets and socio-economic data, we will analyse associations between weather characteristics and health impacts including infectious disease outbreaks. This will provide actionable insights for the public health sector. Special attention will be paid to the role of airborne diseases such as influenza and COVID-19 and vector-borne diseases including tick-borne and mosquito-borne illnesses in shaping the interactions between climate and health variables.

Collaboration with the Multi-Country Multi-City Collaborative Research Network enables us to evaluate both regional and global patterns in the relationship between weather and health. Through this partnership, we can apply state-of-the-art methodological procedures and utilize data from various regions around the world.

7. Climate variability and change throughout atmosphere

Changes in climate variability are a crucial factor influencing changes in the frequency and intensity of extreme events, which pose significant risks. Our research will focus on examining long-term trends in short-term variability of temperature and precipitation. We will use a wide range of datasets to identify specific deficiencies in various data types.

Another key objective will be to develop a new joint scenario of long-term trends in the stratosphere-mesosphere-thermosphere-ionosphere system. This scenario will be created in a broad international collaboration coordinated by our institute. We will focus on addressing gaps in this new scenario and resolving potential controversies, with particular emphasis on the ionosphere and stratosphere. Additionally, we will test the stability of trends over time and investigate the mechanisms driving these changes.

For analysing future climate changes, particularly in relation to extreme phenomena such as heatwaves, cold spells, heavy precipitation and droughts, we will employ regional climate models including those from the Coordinated Downscaling Experiment (CORDEX) initiative. Our work will evaluate the ability of current climate models to reproduce the driving mechanisms and spatial patterns of extremes, which excite atmospheric waves affecting the whole atmosphere-ionosphere system. To better understand and determine future convective precipitation extremes, we will use outputs from convection-permitting climate models.

We will further enhance the stochastic weather generators we have developed for applications in agriculture and hydrology. Beyond their traditional use in constructing future climate scenarios for a variety of climate change impact studies, tools will be effectively utilized for (1) assessing uncertainties in climate change projections derived from both global and regional climate model simulations, and (2) generating synthetic weather series that align with available weather forecasts. This will be particularly useful for seasonal forecasting, such as predicting crop yields.

8. Vertical coupling in the neutral atmosphere-ionosphere system

Ionospheric plasma is formed primarily by ionization of the neutral atmosphere by solar radiation. Besides that, the ionospheric dynamics and variations that affect the propagation of electromagnetic waves also depend strongly on the interaction between the solar wind and the Earth's magnetosphere and on the dynamics in the neutral atmosphere, as the ionosphere is immersed within it.

The main objective of our investigation will be the ionospheric response and changes due to processes that take place below in the neutral atmosphere, such as deep convection, jet-fronts systems, squall lines, sudden stratospheric warmings, and natural hazards (earthquakes, volcano eruptions, etc.). All these processes generate or modify acoustic-gravity waves (AGWs) that couple different layers of the atmosphere by transferring energy and momentum into the middle and upper atmosphere and ionosphere. We will focus on the identification of wave sources. Because of the complexity of gravity wave propagation due to possible dissipation of primary waves and generation of secondary waves, ducting in the mesopause region, wave filtering by winds in the layers below the ionosphere, Perkins instability, etc., the exact source of the observed AGWs or travelling ionospheric disturbances often remains uncertain, except for some specific extreme events. In this context, gravity waves and travelling ionospheric disturbances generated by Joule heating in the ionospheric E region at auroral latitudes and vertical coupling due to electric fields will also be studied. The spatiotemporal scales of disturbances generated by different sources and attenuation of AGWs in the upper atmosphere/ionosphere will be investigated.

In order to carry out our research, we will upgrade our measurements. We shall utilize multi-instrument measurements to obtain comprehensive information about the disturbances, among others the data obtained from our international network of continuous Doppler sounding systems, digital ionosondes (including the one operated by the Institute in Průhonice), and other instruments, operated or hosted by our Institute, including airglow observations and receivers of signals from navigation satellites. Modern methods of data processing and analysis, including deep learning, will be applied.

9. Ionospheric plasma modelling and contribution to the development of the International Reference Ionosphere (IRI)

The ionospheric plasma has a significant impact on propagation of electromagnetic waves, influences accuracy of navigation systems, and serves as a laboratory for investigation of phenomena and processes in the collisional plasma itself. Therefore, modelling of plasma parameters in the Earth's ionosphere is very important.

On the basis of our long-term experience with measurement, processing, and interpretation of ionospheric plasma parameters and their modelling, especially for the IRI model (the working group for IRI being currently chaired by our team), we will focus on the development of new submodels and improvement of existing ones, including their detailed validation. In particular, we will focus on submodels of electron concentration, ion composition, and plasma temperatures and their possible extension to the plasmasphere, increasing their temporal and spatial resolution. We will also investigate probabilities of occurrence of some specific sporadic ionospheric layers (e.g., Es) and better description of the dependence of their occurrence on solar and geophysical conditions including presence of forcings from the magnetosphere and atmosphere.

We will exploit data from new missions (e.g., NanoMagSat where we are involved in the mission Science Advisory Group) and we will test new and promising modelling techniques. For validation, we will also use measurements from our digital ionosonde in Průhonice.

10. Space weather effects on ionosphere

The upper layers of the Earth's atmosphere are significantly affected by space weather. The result is a complex, interconnected and dynamic environment influenced by solar radiation, energy transfer from precipitation particles and other electromagnetic processes, atmospheric winds, waves, tides, electric and magnetic fields, and ionospheric plasma processes. As space weather affects a wide range of modern ground based and space-embedded technologies, a comprehensive system for the direct and accurate detection/prediction of ionospheric disturbances is the cornerstone for the development of mitigation strategies that will support more reliable and safer operation of the technological systems affected.

Changing space weather causes irregular ionospheric variability. An important direction of our research will be the understanding of these processes to obtain the patterns of regular and irregular ionospheric variability and their dependence on the local time, different seasons and solar activity, especially for the European region. These patterns will be used to determine the significance of changing space weather effects on the ionosphere and will find application in ionospheric climatology and forecast models.

Space weather is a significant source of travelling ionospheric disturbances, mainly propagating from auroral regions towards the equator. Therefore, in order to effectively contribute to the design/improvement of prediction models of the activity of travelling ionospheric disturbances over Europe, another important direction of our research will be the intensive investigation of the effects of travelling ionospheric disturbances triggered by different solar wind disturbances under different geomagnetic conditions.

In studying the effects of space weather on ionosphere, we will focus on robust statistical analysis, finding correlations with space weather variations, and describing the resulting daily, seasonal, latitudinal/longitudinal, and solar activity dependencies, and also interhemispheric differences using available experimental data (e.g., ionosonde, incoherent scatter radar, Low Frequency Antenna Array (LOFAR), Global Navigation Satellite System (GNSS), Doppler sounding data and relevant satellite data). At the same time, we will be working on the development of specialised software for faster searching and processing of the necessary parameters of solar, auroral and geomagnetic activity, as well as using machine learning to analyse large data sets more efficiently.

11. Space weather effects on the Van Allen radiation belts

A conventional boundary between the Earth's atmosphere and the outer space is defined by the Kármán line at an altitude of 100 km. Our contribution to the research of the outer space in the nearest environment of our planet will be focused on the growth and propagation of electromagnetic waves and on their effects in the region of Van Allen radiation belts.

Electromagnetic waves not only arise from external sources, as lightning discharges, but also from instabilities of the plasma medium itself. They can be therefore very sensitive to changes in the space environment in the solar system, induced by the variable activity of the Sun. Consequences of these changes are often referred to as "space weather". The electromagnetic waves, in turn, can also influence the space environment. They may significantly contribute to variations of fluxes of energetic particles in the Earth's radiation belts, causing thus space weather effects with serious practical consequences for possible failures of commercial spacecraft for telecommunication or navigation. These effects can therefore represent considerable risks for this critical infrastructure.

We will use archived data of the Cluster and Van Allen Probes missions, on which we actively participated, and measurements of other spacecraft of National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and Centre National d'Etudes Spatiales (CNES). We will analyse nonlinear wave packets of whistler-mode chorus, which accelerate "killer electrons" to relativistic energies, as well as electromagnetic ion cyclotron waves, which contribute to their losses by precipitation into the atmosphere. We will investigate also the properties and effects of other types on electromagnetic waves, like equatorial noise or lightning whistlers.

12. Waves and instabilities in the Solar wind

We will investigate waves and instabilities in the Solar wind, primarily in connection with our instrumentation onboard the European Space Agency's Solar Orbiter spacecraft. This mission is designed to study physical processes in the corona and in the solar wind, including the origin and acceleration of the solar wind, solar wind transient phenomena, such as coronal mass ejections and interplanetary shocks, the origin of solar energetic particles, and the connection of the Sun with the heliosphere. Our institute developed and built the Time Domain Sampler subsystem of the Radio and Plasma Wave instrument onboard the Solar Orbiter spacecraft. Its goal is to capture full multi-component electric and magnetic field waveforms.

We will aim to use radio and plasma wave observations to advance our understanding of plasma instabilities in the solar wind and in particular their energetics, explore the propagation properties of plasma waves, such as wave vector, polarization, and their radial evolution. We will measure intense Langmuir-like waves in the solar wind in association with suprathermal electron beams produced by either solar flares or accelerated by interplanetary shocks. These waves are believed to undergo linear mode conversion and/or nonlinear wave-wave interactions that produce electromagnetic emissions at the local electron plasma frequency and its second harmonic. Since Langmuir wave events are relatively rare, the Time Domain Sampler implements an on-board event detection algorithm, which can identify observations containing potentially interesting phenomena and will only pass these events to the on-board memory for downlink. We will use this capability together with the on-board software of the Time Domain Sampler, which allows us to identify electric field signatures of dust grain impacts and collect statistics of these observations over a longer time interval. We will analyse the flux of interplanetary and interstellar dust with respect to the distance from the Sun and the inclination from the ecliptic plane, as well as temporal variations in the occurrence of dust grains and their parameters, as mass and velocity distributions.

We will utilize novel observations from the European spacecraft mission Solar Orbiter and the American spacecraft mission Parker Solar Probe to further extend our preceding research of energy transport mechanisms in the expanding solar wind by means of kinetic processes such as wave-particle interactions, Coulomb collisions, or the ubiquitous magnetohydrodynamic turbulence. We will aim to study the local balance and dissipation of the internal plasma energy along the solar wind expansion into the heliosphere and to explain the observed non-adiabatic evolution and non-thermal features by use of large or local scales numerical simulations based on hybrid and fully kinetic particle in cell models.

13. Waves and instabilities at giant planets of the Solar System

The data of the currently operating NASA Juno spacecraft at Jupiter have led to the unexpected discovery of rapid lightning whistlers. These interesting phenomena consist of dispersed electromagnetic signals generated by individual lighting discharges at extremely short time scales of several milliseconds to several tens of milliseconds in a frequency range from 50 Hz to 20 kHz. Observations by the microwave instrument onboard the Juno spacecraft have led to a discovery of Jovian lightning sferics at 600 MHz. Evidence of low density holes in the Jovian ionosphere was also found through the presence of electromagnetic signals, called Jupiter Dispersed Pulses. Many unsolved problems are linked to observations of previously unknown spectral types of electromagnetic waves at Jupiter and Saturn. Only the initial crude model of their propagation from their source has been derived, showing puzzling inconsistency of ionospheric plasma densities. We will concentrate on closing these knowledge gaps using the database of the observations of Juno spacecraft at Jupiter and Cassini spacecraft at Saturn.

We will also work on the commissioning of our Low Frequency receiver subsystem of the Radio and Plasma Wave Investigation instrument onboard the European JUICE spacecraft mission to Jupiter and its icy moons (launched in 2023). The receiver has been designed and built in our institute, and we will prepare its tests and scientific operations during the cruise phase, as well as work on processing and calibration of the measurements. Using these measurements and measurements of other interplanetary spacecraft orbiting Jupiter, Saturn, and Mars, we will analyse measurements of the electromagnetic waves in the planetary magnetospheres and ionospheres, investigate electromagnetic signals from lightning discharges, and contribute to measurements of dust particles.

14. Design and development of scientific instruments for future spacecraft missions

We will finalize the development of the flight software for the JUICE mission and continue the development of our hardware and software contributions to other European spacecraft missions: Comet Interceptor mission to a new comet, Vigil space weather mission, LISA mission to detect gravitational waves, and Athena X-ray telescope. We will continue to be active in the consortia on newly proposed European projects in the competitive phase, like Plasma Observatory multi-spacecraft mission to the magnetospheric boundaries, the Mars Magnetosphere ATmosphere Ionosphere and Space-weather SciencE (MATISSE) mission , and upcoming future projects.

The Comet Interceptor is a new type of mission of the European Space Agency, which was launched before its primary target has been found. The Comet interceptor mission is designed to characterize, for the first time, a dynamically new long periodic comet from the Oort cloud or an interstellar object, including its surface composition, shape, structure, and the composition of its gas coma. A unique, multi-point measurement of the comet-solar wind interaction region is to be obtained, complementing single spacecraft observations made at other comets. The three-spacecraft of the Comet Interceptor mission (a larger mother spacecraft and two small daughter spacecraft) will be launched in 2029 and delivered to the Sun-Earth Lagrange Point L2. The spacecraft will reside there until directed to their target. We will work on our subsystem Dust Analyzer and Processing Unit accommodated in the Dust, Field and Plasma instrument boxes on the mother spacecraft and one of the daughter spacecraft of the Comet interceptor mission.

The Vigil spacecraft will be Europe’s first 24/7 operational space weather satellite, providing valuable time to protect critical infrastructure such as power grids or mobile communication networks on Earth as well as satellites in Earth orbit. It will be launched in 2031 to the fifth Lagrange point. By keeping an eagle eye on the ‘side’ of the Sun, the spacecraft will stream a constant feed of near real-time data on potentially hazardous solar activity, before it rolls into view from Earth. We will work on the data processing unit for this spacecraft.

15. Space plasma interactions with solar system bodies via numerical simulations

Space plasma interactions with solar system bodies are fundamental processes that shape their ambient environments and governing their structure and dynamics even down to nearest surface layers. These processes arise from the interaction of solar wind plasma with ionospheres, atmospheres, or directly with surfaces of unmagnetized bodies, and/or magnetospheres in case of magnetized planets or moons; resulting in turn in significant disturbances of the plasma flow itself and carried background electromagnetic fields. Advances in observational and computational techniques enable detailed studies of these interactions, revealing their complexity and variability. Understanding these plasma processes is crucial for interpreting, from global scales, evolution of the heliosphere and its planetary system, space weather phenomena impacts on near-terrestrial environments, or, down to local scales, charging effects on any space satellite missions.

On global scales, based on our extensive heritage in numerical plasma simulations with in-house developed hybrid codes, we will aim to study the interaction of the solar wind with Mercury and its magnetosphere, namely plasma particles precipitation on the planetary surface and formation of trapped magnetospheric energetic particle populations. The study will be conducted in the frame of the recent BepiColombo mission. As a preparation for future JUICE mission observations (launched in 2023 to reach Jupiter in 2031) we will start to adapt a similar model for later studies of Ganymede's interactions with Jovian magnetospheric plasma. On small scales, we aim to further extend our initial research of local plasma interactions with spacecraft bodies. We will analyse disturbance effects on in situ plasma measurements caused by surface charging of the spacecraft structures and photo- and secondary electron emissions due to impacting ambient plasma particle fluxes. We will utilize numerical models implemented in the open framework of Spacecraft Plasma Interaction Software in comparison to observations from recent Solar Orbiter mission.

This research strategy was approved by the Institute Board on February 11, 2025.