Strategic Science Plan 2022 – 2028

Leibniz Institute of Atmospheric Physics at the University of Rostock (IAP)

MAARSY radar, lidar at ALOMAR, and rocket launch facilty at Andøya Space Centre. (Andenes, Andøya Island, Norway, 01/2020)

1 Preface

The Leibniz Institute of Atmospheric Physics at the University of Rostock (IAP) conducts research in the physics of the mesosphere and lower thermosphere (MLT) and adjacent layers. IAP has established a well-respected position in the international scientific community on these topics. As a member of the Leibniz Association, IAP is dedicated to conducting excellent research which has national and international interest and is of societal relevance. The institute is located at Kühlungsborn, it operates a branch station at Juliusruh on Rügen island, and it is a major partner of the ALOMAR[1] facility in northern Norway.

A Scientific Advisory Board regularly supervises the institute's science plan and quality of research. Moreover, IAP is reviewed by an external evaluation organised through the Leibniz Association every seven years (the most recent was in May 2015). The evaluations have been very positive, which guaranteed a stable situation at IAP, including some increases in personnel and infrastructure.

According to the constitution of IAP, it is the responsibility of the director to develop a scientific strategy in close collaboration with the department heads. Thus, this document's purpose is to formulate the Strategic Science Plan for IAP for the next seven years, i.e., 2022–2028. We have developed a strategy based on emerging scientific questions and considering IAP's scientific and technological progress in recent years. An initial version of the document was presented to the Scientific Advisory Board. Their recommendations have been well received and have been used to make final adjustments to the revised document. IAP's Strategic Science Plan has been endorsed by the Scientific Advisory Board and approved by the Board of Trustees in February 2022.

2 Mission

> Advancing scientific knowledge of the mesosphere and lower thermosphere
> by developing and exploiting expertise
> in atmospheric physics, instrumentation, analysis, and modelling
> to serve emerging societal needs.

3 Scientific significance and societal relevance

The mesosphere and lower thermosphere (MLT) ranges between about 50–200 km altitude and constitutes the interface between the terrestrial atmosphere and near-Earth space. The important role that the MLT plays in connecting adjacent atmospheric layers has recently been recognised. As the transition region, the MLT is influenced by the dynamical processes of the lower, middle and upper atmosphere, as well as by solar electromagnetic and particle radiation and by anthropogenic activities. Thus, the MLT is an integrative part of the whole atmosphere concept.

Investigating the MLT requires dedicated experimental and theoretical expertise, which can only be developed and maintained at a competitive level with highly qualified personnel and sophisticated instrumentation and methods. At IAP, the physical and coupling processes which are unique to the MLT are studied. The results of our work are indispensable to understanding Earth's climate trends and weather.

[1] Arctic Lidar Observatory for Middle Atmosphere Research

3.1 Scientific significance

Interface between atmosphere and space. The MLT is a transition region between the terrestrial atmosphere and near-Earth space, where complex processes prevail which are different to or coexist with processes that dominate in the lower and the upper atmosphere and ionosphere; thus, some physical concepts change drastically. Some important peculiarities of the MLT are:

- gravity waves originating in the troposphere that break in the MLT, producing turbulent volumes, which in turn emit new waves in all directions,
- due to certain particularities of the atmospheric circulation scheme, the summer mesopause at polar latitudes is the coldest place on Earth despite permanent sunshine,
- radiation is no longer in local thermodynamic equilibrium with matter,
- gravitational separation of the molecular composition of the atmosphere starts dominating turbulent mixing so that the mixing ratio of air changes gradually with altitude,
- the partially ionized air combined with the Earth's magnetic field, MLT winds, or solar particle radiation allows electric currents to flow more strongly than in the atmosphere above. The corresponding ion drag may cause an additional heating source.

To explain these characteristics, hydro-, thermo-, and electrodynamic processes and atmospheric composition need to be studied. Thus, the MLT is a highly particular region of the atmosphere that requires a dedicated focus to achieve its full exploitation.

Integrative part of the whole atmosphere concept. The MLT is strongly coupled to other atmospheric layers. Upward propagating waves originating in the troposphere or stratosphere, such as gravity, planetary, and tidal waves are crucial to describe structures of the MLT's temperature, winds, density and composition. For example, gravity waves generated in the troposphere propagate upward and indirectly drive the thermal state away from radiative equilibrium by more than one hundred degrees at polar latitudes during local summer. In turn, the high-energy part of the solar particle radiation is absorbed in the MLT, which causes photochemical and dynamical patterns to progress downward, which is believed to also affect weather in the troposphere.

MLT processes influence the ionosphere, the ionized part of the atmosphere, where the highest conductivities exist in the E region (i.e., 100–110 km). At auroral and polar latitudes, the E region's electrodynamics are dominated mainly by solar particle precipitation and its connection to magnetospheric currents. However, at mid- and low-latitudes, the interplay of the conductivity with MLT winds and with the Earth's magnetic field is responsible for the ionospheric dynamo, e.g., the ionospheric electric field and currents have been proven to be modulated by atmospheric wave activity. In turn, the E region electric field shapes the ionospheric plasma and currents globally and up to a few hundreds of kilometres in altitude. Thus, including knowledge of the MLT has become indispensable to understand the entire thermosphere and ionosphere.

Driven by the strong empirical evidence of coupling, the scientific community raises increasing awareness of the *whole atmosphere concept* and develop whole atmosphere models, i.e., from the ground to space, and aims to include different scientific disciplines to simulate global as well as regional scales. In this concept, the MLT has been recognised as the most complex part, which is also due to its poor observational coverage.

Indicator for long-term trends. The terrestrial atmosphere currently undergoes dramatic changes, as recently recognised by the IPCC[2] report in 2021[3]. This change is a combination of anthropogenic influences and natural variability, and it is of utmost importance to disentangle relevant mechanisms and their respective contribution. Temperature trends in the MLT reach values of up to –2 Kelvin/decade (cooling) which is an order of magnitude larger (and of opposite sign) than documented trends in the troposphere. Due to the high sensitivity of the MLT, it is an important indicator to monitor global change. The relevance of the MLT in climate change studies is well-known to scientific funding agencies. For example, IAP has been leading dedicated research activities related to this topic, such as ROMIC[4] supported by BMBF[5] between 2014–2023.

3.2 Societal relevance

Recent decades have seen a sharp increase in public awareness of our shared environment and human activities increasingly depend on space infrastructure, such as satellites, rockets, and global communication systems. The MLT, due to its importance to shape the entire atmosphere, is therefore of the highest societal relevance.

Climate change. Based on climate model predictions built upon physical principles and long-term observations, it is recognised that anthropogenic activities have a severe impact on climate (see IPCC report). Due to its high sensitivity, the MLT is an excellent indicator for climate change scenarios. By developing dedicated physical understanding and running analyses of long term time series, IAP's research makes relevant contribution to better quantify anthropogenic influences and to understand its interplay with variability in solar radiation and atmospheric dynamics.

Space objects at low orbits. The current space age is characterised by a growing number of satellites, e.g., at low Earth orbit (LEO, ca. 300–900 km) and it targets rapidly to spacecraft at so-called very low Earth orbit (VLEO, ca. 100–200 km). Knowledge and prediction of atmospheric density at these altitudes are crucial to satellite operators because it determines the orbit evolution of any object in space. For example, a colder upper atmosphere means that the atmosphere shrinks and thus, it results in lower air density at a particular altitude. This allows satellites a longer lifetime before natural de-orbiting into the dense atmosphere. At the same time, it also prolongs the lifetime of space debris, enhancing the possibility for collisions. So far, the MLT has rarely been populated by anthropogenic objects, e.g., by launches of scientific rockets and short retention times during satellite de-orbiting campaigns. Nowadays, also commercial space activities targets altitudes of 70–110 km. These developments call for an urgent need to better describe and perspectively predict the state and variability of the MLT, to which IAP contributes with observations and modelling efforts. From a long-term perspective, the new assets by commercial space flights may allow IAP to fly scientific instrumentation or release tracers to study MLT dynamics.

[2] Intergovernmental Panel on Climate Change
[3] https://www.ipcc.ch/report/ar6/wg1/
[4] Role of the Middle Atmosphere in Climate
[5] The German Federal Ministry of Education and Research (en)

Space weather. Space weather includes effects due to ionospheric density gradients that disturb radio wave propagation affecting technological systems such as GNSS[6] or diverse applications of HF[7] radio in governmental, military, and civil areas. While HF radio depends on the state of the ionosphere below its peak electron density altitude, GNSS signals are disturbed within the entire ionosphere. The former is in direct relation to the mesosphere. MLT dynamics shape the global ionosphere, including plasma density gradients affecting the latter. For example, so-called equatorial ionospheric instabilities after sunset represent the main threat for GNSS globally. Their normal occurrence is not related to occasional geomagnetic storms, but regular processes originating in the MLT trigger them. Thus, knowledge of the MLT is indispensable in predictive efforts of space weather models.

3.3 Strategic position of IAP

IAP is the German institute for MLT research relevant on national and international levels, and it takes leadership in dedicated areas. As a member of the Leibniz Association, IAP is integrated in a solid research infrastructure that allows conducting scientific aims, such as formulated above, which require long-term planning and many years of development and maintenance of equipment and expertise.

One core asset of the institute is the operations of lidars with specific capabilities at scientifically relevant locations. These are Doppler resonance and Rayleigh/Mie/Raman lidars which can operate also under full daylight conditions, for example, installed at ALOMAR in northern Norway. Recently, IAP has been developing miniaturized mobile lidars, VAHCOLI[8], which aim at monitoring the 3D structure of MLT parameters. It will be capable of operating at dedicated places worldwide, e.g., in conjunction with other instruments. IAP operates state of the art phased and modular array radar instruments at several frequencies, which are used to observe MLT winds continuously. MAARSY[9] is the most flexible and versatile VHF[10] radar worldwide and allows for the detection of, for example, 3D structures in mesospheric ice layers with unprecedented spatial resolution. A new SIMONe[11] system, that allows tomographic MLT wind field observations, has been developed and currently operates in Peru, Argentina, northern Germany, and northern Norway. IAP has a long time experience and unique expertise in conducting measurements using sounding rockets. Apart from its scientific significance, IAP rocket measurements were (and are planned to be) used to validate ground-based and satellite-borne observations. IAP's technical infrastructure is completed by the only operating ionosonde in Germany, which is located at the Rügen island. A detailed overview of instruments and approaches is given later in section 5.

In order to interpret phenomena related to the MLT in a global context, IAP has developed circulation and chemistry-transport models. These describe vertical coupling from the surface to the thermosphere and the interaction across scales from planetary waves to turbulence. Some of these models are unique with respect to their numerical schemes and parametrisation characteristics. Theoretical and experimental studies at IAP also take advantage of reanalysis data, satellite observations, and community models.

The MLT is currently one of the least explored regions of Earth's atmosphere because it is too low for state-of-the-art satellites and too high for regular balloon launches. Nonetheless, it is a region of growing relevance (sections 3.1 and 3.2). The combination of IAP's expertise is unique to tackle this challenge.

[6] Global Navigation Satellite Systems
[7] High Frequency
[8] Vertical And Horizontal COverage by LIdar
[9] Middle Atmosphere Alomar Radar System
[10] Very High Frequency
[11] Spread Spectrum Interferometric Multistatic meteor radar Observing Network (SIMONe)

A particular strategic strength is provided by the close cooperation with the University of Rostock in both, research and education. Active teaching and supervision of students at all university levels, as well as professorships of the director and department heads, allow direct transfer of knowledge to, and recruiting of, early career scientists and engineers at IAP.

Leading of national collaborative programmes, such as ROMIC supported by the BMBF within 2014–2023, and the Priority Programme (SPP) 1788 DynamicEarth supported by DFG[12] within 2015–2022 (IAP lead since 2021), reflects IAP's central role in the German scientific landscape.

IAP's trajectory and research quality are highly recognised internationally and have attracted international scientific guests to deepen its worldwide connection and collaborations. We cultivate the cooperation with agencies and commercial partners to keep IAP's attractive position for governmental and industrial stakeholders.

4 Research themes

In order to accomplish IAP's mission, the overarching research themes are:

- Exploration of the mesosphere and lower thermosphere
- Coupling of the mesosphere and lower thermosphere to atmospheric layers below and above
- Long-term changes in the mesosphere and lower thermosphere and adjacent regions

4.1 Exploration of the mesosphere and lower thermosphere

Exploration. In recent years, the MLT has been recognised as the missing piece in understanding the connection of weather and climate to processes occurring in the upper atmosphere and space. IAP's theme to explore the MLT is rooted in long-standing questions concerning fundamental physical processes. Scientific challenges are various fluid dynamics and other physical peculiarities which do not exist in the lower atmosphere (e.g., troposphere) and require the combination of different physical disciplines. In addition, models of the MLT contain large uncertainties in many parameters, which reflect the limited observational evidence. It creates critical gaps in our understanding of the processes, reducing our ability to quantify and model them adequately.

An ideal data set would be a simultaneous, globally distributed collection of all relevant parameters, including wind, temperature, density, and composition of neutrals and plasma. The MLT is too low for satellites, which could regularly cross various regions and take in situ observations with multi-parameter payload. Thus, until the advent of VLEO satellites, remote sensing ground-based radars and lidars, remote sensing satellites, and occasional scientific rocket campaigns remain the only tools to access the MLT. While remote sensing satellites are good in global coverage, they often cannot resolve small scales of less than a few hundred kilometres. In contrast, though lacking global coverage, ground-based remote sensing instruments and rockets do observe these scales.

IAP is well positioned in successfully running large facilities that include lidars, radars and other instruments, and it has recently developed instruments for mobile operations with selected capabilities (e.g., SIMONe, VAHCOLI). In addition, IAP has a long and successful experience in conducting scientific rocket campaigns. IAP will continue running and upgrading the large facilities to exploit our expertise with a multi-instrument approach and maintain long-term data sets. Furthermore, IAP will invest in

[12] German Research Foundation (en)

mobile capabilities, which will allow cost-beneficial operation and coverage of scientifically interesting regions (e.g., gravity wave hot-spot in southern Argentina). Latitudinal and longitudinal variations of winds are best studied with a chain of radars and/or lidars combined with satellites.

Expertise in studying the mesosphere and stratosphere is particularly strong at IAP. Based on this expertise, we plan to extend our observational and modelling capabilities to the lower thermosphere (90–200 km). Therefore, we will pursue extending lidar and sounding rocket expertise and radar measuring capabilities to those altitudes. To achieve this aim, new expertise in experimental and theoretical (e.g., plasma-neutral coupling) methods will have to be developed.

MLT Dynamics. Important open questions in MLT dynamics are related to the large-scale momentum and energy budgets and corresponding contributions from all kinds of motions such as planetary waves, tides, gravity waves, and turbulence. These motions show very strong interactions, for example, turbulent dissipation becomes a first-order effect in the large-scale energy budget.

Although MLT wind dynamics have been studied for more than three decades using ground- and satellite-based instruments, many observed features of their mean state are still not well represented in GCMs[13]. This is partly due to the relatively poor observational coverage (spatial and temporal), and more importantly, the lack of proper understanding and parameterisation of sub-grid scale dynamics (mesoscales and smaller). Adding further complexity, large scale dynamics interact non-linearly among themselves and also with the smaller scale dynamics. For example, MLT tidal amplitudes observed from ground-based instruments exhibit significant amplitude and phase variability on scales of days, less than the time needed for satellites to measure tidal amplitudes. Thus, both complement well for high resolution and global coverage, respectively.

At MLT mesoscale dynamics, primary and secondary gravity waves co-exist with stratified turbulence. These scales are parameterised in GCMs, but there is no consensus on their general roles so far. As in the case of lower atmospheric research, identifying those roles (e.g., their wavenumber spectra slope) as function of season, latitude, and altitude, are crucial to improve weather and climate models. Furthermore, gravity waves and turbulence are also expected to non-linearly interact with larger scale dynamics like tides and planetary waves, and therefore imprint their signatures on atmospheric regions adjacent to the MLT. Smaller kilometer-scale features are also crucial for understanding mesoscale dynamics since they could come from mesospheric dynamical and convective instabilities, again not well represented in GCMs. The latter scales would need to be studied with the help of state-of-the-art DNS[14] in combination with regional and global modelling. Experimentally, IAP observations should aim at discriminating space-time features to characterise MLT intermittency and identify their main sources, e.g., coming from the lower atmosphere or in situ generated.

Composition. The MLT composition affects radiative transport, leads to chemical heating, and forms layers that are used as tracers of the background atmosphere. For example, these are layers made of icy particles (e.g., NLC[15] and PMSE[16]), layers of metal atoms used by resonance lidars (Na-, K-, Fe-Lidar), or layers of other species leading to airglow (e.g., OH, Na). We will investigate the atmospheric composition to understand the drivers of potential changes and their effects on the layers in the MLT. A detailed understanding of composition main drivers is required. Such knowledge allows us to include

[13] General Circulation Models

[14] Direct Numerical Simulations

[15] NoctiLucent Clouds

[16] Polar Mesospheric Summer Echoes

relevant layers for studying atmospheric processes that can not be observed with other methods (e.g., those at altitudes between 80 and 200 km).

4.2 Coupling of the mesosphere and lower thermosphere to layers below and above

Dynamical coupling between the lower atmosphere and the MLT. The importance of the MLT for the whole atmosphere, including weather and climate close to the surface, originates from vertical coupling due to dynamical processes. Coupling occurs both upward and downward. Upward coupling is mainly due to planetary and gravity waves, which are generated at lower altitudes and propagate upward. So-called "wave mean-flow interactions" lead to a strong dynamical control of the winter stratosphere and the MLT on a global scale. Subtle changes in tropospheric wave generation (e.g., at tropical convection zones, varying storm intensities) can yield strongly amplified signals in the MLT that can be detected by accurate measurements. Nonetheless, understanding upward coupling is complex for various reasons: 1) Wave-wave interactions among planetary waves, tides, and gravity waves, 2) in situ generation of planetary waves in the MLT due to dynamical instability, 3) in situ generation of secondary or multistep gravity waves, and 4) the close relationship between wave breaking and small-scale turbulence.

Downward coupling is basically a far-reaching consequence of upward coupling: Wave breaking causes alterations of the mean flow and thereby changes wave-propagation conditions. As a result, the altitude of the breaking region varies vertically synchronously with the mean-flow alteration. The timescale of this downward progression can be years, as is well known for QBO[17], weeks as in the case of seasonal transitions, or days as in the case of SSWs[18].

IAP is dedicated to further explore the generation, propagation, interactions, and breaking of all relevant atmospheric waves in order to achieve an improved understanding of the dynamical control of and by the MLT.

Coupling between the MLT and the ionosphere. The strongest electric fields and currents of the ionosphere develop at around 100 km altitude in the E region. The ionospheric dynamo driven by MLT winds, in conjunction with the Earth's magnetic field, causes E region electric fields and currents at mid- and low-latitudes, which in turn drive the plasma drifts at all scales in the whole ionosphere up to a few hundred kilometres altitude. Thus, the upper atmosphere is coupled to the lower atmosphere, either directly or indirectly. The former is due to lower atmospheric waves (or their multistep waves) that propagate to the upper altitude. The latter has been shown to be efficient at low and middle-latitudes via the E-region dynamo. For example, particular constellations of planetary waves may change the form and position of the polar stratospheric vortex and can cause SSWs. SSWs are known to be responsible for tidal changes in both temperature and winds. Modified tidal winds produce anomalous zonal electric fields at low and mid-latitude ionospheric altitudes, and diurnal and sub-diurnal tides at low latitudes are responsible for the observed electron density distributions at mid and low latitudes at regional and global scales.

Most of the dynamical coupling studies have focused on planetary and other large scales. It is expected that mesoscale features also contribute to the whole atmosphere and ionosphere weather, either through direct propagation or indirectly. Such scales are suspected to be responsible for the day-to-day variability of, e.g., equatorial plasma irregularities extending from 150 km to the upper ionosphere

[17] Quasi-Biennial Oscillation
[18] Sudden Stratospheric Warming events

and for the variability of low latitude features observed between 90 and 180 km altitude (e.g., sporadic-E layers, tidal ion layers, 150-km echoes, among others).

In that area, the focus of IAP is to contribute to the understanding of dynamical processes in the MLT that evoke ionospheric variability.

4.3 Long-term changes in the MLT and adjacent regions

The MLT is highly sensitive to long-term changes related to anthropogenic activities (e.g., in greenhouse gases) and natural variability. MLT temperature and wind time series are still not long enough for conclusive contributions to long-term studies. Nonetheless, specific indirect measures are available to IAP covering numerous decades, including radio wave lower mesospheric reflection heights (since 1956) and various properties of noctilucent clouds (since 1994). In addition, our studies will also involve the Juliusruh ionosonde observations that constitute the longest ionospheric record in Europe (more than six decades). It provides layer height observations, which are known to decrease/increase with decreasing/increasing thermospheric temperatures. Large (negative) temperature trends in the mesosphere are derived from the reflection heights, which are significantly larger than those in the troposphere, e.g., 1.6 K/decade. On the other hand, NLC heights have remained nearly constant for the past few decades, posing a significant limitation on our knowledge of changes in the MLT area. Mesospheric ice layers remain an essential tool for trend studies since they constitute the longest measurement record in the MLT and are very sensitive to background conditions, i.e., temperatures and water vapour. IAP's long-term studies will continue focusing on decadal-scale observations, complemented by century-scale modelling.

5 Scientific methods

This section summarises scientific methods applied at IAP to follow its mission and research themes.

5.1 Lidars

Unique lidar capabilities have been developed at IAP for application in the MLT. The combination of lidars available at IAP focuses on observing the thermal and dynamical structure from the stratosphere to the lower thermosphere. The Doppler-lidars at IAP are capable of detecting small wavelength changes of the order of $\Delta\lambda/\lambda \approx 10^{-8}$ or smaller. They provide the only reliable technique measuring temperatures and winds, quasi-continuously and covering a unique range of scales. The lidars can operate day and night, and IAP has kept and extended its leading position concerning automated and remote operations of lidars irrespective of the time of day and season, even at challenging remote locations. Mean state conditions, gravity waves, and tides are derived from these observations.

- ALOMAR Lidar. The lidar was recently upgraded with two almost maintenance-free high power diode-pumped lasers providing 100 W each. It is now regularly used for wind measurements with a three times higher power than before. The DORIS[19] technique has proven to measure the slight Doppler shift of the Rayleigh signal caused by winds. Combined with a sophisticated analysis procedure, it delivers 3D gravity wave vectors to identify primary and secondary waves in the middle atmosphere. Such measurements are essential for our understanding of gravity wave propagation and are still unique worldwide. The lidar perfectly complements the capabilities of radars measuring winds at altitudes

[19] DOppler Rayleigh Iodine System

below and above the lidar's observing altitudes. The location close to Andøya space centre and the capability of pointing along rocket trajectories gives unique opportunities for international sounding rocket activities.

- Kühlungsborn Lidar. Like ALOMAR, the Kühlungsborn lidar has been upgraded with diode-pumped lasers (100 W), improving spectral stability, essential for wind measurements. This increase of stability has been accompanied by a significant increase in operation robustness that will contribute to address new scientific topics. Having the instrument in-house allows for a rapid development of new operational modes (e.g., vertical winds, Doppler temperature).
- Mobile lidar. IAP's mobile lidar (VAHCOLI) is currently operated in vertical alignment only, particularly measuring vertical winds. The mobile system has been completely re-designed to allow for horizontal wind measurements, and its operation is planned for the next few months. Since a few years, IAP cooperates with the Fraunhofer ILT in Aachen to develop specific lasers for our purpose. The new lasers are intended to operate for long time (e.g., years) without maintenance which reduces personnel effort. At the same time, the system layout has been substantially simplified to enable autonomous operation and the possibility to manufacture several mobile systems at IAP and in cooperation with commercial partners. Several units of this system shall operate in a localised network for monitoring the 3D structure of MLT parameters.

Using robust diode-pumped lasers in IAP's lidars allows for significantly extending the dataset of combined temperatures, winds, and tracers (e.g., NLC). For example, the new dataset will be used to study large tides in temperatures, NLC, and metal layers and their link to gravity waves. IAP's multi-instrument approach will use lidar, radar, and rocket instruments at large facilities and distributed mobile systems to cover scales from meters to hundreds of kilometres.

In summary, lidars will continue to play a crucial role in the IAP scientific programme in Kühlungsborn and ALOMAR and at other places using mobile systems coordinated with multi-instrumental campaigns.

5.2 Radars

Since its foundation, IAP has designed, implemented, and operated radars with a particular focus in the MLT region. MLT radars, working under all weather conditions, are classified as: (a) mesosphere-stratosphere-troposphere, (b) partial reflection, and (c) specular meteor radars, i.e., MST[20], PRR[21], and SMR[22], respectively. Although the scientific community widely uses MLT radars, IAP MLT radars have unique capabilities that have helped and will help to tackle IAP's research topics outlined in section 4. For example:

- MAARSY is the most versatile and powerful MST radar at northern high latitudes, capable of multi-beam and synthetic aperture radar imaging observations. Given its versatile and modular configuration, it has allowed the implementation of MIMO[23] (first introduced to the atmospheric and ionospheric community by IAP) and therefore the observation of 4D PMSE with unprecedented angular resolution. These capabilities allow for studies of kilometre-scale mesospheric structures (e.g., KHI[24], bore-like structures, etc.). In recent years, MAARSY capabilities have been augmented further to allow for:

[20] Mesosphere Stratosphere Troposphere
[21] Partial Reflection Radar
[22] Specular Meteor Radar
[23] Multiple-Input Multiple-Output
[24] Kelvin-Helmholtz instabilities

(a) simultaneous multi-target observations and (b) multi-static observations. The former has been instrumental in allowing for simultaneous observation of the UTLS[25], mesosphere, and meteor echoes. The latter has been tested using KAIRA[26] to receive MAARSY signals and therefore to study PMSE structures over a larger area. MAARSY will be soon upgraded to MAARSY-3D, where one additional receive-only station (similar to KAIRA), located 60 km from MAARSY, will be installed. This addition will allow tristatic velocity measurements of mesospheric (and meteor-head) echoes, and therefore improved dynamical studies.

- Saura is the largest operating PRR in the world. Similar to any other PRR, it allows wind measurements in the lower mesosphere in addition to electron density measurements of the D-region. Its unique Mills cross antenna configuration and modularity allow for both multi-beam and spaced-antenna modes wind measurements. Saura measurements are sensitive to perturbations of magnetospheric and solar origin in the D region (e.g., particle precipitation, solar flares, solar proton events, etc.) and allow us to investigate the coupling to the ionosphere at these altitudes.

- SIMONe is the most modern implementation of an observational concept using SMRs called MMARIA[27]. SIMONe systems use modern radar practices like MIMO, spread-spectrum and compressed sensing; are easy to implement and operate; and are affordable and reliable. Given their multi-static configuration and consequent observing diversity, horizontally-resolved MLT wind fields can be obtained. Furthermore, spatial and temporal wind-field analyses are also possible inside the observing volume from second-order statistics of line-of-sight velocities. SIMONe has also been proven to observe echoes from E region plasma irregularities (e.g., equatorial and auroral electrojet instabilities), and non-specular meteor echoes. These echoes represent an opportunity to extend IAP studies to higher altitudes.

The aforementioned radar capabilities represent a mix of large facilities (e.g., MAARSY and Saura) and small but distributed facilities (e.g., SIMONe). The large facilities allow local and high-resolution studies of MLT processes that are complemented by rocket campaigns and ground- and satellite-based observations. On the other hand, the distributed facilities are relatively easy to deploy, making them suitable to study MLT mesoscale dynamics by filling observational gap regions (e.g., Southern Argentina), operating close to large non-IAP facilities (e.g., Jicamarca Radio Observatory, EISCAT[28]-3D), or participating on multi-instrument campaigns world-wide.

Traditionally IAP radars have also been used to study large and planetary scale MLT dynamics (e.g., tides and planetary waves) from its single-station observations. In recent years, in collaboration with national and international groups, IAP colleagues have led the spatial (wavenumber) and temporal (frequency) studies of tides and planetary waves by using multiple SMRs at mid and high northern latitudes. These studies will be continued and extended to low latitudes by deploying new systems, collaborating with relevant international groups, and incorporating complementary satellite measurements (e.g., MIGHTI [29] on board the ICON[30] NASA[31] satellite).

[25] Upper-Troposphere and Lower Stratosphere
[26] Kilpisjärvi Atmospheric Imaging Receiver Array
[27] Multi-static Multi-frequency Agile Radar Investigation of the Atmosphere
[28] European Incoherent Scatter Scientific Association
[29] Michelson Interferometer for Global High-resolution Thermospheric Imaging
[30] Ionospheric CONnection explorer
[31] National Aeronautics and Space Administration

5.3 Sounding rockets

IAP primarily uses sounding rockets to measure background parameters and small-scale structures not measurable in the MLT by other means. IAP employs and develops unique rocket instruments and expertise, e.g., for turbulence measurements in MLT by ionization gauges (e.g., CONE[32]) or absolute electron density measurements. Due to well-developed technical infrastructure and successful cooperation with small and medium-sized enterprises, IAP develops new and unique rocket instruments and improves existing in situ measurement techniques. Also, in collaboration with the Institute of Space Systems in Stuttgart, we develop new compact instruments for trace gas concentration measurements (e.g., atomic and molecular oxygen and carbon dioxide). Furthermore, IAP has developed plasma probes for density measurements of all dusty plasma constituents, including aerosols (tiny dust and ice particles). All these measurements combined with lidar and radar observations will be used for 3D studies of neutral and plasma dynamics. This includes studies of gravity waves, turbulent mixing, and energy transfer, as well as plasma-chemical reactions to understand atmospheric emissions (airglow) and non-local thermodynamic equilibrium. The measurements will be made in the frame of sounding rocket projects led by IAP in collaboration with other research groups worldwide.

5.4 Modelling

In order to address topics associated with its research themes, IAP uses and develops analytical and numerical models to quantify dynamical processes of the middle and upper atmosphere and to reach synergies with observations of atmospheric parameters. These activities address large-scale circulation and variability patterns, vertical and interhemispheric coupling, generation and effects of planetary waves, tides, gravity waves, and their interaction, as well as small-scale turbulence and their interplay with large- and medium-scale waves, and transport of photochemical species. To address its complexity, global circulation models and models of specific processes are of particular interest.

Global general circulation models. At IAP, global general circulation models are implemented, run, and used for process studies, as well as to provide synthetic, but as much as possible realistic data to bring observations in a background dynamical context and to initialise IAP's regional models. As an important activity, IAP develops particular dynamical formulations and parameterisations of GCMs and plans to further extend towards a better representation of atmosphere/ionosphere interactions at MLT in the future. Currently, two GCMs are implemented at IAP.

- UA-ICON[33] is the upper-atmosphere extension of the GCM ICON, which provides, e.g., local mass conservation, a flexible grid nesting option, and a non-hydrostatic dynamical core formulated on an icosahedral–triangular grid. It has been jointly developed by the Max Planck Institute for Meteorology and the German Weather Service (DWD) and is currently implemented at DWD for weather analyses, now- and forecasts. The extension to the upper atmosphere was realised within the DFG research unit MS-GWaves[34], in which IAP participated. To address altitudes up to ∼150 km, the main components of UA-ICON are the extension of the dynamical core from shallow- to deep-atmosphere dynamics and the implementation of an upper-atmosphere physics package including an ion drag parameterisation. IAP will focus on validating the performance of UA-ICON at MLT altitudes against own and globally

[32] COmbined sensor for Neutrals and Electrons
[33] Upper Atmosphere - ICOsahedral Non-hydrostatic
[34] Multiscale Dynamics of Gravity Waves

distributed observations. The climatology of simulated atmospheric parameters and dynamics deduced from long-term runs will be tested for different initialisations, for example, increased resolution nesting or the option for advanced gravity wave parameterisation. From there, we will formulate relevant recommendations for future model developments. Active development of the upper atmosphere modules of UA-ICON by enhancing dedicated formulations with respect to dynamics, kinetics, or chemical heating is a goal of IAP.

- KMCM[35] is a hydrostatic global circulation model for general circulations from the surface to the lower thermosphere with particular emphasis on dynamical interaction between different scales and altitude regions. Its radiative transfer scheme and representation of the moisture cycle are idealised, it includes a slap-ocean model, and has no chemistry module. On the other hand, KMCM includes advanced parameterisations of subgrid-scale macro-turbulence at high-resolution. HIAMCM[36] is a vertical extension of KMCM (up to $\sim$450 km) and includes nonhydrostatic dynamic corrections, full molecular viscosity, a variable gas constant, heat capacity, and ion drag. KMCM was developed at IAP over the last 25 years. HIAMCM is now being further developed at NWRA[37] at Boulder, USA in cooperation with IAP. IAP plans to use runs of KMCM/HIAMCM with nudged reanalyses in the lower atmosphere and a newly developed gravity wave scheme at high resolution to complement IAP's dynamical studies.

Models of specific physical processes. IAP runs and develops specific models of atmospheric photochemistry, mesospheric ice particles, and models to overcome imperfect parameterisation of small-scale dynamics and to provide reliable physical formulations to observed evidence.

- CTM-IAP[38] simulates the advective, molecular and turbulent diffusive transport, and the photochemistry of all relevant minor chemical constituents in the upper stratosphere–mesosphere-lower thermosphere. Additionally, it contains modules for the simulation of airglow and simplified plasma chemistry of the D and E regions. The accuracy of airglow simulation was recently improved by introducing validated self-consistent atmospheric band (762 nm) fitting coefficients, and the influence of Lyman-alpha variations was enhanced. We plan to include online calculations of dissociation and ionisation rates and to make use of satellite-derived vertical diffusivities. CTM-IAP can be driven by wind and temperature fields for the middle atmosphere from dynamical models or meteorological analyses to study effects of planetary waves, gravity waves, sudden stratospheric warmings, 11-year solar cycle, and anthropogenic changes on the photo-chemistry and airglow of the mesopause region. As future applications, we consider, e.g., the investigation of the influence of sporadic E-layer on chemistry and emissions, the long-term behaviour of chemical heat, ozone and radio-wave reflection height.

- MIMAS[39] is a 3D Lagrangian ice particle model for the polar mesosphere. Water vapour and an ensemble of 40 million particles are transported by winds from a GCM. Dust/ice particles drift in the atmosphere according to three-dimensional and time-dependent background winds, eddy diffusion, and sedimentation. The model takes into account simplified photochemistry and is well suited to study solar cycle effects on NLC and PMSE. The model has been ideally adapted to investigate the

[35] Kühlungsborn Mechanistic Circulation Model
[36] HIgh Altitude Mechanistic general Circulation Model
[37] North West Research Associates
[38] Chemistry Transport Model at IAP
[39] Mesospheric Ice Microphysics And tranSport model

influence of dynamics on the morphology of NLC from small scales to planetary scales. MIMAS is a unique tool for comprehending observations of icy layers by lidar, radar and cameras.

- Processes leading to small-scale dynamics have been studied in recent years with DNS in collaboration with international groups. Such DNS, although computational demanding, have been proven essential to understand the observed features and to develop theoretical models. With the advent of IAP's new lidar and radar concepts with 3D capabilities, DNS development and implementation will be pursued in collaboration with external peers. For example, to achieve a better one-to-one comparison between observations and DNS predictions, the latter should be pursued using boundary and background conditions provided by high-resolution regional atmospheric models (e.g., by UA-ICON).

5.5 Complementary activities

Satellites and space-based data. IAP will exploit the benefits of satellite observations to reach a global picture of the spatial-temporal variation of atmospheric parameters. Thereby, we want to emphasise the connection between local and global observations/processes by joint analyses with IAP's ground-based data. Furthermore, developments in synoptic or global scale models, e.g., GCM-type models, require global data sets that also cover regions inaccessible by ground-based installations, e.g., over oceans and deserts. Therefore, at IAP some studies will be complemented by (a) remote sensing satellites accessing MLT parameters, and (b) in situ data in the thermosphere and ionosphere.

We have been working with observations of AIM[40], Envisat[41], GOLD[42], MIGHTI/ICON, MLS[43], Swarm, Odin, among others. To Swarm, we are connected by ESA supported contracts to develop new data products, that relate to the interplay between the neutral atmosphere and the ionosphere.

Of particular interest are new initiatives for missions that are dedicated to explore the MLT in situ. In 2020, the Daedalus concept was assessed scientifically as 'highly competitive' by ESA[44]'s Advisory Board for Earth Observation, however, the mission did not reach into the next phase of accomplishment. Nevertheless, the concept will be pursued further and we plan to apply our expertise for relevant product definition and validation.

Passive optics. Ground-based cameras for airglow and noctilucent clouds operated by IAP and collaborators have revealed persistent small-scale processes on the observed airglow layers and noctilucent clouds. In cooperation with our partners, we will complement studies by multi-instrument observations, i.e., lidar and radar provide vertical and time-resolved observations while cameras provide horizontal information. We intend to extend such capability of horizontal coverage, e.g., to complement SIMONe's 3D wind-field structures.

Reanalyses. Meteorological reanalyses are data sets of simulation models with assimilated observations on a daily or higher frequency. These data sets extend from ground up to the mesosphere. We use reanalyses to specify background conditions and initialise MLT model runs. The resulting model predictions will help us to interpret regional observations. We have been applying MERRA[45] and ECMWF[46]

[40] Aeronomy of Ice in the Mesosphere
[41] Environmental Satellite
[42] Global-scale Observations of the Limb and Disk
[43] Microwave Limb Sounder
[44] European Space Agency
[45] Modern-Era Retrospective analysis for Research and Applications
[46] European Centre for Medium-Range Weather Forecasts

reanalyses and will continue doing so. An exciting path is to extend the reanalyses to higher altitudes into the MLT, e.g. by using IAP measurements to assess and validate re-analyses in the MLT.

Whole atmosphere community models. Community models that aim to model the whole atmosphere and near-Earth space are composed of modules developed from relevant disciplines. Examples are the US WACCM-X[47], the Japanese GAIA[48], or the German ICON, the latter has recently been extended to the MLT with its version UA-ICON.

We have been using runs of, e.g., WACCM-X and ICON to support our analyses. We plan to intensify the collaborations with these communities as follows: (1) applying the global synthetic data set as background information to initialise our regional models and (2) contributing with specific model developments at IAP to enhance their performance in dedicated formulations or parameterisation.

Advanced mathematical approaches. The development of new instruments and techniques, derivation of multiple parameters, exploitation of large data sets, etc., require the improvement and implementation of advanced mathematical approaches. Many of these approaches are established, and thanks to available and affordable computational capabilities, they can be now implemented and pursued. In the past few years, we have explored and implemented approaches related to statistical inverse problems and artificial intelligence such as machine learning (e.g., Gaussian Process Regression). In the upcoming years, we plan to continue the exploration of such approaches, including data mining, in close collaboration with experts in mathematics and engineering.

Collaborative campaigns. Traditionally, IAP's research has been focused around its major facilities (e.g., ALOMAR). These efforts have paid off by significantly improving the understanding of polar mesospheric processes (e.g., PMSE). IAP will extend its perspectives to achieve knowledge in a global context and explore other regions and relevant processes. Therefore, with the help of mobile installations (lidars and/or radars, see above) and, of course, with strong international collaboration, we will pursue participation in scientific campaigns worldwide relevant to IAP's scientific objectives. These participations will be realised by efforts led by IAP and by joining collaborative efforts. Examples of possible campaigns are: (a) around large international facilities (e.g., EISCAT-3D, Jicamarca Radio Observatory, HAARP[49]), (b) in conjunction with multi-instrument campaigns (e.g., similar to SouthTRAC-GW[50], PMC-Turbo[51]), and (c) dedicated to particular geophysical conditions or events.

[47] Whole Atmosphere Community Climate Model with thermosphere and ionosphere eXtension

[48] Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy

[49] High Frequency Active Auroral Research Program

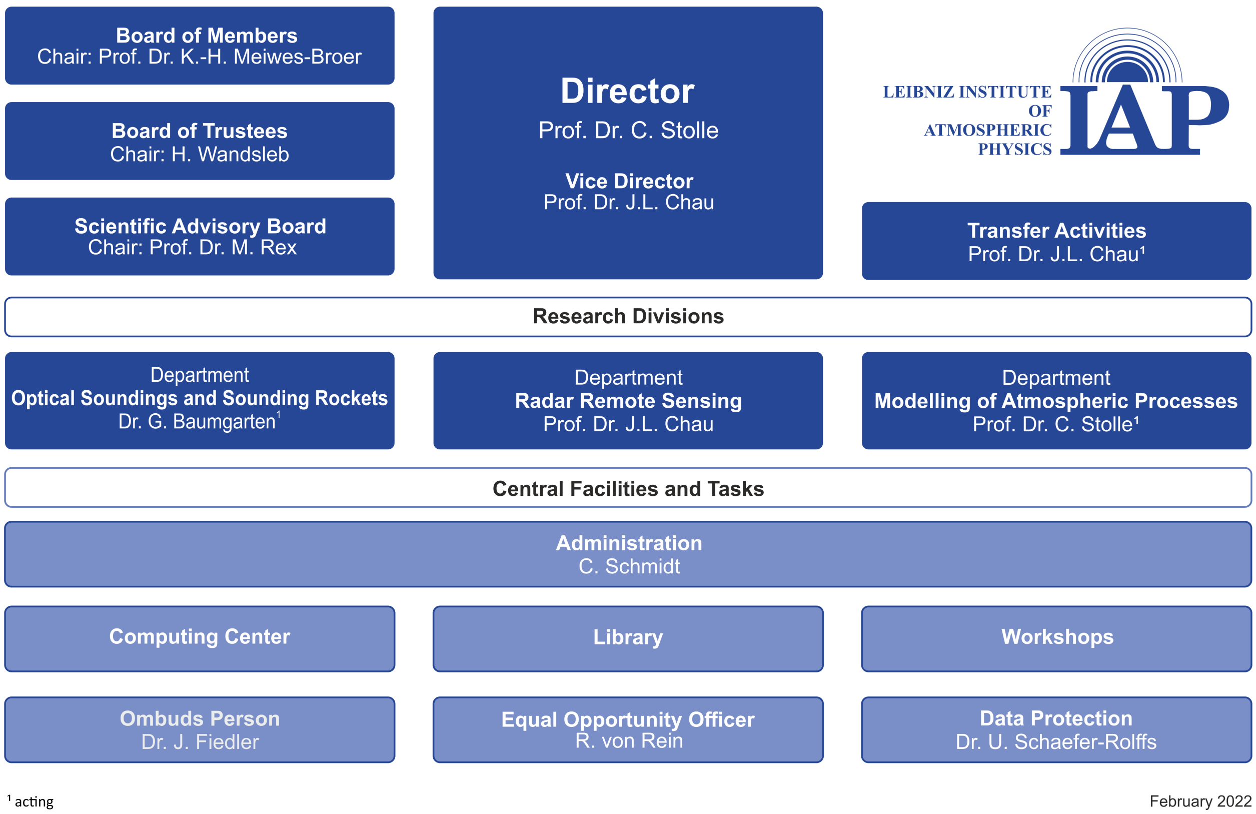
[50] Southern Hemisphere Transport, Dynamics, and Chemistry–Gravity Waves airborne mission

[51] Polar Mesospheric Cloud Turbulence stratospheric long-duration balloon experiment.

6 Implementation

IAP has established and will further develop an institutional and collaborative infrastructure that is most effective in implementing its mission and research themes.

6.1 Internal structure



Organisational structure of IAP

IAP runs three departments dedicated to study the research themes formulated in Section 4 from different experimental and theoretical perspectives. The department heads report to the director and collaborate with her to study these themes. The communication between IAP and the non-academic world is is realised through Transfer Activities. The administrative head assists the director in financial controlling and contractual matters. The Computing Centre, the Library, and Workshops provide supporting infrastructure to all departments. The director reports to the Board of Members and to the Board of Trustees who confirm major strategic and financial decisions of the institute. The Scientific Advisory Board provides independent scientific advice.

Within the upcoming period, IAP will further develop its organisational structure, which will align with the appointment of heads for two departments and respond to needs for personnel with dedicated responsibilities in transfer activities and public relations.

A strong component in exploiting the unique composition of scientific expertise at IAP has been cross-departmental collaborations in specific topics. These groups will form for a duration of several months to a few years and will work on outstanding questions in MLT research. Currently active cross-department collaborating topics are on "Stratified turbulence" and "Noctilucent clouds and mesospheric echoes". These groups consist of both senior, early career scientists, and doctoral students. In addition, doctoral seminars are organised regularly to facilitate discussion on running thesis topics within the institute and to provide broader academic experience to IAP's doctoral students.

6.2 Cooperation with the University of Rostock

IAP is an associated institute of the University of Rostock and holds close relationship in both education and research areas. The director and the department heads hold professorships at the University which allows them teaching classes and supervise undergraduate and doctoral students. IAP, together with the Leibniz Institute for Baltic Sea Research, Warnemünde (IOW, also an associated institute of the University of Rostock), and the University form a specialised master programme "Atmospheric Physics and Oceanography" within the Institute of Physics. In the next few years, the programme will further develop, e.g., together with teaching opportunities by the DLR[52] Institute for Solar-Terrestrial Physics in Neustrelitz, to establish an attractive Earth Science programme that will add aspects of near Earth space and space weather. The disciplinary programme will reflect the interconnection between the different components in the Earth's system.

Direct contact with students is an essential part of attracting early career scientists for IAP and guarantees the transfer of knowledge and expertise to future scientific generations. In turn, it provides a valuable opportunity for postdoctoral members of IAP to expand their teaching experience.

The link to the University of Rostock is an important component in developing an excellent regional research programme in Earth sciences, making Mecklenburg-Vorpommern an attractive area for students at all levels and emitting highly qualified talents nationally and internationally.

6.3 Cooperation with other scientific partners

Cooperation with national and international partners at universities and research centres is of crucial importance to achieve, position, and reflect the research goals of IAP. Besides connecting IAP's scientific output to different communities, these cooperations allow expansions to specific topics which do not lie within IAP's core expertise but are needed to build competitive answers from a multidisciplinary view. Currently active cooperation, national and international, are reported regularly in IAP's biennial institute reports available from the institute's website. Among others, IAP currently cooperates strategically with the following partners:

- Andøya Space and ALOMAR, Norway. Sounding rocket launch, lidar and radar operation sites are part of IAP's large facilities. Frequent joint campaigns with the EISCAT incoherent scatter radars, and in the near future with EISCAT-3D.
- Haystack Observatory at the Massachusetts Institute of Technology, USA. Co-development of wind-field analysis and SIMONe-like systems.
- Jicamarca Radio Observatory at the Geophysical Institute of Peru, Peru. Complementary studies of MLT dynamics and low-latitude electrodynamics.
- UiT The Arctic University of Norway, Norway. Development of sophisticated radar techniques to explore the MLT and the ionized E region at high and low latitudes.

[52] German Aerospace Center (en)

- ILT[53], Aachen, Germany. Co-development of compact diode pumped Alexandrit ring laser for Doppler resonance, Rayleigh, Mie scatter.
- Max Planck Institute for Meteorology, Hamburg and DWD, Offenbach, Germany. Application, implementation and development of the UA-ICON, the German whole atmosphere community model. IAP runs high resolution modes to compare with observations. IAP will contribute to developing the upper atmosphere part of UA-ICON.
- NWRA[54], Boulder, USA. Application, implementation and development of KMCM/HIAMCM. Developing new wave formulation schemes, e.g., by supervising two PhD theses together with NWRA scientists. Application of high resolution HIAMCM runs to compare with observations.
- École Centrale de Lyon, France. Studies of stratified flows, including extreme events, with DNS, theory, and observations.

Employees of IAP serve the community as chairs in international scientific associations such as COSPAR[55], SCOSTEP[56], or URSI[57], which enhances visibility and disposition for continued and new collaborations and opportunities for organising dedicated conferences.

The availability of high-quality facilities run by IAP and its integration into global networks is regarded as a beneficial asset that will further develop in the next period. IAP continuously contribute data to, e.g., GIRO[58], and the European DIAS[59]. We connect our data and research with a considerable number of satellite communities by dedicated research projects partly funded through DLR, ESA or NASA, such as AIM, Envisat, GOLD, ICON, MLS, Swarm, Odin. IAP researchers have also supported the Daedalus concept, which aims to bring satellites into elliptical orbits to realise in situ measurements as low as ∼130 km. To intensify IAP's involvement in working with and participating in satellite missions, we will explore enhancing the cooperation with Space Agencies and the European Commission.

We plan to keep and further develop a guest scientist's programme to foster these collaborations. This consists of visiting to and invitations of colleagues from other institutions for scientific presentations and discussions (either virtually or in person) and research stays of days to weeks, which we see as one effective instrument to maintain national and international collaboration.

6.4 Transfer

Transfer activities refer to the exchange between IAP's research activities and the non-academic world. This strategy follows the definition of transfer of the Leibniz Association[60] closely. Although basic research is the main focus of IAP, transfer activities have become increasingly recognised to justify specialised science topics and to support understanding for its societal need. Our approach includes both exchange directions: from IAP to non-academics and from non-academics to IAP. In the upcoming years, IAP's transfer strategy is to identify and conduct selected activities to promote an efficient and valuable exchange with the following societal groups: general public, commercial partners, as well as authorities and policymakers. Future efforts will be devoted to increase and improve our transfer activities. Examples of these activities are: (a) Public Outreach (e.g., organising IAP public view days,

[53]Institute for Laser Technology
[54]NorthWest Research Associates
[55]Committee on Space Research
[56]Scientific Committee on Solar-Terrestrial Physics
[57]Union Radio-Scientifique Internationale
[58]Global Ionospheric Radio Observatory
[59]DIgital upper Atmosphere Server
[60]https://www.leibniz-gemeinschaft.de/ueber-uns/neues/mediathek/publikationen/leitbild-leibniz-transfer/

issuing posts for journalists, etc.), (b) Training (e.g., training of school students), (c) Capacity Building (e.g., training of foreign professionals), (d) Citizen Science (e.g., sharing our real-time observations, connection to amateur radio and aviation communities), and (e) Technology Transfer by establishing collaboration with industrial partners through projects of commercialised technical development.

6.5 Quality measures

The performance of IAP activities is assessed within different categories.

Science and Technology. A measure for qualitative scientific results is that these are openly discussed and made available to scientific forums. Relevant items are publications (including open access) in recognised journals, and participation in both, national and international meetings. A rough reference of at least one publication per scientific staff member and contribution to an international conference either virtually or in person per year applies. Another relevant criterion is a successful performance demonstration of newly developed instrumentation or software, e.g., by delivering selected time series. The connectivity of IAP's research and technological activities shall be reflected by participation in national and international initiatives, in proposals to funding bodies on both national and European levels, or to some parts in commercial contracts. These initiatives will ensure a sound balance between base and external funding streams.

Education. Besides an active contribution to the teaching programme at the University of Rostock by joint professorships, IAP scientific staff is expected to supervise an adequate number of undergraduate and doctoral students. The interplay between supervisors and student aims at successful graduation and good conditions for students' future opportunities at either IAP or abroad.

Diversity. Scientific development is stimulated by different approaches, perspectives and experiences. IAP regularly monitors its staff diversity in terms of internationality, gender, age, and career level and raises awareness in case of severe imbalance. IAP participates in regular audits on family-friendly policy and has received the certification „berufundfamilie" (carrier and family) continuously since 2014.

Reporting and Reviews. IAP issues a Strategic Science Plan roughly every seven years prior to regular evaluations organised by the Leibniz Association. It is discussed with the Scientific Advisory Board and approved by the Board of Trustees. Finally, the Strategic Science Plan is adopted in the strategic part of the evaluation documents. These documents are assessed by an independent evaluation committee appointed by the Senate of the Leibniz Association and subsequently by the Senate of the Leibniz Association.

Additionally, IAP releases an institute report and a work plan roughly every two years. These documents reflect results achieved and provide implementation strategies for the next two years to realise the Strategic Science Plan, respectively. These documents are then reviewed and approved by the Board of Trustees.

7 Concluding remarks

The Strategic Science Plan formulates IAP's goals for the next several years, which we believe are highly relevant and feasible. Adaptations of the programme are possible due to new emerging topics or changes in IAP's expertise and personnel.

The success of the Strategic Science Plan primarily relies on the scientific and technical personnel working at IAP. It can only be implemented if it is accepted and realised with motivation. We hope to generate enthusiasm for the programme at IAP.

Kühlungsborn, 28. Februar 2022

Prof. Dr. Claudia Stolle

Prof. Dr. Jorge L. Chau

Dr. Gerd Baumgarten