

Grand Challenge Initiative

M/LT Project

White Paper



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Background

The Grand Challenge Initiative CUSP (2018-2021)

The Grand Challenge Initiative (GCI) CUSP is a large-scale international collaboration effort targeting advancement in specific, fundamental issues in space and earth science. The GCI Cusp concept was conceived and developed between 2012 and 2017 by Andøya Space Center (ASC), University of Oslo and NASA. The work culminated in the first GCI project – “GCI Cusp” – to determine the multi-scale physics of heating and charged particle precipitation in the ionosphere specific to the geomagnetic coupling to the solar wind in the cusp region. The GCI Cusp Project is designed to dramatically advance the common understanding of cusp region space physics through coordinated experimental and theoretical research using ground-based instruments, modeling, sounding rocket investigations, and satellite-based instruments. International student participation through space plasma model development and a dedicated student rocket (G-CHASER) is an essential aspect of the GCI concept. Strategic use of public outreach, particularly via the tools of social media, is also a vital component of the GCI Cusp Project. The core of the GCI Cusp Project is 9 sounding rocket missions, independently conceived and developed through the respective space exploration agencies of the US, Norway and Japan. The rockets are launched in conjunction with observations of the cusp from an aggregate of state-of-the-art ground-based scientific instrumentation, including incoherent and coherent backscatter radars, all-sky cameras, meridian scanning photometers, magnetometers, and other instruments, which will operate continuously throughout the launch window. The formulation (and topic) of this initial GCI project followed the recognition of the tremendous increase in scientific return available from coordination of these independently initiated missions. Additional sounding rocket missions from these agencies as well as other national agencies are under consideration to complement the current project and expand further the scale of international collaboration. Until Dec 2019, 9 out of the 12 GCI Cusp rockets have been launched successfully from Andøya Space Center and SvalRak (ASC launch site at Ny-Ålesund, Svalbard).

Why Grand Challenge Initiative – M/LT (2022-2026)?

In the past there have been various activities at several institutes to study the middle atmosphere (more precisely the mesosphere and lower thermosphere, MLT) with sounding rockets. There have been some coordinated efforts to study dynamical processes (e. g., gravity waves) by a combination of sounding rockets and ground-based instrumentation.

Examples: NASA Mountain Waves Ascending Vertically (MacWAVE), and NASA Mesosphere-Lower Thermosphere Turbulence Experiment (M-TEX), DLR-Space Agency-funded WADIS: Wave propagation and dissipation in the middle atmosphere.

However, in most cases these programs involved a limited group of scientists. Obviously, in situ measurements are commonly accompanied by appropriate ground-based observations by, e. g., lidars and radars. However, there has so far not been any attempt to combine airborne remote sensing of the middle atmosphere with rocket borne in-situ measurements. Since airborne platforms have recently been established as a powerful means to study the middle atmosphere and lower thermosphere (e.g., NSF DEEPWAVE, and German GW-LCYCLE and SOUTHTRAC-projects), the combination of both approaches appears as a logical next step.

A coordinated effort for scientific application of all (or at least of several of the) available established research platforms for investigating the middle atmosphere and lower

atmosphere, including (and spearheaded by) sounding rockets, is timely, because all of them have now matured to a state that synergistic use of them promises a large step forward. For all these platforms, an impressive suite of new instrumental techniques has been developed in recent years (see below).

Furthermore, recent theoretical and modeling developments allow us to study dynamical processes on a large range of scales, including the potential impact of small-scale processes on global scales, an ability that appeared inconceivable over many years in the past

The aim of this white paper is to coordinate future activities to study the physics and chemistry of the MLT, on an international level with special emphasis on 4D nature of atmospheric dynamics (from large to very small scales; including , Gravity Wave generation, propagation and dissipation as well as its interaction with and forcing of the mean flow) and on composition (ions, neutrals, and aerosols), at low, middle and high latitudes (research interests determines latitude). The overall strategic aim of GCI-M/LT is to expand and coordinate our science aims regarding the Middle Atmosphere-Lower Thermosphere for the next decade. It is an open initiative, e. g. interested groups or scientists are invited to join, provided their science topic is related to the overall aims of GCI M/LT highlighted below.

GCI M/LT Science Topics

Impressive science results regarding the dynamical, thermal and compositional structure of the MA (middle atmosphere) have been achieved over the past decades and have led to a more detailed understanding of several physical and chemical processes in the MLT region, as well as concerning the coupling mechanisms to below and above. In particular, it has been understood, that small-scale dynamical processes like gravity waves (GW), their propagation in such complicated environment as the Earth's atmosphere resulting in numerous types of interactions, is the most uncertain part of our current understanding of this system. At the same time, it is clear that small-scale dynamics is ultimately connected to larger scale processes and plays a crucial role in the dynamics of the entire atmospheric system. Our knowledge of small-scale dynamics is far from being complete and the main reason for that is lack of empirical data which, in turn, is mainly due to the complexity of experimental investigation of the MA and technical limitations. Previous campaigns and projects concentrated on regional processes within a rather limited range of spatial scales (local observations; profiles at one location etc.). In order to address the most urgent open science questions a broader view on the dynamical processes covering multiple scales is required which includes the transition from large to very small scales.

A compelling example underlining the need for a multi-scale approach to foster progress in MLT science is the vertical coupling of the atmospheric layers where large scale dynamical processes (such as baroclinic instability; scale $O(10.000\text{km})$) are the ultimate source for the excitation of small-scale gravity waves. These gravity waves then propagate upwards, undergo a series of complex physical processes such as horizontal refraction, reflection, tunneling, excitation of secondary waves etc. until they dissipate (spatial scale $O(10\text{m})$) and ultimately deposit their momentum at vast distances from their origin and thereby drive the global circulation in the upper mesosphere (spatial scale $O(10.000\text{km})$). Importantly, the processes sketched above not only affect the dynamical and thermal structure of the whole middle atmosphere, they also directly affect the distribution of important species like ozone,

water vapor and others by corresponding large-scale advection, but also mixing processes involving both gravity wave and turbulent scales.

Sounding rockets are the backbone of significant progress in MLT science by conducting measurements of physical quantities which cannot be measured by any other means and can reach a resolution that is also not possible otherwise. This includes, but is not limited to GW, turbulence, their effect on trace constituents including aerosols or dust particles, ionospheric plasma structures due to waves and instabilities, and chemical processes. Also, we still have very limited knowledge on non-LTE (local thermodynamically equilibrium) processes in the MLT and the role they play in the energy budget of that atmospheric region.

By utilizing modern high-resolution measurement techniques sounding rockets can yield very detailed picture of a phenomenon under investigation. On the other hand, rocket measurements are very localized. Therefore, it is obvious that to investigate atmospheric phenomena at different scales in situ measurements must be closely coordinated with simultaneous ground based (radars, lidars, airglow, etc.), air-borne (Haloe, Geophysica, etc.), and satellite (MATS, AWE, etc.) borne observations.

New observational techniques have recently been (or are currently) developed which allow unprecedented coverage of multiscale processes from Rossby waves to turbulence. This concerns e. g. in-situ (sounding rockets, balloons) as well as ground-based (lidar, radar), air-borne, and satellite techniques.

These new techniques and the related expertise are developed at various institutes. Some examples of new instrumental capabilities which have recently been developed or will be available soon are as follows:

Sounding rockets: multi-probes measure several vertical profiles with ultra-high resolution simultaneously. Examples: TURB3D, chemical releases, re-establishment of rocket borne mass spectrometry.

New sounding rocket motor developments will allow to sound a certain height range within the MA horizontally (Huber-Craft, DLR-Space Operations, Oberpfaffenhofen) or by utilizing the Nucleus Neo hybrid rocket motor currently under development at the Norwegian company NAMMO. The first Nucleus motor was launched into space from Andøya Space Center in September 2018 to an altitude of 107.4 km with a payload weight of 72 kg. The Nucleus Neo will be an improved version with better capacity and TWC.

Ground-based techniques such as lidar and radar were so far limited to local observations (mostly in a single column) but sophisticated recent developments promise to cover much larger regional scales of several hundred kilometers quasi-simultaneously. Examples: MMARIA, VAHCOLI, temperature mapper.

These upcoming capabilities shall be combined with comprehensive and established techniques such as MAARSY and RMR-Lidars.

Recently, also research aircraft have been established as powerful platforms for remote sensing of the whole atmosphere from flight level (typically at ~10 km) to the lower thermosphere. Examples are the very successful NSF-led DEEPWAVE campaign in New Zealand (Fritts et al., 2016), the sequence of German GW-LCYCLE campaigns in the Arctic (e.g., Wagner et al., 2017), and the only recently completed SOUTHTRAC campaign at the Southern tip of South America (<https://www.pa.op.dlr.de/southtrac/>). During all these aircraft campaigns remote sensing instruments (lidars, airglow imagers) for probing the atmospheric column up to 100 km altitude were applied and combined with ground-based measurements with lidars and radars as well as satellite borne remote sensing. Similarly, the last years have

also seen the first successful balloon flight of a lidar that probed the thermal structure as well as aerosol and cloud content of the atmosphere from flight level to ~90 km altitude (Fritts et al., 2019). However, while these recent developments allow for unprecedented insight into horizontal scales of the MLT from a few kilometers to a few thousand kilometers at comparably high spatial resolution (km scale in the horizontal, ~50m in the vertical), these techniques still do not allow to access spatial scales at which dissipation of kinetic energy into heat occurs. Hence, the time for combination of these new experimental platforms with sounding rocket measurements is ripe!

LITOS: for the first time ultra-high-resolution measurements of structures (turbulence) in the stratosphere.

New sophisticated theoretical and modelling ... (DNS, KMCM, CTM, ...)

These new and exciting capabilities are developed at several different institutes. Their application in a common science initiative therefore requires coordinated efforts.

By combining these various research tools, we can advance our knowledge of Earth's atmosphere system as well as in pure academic science related to e.g., turbulence and non-LTE processes. Some examples of the science questions that are to be addressed.

Neutral dynamics:

- Forcing of waves by dynamical processes in the troposphere and their subsequent propagation and interaction with the ambient atmosphere until they reach the MLT or even beyond (e.g., generation of plasma bubbles in the F-region).
- Role of these processes on tropospheric climate. E.g., downward coupling of middle atmosphere perturbations during stratospheric warmings and their effect on regional (extreme) weather events.
- Transition from larger to smaller scales, wave-wave (GW, PW, tides), wave-mean flow, and wave-turbulence interactions and their impact on the atmospheric system.
- Different regimes of turbulence in highly variable atmospheric environment taking into account drastically changing stratification of density (temperature) and of the background flow (wind shear).
 - Their impact on the atmospheric system, in particular role of different turbulence regimes in the energy budget of the MA (heating/cooling), horizontal and vertical mixing and transport, chemical processes (e.g., ion- and photo-chemistry), wave propagation and breakdown.
 - Their interpretation in frame of turbulence science by addressing questions like horizontal and vertical mixing, transport and turbulent diffusion at different scales, energy cascade and scaling laws, relation between energy and scalar spectra for different constituents, wave propagation and breakdown in turbulent media.
- Propagation, breakdown, and its impact on the background of GW in highly variable atmospheric environment (both in space and time).
- Turbulent mixing at high altitudes and turbopause concept: Ar/N₂ (BUGATTI mass spectrometer).
- Relationship between mean conditions and variability. E.g., observed winds are up to 150 m/s, whereas models imply mean of 20 m/s.

- How to separate (understand) role of different scales, since large- and small-scale processes cannot easily be separated because there are many non-linear effects such that the mean effect of the variations is not zero and, also the large-scale processes act as background for smaller scale processes.
- Why is the MLT practically permanently turbulent, as is suggested from observations of PMSE and PMWE?
- Role of secondary GW-generation in the MLT for coupling the lower atmosphere to the thermosphere. Does the generation of secondary gravity waves contribute to wave mixing?

Many of these points can be addressed e.g., by simultaneous wind and turbulence measurements with TMA releases and in situ turbulence measurements by CONE (in the MLT) as well as by balloon-borne measurements by LITOS accompanied by in situ measurements of different scalar spectra and winds (in the stratosphere).

Mesospheric dust:

- Goals of mesospheric dust studies are to better understand the dust origin, evolution and interactions. Remote observations have advanced during the last decade and provide information on average size, composition and spatial distributions. Simulation models also provide information on average size and distribution. It is an open question to what extent properties vary locally. The role of dust in ice formation and dust growth is not clear as well as the formation of PMSE and the role of dust in the PMSE formation. Dust charging, the growth process and the potential role of dust in ice formation need to be approached by a combination of model calculations, remote observations and in-situ measurements including the laboratory study of collected samples. Because of the complexity of the different links simultaneous observations of ionospheric parameters is important.

Plasma dynamics and coupling with neutral atmosphere:

- Which physical processes are involved and dominate in different regions of atmosphere (latitudinal and altitudinal dependences) and at which (different) scales?
- Role of neutral air turbulence in a weakly ionized collisionally dominated plasma (where coupling between neutrals and ions/electrons gets weaker and weaker).
- Effect of ionospheric plasma (including small-scale plasma processes) on the mean neutral state.
- Lightning/High Altitude Discharges
- Impact of particle precipitation on Ozone/NO_x variability

Composition and chemistry:

- Non-LTE is a key problem for interpretation of broadband infrared molecular emission radiometry widely used by satellites. Can easily be addressed by simultaneous in situ measurements of temperature and densities of O, CO₂, and neutral air and corresponding emissions above ~60 km (vibrational vs kinetic temperatures issue)

- Trace gases (passive and active) e.g. atomic oxygen (e.g., deactivation of CO₂).
- Ice and dust particles: their densities, formation mechanism, charging processes, and role of their charged fraction in formation/variability of the observable phenomena NLC, PMC, PMSE, and PMWE.
- Composition (both neutral and charged components).
- Metal layers: ion composition and chemistry. Coupling from/to above and below
- Transport of NO_x from lower thermosphere to stratosphere NOT correctly represented in models.
- What is the appropriate Eddy diffusion coefficient? Increase eddy diffusion, without destroying energy balance in models (is change of Prandtl number is a correct solution?).
- Does (and how) the efficiency of turbulent transport for constituents differs from the transport of heat?

Interhemispheric Coupling:

Student Science:

GCI-M/LT, and for that matter GCI-Cusp, requires scientists, engineers, and technicians to achieve the discoveries these campaigns set out to accomplish. Training new scientists, engineers, and technicians to enable future campaigns is a goal for GCI-M/LT campaign. Like GCI-Cusp, GCI-M/LT will have a science mission that will involve college and university students from partnering institutions and countries on a dedicated sounding rocket flight for students. These students will have the opportunity to learn, experience, contribute their own individual but similar science missions to the overall GCI-M/LT campaign.

This student mission is called GHOST, which stands for “Grand Challenge Initiative: M/LT Student Rocket” and will be based on the successful student mission for GCI CUSP called G-CHASER. Over 100 students from seven teams from Norway, Japan, and the USA participated in the G-CHASER program the culminated in a launch from Andøya Space Center (ASC) in Norway on January 13, 2019. Each student team developed their own science mission complimentary the overall GCI-Cusp campaign over a period of 18 months. Each experiment was designed, built, and tested to a set of specific requirements defined in the G-CHASER User’s Guide.

All experiments were verified at NASA’s Wallops Flight Facility in August 2018 and re-verified at ASC in January 2019. G-CHASER flew on a Terrier Improved Malemute with telemetry and power for the experiments. Both GHOST and G-CHASER are based on the Colorado Space Grant Consortium’s RockSat-C and RockSat-X programs which have launched 20 student sounding rockets at WFF since 2008 engaging over 12,000 students and faculty over 200 experiments.

GHOST will target a launch window in the summer of 2023 with student teams starting in December 2021. Which instruments will eventually fly with GHOST will be determined by the scientific goal of each participating university. Locating and selecting those universities and the actual students is a process that will start around 2021.

Apart of these dedicated student activities, every scientific project involves PhD work of several students.

Technologies, platforms and observatories

Technology:

- 4D space-time In Situ: e.g., 4 CubeSat and Turb3D daughters with GPS transmitters and telemetry to ground
- High Altitude Parachutes released from rockets
- Chemical Release
- Maynard Sphere
- Bobs
- Ampules
- Miniature Instruments - Ion Neutral Mass Spectrometer, ESAs
- New sensors for high resolution measurements of concentration of trace gases (e.g., FIPEX, PHLUX)
- Re-establishment of rocket borne mass spectrometry
- Lidars and airglow imagers on rockets, balloons, and aircraft
- VAHCOLI: 3D wind and temperature measurements with Doppler lidar.
- Meteor Radars
- Chaff
- Falling Sphere, active Falling Sphere
- Photometry (NLC, airglow and aurora) from sounding rockets
- and H resonance fluorescence on sounding rockets
- MAGIC rocket borne meteoric smoke particle sampler

Platforms:

- Rockets
 - NAMMO Nucleus Neo hybrid rocket motor. Nucleus (not Neo which is currently under development) flew from Andøya Space Center in September 2018 to 107.4 km altitude, carrying 72 kg payload.
 - ILR-33 AMBER rocket with a hybrid motor is being developed in Poland, and it is designed to fly to apogees of 100km with 10kg of experiments.
- Ground-based instruments
- Balloons
- Aircraft
- Satellites
- UAV (perhaps for thunderstorm studies)
- Drones (for tropospheric studies)

Ground based instrumentation:

- Andøya Space Center (ASC)
 - IAP radars: MARSSY – SKYiMET – Saura MF – MMARIA

- IAP, ASC and UiT lidars: ALOMAR Observatory RMR-lidar, Resonance-lidars (Fe, Na), Tropo-lidar, Ozone-lidar, MOM-lidar
- AIRIS digital imaging riometer
- IAP VAHCOLI mobile lidar.
- ASC SvalRak (Ny-Ålesund, Svalbard)
- Svalbard (UiT Sousy radar, NIPR meteor radar, KHO OH spectroscopy, EISCAT Svalbard Radar)
- Esrange Space Center
 - ESRAD (IRF) Radar, a continuously operated 52MHz MST-radar for studies of the troposphere, stratosphere and mesosphere,
 - Esrange (MISU) Lidar, a RMR-lidar for studies of the troposphere, stratosphere and mesosphere,
 - All-Sky Imager system, new 8-channel system for optical studies of the aurora and airglow (427.8 nm, 486.1 nm, 552.5 nm, 557.7 nm, 630.0 nm, 670.0 nm, 864.5 nm, 715-930 nm with 18 nm notch at 865.0 nm),
 - SKiYMET, an All-Sky Interferometric Meteor Radar continuously operated at 32.5MHz,
 - Faraday experiment transmitters, four remotely controlled 1kW transmitters at 1300, 2200, 3883 and 7800 kHz that are normally used with a receiver on a sounding rocket to measure electron density in the ionosphere,
 - Magnetometer and Riometers.
- EISCAT (EISCAT 3D)
- TGO magnetometers and riometers
- Mobile lidar systems of DLR: CORAL and TELMA
- Antarctica
- NASA Wallops Flight Facility
Kwajalein

Other Assets:

- Global chemistry-climate models WACCM and WACCM-X (Leeds Uni)
- Arecibo Observatory
- ICON/GOLD
- AIM
- TIMED
- COSMIC-2
- GPS-Radio Occultation Satellites (beyond COSMIC like EUMETSAT and others)
- ESA Aeolus mission: wind profiles (0-35km altitude)
- AURA? May or may not still be available
- NPP/SUOMI?
- Sentinel-5
- ALTAIR?
- ACE/FTS
- Odin and MATS (asongoing and upcoming Swedish satellite missions)
- Esrange Space Center:
 - Sounding rockets
 - Balloons
 - UAVs

- Odin (ongoing Swedish satellite mission, since 2001)
- MATS (Mesospheric Airglow/Aerosol Tomography and Spectroscopy, upcoming Swedish satellite mission)
- Arena Arctica (Research aircraft base in Kiruna, Sweden)
- Andøya Space Center:
 - Sounding rockets
 - Balloons
 - RPA
- Institute of Experimental Meteorology (Obninsk), Tiksi rocket range «Tiksi» atmospheric rocket sounding station:
 - MH-300 rocket missile system MP-30 (appendix)

Timeframe and national info

Funding determines the final time line, but 2022 – 2026 is a guideline!

Norway:

University of Oslo:

Norway is lacking dedicated funding for a rocket program. However, the Research Council of Norway National Infrastructure program provides a feasible funding strategy with its next call in 2020. If funded through this channel, Norwegian participants will have their funding available by the end of 2021, following a two-year payload build process with a potential launch campaign in 2023/24.

As the Norwegian partners in GCI-M/LT the University of Oslo and the Arctic University of Norway in Tromsø will apply for 3 rockets from Andøya and 1 rocket from Svalbard.

Participating in an international GCI-M/LT will strongly enhance the funding opportunities for Norwegian rockets.

Kjell Henriksen Observatory (KHO):

The Kjell Henriksen Observatory (KHO) in Svalbard is an optical observatory located at the archipelago Svalbard 1000 km north of mainland Norway (78° N 16° E). 24 different institutions from 14 nations are present at KHO.

During the auroral winter season from November to the end of February, 26 optical instruments operate 24 hours a day. The 17 non-optical instruments run all-year-round 24 hours a day. KHO serves as the main laboratory for hands on training and teaching of UNIS students. Six courses with a grand total of 75 ECTS are offered. KHO has supported several ASC rocket campaigns over the last 3 decades.

Sweden:

Sweden has a long history of atmospheric research using sounding rockets starting with the first scientific rocket launched in 1961. The Swedish National Space Agency, SNSA (formerly, the Swedish National Space Board, SNSB) has supported research on sounding rockets, including atmospheric research, for a long time. In 2012 SNSA established a new Swedish National Balloon and Rocket program enabling Swedish scientists to carry out

research using balloons and sounding rockets from the Esrange Space Center. Calls for new balloon and rocket projects are issued on regular basis thus ensuring continuity as regards both the science and the technology concerned.

As to national sounding rockets, four missions have been implemented in the program since its start in 2012. The first mission was O-STATES (Oxygen Species and Thermospheric Airglow in The Earth's Sky) from the Department of Meteorology Stockholm University (MISU) with two launches with the same payload at different atmospheric conditions in 2015. The next project was SPIDER (Small Payloads for Investigation of Disturbances in Electrojet by Rockets), by the Space and Plasma physics department of KTH; and LEEWAVES (Local Excitation and Effects of Waves on Atmospheric VERTICAL Structure) that was a collaboration between KTH and MISU and launched on the same rocket as SPIDER, launched in 2016. In early 2020 KTH's project SPIDER-2 (Small Payloads for Investigation of Disturbances in Electrojet by Rockets) is scheduled for launch.

The next call for proposals within SNSA's national balloon and rocket program is foreseen in 2020

Kiruna Atmospheric and Geophysical Observatory (KAGO) within Swedish Institute of Space Physics (IRF) operates several standard observatories (long-term monitoring) instruments such as magnetometers, riometers, ionosondes and all-sky cameras at several locations in Sweden. KAGO also operates long-time monitoring of infrasound, various instruments for atmospheric studies (e.g. mm-wave radiometers, FTIR).

In addition, a new multistation imaging facility, ALIS_4D became operational during 2019. At present this system consist of four remote operated imaging stations with approximate 50 km separation. The stations are equipped with EMCCD imagers with narrow-band interference filters enabling high temporal resolution measurements of low-light emissions (such as Aurora and airglow etc.) in the upper atmosphere.

With the IRF-based mm-wave radiometer KIMRA horizontal wind observations can be pursued between roughly 25 to 60 km, thus extending the GCI MLT project further down in altitude. A PhD thesis is planned to be finalized within the next two to three years.

Regarding mesospheric dynamics in general mm-wave observations of strato- mesospheric CO have been published (Ryan2016) using CO as a tracer for airmass descent during the course of the winter (between 45 and 85 km), even though Ryan (2018) points out some limiting issues for such a methodology.

Continuous ozone monitoring can provide insight into high altitude effects on the middle atmosphere especially during events of strong electron precipitation. (Manuscript in preparation)

The Solar Terrestrial and Atmospheric Research Program (STAR) within IRF studies the atmosphere of the Arctic, the near-Earth environment in space and the effects of the Sun's activity on both the Earth and its atmosphere. Instruments include e.g. an atmospheric LIDAR-system used for studying polar stratospheric clouds and cirrus clouds and as a global network of cameras for studies of noctilucent clouds. Research regarding the lower part of the atmosphere started with the ESRAD MST radar at Esrange, a joint venture with SSC Esrange initiated in 1994. The group expanded its research to Antarctica with MARA (Moveable Atmospheric Radar in Antarctica) which was first deployed in 2006 at the Swedish station Wasa, and has since been moved first to the Norwegian station Troll and then to the Indian station Maitri (where it has been since early 2014), in all cases in collaboration with the relevant national Antarctic research organizations including Swedish Polar Research Secretariat.

Recent involvement in national/international projects includes: Antarctic operations in collaboration with Finland, Norway, India; supporting measurements with ESRAD for EUFAR/LEEWAVES in 2016 (combined Swedish sounding rocket campaign at Esrange / EU research aircraft based in Kiruna) and PHOCUS in 2011 (Swedish sounding rocket campaign). Ongoing projects/collaborations include: real-time delivery of ESRAD wind profiles to E-PROFILE (EU project gathering data from all wind profilers in Europe); ESRAD wind measurements for 'Atmospheric dynamics and research infrastructure in Europe' project (H2020); radar support for balloon-borne in-situ ice cloud measurements (Swedish balloon project) and for PMWE (German rocket campaign to study the winter mesosphere at Andøya, Norway), and validation of stratospheric winds measured by the Aeolus satellite.

In addition, a network of optical cameras for NLC studies around the globe are operated by IRF. The cameras are in Sweden, Denmark, Scotland, Canada, Japan, Russia, Lithuania and Kazakhstan for long-term continuous monitoring of NLC dynamics in space and time. Some of the sites are equipped with two-three cameras for making the triangulation of NLC and estimating their dynamics in 3D space.

We also conduct balloon-borne studies of NLC. Two balloon flights have been done so far. The balloon-borne observations allow to register NLC both at very small scales (1-100 meters) and at very large scales

(1000-2000 km) for studies of both small-scale/turbulence processes as well as large-scale NLC dynamics (gravity waves of various scales). In case of a long-duration flight (planned) one can study the influence of solar tides and planetary waves on the NLC evolution.

We have recently installed a new Japanese infrared spectrograph registering airglow emissions coming from the OH layer (82-92 km) which provides us with continuous measurements of the temperature at the mesopause region. Soon, we plan to install a new temperature mapper in Kiruna which will allow us to construct temperature maps at the mesopause region above the Kiruna area.

EISCAT Scientific Association

EISCAT is an international association, currently with Norway, Sweden, Finland, the U.K. China and Japan as associates. The radars of the EISCAT Scientific Association are high-power, large aperture radars for ionospheric incoherent scatter observations, a technique that provides basic ionospheric parameters from roughly 70 to 600 km altitude and independent from weather conditions. The same observations also provide information on meteors and coherent radar echoes that form in the presence of charged ice particles (i.e. Polar Mesospheric Summer Echoes, PMSE). The EISCAT radars are frequently operated during rocket campaigns. They are in Northern Scandinavia near Tromsø (69°N, 19.2°E) and on Svalbard (78°N, 16°E). The radars operate at three frequencies: 933 MHz, 500 MHz and 224 MHz and partly at overlapping volumes in the atmosphere. At present EISCAT_3D, an advanced incoherent scatter radar facility is under construction. This multi-static phased-array at 233 MHz will be located about 50 km from Tromsø (69.4°N, 20.3°E). Observations with EISCAT_3D will provide higher time-resolution, spatial resolution and for first time detailed vector parameters to reveal winds, currents, and PMSE structures as well as their variation in time and space.

USA:

G. Lemacher, Clemson Univ. – “VortEx”:

NASA has approved the sounding rocket experiment "VortEx" to be launched from Andoya Space Center in January/February 2022. The project is currently in the design phase. On two launch nights we plan to launch two rocket each, with instrumented and chemical release payloads, to study gravity wave breaking and mesoscale dynamics below and above the mesopause. Key region is 80 to 140 km. It is supported by ground-based airglow and temperature imaging, lidars and meteor radars. The novel techniques such as chemical release ejectable ampules, and multiple radar transmitters and receivers have the common goal to perform horizontally distributed observations of winds. This experiment is highly relevant for the Grand Challenge Initiative Mesosphere and Lower Thermosphere (GC/MLT), since it addresses important science questions collected in the Grand Challenge white paper. It may be seen as initial start of the GCI/MLT and to field-test new rocket and ground based techniques that may find wider application in the following years. Principal Investigator is Gerald Lemacher with Co-PIs from Clemson University, Embry-Riddle University, Utah State University and Institute for Atmospheric Physics. More information can be found in *Lemacher et al., Proc. 24th. Symp. Europ. Rocket and Balloon Progr., ESA SP-742, October 2019.*

Germany:

The Space Agency of the German Aerospace Center (DLR) has been supporting a continuously running national sounding rocket program for the past decades. The sounding rocket activities are a part of the German national research program on extraterrestrial space physics. The currently running German sounding rocket project PMWE is devoted to investigation of Polar Mesosphere Winter radar Echoes and their application in studies of atmospheric dynamics. This project consists of two field campaigns to be conducted at ASC. The first campaign PMWE-1 was successfully conducted in April 2018. The second campaign PMWE-2 is scheduled for 1-15 October of 2020. Two instrumented sounding rockets will be launched either in a short salvo or in two salvos into different PMWE events, depending on scientific conditions. Additionally, several meteorological rockets to be launched in this(these) salvo(s) for high resolution wind measurements with CHAFF. Extensive support by ALOMAR ground-based instrumentation is necessary for proper interpretation of collocated rocket and radar measurements and related dynamics.

The next German sounding rocket project is neither funded nor properly preconfigured yet. However, a huge preliminary work on development, testing, and preparation of new instrumentation has been already made. The next rocket project will be devoted to investigation of 3D (or 4D, i.e. space-time, depending on available resources and funding) nature of atmospheric dynamics, specifically turbulence and gravity waves and their ensemble.

At the same time, the research branch of the German Aerospace Center (with its Institute of Atmospheric Physics, DLR-IPA) has been active to establish research aircraft as powerful platforms for remote sensing the whole atmosphere up to the MLT. This followed an initial attempt of NSF in which the NCAR-G5-aircraft was deployed to New Zealand to investigate the deep propagation of gravity wave. DLR-IPA has both utilized the jet aircraft DLR-Falcon (maximum flight duration 3,5 hours) as well as the new German research Aircraft HALO (a G55-type modified business jet, maximum flight duration 10 hours) to obtain measurements of gravity waves from their forcing region in the troposphere up to their region of dissipation

in the MLT. Typical instruments onboard these aircraft were upward and downward looking lidar systems as well as airglow imagers to probe the horizontal structure of waves in the 85km altitude range.

DLR-IPA has just completed a major aircraft campaign at the Southern tip of the Andes which is known as the strongest gravity wave hotspot worldwide. For December 2021, DLR-IPA is planning the WAVEGUIDE campaign during which the HALO aircraft is to be deployed to the Arctic region in order to characterize the excitation and/or propagation of gravity waves by/in the polar night jet. As for the GCI-MLT initiative this offers an exciting possibility to combine this airborne campaign with as many other observations as possible. Ideally, the horizontally resolved airborne measurements could not only be combined with a vast range of ground based and satellite observations but also with rocket borne in situ measurements. This would allow for the worldwide first characterization of MLT dynamics over a range of scales from several thousand kilometers (flight endurance of aircraft) to the meter-scale (= resolution of sounding rocket in situ measurements).

Russia:

Possible contribution of a Russian scientific team:

1. Synchronous to Andøya, rocket launches with scientific payload in the Russian Arctic (scientific team is already ready and will be ready for it, but the financing situation is not clear now). A ceiling height of rocket flight (300, 100 or 70 km) also depends on the financing (V.Yushkov, A.Pozin).
2. Ground-based measurements of middle atmosphere characteristics from the territory of Russia during the Project:
Airglow measurements, - Moscow: spectrographs (V. Perminov, N. Pertsev), Irkutsk: spectrographs (I. Medvedeva), Yakutsk: all-sky cameras and meridional chain of spectrographs (S. Nikolashkin, I. Koltovskoi).

In summertime- network for automatic photo registering of noctilucent clouds (several cameras located over a large territory from Moscow to Petropavlovsk Kamchatskiy, coordinators – P. Dalin, N. Pertsev).

In summertime – polarization measurements of noctilucent clouds scattered light (transportable system, O. Ugolnikov)

Meteor radars including 4 radars in the Arctic with coordinates (67°N, 32°E); (69°N, 86°E); (72°N, 129°E); (65°N, 178°E), coordinator E. Merzlyakov

Several infrasound receiving stations, including two ones in Arctic (Kandalaksha and Yakutsk), coordinator Yu. Rusakov

Several lidars providing temperature profiles up to 70 km, including a lidar in Sankt-Petersburg, (V. Korshunov) and Yakutsk (S. Nikolashkin).

3. Determination of dynamical parameters of wind currents in MLT: parameters of tidal wind oscillation and their variability, parameters of planetary waves and their variability, interaction of tides and planetary waves (coordinator E.

Merzlyakov).

4. Russian space-born observations (from “Meteor” satellite) of solar cosmic rays (E. Ginzburg) and analysis of their influence on D-region, with applying 3D simulation (A. Krivolutsky).
5. Accompanying modeling of tidal oscillations and planetary waves using model MUAM (Middle and upper atmosphere model) in stratosphere and MLT (A. Pogoreltsev, A. Koval). Accompanying high-resolution modeling of gravity wave propagation from the lower atmosphere to the MLT region (N. Gavrilov, A. Pogoreltsev).

Canada:

Poland:

Polish researchers are planning to focus their research in troposphere dynamical processes, study of effects affecting propagation of electromagnetic signals, propagation of waves as well as relationship of waves, winds and turbulences with disturbances in the lower thermosphere. In addition, we propose to use high-rate GNSS receivers, both on the ground and on rockets which will give additional information about disturbances in the lower ionosphere. This measurement concept is planned to be verified in-flight in cooperation between the Institute of Meteorology and Water Management with the Institute of Aviation. In addition, numerical simulations can be supported with TASK computing infrastructure on Gdansk University of Technology. With numerous successful student teams (i.e. in REXUS), Polish students are well-prepared to take part in the GHOST student mission.

Poland proposes to use the ILR-33 AMBER rocket for atmosphere sounding within the framework of the project. It is a small (230mm diameter), low-cost rocket optimized to fly to altitudes required by the GCI M/LT. It is designed to fly to 100km with 10kg of payload, and allows flexible mission planning thanks to a hybrid motor. The rocket was already tested 3 times in low apogee flights.

Poland can also offer additional rocket launch site near Ustka on Polish coast. The site has an UNL air zone, which means there are no limits to rockets' altitude as long as other safety aspects (i.e. dispersion, landing within range boundaries) are met. Current boundaries of the site enable rocket flights to ~60km altitude with an unguided rocket.

Funding in Poland can be obtained from several institutions: National Science Centre – a dedicated entity supporting basic research, The National Centre for Research and Development, and the Polish Space Agency, which has declared support for sounding rockets development in the Polish Space Programme. The Institute of Aviation is a part of Łukasiewicz Research Network – Europe's 3rd largest research network with 38 research institutes supporting each other, and is a potential source of funding in the future. Polish and Norwegian scientists can apply together to the so-called Norwegian Financial Mechanism, which provides funds for projects involving both Polish and Norwegian researchers.

Additional support enabling exchange of students and academic staff between Polish team institutions and other GCI M/LT consortium members can be obtained from the Polish National Agency for Academic Exchange NAWA.

UK:

The main contribution from the UK would be in modelling. At the University of Leeds, the global chemistry-climate models WACCM and WACCM-X which extend from the surface to 140 and 500 km, respectively, are operational. The Leeds group have a version of WACCM called WACCM-D, which contains all the chemistry for cluster ions from the Sodankyla Ion Chemistry (SIC) model. There are also versions of WACCM and WACCM-X with the chemistry of the meteoric metals (Na, K, Fe, Mg etc.). These models can be both free-running and nudged by meteorological re-analysis of winds and temperature in the stratosphere. Planned work at Leeds during the next 3 years is to develop a regionally refined version of the model which goes down to 14 x 14 km resolution, which would be particularly useful for interpreting rocket experiments. There is also an experimental program at Leeds for laboratory studies of the underpinning science (e.g. measurements of reaction rate coefficients, complemented by theoretical calculations).

Japan:**Potential research partners**

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Franz-Josef Lubken, Boris Strelnikov
2. Institute of Atmospheric Physics, IPA, DLR, Oberpfaffenhofen
Markus Rapp
3. Institute of Space Systems (IRS)
Prof. Dr.-Ing. Stefanos Fasoulas
4. University of Oslo, Norway
Jøran Moen, Wojciech Miloch
5. Arctic University of Norway, Tromsø., Norway
Ingrid Mann
6. Clemson University, USA
Miguel Larsen, Gerald Lehmacher
7. University of Alaska, Fairbanks, USA
Rich Collins, Fairbanks, USA
8. NASA Goddard, USA
Douglas Rowland, Rob Pfaff, Diego Janches
9. Embry Riddle Aeronautical Univ, USA
Aroh Barjatya
10. LASTP, Univ. of Colorado, USA
Zoltan Sternovsky
11. MISU, Sweden
Jorg Gumbel, Jonas Hedin
12. KTH, Sweden
Mykola Ivchenko

13. Swedish Institute of Space Physics
Urban Brändström, Johan Kero
14. University of Leeds, UK
John Plane, Daniel Marsh, Wuhu Feng
15. ISAS/JAXA, Japan
Takumi Abe, Yoshifumi Saito
16. Naval Research Lab, USA
Paul Bernhard
17. UNIS, Svalbard, Norway
Fred Sigernes, Lisa Baddeley, Dag Lorentzen
18. Institute of Experimental Meteorology (Obninsk), Russia
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Tomasz Noga, Michał Pakosz
22. Gdansk University of Technology, Gdansk, Poland.
Grzegorz Nykiel, Mariusz Figurski

Scenarios

{operational scenarios referenced in the problem statement}

Options

{list of enhancements referenced in the proposed solution}

- Leeds University runs the global chemistry-climate models WACCM and WACCM-X, which extend from the surface to 140 and 500 km, respectively. They have a version of WACCM called WACCM-D, which contains all the chemistry for cluster ions from the Sodankyla Ion Chemistry (SIC) model. There are also versions of WACCM and WACCM-X with the chemistry of the meteoric metals (Na, K, Fe, Mg etc.) available. These models can be both free-running and nudged by meteorological re-analysis of winds and temperature in the stratosphere. Planned work at Leeds is to develop a regionally refined version of the model which goes down to 14 x 14 km resolution, perhaps more useful for rocket experiments.

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- c) Prof. Dr. Miguel Larsen, Clemson University, USA
- d) Chris Koehler, Director, Colorado Space Grant Consortium, University of Colorado at Boulder

- e) Prof. Jøran Moen, Physics Dept., University of Oslo, Norway
- f) Prof. Dr. Markus Rapp, German Aerospace Center (DLR), Institute of Atmospheric Physics, Oberpfaffenhofen, Germany.
- g) Professor John Plane, School of Chemistry, University of Leeds, UK
- h) Fred Sigernes. Professor, Optics and Atmospheric Research. Chief of the Kjell Henriksen Observatory. Arctic Geophysics
- i) Ingrid Mann, Professor / Group Leader Space Physics Department of Physics and Technology Campus Tromsø
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References

This initial white paper is partly based on the white paper for the COSIMA: “COMBINED Science initiative for In-situ measurements in the Middle Atmosphere” project. The COSIMA project was an idea by Prof. Dr. Franz-Josef Lubken, Leibniz-Institute of Atmospheric Physics, Kuhlungsborn, Germany and Prof. Dr. Miguel Larsen, Clemson University, USA. 28. August 2017 (V2).

- a) COSIMA: “COMBINED Science initiative for In-situ measurements in the Middle Atmosphere” project. The COSIMA project was an idea by Prof. Dr. Franz-Josef Lubken, Leibniz-Institute of Atmospheric Physics, Kuhlungsborn, Germany and Prof. Dr. Miguel Larsen, Clemson University, USA. 28. August 2017 (V2).
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