How is **S**pace **T**ransforming the polar **A**tmospheric **R**egions?

1. Excellence

The STAR project aims to bridge the gap between space physics and climate research communities.

Over the past decades, observations and model studies have provided substantial evidence that Energetic Electron Precipitation (EEP) from space affects the chemistry and dynamics of the stratosphere. Concurrently, stratospheric variability has emerged as an important component of subseasonal and seasonal forecasts during winter. However, little effort to combine these two research fields has left a critical gap, limiting our ability to fully understand and predict polar climate variability.

This project has transformative potential. It will uncover critical insights into how EEP influences mesospheric chemistry and dynamics, the key EEP ionization rates and the atmospheric preconditions required for significant impacts on stratospheric dynamics. Building on this foundation, the project will determine how EEP affects the occurrence and evolution of sudden stratospheric warmings—phenomena that are closely linked to changes in polar tropospheric circulation.

Incorporating the knowledge gained from STAR into forecast and climate models will improve predictions of the polar winter climate on seasonal to decadal timescales.

1.1 Advancing the state of the art

Energetic Electron Precipitation (EEP) from near-Earth space continuously affects the polar atmosphere by ionizing, dissociating, and exciting neutral gases from the thermosphere down to the upper stratosphere (Nesse et al., 2022). This triggers a cascade of chemical reactions that increase the levels of odd nitrogen (NO_x, N, NO, NO_2) and odd hydrogen (HO_x, H, OH, HO_2), both of which contribute to catalytic ozone (O_3) depletion in the mesosphere and stratosphere (Sinnhuber et al., 2012). Compositional changes caused by EEP at the altitude of precipitation are referred to as the direct effect, while those resulting from vertical transport of EEP-produced species are termed the indirect effect (Randall et al., 2005).

While HO_x has a short lifetime, NO_x can persist for months in the polar night, allowing it to be transported downward to the stratosphere by seasonal circulation. Consequently, NO_x abundance in the middle atmosphere during winter reflects the cumulative impact of EEP, scaled by the efficiency of the downward transport (Funke et al., 2016). As such, EEP-induced O_3 depletion depends on the season, background atmospheric dynamics, and interactions with other ozone-depleting substances (Damiani et al., 2016, Zawedde et al., 2019, Gordon et al., 2021). In mid-winter, negative O_3 anomalies disrupt the atmospheric radiation balance, leading to effective warming in the upper stratosphere and lower mesosphere (Sinnhuber et al., 2018). This alters zonal wind speeds, modifies wave refraction, and influences the circulation, ultimately strengthening the winter polar vortex through complex feedback mechanisms (e.g. Seppälä et al., 2013).

Variations in the stratospheric polar vortex, in turn, affect tropospheric circulation dynamics. Sudden Stratospheric Warmings (SSWs), classified as minor or major depending on the extent of vortex disruption, can weaken or even reverse the polar vortex. Major SSWs, which involve a complete reversal of the zonal winds, typically shift storm tracks and the tropospheric jet stream equatorward, thereby modulating the North Atlantic Oscillation (NAO) (Baldwin et al., 2021). As a key driver of atmospheric circulation, the NAO shapes weather patterns across Europe, North America, and the Arctic. Accurate prediction of SSWs in seasonal forecasts of Northern Hemisphere winters is therefore essential for scientific and societal purposes.

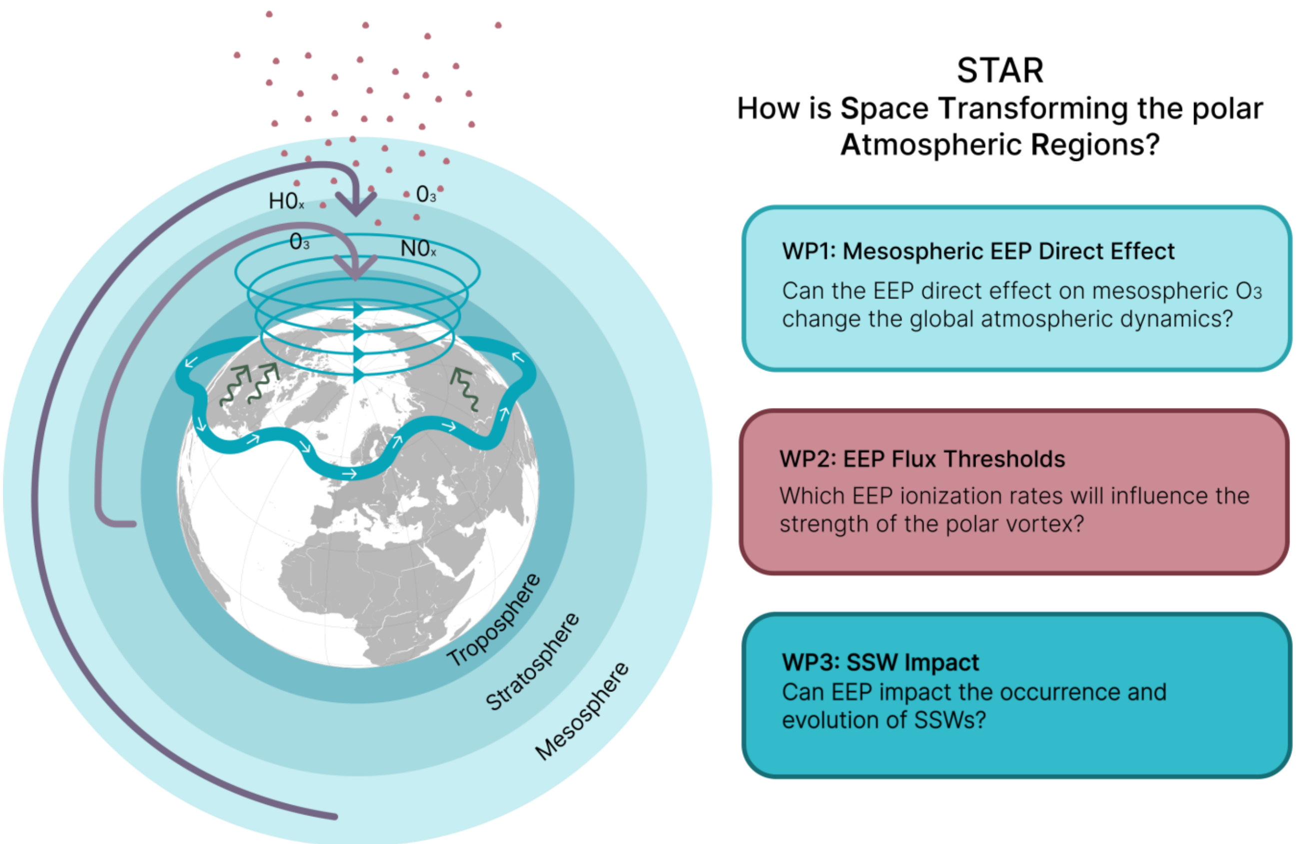
Recent studies now suggest a link between EEP and SSW occurrence (Salminen et al., 2020; Vokhmyanin et al., 2023), but critical aspects such as timing, duration, and strength remain largely unexplored. Gaining a better understanding of how EEP contributes to the evolution of SSWs could significantly help improve seasonal and climate forecasting by accounting for the influence of EEP on tropospheric circulation and surface climate patterns.

To fully understand if, how, and when EEP impacts Earth's weather, a cross-disciplinary approach is essential. The STAR project will target fundamental knowledge gaps, including**: 1) The importance of the EEP direct effect in the mesosphere, 2) The EEP flux levels required to influence the strength of the polar vortex under varying atmospheric background conditions**, **3) How the occurrence and evolution of SSWs are affected by EEP**.

Anthropogenic climate change amplifies the impact of EEP on the stratosphere, due to both strengthened circulation patterns and declining levels of chlorofluorocarbons (CFCs) (Maliniemi et al., 2020, 2021, 2022). This emphasizes the critical importance to understand the open question: **How is space transforming the polar atmosphere?** Building on our interdisciplinary expertise in space physics, atmospheric dynamics, and climate science, STAR aims to make **groundbreaking, high-impact discoveries on how and when EEP influences the atmosphere and polar surface climate.**

1.2 Research questions and hypotheses, theoretical approach, and methodology

The STAR project comprises three interconnected work packages (WPs). Each WP builds upon the findings of the others. This approach ensures a comprehensive and unique understanding of how EEP forcing and atmospheric preconditions collectively determine its overall impact across all atmospheric layers, extending to the surface.



WP 1: Can the EEP direct effect on mesospheric O_3 change the global atmospheric dynamics?

Objective: Quantify the direct effect of EEP on mesospheric O_3, temperature, NO transport, and pole-to-pole circulation.
Hypothesis: The EEP direct effect on the mesosphere modifies the deposition of gravity wave momentum, which in turn strengthens the zonal wind and weakens the pole-to-pole circulation.
Impact: Revealing the EEP direct effect as a critical factor in estimating NO transport from the thermosphere to the stratosphere, will ultimately improve our understanding of EEP's indirect effect on stratospheric dynamics.

Fundamental knowledge gaps: Recent studies reveal a breakthrough in that the EEP direct effect on mesospheric O_3 influences atmospheric dynamics (Zúñiga López et al., 2022; Seppälä et al., 2025). These findings demonstrate that EEP can play a pivotal role in influencing mesospheric temperature, wave breaking and refraction, and, hence, atmospheric winds and circulation. However, quantifying EEP's mesospheric influence on dynamics remains unresolved.

Task (T) 1.1 *Run WACCM-SD to isolate the **direct** effect of EEP on the mesosphere:*
We will run the Whole Atmosphere Community Climate Model (WACCM) in specified dynamics (SD) mode throughout the stratosphere, following the setup in Zúñiga López et al. (2022). In this setup, the stratospheric forcing remains consistent across scenarios with and without EEP, allowing for an ideal study isolating the impact of EEP in the mesosphere. The simulation period will cover a full solar cycle (2004—2014). We will apply a stronger, more realistic EEP forcing based on the solar forcing dataset recommended for the Coupled Model Intercomparison Project Phase 7 (CMIP7) (Funke et al. 2024). To robustly assess EEP's direct impact on mesospheric dynamics, we will compare five-member ensemble simulations with and without EEP.

T1.2 *Analyze EEP **direct** effect on wave dynamics in the mesosphere:*
Using the model projections from T1.1, we will analyze how EEP-driven mesospheric O_3 depletion modifies temperature gradients and subsequently influences gravity wave breaking. To distinguish the primary radiative effects of O_3 loss from secondary dynamical impacts, we will focus on time-isolated EEP events, assess transport shifts relative to baseline simulation, and examine additional trace species whose chemistry is not significantly affected by EEP.

T1.3 *Assess the impact of EEP-altered wave momentum on global circulation and NO transport:*
If T1.2 confirms that the EEP direct effect modifies gravity wave momentum deposition in the mesosphere, we will investigate how this further affects the global pole-to-pole circulation. We will also evaluate the resulting adiabatic heating/cooling and the implications for NO transport throughout the mesosphere.

T1.4 *Compare model predictions with satellite observations:*
We will compare the model predictions from T1.1 with satellite observations. Any discrepancies will be analyzed in context of the dynamical responses identified in T1.2 and T1.3. Mesospheric O_3 response will be compared to MLS/Aura data, temperature gradients to MLS/Aura and TIMED/SABER observations, and NO_x production and transport to measurements from SOFIE/AIM, MIPAS/Envisat, and SCIAMACHY/Envisat.

WP 2: Which EEP ionization rates influence the strength of the polar vortex?

Objective: Determine which EEP ionization rates affect the polar vortex strength under different atmospheric conditions and assess whether the relationship is mechanistic or probabilistic.
Hypothesis: The EEP ionization rates needed to influence polar vortex dynamics depend on atmospheric preconditions. Under similar conditions, the dynamical impact will scale with the magnitude of EEP ionization rates.
Impact: Determining the ionization rates at which EEP affects the polar vortex will help develop a new EEP parameterization for meteorological reanalysis and seasonal forecast models.

Fundamental knowledge gaps: The conditions under which EEP impacts the middle atmosphere dynamics remain poorly constrained. While recent modeling by Zúñiga López et al. (2022) suggests that both the magnitude of EEP ionization and the background atmospheric state shape the response, the ionization levels required to trigger dynamical changes are still uncertain. This complexity is compounded by the coexistence of direct and indirect EEP effects—driven by different parts of the energy spectrum and acting on different timescales—as each may require distinct atmospheric preconditions that determine whether, and how strongly, they influence the polar vortex.

T2.1 *Identify ionization rates needed for the EEP **direct** effect to impact mesospheric dynamics:*
Using WACCM-SD runs from T1.1, we will identify: (a) periods with comparable EEP forcing but different dynamical preconditions, and (b) periods with different EEP forcing but similar dynamical states. This approach will allow us to assess whether the atmospheric response scales with EEP strength or if a threshold exists beyond which dynamical feedback are triggered in the mesosphere.

T2.2 *Run WACCM to isolate **direct and indirect** effects of EEP:*
We will apply WACCM in free-running mode (five ensemble members) for the same period and external forcing as in T1.1, with and without EEP. Two baseline configurations will be used to isolate the effects of EEP: one without the CMIP7 EEP, and another with both the Kp-scaled auroral forcing and the NO upper boundary condition switched off (Marsh et al., 2004). This setup will allow us to assess separately the direct impact of EEP (local NO_x production in the thermosphere/mesosphere), and the indirect effects associated with NO transport from higher altitudes.

T2.3 *Determine ionization rates for the EEP **indirect** effect to impact stratospheric dynamics:*
To accurately determine the EEP ionization rates required to influence the polar vortex, we will first investigate whether the stratospheric NO_x threshold for affecting stratospheric winds depend on the atmospheric dynamical state. Using the WACCM projections from T2.2, we will identify: (a) periods with comparable NO levels but different dynamical preconditions, and (b) periods with different NO levels but similar dynamical backgrounds. This comparison will allow us to examine how initial conditions affect NO_x transport efficiency and the resulting stratospheric wind responses. From this, we will identify the EEP flux levels and energy spectra most effective at modifying stratospheric dynamics.

WP 3: Does EEP impact the occurrence and evolution of sudden stratospheric warmings, and can it improve seasonal surface weather predictions?

Objective: Unveil if and how the total effect of EEP (direct and indirect) impacts the occurrence rate, onset time, duration and strength of SSWs.
Hypothesis: The combined dynamical impact of direct and indirect EEP effects on the mesosphere and stratosphere affects the occurrence and evolution of SSWs. This interaction provides a pathway for EEP to impact the NAO and polar regional winter surface weather.
Impact: Identifying EEP as a significant modulator of SSW dynamics will deepen our fundamental understanding of the atmosphere and pave the way for pioneering advancements in subseasonal to seasonal weather and decadal climate forecasting.

Fundamental knowledge gaps: The extent to which EEP influences the occurrence and evolution of SSWs remains unresolved. Reanalysis studies suggest that geomagnetic activity modulates the likelihood of SSWs (Salminen et al., 2020). Model experiments further indicate that EEP may affect the onset timing, duration and strength of wind reversals during SSWs (Zúñiga López et al., 2022), as well as temperature anomalies associated with minor events (Edvartsen et al., 2023). These findings point to a potential link between EEP and SSW dynamics. However, the underlying mechanisms and conditions that enable such influence are still poorly understood.

T3.1 *Investigate whether EEP impacts the occurrence and evolution of SSWs:*
In the WACCM-SD run (T1.1), the stratospheric wave forcing causing SSWs in the upper stratosphere and lower mesosphere remains consistent across scenarios with and without EEP. This consistency allows us to investigate how the direct effect of EEP alters the mesospheric signature of both major and minor SSWs. To determine the extent of EEP-induced changes in the stratosphere, we also employ WACCM in free-running projection (T2.2). In the WACCM free-running mode, the stratospheric wave forcing may vary, causing SSWs to occur at different times across different scenarios and ensemble runs. Consequently, the SSWs will not be

comparable on a case-by-case basis. To address this challenge, we will adopt a statistical approach to compare the occurrence, duration, and strength of model-generated SSWs in scenarios with and without EEP. Additionally, we will examine the timing of seasonal transitions, which share dynamic characteristics with SSWs.

<u>T3.2 *Reevaluate the timing between geomagnetic activity and surface response*</u>*:*
We will reassess the timing between EEP forcing and surface response by comparing early and late winter conditions. Along with results from T2.1 and T2.3, this will help determine whether the observed 1–2-month delay is due to a true lag caused by EEP-induced NO_x descent from the thermosphere to the stratosphere, as commonly assumed (e.g. Seppälä et al. 2009), or if the dynamical impact of EEP primarily occurs during periods of enhanced atmospheric instability, such as before or during SSWs (Asikainen et al., 2020). If atmospheric preconditions are found to be the main driver of the response, it will challenge the current understanding of the EEP impact on surface pressure and temperatures. It will shape the methodological approach to incorporating and parameterizing EEP impact on the atmospheric dynamics.

<u>T3.3 *Examine whether EEP explains systematic biases in SSW forecasts*</u>*:*
We will investigate whether the probability, timing (onset and duration), and intensity of SSWs in operational subseasonal to seasonal forecast models are influenced by EEP. Using the same dataset as Garfinkel et al. (2025) and historical SSW events identified in ERA-reanalysis data, we will evaluate the accuracy of these forecast models in capturing SSW events relative to geomagnetic activity levels, which serve as a proxy for EEP. Previous studies, such as Chwat et al. (2022), have identified several factors that can affect the predictability of SSWs. While these factors may sometimes overshadow the influence of EEP, analyzing a sufficiently large dataset will enable us to detect potential systematic biases in SSW probabilities.

<u>T3.4 *Implement EEP as a predictive parameter in a subseasonal to seasonal weather forecast*</u>*:*
The results from T3.3 pave the way for incorporating geomagnetic activity/EEP into operational forecasting. WP2 and T3.2 provide the necessary framework to achieve this realistically in the operational subseasonal to seasonal forecasts issued by NCAR-CESM (Richter et al., 2022). Furthermore, based on the results from T3.3, we will identify the forecasting system most likely to benefit from EEP input and engage with its development team to design an effective implementation strategy, accounting for scientific relevance and computational constraints. While this represents a significant challenge from both scientific and collaborative perspectives, the potential high impact of bridging space and atmospheric communities outweighs the associated risks.

Insight and risk management: Across all WPs, some results may not confirm our hypotheses or may remain inconclusive. Such scientific uncertainties, however, still offer valuable insights: they help rule out assumptions, narrow down plausible explanations, deepen our understanding of key processes, and guide future research. A detailed assessment of project risks and mitigation strategies—addressing operational, logistical, and technical challenges—is provided in Section 3.2 (Project organization and management).

WP3 Pre-study: To evaluate the feasibility of WP3, we conducted a preliminary study analyzing 25 individual ensemble members from the European Centre for Medium-Range Weather Forecasts (ECMWF) daily seasonal forecast data. SSW events were defined as zonal-mean wind reversals from westerly to easterly at 10 hPa and 60°N. The probability of SSW occurrence was estimated by calculating the fraction of ensemble members predicting an event within ±14 days of the observed onset in ERA5 reanalysis data. For each SSW event, we computed the average Ap geomagnetic index over the two months preceding onset and categorized the QBO phase based on September wind conditions. The SSW events in our dataset occurred between the 18th and 23rd of the winter months (December-February), ensuring a consistent lead time from the forecast initialization date, which was fixed to the 1st of each month in the available data. Tentative results show that only 53% of the ECMWF ensemble members predicted SSWs at the beginning of the respective month in QBO-E winters characterized by low geomagnetic activity. In comparison, Salminen et al. (2020) suggest an 88% occurrence rate under similar conditions. Although further analysis is needed to draw firm conclusions, these results demonstrate that publicly available forecast model data can serve as a useful first step in evaluating the potential for EEP to improve seasonal weather and climate pattern predictions.

1.3 Ethical issues

The proposed project will follow the ethical research guidelines provided by the National Research Ethics Committee. It is based solely on the use of open-access or institutionally provided datasets and does not involve human subjects, personal or sensitive data, animal testing, or any activities requiring ethical approval. We will make research results, data and code available to others for verification.

The knowledge gained from this project aligns with sustainable development goals. There is substantial evidence linking global climate change to increasing levels of man-made greenhouse gases. By determining the contribution of natural climate variability, which underlies human-induced atmospheric changes, this project will enhance future climate predictions. The researchers are committed to contributing to public discourse and disseminating findings to relevant stakeholders, as further detailed in Section 2: Impact.

1.4 Novelty and ambition

Identifying EEP as a crucial force in SSW dynamics will not only deepen our fundamental understanding of the atmospheric dynamics but also pave the way for pioneering advancements in subseasonal and seasonal weather and decadal climate forecasting. It will initiate new cross-disciplinary research on how to include the EEP forcing in seasonal forecasts and climate models.

2. Impact

2.1 Potential for academic impact of the research project

With the STAR project, we propose an ambitious, interdisciplinary research plan spanning space physics, atmospheric dynamics, and seasonal forecasting. Through its work packages, the project seeks to deliver a paradigm shift in how EEP's influence on the polar winter climate is studied and understood. One of the objectives is to determine the ionization thresholds at which EEP begins to affect the polar vortex—advancing fundamental knowledge of whether its dynamical impact is mechanistic or probabilistic. Achieving this requires a comprehensive understanding of both the direct and indirect effects of EEP, as well as their combined influence. The results will provide candidate criteria to represent EEP in seasonal forecast models. In turn, this will enable new diagnostics and tools for future observational and modeling studies, while opening new directions for cross-disciplinary research on polar climate variability.

2.2 Potential for societal impact of the research project

The STAR project addresses a critical gap: EEP remains an underrepresented driver in many seasonal forecast and climate models, despite its role in shaping stratospheric variability and thereby modulating the NAO, a dominant mode of northern winter climate. In some regions, NAO-related variability exceeds long-term anthropogenic climate trends, making it essential to understand natural drivers like EEP. Looking ahead, understanding EEP's effects will become increasingly important in a changing climate. Anthropogenic changes amplify the impact of EEP on stratospheric composition and dynamics: enhanced greenhouse gas concentrations strengthen circulation patterns, while levels of CFCs are declining following the Montreal Protocol, both of which increase EEP's relative contribution to ozone loss (Maliniemi et al., 2020, 2021, 2022). With STAR, we aim to achieve a deeper understanding of EEP variability and its atmospheric impact—crucial for anticipating how Earth's atmosphere will respond to both space weather and human-driven climate change in the decades to come. Improving the predictability of stratospheric dynamics and their influence on northern winter weather is central to preparing for extreme events and supporting economic resilience.

2.3 Measures for communication and exploitation

The STAR project aims to produce a minimum of nine peer-reviewed publications in high-impact journals, as outlined in Table 1. The fundamental insights anticipated from this research—particularly in WP3—position us to target top-tier interdisciplinary journals such as *Science* or *Nature*. To ensure timely communication and feedback, we will present our results at major international conferences, including EGU, AGU, and HEPPA-SOLARIS, engaging both the space and atmospheric science communities. In addition, we will host online seminars specifically for stakeholders to discuss key findings, gather feedback, and incorporate relevant perspectives into the project's final outputs.

To complement our academic dissemination efforts, we will also prioritize public engagement and communication. STAR will have its own webpage showcasing key scientific results, with updates and milestones shared via social media platforms such as Instagram and LinkedIn. We will also give public talks and interviews and write popular science reports to communicate our progress and promote broader awareness of the project's relevance.

Additionally, we plan to organize a cross-disciplinary one-week research school for students and researchers during the spring semester of 2028. The course will address the "Solar impact on the winter polar atmosphere – from space to surface," integrating the latest advancements and results from the STAR project. The PM has previously organized similar successful research schools at the University of Bergen (UiB) in 2015, 2017, and 2019. These events not only trained a new generation of cross-disciplinary scientists but also served as catalysts for collaborative research, resulting in two successful project proposals funded by the Research Council of Norway.

3. Implementation

3.1 Project manager and project group

The successful implementation of STAR relies on a strong project manager and a highly skilled, interdisciplinary team. The project group brings together expertise in space physics, atmospheric dynamics, and climate science to ensure scientific excellence and effective collaboration throughout the project.

Core team

Project Manager (PM): Prof. Hilde Nesse is an expert in energetic particle precipitation and its impact on the upper and middle atmosphere, with extensive experience as a project manager. From 2013 to 2023, she was one of three team leaders at the Centre of Excellence, Birkeland Centre for Space Science at UiB. She led the 10–15-member Energetic Particle Precipitation group, bridging space physics and atmospheric science by exploring the effects of EEP on the atmospheric system. Prof. Nesse has secured multiple research grants as both principal and co-investigator, supervised six successful PhD students and four postdoctoral researchers, and led international working groups. She has had a central role in developing the solar forcing component for CMIP7. In addition, she is the lead author of the recently submitted review paper titled "Why is energetic particle precipitation important for climate research and seasonal forecasting?".

Postdoctoral researchers (PDs): Two postdocs (PD1 and PD2) will be recruited specifically for this project and employed at UiB. While each PD will take primary responsibility for one work package, the PM will emphasize synergy and the development of complementary scientific skills to ensure that, by the end of their postdoctoral period, both researchers have gained versatile, cross-disciplinary experience across space physics, atmospheric dynamics, and their relevance for seasonal climate variability and prediction.

Senior Researcher (SR): Dr. Thomas Toniazzo is a senior research scientist at NORCE Norwegian Research Centre in Bergen, Norway. His work is highly interdisciplinary with a strong focus on climate science, particularly atmospheric modelling, and the interactions between the atmosphere, ocean, and sea ice. He is familiar with numerous numerical models and is actively involved in the development of the Community Atmospheric Model (CAM) and the Norwegian Earth System Model (NorESM) in collaboration with the Norwegian Meteorological Institute and the National Center for Atmospheric Research (NCAR).

Confirmed collaborators

Prof. Daniel Marsh (C1) is the Priestley Chair in Comparative Planetary Atmospheres at the University of Leeds, with affiliations in both the School of Physics and Astronomy and the School of Chemistry. He joined Leeds in January 2018 after serving as a senior scientist and head of the Global Chemistry Modeling Group at NCAR in Boulder, Colorado. While at NCAR, he led the development of WACCM, which will be used in this project. Prof. Marsh is an expert in the chemistry and dynamics of the stratosphere and mesosphere, their response to climate change, and their influence on tropospheric climate. We have budgeted for a two-week research stay at the University of Leeds for the PM and one of the PDs.

Dr. Bernd Funke (C2) is a senior researcher at the Instituto de Astrofísica de Andalucía (CSIC) in Spain. He has played a leading role in the development and application of the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), which has provided critical data on various atmospheric constituents. Dr. Funke's research focuses on atmospheric sciences, particularly the chemistry and dynamics of the stratosphere and mesosphere. We have allocated funding for a one-week visit to CSIC for the PM and both PDs.

Prof. Chaim Garfinkel (C3) from the Hebrew University of Jerusalem is an expert in middle atmosphere dynamics and stratosphere-troposphere coupling. His research focuses on subseasonal to seasonal predictability and the role of key large-scale oscillations, such as the Quasi-Biennial Oscillation (QBO) and El Niño-Southern Oscillation (ENSO), in shaping global climate variability. Prof. Garfinkel has a leading role in the World Climate Research Programme's core project *Atmospheric Processes And their Role in Climate* (APARC), where he oversees two major activities: LEADER (Large Ensembles for Attribution of Dynamically-driven ExtRemes) and SNAP (Stratospheric Network for the Assessment of Predictability). The project budget includes two-week work stays at UiB for Prof. Garfinkel to collaborate with the project team.

The PM and collaborators are actively engaged in the SOLARIS-HEPPA community, which provides a strong foundation for international and interdisciplinary collaboration. As the project progresses, the team will continue to identify and involve additional experts to address emerging challenges.

Gender and equality considerations

The PM of this project is female and has a proven track record of promoting diversity in terms of gender and nationality. This commitment to inclusion will be maintained throughout the STAR project. For the upcoming postdoctoral positions, qualified female candidates have already been identified and will be actively encouraged to apply. The PM also recognizes that building a supportive and inclusive working environment—particularly for early-career researchers and underrepresented groups—directly contributes to high-quality scientific results.

3.2 Project organization and management

Responsibilities and time schedule

The STAR project is structured into three work packages (WPs), with responsibilities shared across the project team. Table 1 provides an overview of the project schedule, including WPs, associated tasks, milestones, deliverables, and the assignment of responsibilities. Detailed descriptions of the WPs and tasks can be found in Section 1.3. The distribution of roles is further elaborated below.

Prof. Hilde Nesse (PM) will dedicate 30% of her time to overseeing all WPs and leading tasks T2.1 and T2.3. She will also supervise the two postdoctoral researchers. Dr. Thomas Toniazzo (SR) will contribute 20% of his time, focusing on setting up WACCM simulations (T1.1 and T2.2), providing technical guidance to the postdoctoral researchers, and supporting related analyses. The two postdocs (PD1 and PD2) will be responsible for WP1 and WP3, respectively, and will contribute to all aspects of the project. The positions are for 3.25 years (PD1) and 3.5 years (PD2), respectively, including three months each allocated to career-promoting measures, as required by UiB. During this time, the PDs will engage in outreach activities, manage the project's website, run online seminars, and organize the cross-disciplinary research school (see Section 2.3).

Collaborators Prof. Daniel Marsh, Dr. Bernd Funke, and Prof. Chaim Garfinkel (C1, C2, C3 in Table 1, respectively) will contribute their expertise to specific tasks across the WPs. Their involvement will include research visits and regular online coordination to carry out joint analyses with the core team. To support this collaboration, weekly meetings will be held with core group members and relevant collaborators to discuss theory, methods, results, and any unforeseen challenges. Progress and discussions will be displayed on a digital platform (e.g., Slack) accessible to all project members, maximizing integration between tasks and ensuring engagement and continuity for external collaborators.

		2026				2027				2028				2029			
Management and Work Packages (WPs) :	*Assigned to :*	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Recruitment (R), PD Start (S1, S2)	**PM**	R	S1	S2	Supervision and Project Management of all WPs												
WP1: EEP direct effect on mesosphere																	
T1.1 Run WACCM in specified dynamics mode	**SR**, PD1, PM																
T1.2 Analyse impact on wave dynamics	**PD1**, PD2, C1, PM							p									
T1.3 Assess implications for global circulation & NO transport	**PD1**, PD2, C1, PM								@C1				p				
T1.4 Compare model predictions to satellite observations	**PD1**, PD2, C2, PM										@C2				p		
WP2: EEP influence on the polar vortex																	
T2.1 Identify ionization thresholds (direct/mesosphere)	**PM**, PDs, C2							p									
T2.2 Run WACCM in free-running mode	**SR**, PDs, PM																
T2.3 Determine ionization thresholds (indirect/stratosphere)	**PM**, C2, PDs										@C2		p				
WP3: EEP impact on SSWs & surface weather predictability																	
T3.1 Investigate impact on SSW occurence and evolution	**PD2**, PD1, C1, PM									p							
T3.2 Reevaluate timing of EEP–surface response	**PD2**, PD1, C2, PM										@C2				p		
T3.3 Examine impact on SSW predictability	**PD2**, PD1, C3, PM					C3@ uib			p								
T3.4 Implement EEP in seasonal forecast model	**PD2**, PD1, C3, SR, PM																p

Milestones and deliverables :
Research stay with collaborator (@C1-2, C3@uib)
Research school (RS), incl. planning and coordination (prep.)
Paper submission + dissemination (p)

Risk: low, medium, high

prep. (**PDs**) RS
Nature paper

Table 1: Time schedule for management and WPs.
Legend: PM = project manager, SR = senior researcher, PDs = postdoctoral researchers, C1-3 = confirmed collaborators

Risk assessment and mitigation

In addition to the **scientific uncertainty** highlighted at the end of Section 1.2, the STAR project also faces **structural uncertainty**, as several tasks depend on the outcomes of preceding project stages. To optimise synergy and maintain flexibility, all three WPs–each combining low- and medium/high-risk components (see Table 1)—will be pursued in semi-parallel throughout the four-year timeline. Low-risk tasks will ensure steady progress and provide postdoctoral researchers with timely, publishable results that contribute to their career development. More complex, higher-risk tasks will be facilitated through research stays with collaborators, enabling focused problem-solving and expert input. Additional mitigation strategies for these tasks are summarized in Table 2.

Task	**Risk description**	**Mitigation strategy**
T1.3	Dependency on T1.2; unclear cause-and-effect relationships	Conduct test run where EPP is applied only in one hemisphere to isolate effects. Research visit to C1.
T2.3	Variable NOx–dynamics relationship; different EEP scenarios may produce similar stratospheric NOx levels	Allocate additional time and resources for testing multiple EEP forcing scenarios. Potential MSc student involvement for support with anlysis. Research visit to C2.
T3.2	Ambiguous interpretation due to dependence on variable preconditions affecting the EEP-surface response link	Use multiple data sources (model simulations and reanalysis) to contrain uncertainties. Research visit from C3.
T3.3	EEP influence on SSW forecasts may be too weak or inconsistent to isolate from dominant dynamical drivers	A pre-study has already been conducted to test the added predictive value of EEP in publicly available forecast data (see paragraph below).
T3.4	Dependency on T3.3; high computational cost	Use in-house computational expertise to optimize resources. Explore new collaborations. Limit initial output to proof-of-concept demonstration.

Table 2: Anticipated medium/high scientific risks and corresponding mitigation strategies for selected tasks.

Additional risk areas and mitigation

STAR also includes resource-intensive tasks that carry **technical risks**, such as limited access to supercomputing resources. This is addressed by bi-annual allocations from the Norwegian Sigma2 e-infrastructure, ensuring baseline access and flexibility. **Risks related to team members**—such as delays, lack of engagement, or unexpected absences—are mitigated through strong group management, including clear communication of expectations, shared planning, regular meetings, active follow-up, and ensuring knowledge continuity.

Altogether, STAR is designed to be both robust and adaptable, capable of sustaining scientific progress, responding to challenges, and delivering meaningful results across a range of potential outcomes.

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Proposers and collaborators are highlighted in bold.

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