REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation: Switzerland

Principal Investigator[1]: Dr. Hanna Joos, Dr. Ming Hon Franco Lee

Affiliation: Institute for Atmospheric and Climate Science, ETH Zurich

Address: Universitätstrasse 16, 8092 Zürich
Switzerland

Other researchers: Prof. Dr. Franziska Aemisegger, Dr. Michael Sprenger, Dr. Seraphine Hauser, Dr. Ambrogio Volonté, Rémi Bouffet-Klein, Eva Glock, Lena Fasnacht, Prof. Tobias Günther, Prof. Heini Wernli

Project Title: Diabatic processes and their impact on extratropical dynamics and the hydrological cycle

To make changes to an existing project please submit an amended version of the original form

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP**CHBOJO	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES ☐X	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	2 620 000	560 000	280 000
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	116 500	145 500	159 500

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

EWC resources required for project year:		2027	2028	2029
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

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Extended abstract

Diabatic processes, including cloud formation, radiation, and turbulence, can strongly influence various weather systems, such as extratropical cyclones and their associated warm conveyor belts (WCBs), as well as the jet stream via the modification of potential vorticity (Hoskins et al., 1985). Furthermore, cloud and precipitation processes act as sources and sinks of atmospheric water vapour and therefore play a key role in the hydrological cycle.

In this special project we would like to make use of our special IFS version that allows for hourly output of all temperature, momentum and moisture tendencies from parameterised physics and evaluate these tendencies in a Lagrangian framework describing the weather system of interest. This special IFS version has been developed in close collaboration with Dr. Richard Forbes and has been successfully applied in numerous studies and publications as part of our previous special projects.

More specifically, we aim to investigate a range of weather systems and flow configurations observed during the international field campaign NAWDIC (https://www.nawdic.kit.edu). This includes examining the role of diabatic processes in (i) jet dynamics and mixing at the tropopause (WP1, WP2), (ii) the formation of sting jets (WP3), (iii) the intensification of high-impact cyclones (WP4) and (iv) their contribution to moisture supply in different weather systems (WP5, WP6).

In the following, the work packages are described in more detail, including an estimation of the required computer resources.

Work packages

WP1: PV modification and turbulent mixing at the tropopause (Dr. Ming Hon Franco Lee, Dr. Michael Sprenger, Dr. Hanna Joos)

Turbulence has been identified as an important process in modifying potential vorticity (Spreitzer et al., 2019) and causing stratosphere-troposphere exchange (STE) (e.g. Shapiro, 1980; Stohl et al., 2003) near the tropopause in previous studies. During the previous phase of the project (2024-2026), the simulations performed with the special IFS version revealed the systematic PV modification by turbulence along the upper-level jet stream, forming a vertical PV tendency tripole in the shear zones above and below the jet core (Lee, 2025). The accumulation of these PV tendencies over time led to coherent PV changes near the tropopause, changing the PV gradient locally above the jet and dissipating the tropopause fold beneath the jet. While the results are consistent with other studies based on numerical simulations (e.g., Hartjenstein, 2000), the comparison of these tripolar signals with atmospheric measurements remains unexplored.

In the recent NAWDIC field campaign, multiple research flights have been conducted to investigate the turbulent mixing across the tropopause. The mixing ratios of trace gases are measured to infer stratospheric influence in the upper troposphere. It therefore provides an opportunity to compare PV modification signals with actual mixing in the atmosphere. In this project, we would like to perform simulations with the special IFS version to answer the following questions:

1) Is there a match between the simulated PV modification and the measured mixing by turbulence in space and time?
2) Are there any differences in the Lagrangian history of air parcels which show different tracer characteristics?
3) Does the time scale of material PV change correspond to the tracer-tracer correlation shown from measurements?

Technically, we would like to perform three 5-day forecasts with a resolution of TCo639 and three 3-day forecasts with a resolution of TCo1279 with hourly output. The simulations are planned to start in 2027.

WP2: Jet stream acceleration due to diabatic processes (Dr. Michael Sprenger, Dr. Hanna Joos, Dr. Franco Lee, Prof. Dr. Tobias Günther (University of Erlangen))

Jet streams are key weather features of the mid-latitude, as they influence and co-evolve with several synoptic- and mesoscale weather systems, e.g., extratropical cyclones, warm conveyor belts (WCB), atmospheric blocks. The intensity of jets and embedded wind speed maxima, i.e., jet streaks (Bukenberger et al., 2023), but also their meridional excursions are essential to better understand their impact on the local flow, e.g., by inducing vertical lifting and precipitation, and the flow evolution further downstream, e.g., by triggering Rossby waves that amplify and are often associated with severe weather.

In this work package, we aim to study the acceleration of jet stream and streaks due to diabatic processes. To this aim, we will specifically use the momentum tendencies due to convection and turbulence provided by this special project to diagnose how these tendencies lead to zonal and meridional accelerations and thus affect the strength and meandering of the jet streams.

This project builds on our recent efforts in objectively extracting jet-core lines from IFS simulations (Bösiger et al., 2022). Figure 1 shows an example from this study that illustrates the extracted jet-core lines and how the jet is locally accelerated while interacting with a WCB outflow. In autumn 2026, Tobias Günther (University of Erlangen, Germany) will join our research group for a four-month sabbatical to refine the methodology of the jet-core extraction, which will be applied to IFS simulations and to ERA5.

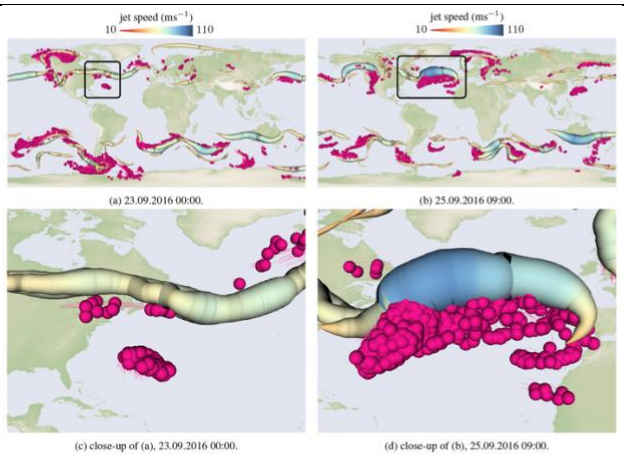

Fig. 1: Visualization of jet streams and WCB particles. Panel (a) shows a WCB outflow moving northwards in direction of the jet stream. Panel (b) shows the situation 2 days later. The WCB approached the jet stream and a considerable acceleration of the wind speed at the jet core is observable (dark blue jet). For both images, close-ups are shown in panels (c) and (d). Jet speed is mapped to tube color and tube radius [taken from Bösiger et al. (2022)].

Specifically, we plan to perform 2-3 case studies of jet stream accelerations. First, we will apply the objective algorithm to extract the jet-core line, then we will study along these core lines (and their surrounding) the processes leading to the jet acceleration. Specifically, we will address the following research questions:

1. To which degree do diabatic momentum tendencies explain accelerations along the jet core? How temporally and spatially coherent are the areas with substantial tendencies, and how does the coherence affect the jet acceleration?
2. Which weather systems (e.g., WCB, upper-level fronts, potential vorticity streamer) are associated to the momentum tendencies, and how do these systems provide the coherence for substantial tendencies?

Technically, we would like to perform two 5-day forecasts with a resolution of Tco1279 and hourly output of all temperature and momentum tendencies.

WP3: Revealing the role of individual cloud processes in the formation of sting jets in extratropical cyclones (Dr. Ambrogio Volonté, Dr. Hanna Joos)

Sting jets (SJs) are airstreams that can produce extreme and damaging surface gusts as they accelerate while descending off the tip of the cloud head of an intense extratropical cyclone (Clark and Gray, 2018). They can develop in Shapiro-Keyser cyclones, and are most likely to be found in explosively deepening cyclones characterised by vigorous diabatic processes (Gray et al., 2024). SJs are not resolved by standard global climate models, due to their small-scale and short-lived nature requiring convection-permitting models for their simulation (Manning et al., 2023). As they are also projected to increase in frequency in the future (Martínez-Alvarado et al., 2018), SJs represent an emerging hazard.

SJs have been the subject of active research since they were first identified in observations and hindcast simulations of the Great Storm of October 1987 (Browning, 2004; Clark et al., 2005) and there is now a consensus that their descent is associated with the release of symmetric instability, which is indicated by negative PV, (Volonté et al., 2018, 2020). However, the identification of the individual diabatic processes that reduce PV along the SJ as it travels in the cloud head, therefore driving the onset of symmetric instability, is still an open question. We started addressing it in Volonté et al. (in press) by using our special IFS version including diabatic tendencies to simulate Storm Ciarán, a highly diabatic windstorm that featured a SJ associated with damaging winds.

The results of this study highlighted the complexity of the environment in which the SJ develops, fast-changing, fully three-dimensional and characterised by steep gradients. Condensation of water vapour emerged as the most active process around the SJ, with large variability in PV changes across the SJ trajectories computed, together with melting of ice and snow along the bent-back warm front. Sublimation of snow showed a much more robust signal of moderate PV decrease, and cooling, along SJ trajectories. A schematic of the results is presented in Figure 2.

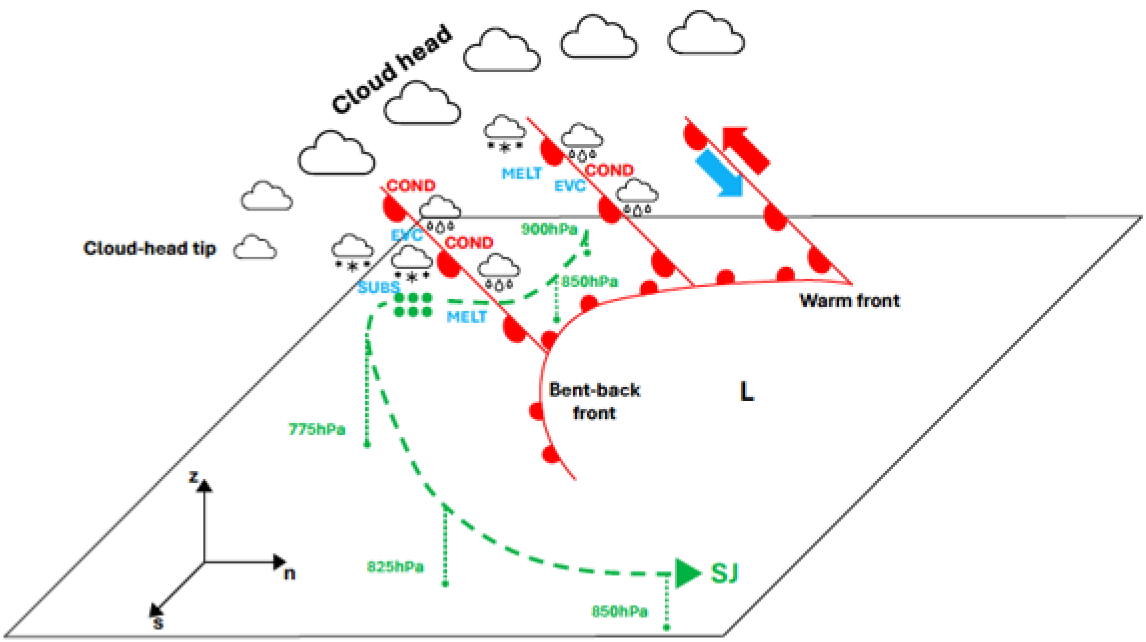

Fig. 2: Schematic representation of the path of SJ trajectories during their ascent in the cloud head and subsequent descent (green dashed lines, with pressure indication and projection on the ground shown by green dotted lines. Green dots indicate the location of SJ trajectories near the end of their ascent. s and n coordinates are oriented along and across the direction of travel of the trajectories at the end of their ascent, with z indicating the vertical direction. Warm and bent-back warm fronts are indicated at the surface and up towards the upper troposphere. The extent of the cloud head is indicated, together with the type of precipitation taking place, by cloud icons. Red and blue arrows indicate heating and cooling, respectively, on each side of the front. Condensation of water vapour (COND), evaporation of cloud water (EVC), melting of snow and ice (MELT) and sublimation of snow (SUBS) are indicated (in red or blue depending on whether they are associated to heating or cooling) near the locations where they are taking place. Figure and text taken from Volonté et al., in press.

While these results provide initial insights on the role of individual cloud processes in the evolution of sting jets, they only refer to a specific windstorm. SJ cyclones can cover a range of frontal strengths, freezing level heights and rates of snowfall and rainfall, all of which could impact on the relative importance of the different cloud processes. It is therefore key to explore cases with different environmental conditions and assess their influence on the role of individual cloud processes in changing PV along the SJ. This task is particularly important given the control seemingly exerted by melting and sublimation of snow on buoyancy and onset of instability along the SJ. An hypothesis to be verified would be whether storms that develop in a warmer environment and have a higher freezing level contain SJs with a more extended descent and thus, possibly, larger acceleration and higher impact. Alongside this hypothesis, a generalisation of the results in Volonté et al. (in press) would allow a more robust assessment of the role of the different cloud processes driving the evolution of SJs, allowing us to make credible hypotheses on their future changes as the climate warms and importance of diabatic processes such as latent heating in the development of windstorms increases.

To do so, our plan is to use our special IFS version to simulate up to 10 recent SJ windstorm. They will include two cases occurred the NAWDIC field campaign (Storm Goretti and Storm Kristin) and one, particularly intense, during the dry run in the season preceding the campaign. By doing so, we would benefit from being able to compare our simulations against additional observations (mainly Goretti) and several dedicated simulations at different resolutions. This comparison would allow us to assess the plausibility of our simulations in terms of SJ evolution, and therefore the role of cloud processes in it.

Technically, we would like to perform eight 1-day and two 2-day forecasts with a resolution of TCo1279 and hourly output of all temperature and momentum tendencies.

WP4: The role of latent heat release for the deepening of high-impact extratropical cyclones (Dr. Seraphine Hauser, Prof. Heini Wernli)

This part of the project is dedicated to the role of latent heat release in the intensification of rapidly deepening extratropical cyclones, which frequently cause high surface winds, heavy precipitation, and flooding in populated areas (e.g., Pfahl and Wernli 2012; Catto and Pfahl 2013). Over recent decades, substantial research has been conducted to quantify the role of latent heat release in the evolution of high-impact extratropical cyclones using various approaches (e.g., Büeler et al., 2017; Christ et al., 2026). However, the resulting contribution of latent heat release appears to depend heavily on the method used. Consequently, further research is necessary to (1) employ a wider range of quantification methods, and (2) reconcile the differing contributions across these methods. One method frequently used to quantify this contribution is the “dry simulation” setup within numerical weather prediction modeling, in which latent heat release (or, in some cases, moist dynamics) is switched off (e.g., Stoelinga, 1996). While such experiments were widely conducted in the 1980s and 1990s, the approach has received only limited attention since then.

In this project, we aim to perform modified latent heating (MLH) experiments using a specialized version of the ECMWF Integrated Forecasting System (IFS). For selected rapidly deepening, high-impact extratropical cyclones across the North Atlantic, we will conduct control and MLH experiments to investigate the differences in storm development within the respective IFS simulations. These results will then be compared to simulations featuring identical horizontal grid spacing, initial conditions (IFS analysis), and initialization times conducted in both the ICOsahedral Nonhydrostatic (ICON) model (by the German Weather Service; Zängl et al., 2015) and the Portable Model for Multi-Scale Atmospheric Prediction (PMAP) model, currently under development at ECMWF and ETH Zürich. Using the special IFS version within a pool of other models would provide the very first cross-model intercomparison of MLH experiments, offering valuable insights into the differences between the models.

Technically, we would like to perform four 5-day forecasts with a resolution of TCo1279 with hourly output of all temperature and momentum tendencies.

WP5: Diabatic processes enabling deep incursions of Atmospheric Rivers into East Antarctica and the Antarctic Plateau (Eva Glock (University of Bern), Prof. Franziska Aemisegger (University of Bern))

A dedicated IFS q and t-tendency output simulation of the Atmospheric River event of December 2018 documented in Dutrievoz et al. 2026, which led to substantial surface warming on the Antarctic plateau (+18°C at the Concordia station) offers a unique opportunity to disentangle the contributions of individual microphysical processes to moisture loss and

recycling along the Lagrangian flow pathway. This will enable us to test two key hypotheses: First, we hypothesise that efficient transport of moisture towards Antarctica relies on a "hand-over" between successive cyclones and anticyclones along the Southern Ocean storm track, whereby moisture is built up by transferring moisture between weather systems in particular from cyclone-anticyclone interaction zones as well as the cyclones' cold sectors towards the next cyclone's warm sector (Papritz et al. 2021). Second, we hypothesise that internal atmospheric moisture recycling, particularly through sublimation and re-evaporation processes, is a prerequisite for deep continental incursions of ARs that reach the Antarctic Plateau and produce substantial snowfall and surface warming far inland (similar to the Domino process described in Rieder et al. 2024). By combining q-tendency diagnostics with Lagrangian moisture tracking (Fasnacht et al. 2026), the simulations will provide new process-level constraints on the cloud-microphysics-circulation interactions that control Antarctic precipitation efficiency and the inland impact of extreme moisture intrusions as motivated in the Antarctica InSync Theme 6 Whitepaper (Schmale et al. 2026).
With this work we plan to address the following 3 research questions:

1) Which dynamical ingredients are required in the moisture uptake region of Antarctic AR events to build up intense and persistent poleward moisture transport towards East Antarctica?
2) Which cloud-microphysical processes most strongly control moisture loss and recycling, and thus determine precipitation efficiency along Antarctic Atmospheric River trajectories? What is the role of atmospheric internal moisture recycling along the flow (snow and ice sublimation, rain evaporation in mixed-phase parts of the clouds) for enabling ARs to reach the interior of the Antarctic Plateau
3) How do interactions between cloud microphysics and dynamics determine precipitation efficiency during extreme warming events over the Antarctic Plateau? I.e. which dynamical features within the moist-warm filaments favour intense moisture recycling along the flow (e.g. Foehn-like structures in the lee of the Queen Maud Land)?

Technically, we plan to perform three 10-day forecasts with a resolution of TCo639 and hourly output of all moisture tendencies.

WP6: Diabatic processes and moisture sources in weather systems measured during NAWDIC (Rémi Bouffet-Klein, Lena Fasnacht (University of Bern), Dr. Hanna Joos, Prof. Franziska Aemisegger (University of Bern), Dr. Franco Lee)

During the NAWDIC field campaign, several weather systems, including extratropical cyclones, atmospheric rivers, WCBs and dry intrusions (DIs) have been measured by one or more of the involved airplanes. Preliminary results from the PhD work of R. Bouffet-Klein, which are based on IFS simulations including detailed output of all moisture tendencies indicate that cloud processes can significantly contribute to a moistening of airstreams feeding into a WCB and can therefore not be neglected (see Figure 3). We therefore plan to simulate several cases, selected based on the NAWDIC IOPs, to investigate the following research questions:

1) Which processes lead to a moistening of the air along DI trajectories, including cloud microphysical processes and surface fluxes?
2) What is the role of ARs and DIs in providing moisture for the WCB inflow?
3) How do the simulated moisture content and moisture fluxes compare to measurements?
4) How important is the dry-intrusion-boundary layer cloud interaction during a cold air outbreak for dynamically enabling rapid and intense moisture uptake feeding the subsequent cyclone's WCB?

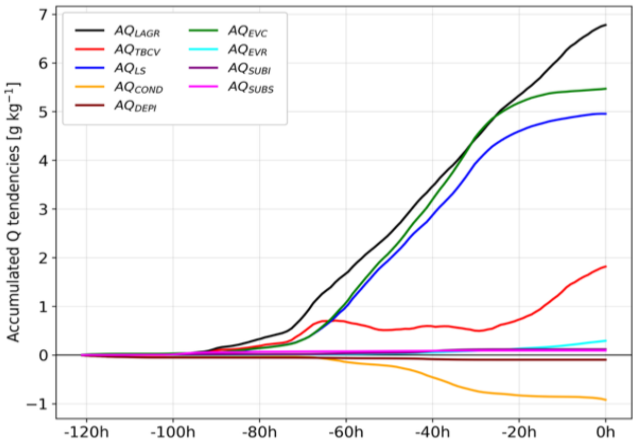

Fig. 3: Accumulated moisture tendencies along 5-day backward trajectories started from a WCB inflow region. Coloured lines indicate moisture gain due to turbulence and convection (TBCV, red), the large-scale cloud scheme (LS, blue), which can be split up in contributions from condensation (COND, yellow), evaporation of clouds (EVC, green), depositional growth of ice/snow (DEPI, brown), evaporation of rain (EVR, cyan), sublimation of ice (SUBI, purple), sublimation of snow (SUBS, pink) and the total accumulated moisture tendency (LAGR, black).

To investigate these questions, we would like to perform four 7 day forecasts with TCo1279, with hourly temporal resolution and output of all moisture tendencies. In particular, the cold air outbreak and warm air intrusion of 13.2.-14.2.2026 with coordinated flights of the HALO (upper levels), ATR (mid troposphere) and Cessna (lower troposphere below and above boundary layer clouds) will be a particularly interesting case to study in detail given the wealth of available observations.

Estimation of Computer resources

Year	Description of the forecasts	Estimation of billing units and data storage
2027	***WP1:*** i) 3 case studies, TCo639, 5-day lead time, 1-hourly output of all temperature and momentum tendencies ii) 3 case studies, TCo1279, 3-day lead time, 1-hourly output of all Temperature and momentum tendencies ***WP2:*** i) 2 case studies, TCo1279, 5-day lead time, 1-hourly output of all temperature and momentum tendencies ***WP3:*** i) 3 case studies, TCo1279, 1-day lead time, 1-hourly output of all temperature and momentum tendencies	120 000 SBU 6 Tb 300 000 SBU 13.5 Tb 400 000 SBU 15 Tb 120 000 SBU 6 Tb

	ii) 2 case studies, TCo1279, 2-day lead time, 1-hourly output of all temperature and momentum tendencies ***WP4:*** i) 4 case studies, Tco1279, 5-day lead time, 1-hourly output of all temperature and momentum tendencies ***WP5:*** i) 2 case studies, TCo639, 10-day lead time, 1-hourly output of all temperature, momentum and moisture tendencies ***WP6:*** i) 2 case studies, TCo1279, 7-day lead time, 1-hourly output of all temperature, momentum and moisture tendencies	160 000 SBU 8 Tb 800 000 SBU 30 Tb 160 000 SBU 10 Tb 560 000 SBU 28 Tb
2028	***WP3:*** i) 5 case studies, TCo1279, 1-day lead time, 1-hourly output of all temperature and momentum tendencies ***WP5:*** i) 1 case study, Tco639, 10-day lead time, 1-hourly output of all moisture tendencies ***WP6:*** i) 1 case study, TCo1279, 7-day lead time, 1-hourly output of all temperature, momentum and moisture tendencies	200 000 SBU 10 TB 80 000 SBU 5 Tb 280 000 SBU 14 Tb
2029	***WP6:*** i) 1 case study, TCo1279, 7-day lead time, 1-hourly output of all moisture tendencies	280 000 SBU 14 Tb

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