EMI R&D PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2026………………………………………………….……
Project Title:	Diabatic processes and their impact on extratropical dynamics and the hydrological cycle
Computer Project Account:	SPCHBOJO……………………………….……
Principal Investigator(s):	Dr. Hanna Joos, Dr. Michael Sprenger
Affiliation:	Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr. Richard Forbes
Start date of the project:	1. January 2024
Expected end date:	31. December 2026

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	1 010 000	487 241	510 000	69 935
Data storage capacity	(Gbytes)	30 000		40 000	

Summary of project objectives (10 lines max)

In this project, we make use of our special IFS version which allows for hourly output of all temperature, momentum and moisture tendencies due to parameterized physics. The momentum and temperature tendencies are used to investigate the effect of clear air turbulence on the dynamics at the tropopause (WP1), the modification of potential vorticity along sting jet trajectories (WP2), and the effect of radiative cooling on the strength of cold air outbreaks and the associated formation of cyclones (WP3). In WP4 the moisture tendencies are used to analyse the moisture sources for warm conveyor belts, strongly ascending airstreams in extratropical cyclones that are responsible for a large part of precipitation falling in the extratropical storm tracks.

Summary of problems encountered (10 lines max)

We did not encounter any problems

Summary of plans for the continuation of the project (10 lines max)

We plan to perform further simulations to work on the following projects: (WP3) Simulations of cold air outbreaks (CAO) with modified radiative temperature tendencies over the upstream continents to assess the importance of these processes for the formation of strong CAOs and the subsequent formation and intensification of extratropical cyclones. (WP4) Simulations of warm conveyor belts in different regions and seasons to assess the case-to-case variability of moisture sources that contribute to the WCB inflow. We also submitted a request for the continuation of this special project to perform simulations of weather systems and their moisture sources and of extratropical cyclones featuring sting jets that occurred during the NAWDIC field campaign.

List of publications/reports from the project with complete references

Volonté, A., Joos, H., Lee, M. H. F., Forbes, R. M., and Bouffet-Klein, R. (in press) Identifying the diabatic processes driving the evolution of a sting jet: the case of Storm Ciarán, Weather and Climate Dynamics. Preprint available at: https://doi.org/10.5194/egusphere-2025-5225.

Lee, M. H. F.: Clear-air turbulence - generation, predictability, and feedback in weather systems, Ph.D. thesis, ETH Zurich, https://doi.org/10.3929/ethz-c-000795586, 2025.

Summary of results

WP1: Potential Vorticity Modification and Clear Air Turbulence in the Tropopause Region (Dr. Franco Lee, Dr. Michael Sprenger, Dr. Hanna Joos)

In this work package, we aimed at revealing the effect of turbulence on the large-scale flow near the tropopause by studying how it modifies potential vorticity (PV). We used two forecast experiments based on the IFS model (CY47R3) at TCo1279 resolution and the extra output of temperature and momentum tendencies allowed us to compute the PV tendencies for each parametrised process. Apart from the instantaneous tendencies, we further explored the material PV changes of air parcels using backward trajectories.
The analysis shows that turbulence usually generates a vertical tripole of PV tendency centred at the turbulent layer, which experience a PV decrease. This pattern is observed in the shear zones associated with the upper-level jet as well as at the outflow boundary of a warm conveyor belt (see schematic in Figure 1). With an analytical framework, we can understand the emergence of this general pattern. The vertical PV tendency tripoles are manifested on isobaric surfaces as elongated bands with alternating signs. Air parcels are found to travel along or together with these bands,

allowing a steady and consistent material PV change. Turbulence is thus systematically modifying PV in the vicinity of the tropopause and is important at short-time scales in shaping the PV distribution, inviting future studies on this up-scale feedback by turbulence.

The results are reported in the doctoral thesis (Lee, 2025) and will be submitted for publication this year.

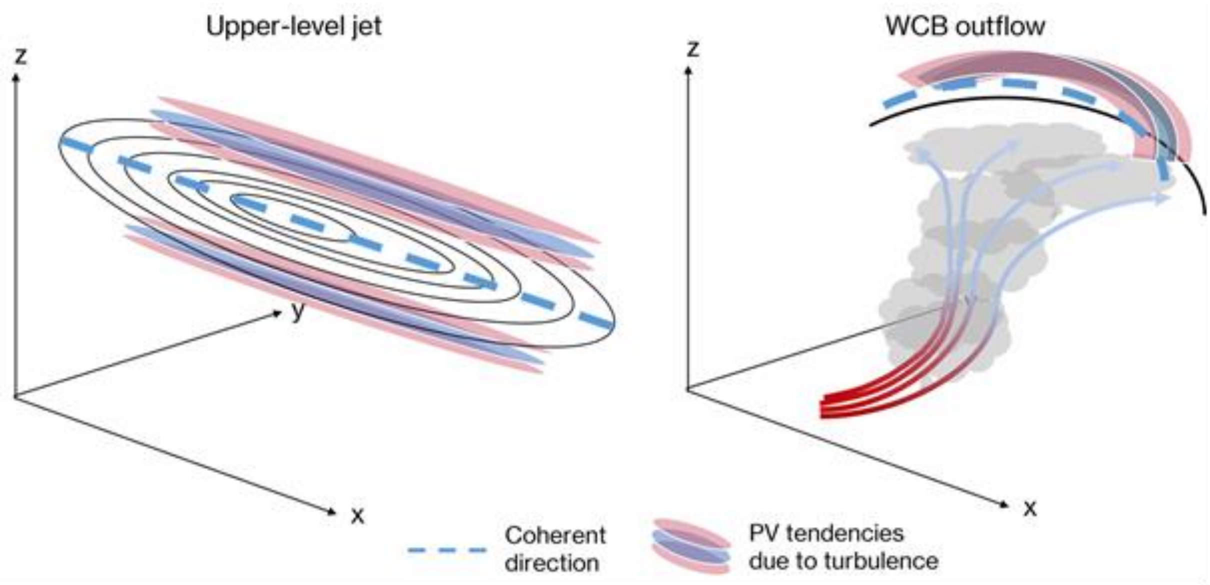

Fig. 1 Schematic illustrating the formation of vertical PV tendency tripoles at the turbulent layer in (a) the shear zones associated with the upper-level jet, and (b) at the outflow boundary of a warm conveyor belt due to turbulence.

WP2: Sting jet in storm Ciarán (Dr. Ambrogio Volonté (University of Reading), Dr. Hanna Joos, Dr. Franco Lee, R. Bouffet-Klein, Dr. R. Forbes (ECMWF))

We used the IFS model CY47R3 with a resolution of TCo1279 (~9km) and hourly output of all temperature tendencies to perform a case study simulation of storm Ciarán, which occurred in November 2023 in the eastern North Atlantic and impacted west Europe bringing severe damage. The storm featured a small-scale region of extremely strong low-level winds (> 50 m/s at 850 hPa) belonging to the airstream called "sting jet"(SJ), whose acceleration is associated with the release of symmetric instability (indicated by negative PV). The sting jet developed while travelling in the cloud head and became part of a filament of negative potential vorticity (PV) while surrounded by multiple PV bands. The impact of diabatic processes on the evolution of PV along SJ trajectories was analysed based on the output of temperature tendencies, which allow the calculation of the associated PV tendencies. We identified four moist processes actively changing PV: condensation of water vapour, evaporation of cloud water, melting of ice and snow and sublimation of snow. Condensation emerged as the process producing the largest PV changes around the SJ, but with large variability across SJ trajectories, 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. However, it must be mentioned that the method of calculating PV tendencies based on hourly output comes to a limit because higher spatial and temporal resolution would be required to fully capture the temperature and PV tendencies in this fast-changing environment near the bent-back front. The results are schematically summarized in Figure 2 and have been accepted for publication in "Weather and Climate Dynamics".

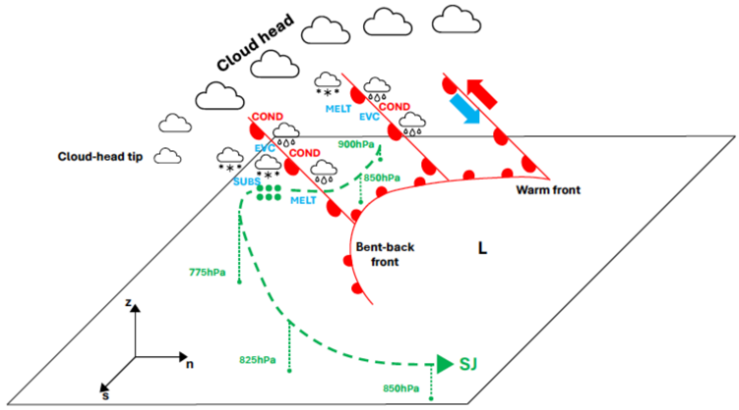

Fig. 2: Schematic representation of the path of SJ trajectories during their ascent in the cloud head and subsequent descent (green dashed lines, with pressure indication and projection on the ground shown by green dotted lines. Green dots indicate the location of SJ trajectories near the end of their 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.

Volonté, A., Joos, H., Lee, M. H. F., Forbes, R. M., and Bouffet-Klein, R. (in press) Identifying the diabatic processes driving the evolution of a sting jet: the case of Storm Ciarán, Weather and Climate Dynamics. Preprint available at: https://doi.org/10.5194/egusphere-2025-5225.

WP3: Diabatic processes at the entrance of the storm tracks and their role for extratropical cyclone dynamics (Dr. Jacopo Riboldi, Franziska Schnyder)

We use the special version of the IFS model (Cy49R1) to perform a case study of a cold air outbreak (CAO), that occurred in January 2023 in the Japan Sea. We aim to compare a control simulation, computed with the original source code of the IFS, to a simulation, where the near-surface cooling over Siberia is modified, to understand its impact on the intensity of the CAO downstream. The control run is already calculated (Figure 3), and we are currently doing tests, where the exchange coefficient in the boundary layer scheme is modified (thereby modifying the surface sensible heat flux).

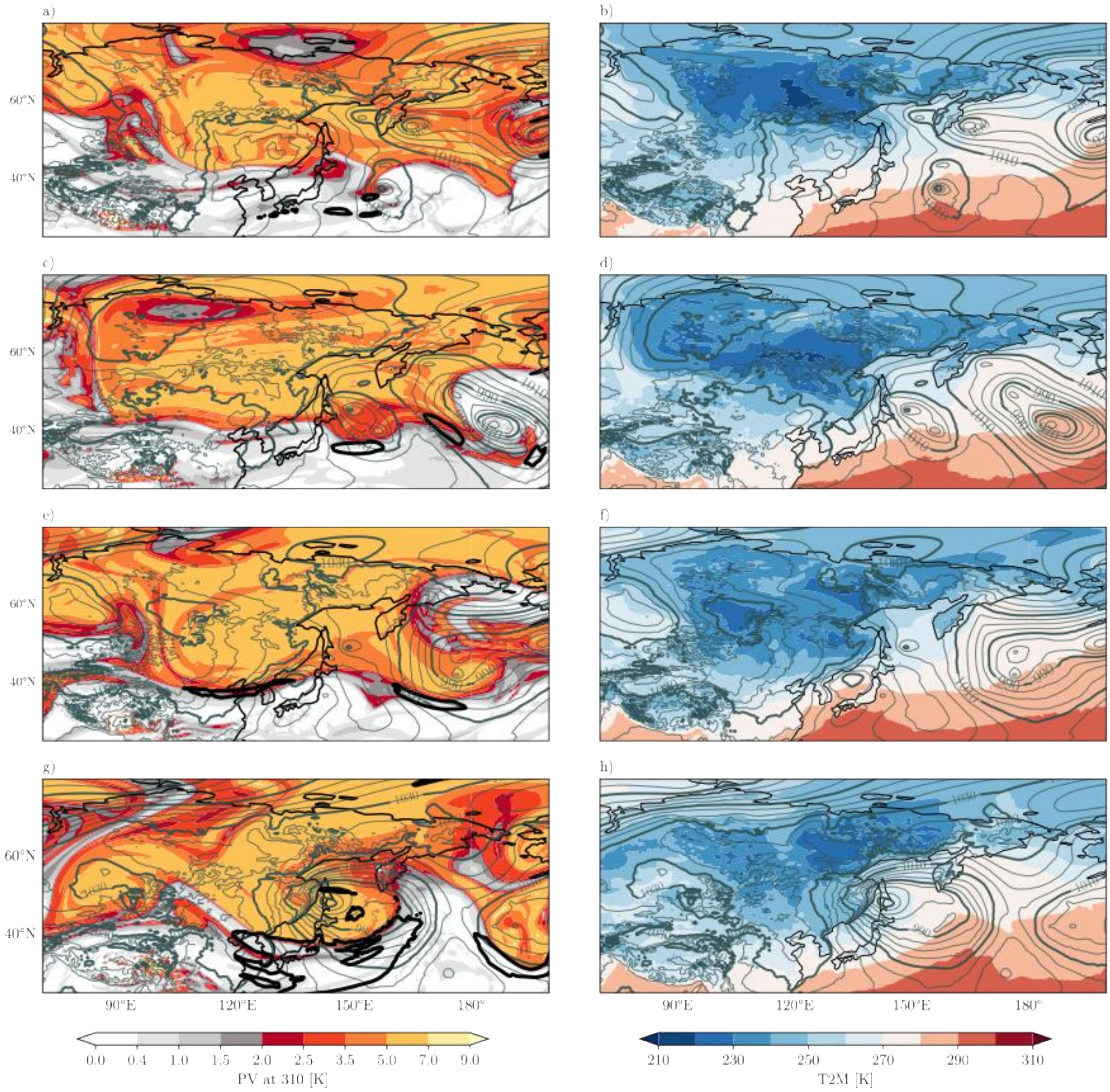

Figure 3: Simulation of case study of CAO in January 2023 initiated on 00UTC at 18 January 2023. Shown are the time steps: (a,b) 00UTC on 19 January 2023, (c,d) 00UTC on 21 January 2023, (e,f) 00UTC on 23 January, and (g,h) 00UTC on 25 January 2023. In the left panel we show PV at 310K (colour), mean SLP (gray contours, every 5hPa) and wind speed at 500hPa (bold black contours, 40 and 60m s^{-1}). In the right panel the 2m temperature is indicated (colours), as well as mean SLP (gray contours, every 5hPa).

WP4: Moisture sources of warm conveyor belts (Rémi Bouffet-Klein, Franco Lee, Dr. Hanna Joos, Dr. Michael Sprenger)

We used our special version of the IFS model (Cy47R3) to perform a simulation of a warm conveyor belt (WCB) that occurred in February 2022 in the North Atlantic, including hourly output of all moisture tendencies from parameterized physics. This includes contributions from turbulence and convection and the large-scale cloud scheme, which can further be split up in in the contributions from the different microphysical processes, namely evaporation/condensation of clouds, evaporation of rain and sublimation/depositional growth of ice and snow. We evaluated the contribution of these processes to the total water mass in the WCB inflow by accumulating all tendencies along 5-day backward trajectories started from the WCB inflow. The results (Fig. 4, left) indicate that turbulence/convection and the large-scale cloud scheme each contribute roughly 50% to the total water mass. Within the large-scale cloud scheme, cloud evaporation is the dominant process, while rain evaporation and the sublimation of ice and snow provide smaller contributions.

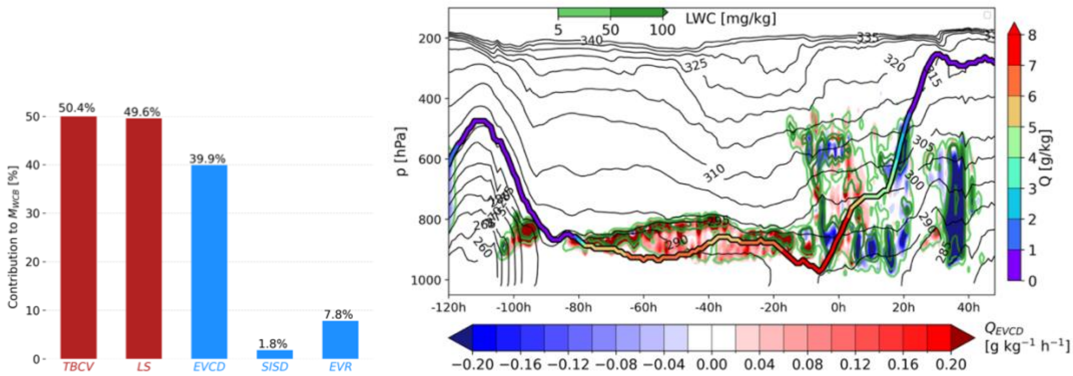

Fig. 4: left: contribution of different processes to the total water mass in the WCB inflow (in %): Turbulence and Convection (TBCV), the large-scale cloud scheme (LS), evaporation and condensation of cloud liquid (EVCD), sublimation and depositional growth of snow and ice (SISD) and evaporation of rain (EVR). Right: Time-height section along an example trajectory (coloured line, Q [g/kg]). Colour shading shows the moisture tendency due to evaporation of clouds (QEVCD in g/kg h), green lines liquid water content (LWC in mg/kg) and black lines isentropes (in K).

A detailed analysis of a trajectory experiencing strong moisture supply by the evaporation of cloud liquid is shown in Figure 4, right. The trajectory strongly descends as part of a dry intrusion. When it encounters liquid clouds at the top of the boundary layer, they start to evaporate and moisten the air parcel. The results highlight the manifold processes that are relevant in moistening the inflow of a WCB and the subsequent formation of precipitation.