REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: Switzerland………………………….…

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Project Title:

Diabatic heating rates and moist tendencies along airstreams associated with different weather systems

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.)	2021	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	1 000 000	800 000	200 000
Accumulated data storage (total archive volume)[2]	(GB)	20 000	43 000	48 000

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special 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.

Principal Investigator: Hanin Binder and Hanna Joos……………………………………

Project Title: Diabatic heating rates and moist tendencies along airstreams associated with different weather systems

Extended abstract

Motivation

The formation of clouds and precipitation is strongly linked to the atmospheric circulation. On the one hand, clouds are formed due to dynamically and thermally forced updrafts in different weather systems. On the other hand, the formation of clouds and the associated latent heat release feed back to the atmospheric circulation. This feedback can be nicely described by the concept of the modification of potential vorticity (PV) by diabatic processes (Hoskins et al.,1985). The processes leading to a PV modification are numerous: convection, boundary layer turbulence and gravity wave drag, latent heat release or consumption during cloud formation or dissipation, and short-wave and long-wave radiative heating effects (e.g. Parker and Thorpe, 1995; Grams et al., 2011; Joos and Wernli, 2012; Igel and van den Heever, 2014; Hardy et al., 2017; Crezee et al., 2017; Saffin et al., 2017). Depending on the flow situation, the relative importance of the aforementioned processes can significantly vary in their intensity and thus, how they contribute and impact on the atmospheric circulation. In addition to the potential for modifying PV, these processes can also lead to a redistribution of moisture in the atmosphere. For instance, evaporating or sublimating hydrometeors potentially lead to substantial moistening of air parcels, quite in contrast to cloud formation where moisture is taken away from the environment.

In the framework of the ongoing special project (SPCHBOJO), ending in December 2020, we investigated in detail the relevance of diabatic processes in different case studies with a focus on PV modification in extratropical cyclones and in the tropopause region by using a special IFS versions, which allows to output hourly all temperature and momentum tendencies from parameterized physics. In order to generalize the findings, the analysis has been extended to a one year simulation (Spreitzer et al., 2019; Attinger et al., 2019; Spreitzer, 2020; Attinger, 2020).

In this project we would like to make further use of this special IFS version to extend our knowledge on how diabatic processes influence the hydrological cycle in different regions and weather systems (Part 1) and how they interact with the circulation via their potential to modify PV along different airstreams (Part 2).

Part 1: Moisture sources and moisture recycling

In the available literature, the sources of atmospheric moisture have been investigated mainly using back-trajectories based on reanalysis wind fields (Stohl and James, 2004; Sodemann et al., 2008) or with tracer experiments in numerical models (Sodemann et al., 2009). These methods have been applied in various contexts such as to investigate the moisture sources of ice core drill sites on polar ice sheets (Sodemann and Stohl, 2009) in studies on the isotope composition of atmospheric waters (Pfahl and Wernli, 2008; Aemisegger et al., 2014; Thurnherr et al., 2020) or for assessing the moisture sources of heavy precipitation events (Winschall et al., 2014). The sophisticated approaches used in all these studies, however, have one major limitation. All the moisture uptakes within these studies are implicitly (for the Lagrangian studies) or explicitly (for the Eulerian tracer experiments) associated with surface evaporation. For example, in the method of Sodemann et al. (2008), changes in specific humidity along an air parcel trajectory that occur within the boundary layer are implicitly associated with surface latent heat fluxes. In moisture tagging experiments, the fate of the water vapour from surface evaporation in various regions can be investigated. More detailed attribution studies of the sources of atmospheric water vapour variability in the troposphere due to microphysical processes, turbulence, convection or surface fluxes in different regions and weather systems would provide useful insights into the relative importance of these parametrized moist diabatic processes.

In this project we would like to focus on two different regions and phenomena in order to assess in detail the moisture sources, namely (i) extratropical dry intrusions, which can have a pronounced impact on the atmospheric environment in the subtropics, where shallow clouds develop (Mapes and Zuidema, 1996) and (ii) extratropical cyclones, which are linked to the formation of liquid, mixed-phase and ice clouds as well as precipitation and where therefore manifold processes can potentially influence the moisture cycle.

1.1 Extratropical dry intrusions

Robust prediction of future climate is currently hampered by our limited understanding of how clouds and their organisation interact with the circulation (Ceppi and Hartmann, 2016). The change in low clouds due to warming remains the greatest source of uncertainty in climate projections (Schneider et al., 2019). The observed patterns of clouds in the trade wind region resulting from the organisation of shallow convection is embedded in and interacts with the descending large-scale flow that is typically associated with the circulations of the tropical Hadley and the midlatitude Ferrel cells. Dry air masses originating from the tropical deep convective outflows, the extratropical jet stream region or from the subtropical mid-troposphere descend towards the surface, thereby stabilising and dehydrating the atmosphere above the cloud layer (Yoneyama and Parsons, 1999; Cau et al., 2005). The descent pathways and progressive moistening of theses airstreams by surface fluxes, turbulent mixing and convection (Lee et al., 2011; Brown et al., 2013) are key preconditioning factors that shape the atmospheric environment in which shallow convective clouds develop. A dynamical phenomenon with a particularly strong impact on the vertical extent of shallow cumulus clouds are so-called extratropical dry air “intrusions” (Mapes and Zuidema, 1996). These dry intrusions have been shown to be induced by midlatitude jet stream dynamics (Yoneyama and Parsons, 1999) using soundings and global atmospheric analysis datasets from the Coupled Ocean–Atmosphere Response Experiment of the Tropical Ocean and Global Atmosphere programme (TOGA COARE, Webster and Lukas, 1992).

A comparison of the thermodynamic history of an extratropical dry intrusion airstream and a typical trade wind airstream, which both arrive in the sub-cloud layer above the Carribean island of Barbados in 2018 is shown in Fig. 1 (red vs. blue pathway in the thermodynamic diagram).

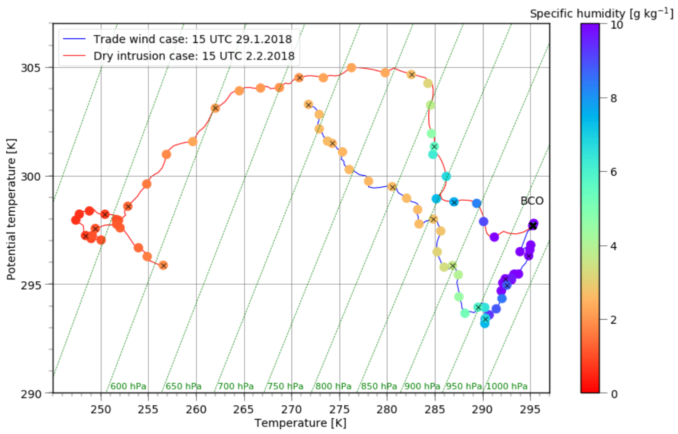

Figure 1: Thermodynamic diagram summarising the 10 days Lagrangian history of two airstreams with contrasting thermodynamic history, which arrived in the sub-cloud layer (p > 940 hPa, 40 trajectories) above the Carribean island Barbados (black thick cross) at 15 UTC on 29.1.2019 (blue line) and at 15 UTC on 2.2.2018 (red line). The trajectories were calculated based on ERA5 wind fields. The colours of the filled circles indicate the specific humidity of the air parcels every 6 hours. The thick black cross indicates the arrival conditions above Barbados, the thin black crosses indicate daily time steps backwards in time. The slanted green lines show isobars, the horizontal lines isentropes and the vertical lines isotherms. Horizontal motion towards the right hand side corresponds to adiabatic warming, vertical motion towards the bottom of the diagram indicate strong diabatic cooling. Slantwise motion from lower left to the upper right along the green lines indicates isobaric motion.

The extratropical dry intrusion airstream (red line in Fig. 1) is taking up large amounts of moisture within 3 days before arrival, whereas the trade wind airstream has been moistened much earlier (7 days prior to arrival), when descending over western North Africa (not shown). This rapid thermodynamic modification and moistening of extratropical dry intrusions during their descent will be investigated in detail with an IFS simulation including diabatic heating and humidity tendencies in work package 1 (WP1).

1.2 Moisture recycling in extratropical cyclones

Extratropical cyclones can be described by three Lagrangian airstreams, a strongly rising warm conveyor belt (WCB), a moderately rising cold conveyor belt (CCB) ahead of the surface warm front and a dry intrusion (DI) that strongly descends behind the cold front (e.g. Green et al., 1966; Harrold, 1973; Browning et al., 1973; Carlson, 1980). In the ascending airstreams, strong cloud formation occurs (Browning et al., 1973), including liquid, mixed phase and ice clouds (e.g. Joos and Wernli, 2012). These clouds can be vertically and horizontally extended and lead to pronounced precipitation in the form of snow or rain. The falling sublimating and/or evaporating hydrometeors are responsible for a vertical redistribution of moisture in the cyclone. This leads to a coupling of the different, otherwise spatially separated airstreams (e.g. Attinger et al., 2019; Spreitzer, 2020). For example, precipitation that forms in the ascending WCB can sediment behind the warm front and start to evaporate/sublimate below cloud base in air masses that belong to the CCB. The CCB is therefore moistened by this process and can subsequently transport this additional moisture into the cyclone centre. Thus, moisture that was taken up in the warm sector of the cyclone in the WCB inflow is redistributed and potentially contributes to more than a single cloud formation event in the same cyclone (Spreitzer, 2020).

Spreitzer (2020) investigated how different airstreams in an extratropical cyclone are affected by snow sublimation. Figure 2, left, shows an airstream that experiences substantial cooling due to sublimation of snow and is therefore strongly moistened by this process. The airstream originates to the north-east of the cyclone centre and travels to the north of the surface warm front towards the cyclone centre where it slightly rises. The evolution of moisture along this airstream is shown in Fig.2, right. Until t=12h, the airstream takes up moisture. Thereby the dominant contribution to this moisture uptake comes from the large-scale cloud scheme (yellow line), whereas the sublimation of snow (blue line) is the main contributor within the large-scale cloud scheme. Close to the cyclone centre, this airstream leads to the formation of a cloud. In summary, part of the moisture that leads to this cloud formation has been taken up from sublimating snow that originated from an ascending airstream originating in the warm sector of the cyclone.

This example nicely illustrates how complex the pathways of moisture in an extratropical cyclone can be. With this project we would like to expand our knowledge on moisture cycles/moisture recycling in extratropical cyclones and to assess the importance of below-cloud processes for moisture availability and cyclone dynamics (work package 2).

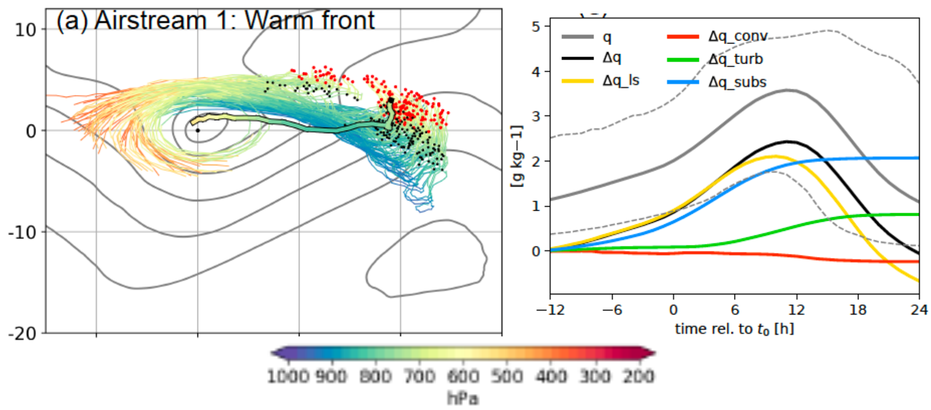

Fig.2: left: trajectories of an airstream experiencing strong sublimation of snow, coloured with pressure. Red dots show the start points of the airstream. Right: Temporal evolution of specific humidity (grey, with 10th and 90th percentiles in grey dashed), evolution of specific humidity relative to q at t=0-6h in black, contribution of the large-scale cloud scheme (ls) to the net change of q in yellow, of snow sublimation (subs) in blue, of convection (conv) in red and turbulent mixing (turb) in green. Pictures taken from Spreitzer (2020).

Part 2: Diabatic PV modification

2.1 Stratosphere-Troposphere exchange

Stratosphere-troposphere exchange (STE), i.e. the transport of air masses and atmospheric tracer substances across the tropopause, significantly influences the chemical composition of the atmosphere because it changes the oxidative capacity of the troposphere (e.g Kentarchos and Roelofs, 2003) and also has potential to affect the climate system because ozone and water vapour, as two major distinguishing tracers between the two spheres, are potent greenhouse gases (e.g. Gauss et al., 2003; Forster et al., 2007; Škerlak et al., 2014). However, so far the relative importance of this exchange for the near-surface ozone budget is not yet entirely certain and remains a topic of debate. For instance, although surface ozone concentration along the west coast of North America and around the Tibetan Plateau are likely to be influenced by deep stratospheric intrusions (Škerlak et al., 2014), the relative importance, spatial and temporal structure of these deep intrusions in theses well-studied regions remains still unclear.

The dynamical tropopause is defined as the 2-PVU isosurface with PV values in the stratosphere larger than 2 PVU and in the troposphere smaller than 2 PVU. A crossing of the dynamical tropopause therefore must be associated with diabatic processes due to PV's conservation principle under adiabatic and frictionless flow. In the upper troposphere, PV can be modified by cloud diabatic processes, radiative heating and/or cooling as well as by turbulence. However, the degree to which these processes contribute to the crossing of the 2 PVU barrier remains poorly understood. In a detailed case study, Spreitzer et al. (2019) studied the PV evolution in a tropopause fold using the IFS model with hourly output of all temperature and momentum tendencies from parameterized processes. She could show that turbulence was eroding PV in this specific tropopause fold, which finally lead to significant STE – thus confirming the relevance of tropopause folds for STE. However, a complete understanding of this exchange and the importance of different processes in different flow situation is still missing. More specifically, in addition to tropopause folds many other weather systems have been found to be associated with STE, e.g. PV streamers and cutoffs (Sprenger and Wernli, 2007). Furthermore, the diabatic PV changes are often linked to clear air turbulence, e.g. due to breaking gravity waves, near the tropopause level. How the different processes and synoptic/mesoscale weather systems 'interact' to foster STE remains unclear, and asks for a fine-scale analysis of PV-modifying processes.

In work package 3 we therefore would like to investigate in detail by means of case studies, which diabatic processes are relevant for an exchange of airmasses between the stratosphere and the troposphere, and how they differ between distinct weather systems.

2.2 Model intercomparison of diabatic heating and PV rates in a warm conveyor belt

As warm conveyor belts (WCBs) are strongly rising, cloud producing airstreams, latent heat is released due to various microphysical processes (e.g. Joos and Wernli, 2012). The latent heat release leads to the formation of a positive PV anomaly in the lower or mid troposphere and a negative PV anomaly in the upper troposphere (e.g. Wernli, 1997; Pomroy and Thorpe, 2000; Grams et al., 2011). In this way, WCBs provide an environment where small-scale cloud microphysical processes are directly linked to large-scale atmospheric dynamics in and around extratropical cyclones. As the small-scale microphysical processes cannot be resolved by numerical weather prediction or climate models, these processes have to be parameterized. This, however, introduces significant uncertainties in the representation of these processes. In order to improve our understanding of the impact of different microphysical parameterizations on the large-scale atmospheric flow, it is insightful to compare the representation of microphysics and the impact on the atmospheric circulation in the ICON and IFS model.

As the WCB is an airstream that is strongly heated due to diabatic processes, its detailed ascent behaviour and subsequent interaction with the upper-level flow critically depends on the integrated parameterized heating from mostly microphysical processes, including also parameterized convection. Both models, the ICON and IFS use different schemes for the parameterized physical processes. Hence, a comparison of the detailed WCB ascent behaviour will reveal any potential differences the physics might have on the flow evolution. Earlier work comparing the IFS and COSMO physics already confirmed such differences (Joos and Wernli, 2014) and sensitivities of the upper-level tropopause structure to the set of physical parametrisations were found (Joos and Forbes, 2016).The ICON model that will be used in this project has adopted the COSMO physics parameterizations. Nevertheless, comparing the up-to-date model versions at higher spatio-temporal resolution, and with new diagnostic capabilities will provide important new insight in different model representations of the WCB. Special versions for both models enable the analysis of temperature/momentum (and PV) tendencies from the individual parameterization schemes. This allows for a quantification and comparison of (i) the total heating budget and (ii) the contributions from each parameterization scheme along the WCB ascent. This will be described in more detail in work package 4.

Summary of objectives of this project:

1) How do descending extratropical dry intrusions interact with subtropical/tropical shallow clouds? What role do the different diabatic processes play in moistening these airstreams?

2) What is the contribution of diabatic (especially below-cloud) processes for the moisture cycle in extratropical cyclones and what are the dynamical implications?

3) Which diabatic processes lead to a stratosphere – troposphere exchange in different weather systems?

4) Why are the diabatic heating rates along a warm conveyor belt different in two different numerical weather prediction models and what are the dynamical implications?

Four work packages (WP) are planned to address the above mentioned research questions. In all WPs we will make use of a special IFS version which has been developed together with Dr. Richard Forbes. It allows to output the temperature and momentum tendencies from all physical parameterizations (large-scale cloud scheme, convection, radiation, turbulence, gravity wave drag) as well as all moisture tendencies at a high time resolution. This model setup has been successfully used for several studies (Joos and Forbes, 2016; Attinger et al., 2019; Spreitzer et al., 2019; Steinfeld et al., 2020) and is also of great importance for this special project. As in the previous projects we plan to collaborate closely with Dr. Richard Forbes who provides extremely valuable technical support and scientific advice.

In the following, the work packages are described in more detail, including an estimation of the billing units and data storage.

Work packages:

WP1: Case studies on the importance of different moistening processes of extratropical dry intrusions into the tropical North Atlantic boundary layer (PhD Leonie Villiger):

Intrusions of dry upper-level extratropical air into the tropics (Fig. 2b, Raveh-Rubin, 2017) play an important - often underestimated - role in shaping the variability of the vertical thermodynamic profile and low-level cloud cover over the tropical North Atlantic. Low-level clouds are responsible for a large part of the uncertainty in current estimates of climate sensitivity by climate models (e.g. Bony and Stevens, 2012; Schneider et al., 2019). Therefore, improving our understanding of how they form and how they interact with the large-scale flow is one of the key challenges of atmospheric science in the coming years (Bony et al., 2015).
In this work package we will perform IFS simulations to analyse the physical tendencies associated with dry intrusion cases into the Caribbean from a Lagrangian perspective and one reference deep trade wind layer case with an easterly flow across the North Atlantic. These case studies have been carefully chosen in periods for which high time resolution observations from two field campaigns are available: 1) at the Barbados Cloud Observatory (Stevens et al., 2016) on the Caribbean island of Barbados (IsoTrades, January-February 2018) and 2) on board the French ATR aircraft during the international field campaign EUREC4A (Bony et al., 2017). The results from the IFS simulations will be compared to lidar and cloud radar data based on the R/V Meteor, the BCO and the ATR aircraft, radio soundings and stable water isotope measurements, which provide observational tracers for moist atmospheric processes (Aemisegger et al., 2015; Aemisegger and Sjolte, 2018).

The questions that will be addressed in this work package are:

1) How do descending extratropical dry intrusions interact with shallow clouds when reaching the boundary layer top?

2) What is the difference in the history of a dry intrusion airstream compared to a typical trade wind airstream in terms of thermodynamics? In particular, which processes play a dominant role in the fast thermodynamic modification of the dry intrusion airstream?

3) What is the relative importance of turbulent mixing, surface fluxes, convection, in-cloud and below cloud microphysical processes for the progressive moistening of a typical extratropical dry intrusion penetrating into the tropics compared to a trade wind airstream?

Technically we would like to perform two 10-day forecasts for isotrades and three 10-day forecasts for EUREC4A with a resolution of TCo639 L137 and hourly output of all temperature, momentum and moisture tendencies.

WP2: Moisture cycle and moisture recycling in extratropical cyclones (Dr. Hanin Binder, Dr. Roman Attinger)

In this project we will focus on the origin of moisture that leads to cloud formation and precipitation in extratropical cyclones. We will apply a Lagrangian approach which allows to select airstreams that have been strongly modified by the process of interest, as for example evaporation of rain or sublimation of snow, which leads to a cooling and moistening of these airstreams. We will investigate the pathways of this moisture as well as its relevance for subsequent cloud / precipitation formation and the associated change in potential vorticity with its impact on the atmospheric dynamics. The main questions in this project are:

1) Which processes lead to substantial moistening of coherent airstreams? What is the relative contribution of the different moisture sources to the total moisture content of an airstream?

2) Where does the moisture uptake take place relative to the cyclone?

3) What is the pathway of the moisture in and around the cyclone?

4) What are the dynamical implications?

Technically, we would like to perform three to five 5 day forecasts with a resolution of TCo639 with hourly output of all diabatic heating and momentum tendencies as well as all moisture tendencies.

WP3: Stratosphere – Troposphere exchange (Dr. Michael Sprenger, Dr. Maxi Boettcher)

The exchange of airmasses between the stratosphere and the troposphere are of great importance for atmospheric chemistry and for the dynamical coupling of the two spheres. However, so far it is not fully understood, which diabatic processes are relevant for the modification of potential vorticity that is necessary in order to cross the barrier between the stratosphere and the troposphere. In this project we would like to make use of the special IFS version allowing for a detailed output of all temperature and momentum tendencies in order to answer the following questions:

1) Which PV-modifying processes act at the time and location of the tropopause crossing?

2) What is the link to additional IFS fields, e.g. clear air turbulence indices, and to distinct weather systems (structures of/at the tropopause; e.g., tropopause folds, PV streamers and/or cutoffs)?

3) How important are microphysical, radiative and frictional processes for the evolution of the tropopause in comparison to dry dynamical factors near STE locations?

In this work package we would like to perform three to five 5 days forecast with a resolution of TCo639 and one selected case with a higher horizontal resolution (TCo1279) and/or higher frequency of written output.

WP4: Diabatic heating and PV rates in a warm conveyor belt in the ICON and IFS model (Dr. Annika Oertel)

The selected North Atlantic WCB case study occurred in October 2016 in the North Atlantic during the NAWDEX field campaign. This WCB is characterized by a distinct ascent phase and the WCB modifies the large-scale upper-level flow, resulting in an amplification of the downstream ridge with subsequent blocking onset (Steinfeld et al. 2020). Hence, we hypothesize that differences in the WCB ascent might potentially also modify the downstream flow evolution.
The direct model comparison will reveal whether both models adequately simulate the synoptic situation and whether differences in the larger-scale flow evolution are present within the approximate five-days simulation of the WCB event. Potentially, differences in the upper-level PV distribution can be linked to the detailed WCB ascent behaviour, its integrated heating, and the associated PV tendencies. As the parameterized heating strongly influences the cross-isentropic ascent strength, differences between the models might lead to a differing location and stratification of WCB trajectories into rapidly and slantwise ascending trajectories.
Independent of the difference/similarity of the detailed WCB ascent in both models, a budget analysis of total heating and cloud-microphysical processes in the large-scale WCB airstream will be performed. Tracing the temperature tendencies along offline WCB trajectories for both simulations allows for a comparison of the total heating budget in the WCB and the according temperature and PV tendencies from the individual parameterization schemes for this strongly diabatically heated airstream. Moreover, it will enable a detailed comparison of cloud condensate content and the liquid/ice phase partitioning within the WCB between both models. We assume that

the dominant processes will be related to the microphysics and the convection schemes. However, the relative contributions from each scheme in each model are not known.

With the model intercomparison we would like to address the following questions:

1) How is the partitioning between the different cloud condensate variables (ice, liquid, rain, snow) along a WCB in the IFS and ICON?

2) Which microphysical processes act during cloud formation in IFS and ICON and how do they modify the PV?

3) What is the impact of different representations of microphysical processes in both models on the WCB ascent behavior?

4) What is the subsequent impact on the upper-level PV structure and downstream flow evolution?

Technically, we would like to simulate a five-day case study with a resolution of TCo1279 with the special version that allows the additional output of all 3D temperature and momentum tendencies. This setup will be comparable to a global ICON run at 13 km resolution.

This work packages will be done in collaboration with Dr. Annika Oertel from the Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany.

Year	Description of the forecasts	Estimation of billing units and data storage
2021	*WP1:* 4 case studies, TCo639, L137, 10-day leadtime, 1-hourly output of all heating/momentum and moisture tendencies *WP2:* 3 case studies, TCo639, L137, 5-day leadtime, 1-hourly output of all heating/momentum and moisture tendencies *WP4:* 1 case study, TCo1279, L137, 5-day leadtime, 1-hourly output of all temperature/momentum tendencies	500 000 SBU 8 Tb 200 000 SBU 8 Tb 300 000 SBU 4 Tb
2022	WP1: 1 case study, TCo639, L137, 10-day leadtime, 1-hourly output of all heating/momentum and moisture tendencies WP2: 2 case studies, TCo639, L137, 5-day leadtime, 1-hourly output of all heating/momentum and moisture tendencies	100 000 SBU 3 Tb 100 000 SBU 5 Tb

	WP3: 5 case studies, TCo639, L137, 5-day lead time, 1-hourly output of all heating/momentum tendencies 1 case study, TCo1279, L137, 5-day lead time, 1-hourly output of all heating/momentum tendencies	300 000 SBU 12 Tb 300 000 SBU 3 Tb
2023	additional simulations for WP 1, 2, 3 and 4	200 000 SBU 5 Tb

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