SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Diabatic effects in mid-latitude weather systems
Computer Project Account:	SPCHBOJO
Start Year - End Year :	2018 - 2020
Principal Investigator(s)	Maxi Boettcher, Hanna Joos
Affiliation/Address:	Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland
Other Researchers (Name/Affiliation):	Heini Wernli, Roman Attinger, Daniel Steinfeld, Elisa Spreitzer , Insitute for Atmospheric and Climate Science, ETH Zurich, Switzerland

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

In this project we performed simulations with a special version of the IFS model which allows for hourly output of all heating/momentum tendencies due to parameterized processes. The simulations have been used in order to improve our understanding of the modification of the atmospheric circulation by diabatic processes. In more detail, we addressed the following research objectives; i) quantification of the diabatic PV modification in extratropical cyclones by means of a detailed case study and a climatological analysis where we made use of a one year simulation including the detailed output of all temperature/momentum tendencies, ii) improve the understanding of the influence of diabatic processes on the extratropical tropopause and iii) investigate the importance of diabatic processes for the formation and maintenance of atmospheric blocking.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

No major problems were encountered and the technical support is highly appreciated and very helpful.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application procedure for new special projects is very easy to follow as well as the progress reporting. We are very happy with the handling of all administrative aspects and also with the help with questions.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

The results which were obtained during this special project have been essential for three dissertations and for MSc and BSc projects and lead so far to four publications and several conference contributions. In the following we only briefly summarize the results from the different projects. The full refences can be found below.

1) Diabatic processes in extratropical cyclones (Dr. R. Attinger)

In order to quantify and improve our understanding on how and when diabatic processes modify PV in extratropical cyclones, a case study of a North Pacific extratropical cyclone has been performed and all temperature and momentum tendencies due to parameterised processes are output hourly. Based on this model output, 24h accumulated PV tendencies have been calculated along backward trajectories that started in negative and positive PV anomalies at the cyclones' warm and cold front as well as in the cyclone centre. It could be shown that many different processes like condensation, melting and sublimation of snow, long-wave radiative cooling and turbulence play a role in modifying the PV. The main findings are illustrated in figure 1 which shows a schematic of the PV modifying processes which are most important in different locations in the cyclone. The results of this study are published in Attinger et al. (2019).

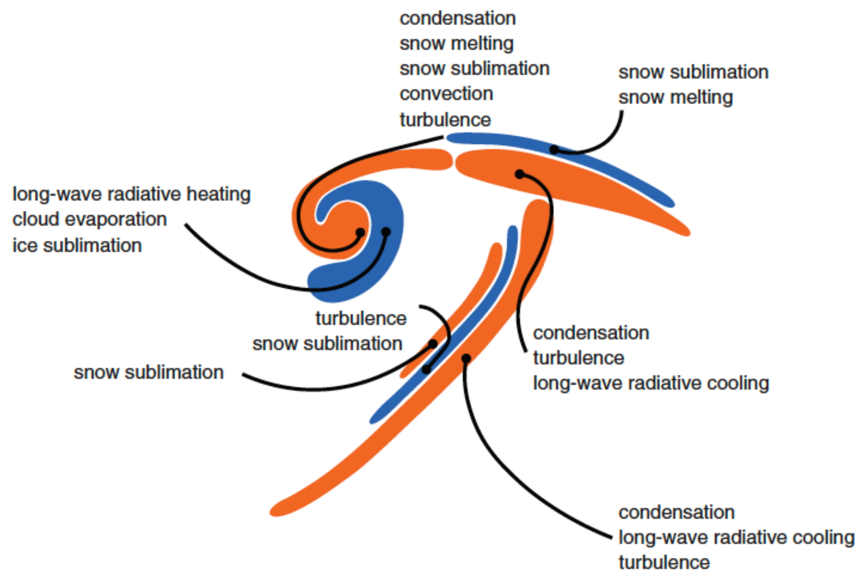

Figure 1: Synthesized depiction of the low-level PV field at the time of maximum cyclone intensity (1700 UTC on 10 April 2017). Areas of anomalously negative and positive PV are displayed in orange and blue, respectively. The origin of air masses is shown by the lines and the most important processes are indicated for each feature (taken from Attinger et al. (2019), figure 10).

The findings of this case study have been expanded by a systematic analysis of PV modifying processes in 144 rapidly intensifying extratropical cyclones which were identified in a series of 12 35-day simulations covering a whole year, including the detailed output of all temperature and momentum tendencies. To this end, PV tendencies associated with each parameterized process in the model are accumulated along 15h backward trajectories. The trajectories that originate from positive or negative anomalies are then investigated in detail. First of all, a pronounced case-to-case variability can be seen in the processes that dominate the PV modification in the different cyclones. For each negative/positive PV anomaly at the cold/warm front and in the cyclone centre a ranking is performed such that it is possible to determine the most important diabatic processes that lead to the formation of the considered anomaly. As an example, the results for the positive/negative PV anomalies at the cold and warm front as well as in the cyclone centre are shown in figure 2.
The results of this systematic analysis are discussed in more detail in Attinger et al. (2021).

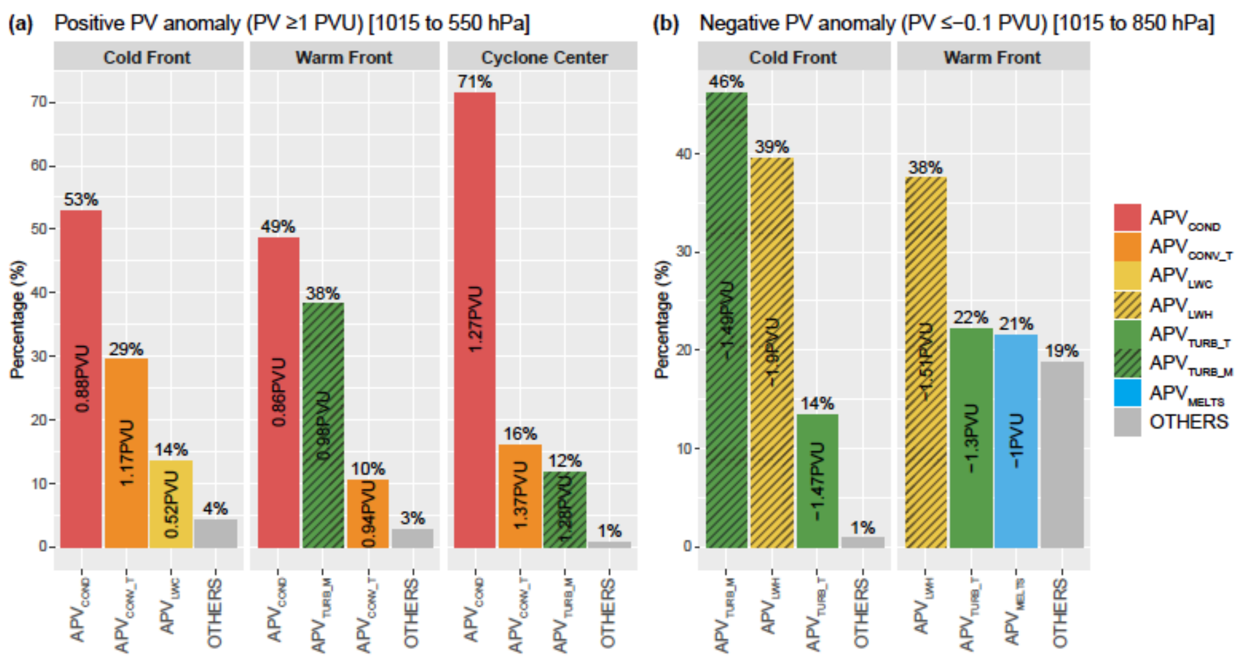

Figure 2: Prevalence of the dominant processes for the generation of (a) the positive PV anomaly (PV > 1 PVU) between the surface and 550 hPa and (b) the negative PV anomaly (PV <−0.1 PVU) between the surface and 850 hPa during the cold season. Ranks are computed from the area-weighted mean APV of each process averaged over the entire 24 h period of most rapid cyclone intensification. Percentages indicate the fraction of cyclones with a specific process as the most important one and numbers show the area-weighted mean APV averaged over all cyclones (taken from Attinger et al. (2021), figure 4).

2) Diabatic processes near the extratropical tropopause (Dr. E. Spreitzer)

Based on the special IFS version, a case study of the role of diabatic processes modifying the characteristics of the extratropical tropopause region associated with a North Atlantic cyclone, is performed. Lagrangian backward trajectories are calculated and the PV tendencies from the parameterized processes are integrated along these 24h backward trajectories. It was found that (clear-air) turbulence at the jet stream is an important process in shaping the PV structure of the upper-level front-jet system and for the decay of a tropopause fold and in the ridge, the accumulated turbulent PV leads to a distinct vertical pattern. In contrast, cloud processes influence the PV distribution above the WCB outflow and above the cold-sector convection. The results of this study are published in Spreitzer et al. (2019).

The results of the PV modifying processes near the tropopause have been expanded by applying the PV tendency diagnostic to the simulation of a three month winter season in the North Atlantic. A systematic analysis shows that in ridges, turbulent mixing leads to a strong decrease of PV in the lowermost stratosphere, smoothing the vertical PV gradient at the tropopause, whereas in troughs, the interplay of cloud processes and radiation sharpens the PV gradient. The results of this analysis are part of the PhD thesis by Dr. E. Spreitzer (see Spreitzer, 2020).

In figure 3, the mean accumulated PV tendencies are shown for troughs and ridges.

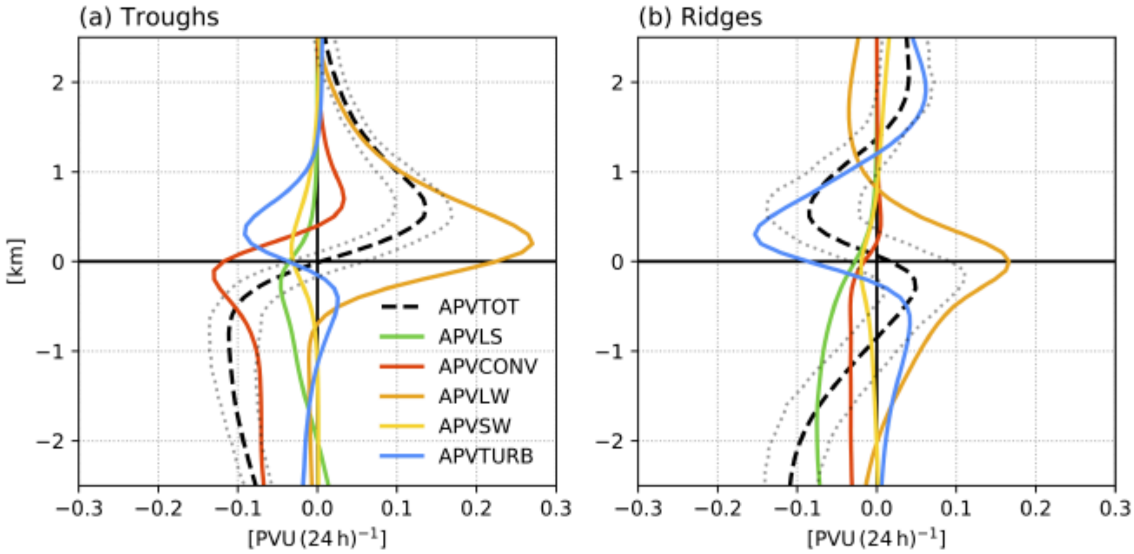

Figure 3: Average vertical profiles for the DJF simulations of (a,b) 24-h accumulated PV tendencies for each parametrized process. The grey dotted lines indicate the interquartile range of APVtot (taken from Spreitzer, 2020).

In a third part of the thesis, the effect of below cloud processes is investigated. Exemplarily, coherent airstreams that are cooled due to sublimation of snow in an extratropical cyclone are selected. In airstreams in the lower troposphere at the cold front and in the cyclone centre, snow sublimation contributes locally to the formation of positive PV anomalies. Another airstream which travels ahead of the warm front towards the cyclone centre is moistened by sublimating snow before it ascends into the cloud head and leads to cloud formation there. This illustrates how moisture can be redistributed in extratropical cyclones. Additionally, two airstreams were identified that were strongly cooled by snow sublimation before they ascended ahead of the cold front to tropopause levels, illustrating how processes acting at low to mid-levels can have an impact even in the upper troposphere. The results are described in more detail in the PhD thesis of Dr. E. Spreitzer (Spreitzer (2020)).

3) The sensitivity of atmospheric blocking to upstream latent heating (Dr. D. Steinfeld)
In this study, the IFS has been used for sensitivity studies in order to investigate the effect of latent heating on the formation and maintenance of five blocking anticyclones. To this end, the latent heat release due to cloud processes in clouds upstream of the blocking has been eliminated in the simulations. All blocking systems are highly affected by this elimination whereas there is a large case-to-case variability. Some blocking anticyclones do not develop at all without heating, others are affected in their amplitude, size and lifetime. In figure 4, the evolution of the dynamical tropopause is shown for the onset of the blocking anticyclone Thor for different sensitivity runs where the latent heating has been multiplied with α (α=1 equals the control run). The results of this study are a part of the PhD thesis of Dr. D. Steinfeld (Steinfeld, 2019) and are published in Steinfeld et al. (2020).

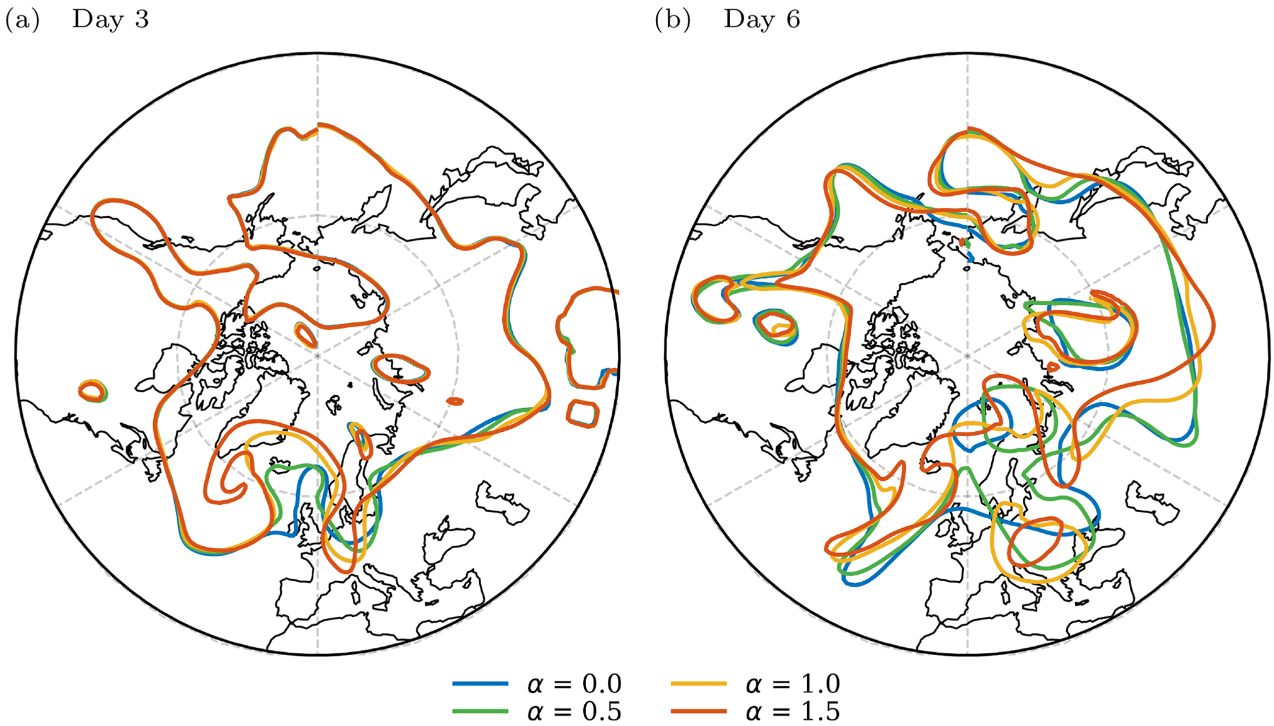

Figure 4: Dynamical tropopause (upper-level 2pvu contour) for sensitivity runs of the onset of block Thor on a) 3 October 2016 (day 3) and b) 6 October 2016 (day 6) for different α values (blue for α=0 (no latent heating), green for α=0.5, yellow for α=1 (control run), and red for α=1.5). Figure taken from Steinfeld et al. (2020, figure 6).

Furthermore, data and simulations which have been performed under this special project were used for two BSc and one MSc thesis, which are briefly described below.

4) MSc and BSc thesis at ETH Zurich

a) The origin and life cycle of diabatically modified PV anomalies in atmospheric blocks (MSc thesis K. Heitmann)
By means of a case study of an atmospheric blocking over the North Atlantic in February 2018 it is investigated by which diabatic processes air parcels that end in the atmospheric blocking have been modified and thus lead to the modification of the PV in the upper troposphere. It has been found that condensation, convection and depositional growth of ice/snow particles were responsible for the largest amount of heating and PV destruction. Thus, air parcels that passed through clouds before they reached the anticyclone lead to an intensification of the negative PV anomaly.

In two BSc theses the Lagrangian evolution of PV along trajectories has been investigated (BSc thesis G. Vollenweider) and the effect of diabatic processes on atmospheric blocking was analysed in a case study by performing sensitivity runs where the latent heating in the upstream cloud band has been modified (BSc thesis M. Egli).

5) Contributions to the Virtual Workshop: Warm conveyor belts – a challenge to forecasting, ECMWF, Reading, March 2020

Research that is based on the special IFS version described in this report lead to 3 contributions at the Virtual Workshop: Warm conveyor belts – a challenge to forecasting.

- Spreitzer, E., Attinger, R., Boettcher, M., Forbes, R., Wernli, H. and Joos,H.: The effect of clouds, radiation and turbulence on upper-level PV, oral presentation
- Heitmann, K., Attinger, R., Wernli, H. and Joos, H.,: The origin and life cycle of diabatically modified PV anomalies in atmospheric blocks: a case study, poster presentation
- Steinfeld, D., Boettcher, M., Forbes, R. and Pfahl, S.: The sensitivity of atmospheric blocking to changes in upstream latent heating, poster presentation

List of publications/reports from the project with complete references

Publications:
1) Attinger, R., E. Spreitzer, M. Boettcher, R. Forbes, H. Wernli, and H. Joos, 2019. Quantifying the role of individual diabatic processes for the formation of PV anomalies in a North Pacific cyclone. *Quart. J. Roy. Meteorol. Soc.,* **145,** 2454–2476.
2) Spreitzer, E., R. Attinger, M. Boettcher, R. Forbes, H. Wernli, and H. Joos, 2019. Modification of potential vorticity near the tropopause by nonconservative processes in the ECMWF model. *J. Atmos. Sci.,* **76,** 1709–1726.
3) Steinfeld, D., M. Boettcher, R. Forbes, and S. Pfahl, 2020. The sensitivity of atmospheric blocking to upstream latent heating – numerical experiments. *Weather Clim. Dynam.,* **1,** 405–426.
4) Attinger, R., Spreitzer, E., Boettcher, M., Wernli, H., and Joos, H.: Systematic assessment of the diabatic processes that modify low-level potential vorticity in extratropical cyclones, Weather Clim. Dynam. Discuss. [preprint], https://doi.org/10.5194/wcd-2021-37, in review, 2021

Dissertations:
1) Attinger, R., 2020. Quantifying the diabatic modification of potential vorticity in extratropical cyclones. PhD thesis, ETH Zurich, No 26547, 146 pp., https://www.research-collection.ethz.ch/handle/20.500.11850/432253

2) Spreitzer, E. J., 2020. Diabatic processes in mid-latitude weather systems – a study with the ECMWF model. PhD thesis, ETH Zurich, No 26649, 121 pp., https://www.research-collection.ethz.ch/handle/20.500.11850/438728
3) Steinfeld, D., 2019. The role of latent heating in atmospheric blocking: climatology and numerical experiments. PhD thesis, ETH Zurich, No 26021, 155 pp.

MSc thesis:
1) Heitmann Katharina: The origin and lifecycle of diabatically modified PV anomalies in atmospheric blocks: a case study, supervisors: R. Attinger & H. Joos, Sep 2018 – April 2019.

BSc thesis:
1) Gabriel Vollenweider: Lagrangian evolution of potential vorticity: investigating the effects of non-conservative physical processes, supervisors: E. Spreitzer & S. Schemm, Feb – July 2020.
2) Marius Egli: A case study on the impact of cloud diabatic processes on atmospheric blocking, supervisors: M. Boettcher & D. Steinfeld, Feb – July 2018.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We will further use the 1- year IFS simulation which has been computed in order to assess the systematic modification of PV in extratropical cyclones (Attinger et al., 2021) for investigating the effect of radiative heating and cooling rates on PV in the troposphere and for quantifying the PV modification in Mediterranean cyclones. Furthermore our special IFS version which allows for hourly output of all diabatic heating rates will be used in several studies which are described in more detail in the new request report for the special project continuation for the years January 2021 – December 2023.