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 :	2015 - 2017
Principal Investigator(s)	Hanna Joos and Maxi Boettcher
Affiliation/Address:	ETH Zurich Institute for Atmospheric and Climate Science Universitätstrasse 16 8092 Zurich Switzerland
Other Researchers (Name/Affiliation):	Roman Attinger*, Daniel Steinfeld*, Elisa Spreitzer* *ETH Zurich, IAC

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project aims on investigating the various microphysical heating rates that have an impact on the dynamics of weather systems. With a special model version of the IFS, which enables the output of all heating rates occurring due to microphysical processes and radiation (provided by Richard Forbes), we are able to investigate in detail the impact of microphysical/radiative processes on the modification of potential vorticity (PV) and thus the impact on dynamics and hence the evolution of weather systems. Via a Lagrangian approach, air parcels which experience a diabatic PV modification are selected, as e.g. in extratropical cyclones, diabatic Rossby-waves, or blocking situations and so, the influence of microphysical processes on the dynamics of these systems can be determined.

Summary of problems encountered

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

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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 as well as the need for final and progress reports are all well communicated and transparently handled. We don’t see any problems with the strategy of obtaining and reporting about special projects.

Summary of results

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

The special project consisted of 4 work packages whose results or preliminary results are described below:

WP 1: Impact of different IFS microphysics on a warm conveyor belt and the downstream flow evolution

The influence of microphysical processes on the upper-level flow features associated with an extratropical cyclone is investigated with the ECMWF global atmospheric model. A control simulation with the model version operational at ECMWF during 2014/early 2015 and a simulation with new parametrizations of rain autoconversion/accretion, rain evaporation and snow riming operational since May 2015 are compared in detail. In order to investigate the impact of each microphysical process separately, the diabatic heating rate for each microphysical process and the associated change in potential vorticity (PV) is calculated and compared for the two simulations. The influence on the upper-level ridge building and the downstream flow evolution is investigated. The changes in the microphysical parametrization led to differences in the position of the warm conveyor belt (WCB) outflow. The WCB reaches the upper troposphere with low PV values and shifts the location of the tropopause in a slightly different way in the two simulations. Although these differences are relatively small at the beginning, they are advected downstream and amplify, leading to distinct differences in the upper-level PV pattern. These results highlight the importance of correct representation of microphysical processes for large-scale flow features. Additionally they emphasize the need for detailed microphysical measurements in extratropical cyclones in order to better understand and constrain the microphysical processes in NWP models.

The results have been published as:

Joos, H., and R. Forbes, 2016. Impact of different IFS microphysics on a warm conveyor belt and the downstream flow evolution, Q. J. R. Meteorol. Soc., 142, 2727-2739, doi:10.1002/qj.2863

and parts of the results are also discussed in the ECMWF Newsletter 154 "Why warm conveyor belts matter in NWP".

WP 2: The sensitivity of atmospheric blocking to changes in latent heating

In order to investigate the effect of moist-diabatic processes on large-scale circulation anomalies such as blocking, a special IFS has been developed by Richard Forbes and Daniel Steinfeld which allows to modify the temperature tendencies due to convection and cloud scheme in a predefined 3D box. This allows for systematic investigation on how sensitive the upper-level wave dynamics and downstream impacts to the details of cloud microphysics and convection are.
In a first case study, a prolonged Scandinavian blocking event in October 2016 (during the NAWDEX Field Campaign) was simulated with a single control forecast (CNTRL run) and a single forecast where latent heating was artificially turned off in the WCB region over the North Atlantic within the layer 900–500 hPa (noLH run). For the control forecast (Fig. 1a) we see that strong ascent leads to upper-level divergent outflow on the western flank of an amplifying ridge. In the event this ridge then broke anticyclonically and led to the onset of blocking conditions (not shown). When latent heating is turned off (Fig. 1b), the ascent and outflow are reduced, the ridge does not amplify and, in the absence of wave-breaking, the block is not initiated.
This example illustrates how the physics within WCBs can play a crucial role in the initiation of blocking anticyclones, and for the upper-level wave dynamics in general.

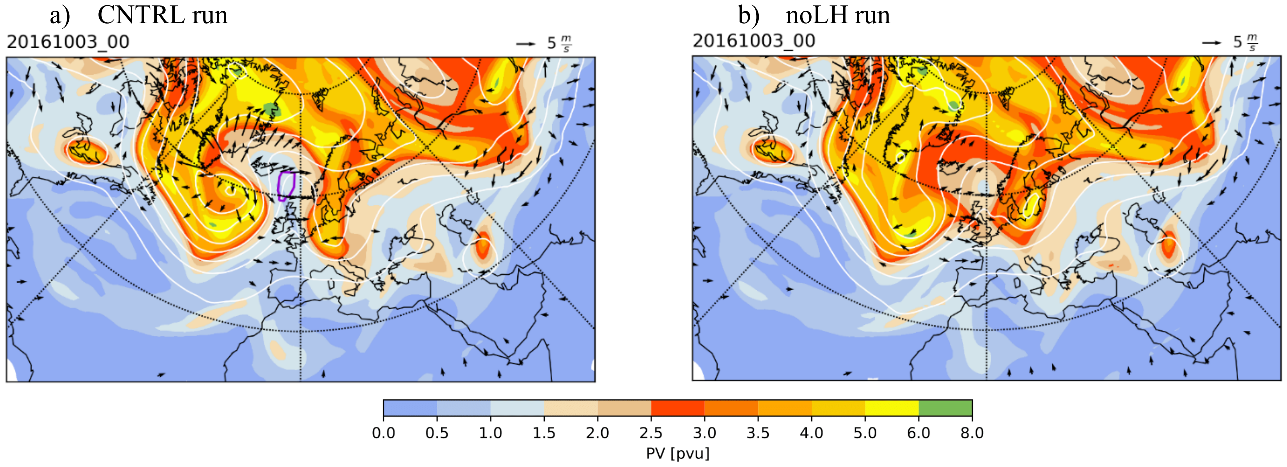

Figure 1: Vertically averaged PV between 500 and 150 hPa (shading), 500 hPa geopotential height (white contours), diagnosed block (purple contour), and vertically-averaged divergent wind between 500–150 hPa (arrows) for (a) the IFS control simulation after 3 days, (b) a sensitivity experiment with latent heating turned off, after 3 days.

WP 3: Importance of microphysical processes for the generation of PV anomalies in weather systems

In this project, the diabatic modification of potential vorticity (PV) associated with an extratropical cyclone over the Pacific basin was investigated. To this end, a modified version of the IFS was developed that outputs diabatic heating rates associated with microphysics, convection, radiation and turbulent mixing as well as diabatic momentum tendencies due to gravity wave drag, vertical diffusion and convection. For each of these processes, an instantaneous diabatic PV rate was computed. These PV rates were then traced in a Lagrangian framework and integrated in order to assess the diabatic modification of PV.

The special IFS version was initially developed for the study by Joos and Forbes, 2016 when investigating the influence of different microphysics on the development of a warm conveyor belt. The existing version was extended to include both diabatic heating and momentum tendencies due to turbulent mixing to minimize the residual associated with the total PV budget.

In order to identify the area associated with the case-study cyclone as well as its corresponding fronts, an algorithm to automatically identify cyclones in general circulation model output was developed. This tool combines information from sea level pressure and relative vorticity fields to determine the region of interest associated with anomalous PV.

The cyclone investigated developed on the 9th of April 2017 12:00 UTC off the coast of Japan from a low-level positive PV anomaly and deepened to a minimum pressure of 965 hPa within 27 hours. IFS model simulations were started on the 8th of April 12:00 UTC and ran for 6 days. The Lagrangian diagnostic to ascertain the influence of individual diabatic processes on the PV budged along air-streams was applied at every hourly time-step. Fig. 2 shows the lower tropospheric diabatic modification of PV shortly after the lowest central SLP. Note that each panel shows the integrated effect of the indicated diabatic process along 24 hourly backward trajectories and not the instantaneous field. Panel (a) shows the cumulative effect of all diabatic processes considered, i.e. the sum of panels (c-i). Marked regions of increased PV along the cold, warm, bent back front and cyclone centre are found. Two bands of negative PV tendencies are observed behind the cold front. Considering the residual (b), i.e. the difference between the actual change in PV and the computed diabatic PV change, good agreement is found especially along the fronts. However, the Lagrangian diagnostic overestimates the negative PV tendency behind the cold front. The distinct increase of PV along the cold front is mainly due to the condensation of cloud droplets (c). Minor negative PV tendencies are found just behind the cold front, due to the evaporation of clouds. Condensation (c) and melting of snow (d) strongly increase PV along the bent back front and in the centre of the cyclone while the sublimation of snow (e) mainly modifies PV in the centre. Air parcels traveling towards the centre along the bent back have thus first experienced strong condensation, i.e. heating, above their position, which increased their stability and PV. Later during their journey, they crossed a region where snow started melting below their position, which again increased the stability. Finally, they were located above an area of strong cooling due to the sublimation of snow, which further enhanced their stability. Conversely, air parcels arriving behind the cold front from the west experienced a decrease in stability as they were located below sublimating snow. The convection scheme is responsible for a broad increase of PV in the cyclone centre and in its adjacent cloud bands (f). Turbulent mixing however counteracts this process (g), exhibiting negative PV tendencies of up to 10 PVU in the cyclone centre. Less marked negative tendencies are found in three coherent regions behind the cold front. Further, turbulent mixing enhances PV along the warm front. Long-wave radiation (h) describes an inconsistent behaviour with regions of increased PV along the cold and warm front and areas of negative PV tendencies in the centre, along the bent back front and in front of the cold front. Finally, sublimation of ice (j) results in a broad decrease of PV in the centre. This work was presented during the 18th cyclone workshop in Sainte Adele, Quebec and discussed as part of the article "Why warm conveyor belts matter in NWP" in the ECMWF Newsletter 154.

In a next step, the cyclone tracking scheme will be extended to identify different frontal regions associated with the cyclone. Thereby, the temporal evolution of the processes that modify PV along the cold front, warm front, bent back front and cyclone centre can be assessed. The findings of these investigations are currently prepared for publication.

Moreover, the methodology developed using the case-study will be applied to monthly IFS simulations during the next phase of the project. This allows detailed insights into how diabatic processes modify PV in a large number of extratropical cyclones and blocks.

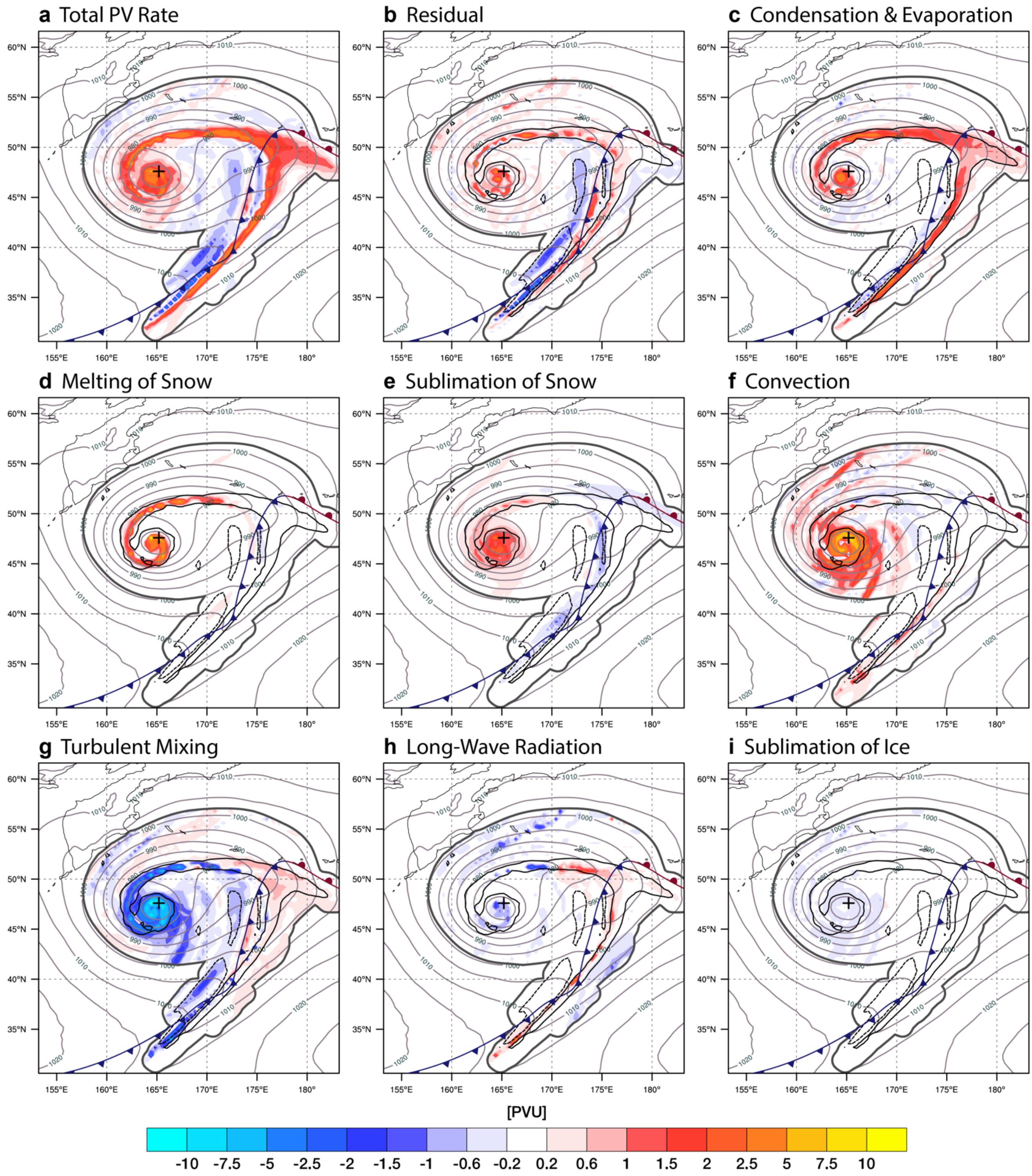

Figure 2: The Pacific cyclone after 56 hours of simulation in terms of integrated low-level (between 950 and 850 hPa) PV rates and SLP (grey contours). Plots show the total diabatic PV rate (a), the residual (b), the PV rate due to condensation and evaporation (c), due to the melting of snow (d), due to the sublimation of snow (e), due to convection (f), due to turbulent mixing (g), due to long-wave radiation (h) and due to the sublimation of ice (i). The cyclone mask is shown by the thick grey outline, regions of increased (decreased) PV are indicated by the solid (dashed) black outline in panels (b-i) while the warm and cold front are indicated using the usual symbols.

WP 4: Impact on microphysically influenced coherent air streams in an extratropical cyclone

This project aims to improve the understanding of the way in which below-cloud processes, such as rain evaporation, melting and sublimation of snow, can impact the dynamics, moisture distribution, and cloud structure within extratropical cyclones. Whenever a cloud-diabatic process consistently modifies a coherent airstream, this process is potentially relevant for the weather system. Therefore, a novel diagnostic framework is introduced to describe extratropical cyclones in terms of microphysical processes and associated airstreams.
To investigate the effect of below-cloud processes, a case study of an extratropical cyclone that crossed the North Atlantic in February 2017 is simulated with the IFS, cycle 43R1, with a horizontal resolution of TCo639 and 137 vertical levels. As additional output, hourly three-dimensional fields of instantaneous temperature tendencies from the model physics are saved, in particular the temperature tendencies for all individual microphysical processes that are included in the large-scale cloud scheme. Instantaneous, local tendencies do not suffice to adequately analyse the role of the associated processes for the cyclone. For this, the Lagrangian viewpoint provides a more insightful framework. Thus, forward and backward trajectories are computed from a grid around the cyclone using the Lagrangian trajectory analysis tool LAGRANTO. The temperature tendencies are traced and accumulated along the trajectories.
The first below-cloud process to be studied is snow sublimation. The air parcels that undergo a diabatic cooling due to snow sublimation of more than 2.5 K in 12 h are selected. This is to extract the air parcels that are most strongly affected by this process of all air parcels within the system. The selected set of trajectories is divided into four coherent airstreams using a clustering technique. They are shown in Fig. 3, as 24 h long cyclone relative trajectories together with the cluster mean trajectory.
The first airstream is part of the cold conveyor belt that travels ahead of the warm front and towards the cyclone centre and part of it later ascends into the cloud head. It experiences sublimation of snow that originates from the ascending warm conveyor belt above. By design, this airstream is strongly moistened by snow sublimation. The black line in Fig. 4a depicts the median evolution of specific humidity along the airstream. Note that the prescribed cooling phase is from –6 h to 6 h. It is remarkable, that the strong increase of specific humidity from 1 g kg^{-1} to 3 g kg^{-1} in the time interval from –12 h to 6 h is almost entirely attributable to snow sublimation (orange line). Later, the specific humidity is decreased again by the large scale cloud scheme (blue line), indicating cloud formation. This result suggests that the airstream ahead of the warm front contributes to the cloud structure and plays a role in the transport and recycling of moisture in the system.
The second airstream is part of the warm sector flow and is located in the mid-levels ahead of the cold front, where it later ascends, with parts of the airstream reaching tropopause level. Fig. 4b shows the median accumulated heating rates along the airstream. In the prescribed cooling phase, snow sublimation (orange line) is the dominant of the large-scale cloud processes (blue line), but is in largely compensated by convective heating (green line). After the cooling phase, the airstream ascends to higher isentropic levels (mostly due to convection), with the median of the total accumulated heating rates (black line) being 5 K, corresponding to an increase of potential temperature of 5 K compared to the start. The fact that trajectories that have been strongly cooled by a below-cloud process reach the tropopause, highlights the potential of below-cloud processes to affect the upper-level flow.
The third airstream wraps around the cyclone centre in the lower levels, while experiencing sublimation of snow that falls from the cloud head above. The snow sublimation in this airstream contributes to the positive PV anomaly in the cyclone centre (not shown).
The fourth airstream travels behind the cold front in mid- to lower levels. The sublimating snow within this airstream originates from air that ascends ahead of the cold front and forms the cold frontal cloud band. Snow sublimation contributes to PV anomalies at the cold front (not shown).

The first results from this study illustrate the various ways in which below-cloud processes can impact cyclone dynamics. It is planned to investigate the role of the identified airstreams over the life cycle of the cyclone and to apply the method to further case studies and processes. Additional sensitivity experiments are subject to future studies.

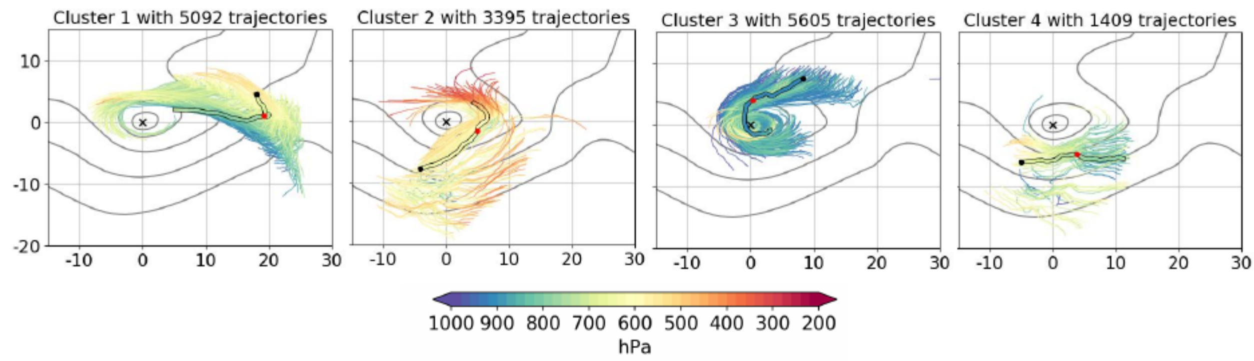

Figure 3: The four airstreams that experience the strongest cooling due to snow sublimation. The trajectories are shown for 24 h. The thick lines denote the mean cluster trajectory of the respective airstream. The black dots indicate the mean starting position, the red dot s indicate the respective mean position after 12 h. The trajectories are shown relative to the cyclone centre (black cross). Grey contours indicate the mean sea level pressure, averaged over the 24 h.

a) b)

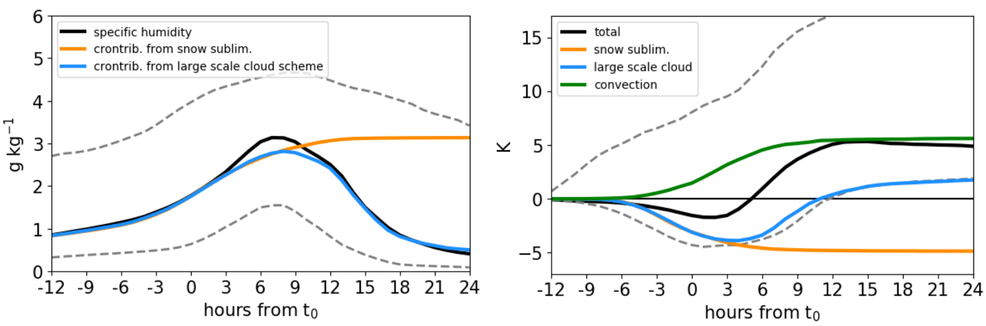

Figure 4: Left: Evolution of moisture along the trajectories of airstream 1. The black line indicates the median evolution of specific humidity, grey dashed lines indicate the 10 and 90 percentiles, respectively. In blue, the median contribution from the large-scale cloud scheme to the moisture changes is shown, in orange the contribution from snow sublimation. Right: Evolution of accumulated diabatic heating rates along the trajectories of airstream 2. The black line indicates the median accumulated total diabatic heating rate, grey dashed lines indicate the 10 and 90 percentiles, respectively. Blue shows the accumulated heating rates from the large-scale cloud scheme, orange from snow sublimation, and green from convection.

WP 5: Diabatic heating rates in cutoff cyclone "Sanchez" during the NAWDEX campaign

Cyclone Sanchez has been probed by aircraft measurements over the central North Atlantic during the NAWDEX campaign. The surface cyclone of Sanchez developed at the southern tip of an upper-tropospheric PV streamer while the streamer broke off. Below the zone where the cut off process took place at upper levels, strong diabatic activity at the bend-back front of cyclone Sanchez could be observed. In this study, the question will be addressed what moist-diabatic, radiative and turbulent processes are involved in the break-up of the PV streamer and how they are related to the surface cyclone. The case has been simulated with our special version of the IFS version TCo 639 L137 with output of all available diabatic temperature tendencies. The study is still in progress and will be continued in the next phase of the special project.

List of publications/reports from the project with complete references

Joos, H., and R. Forbes, 2016. Impact of different IFS microphysics on a warm conveyor belt and the downstream flow evolution, Q. J. R. Meteorol. Soc., 142, 2727-2739, doi:10.1002/qj.2863

Rodwell, M., Forbes, R. and Wernli, H., 2018: "Why warm conveyor belts matter in NWP", ECMWF Newsletter, Number 154, doi:10.21957/mr20vg.

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.)

The research described above is continued in the next special project phase 2018-2020. The basis that is established now will be extended by 1) generalizing the case studies into more systematic investigations using further IFS simulations, 2) including diabatic temperature tendencies from the turbulence scheme and 3) more detailed analyses of the existing data sets.