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 :	2012 - 2014
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):	Heini Wernli

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project aims at investigation of diabatic processes in extratropical cyclones, in particular in strongly ascending air masses which are called warm conveyor belts (WCBs). Latent heating related to cloud-microphysical processes during the WCB ascent lead to a charact- eristic potential vorticity (PV) structure. The resulting high PV in low to mid troposphere levels and low PV in the outflow in the tropopause region can have an impact on the surface cyclone intensification as well as on the upper-level waves downstream of the cyclone.
In part 1 of the project the contributions from the various cloud-microphysical processes acting as sources and sinks for PV are evaluated. Case studies are performed to estimate the importance of hese processes for the WCB ascent. Part 2 investigates the dynamics of the WCB by artificial moisture modification in the low-level inflow which is hypothesized to determine the WCB ascent.

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.)

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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.)

In order to investigate the effect of diabatic processes on mid-latitude weather systems a special version of the IFS has been developed by Richard Forbes which allows to output all diabatic heating rates (DHR) which occur due to microphysical processes, convection and radiation at every model output step. Based on these DHRs, the associated change in potential vorticity (PV), the diabatic PV rates (DPVR) can be calculated for each process separately. This method allows to quantify the contribution of each process to PV modification and therefore to link the cloud formation processes to changes in dynamical features.

In a first project, a case study of an extra-tropical cyclone with an associated warm conveyor belt (WCB) which occurred in January 2009 in the North Atlantic has been simulated with the IFS and the NWP model COSMO from the German and Swiss Weather Service where all DHRs due to microphysical and radiative processes have been written out. Additionally, a Lagrangian framework is used in order to calculate trajectories and to analyse the evolution of hydrometeors, DHRs and DPVRs along selected air parcel trajectories.

In the following, the microphysical processes occurring in and below the WCB and their effect on dynamical features are compared between both models [1].

The overall representation of the WCB is very similar in both models in terms of the inflow and outflow region and the number of ascending trajectories. Also the total condensate which is traced along the ascending trajectories is similar and exhibits peak values of ~800 mg/kg at a height of ~600 hPa. However, the partitioning of the total condensate between the different hydrometeor species cloud liquid (LWC), cloud ice (IWC), snow (SWC) and rain (RWC) strongly differs between both models. In Fig. 1, the evolution of the hydrometeor mass along ascending WCB trajectories is shown.

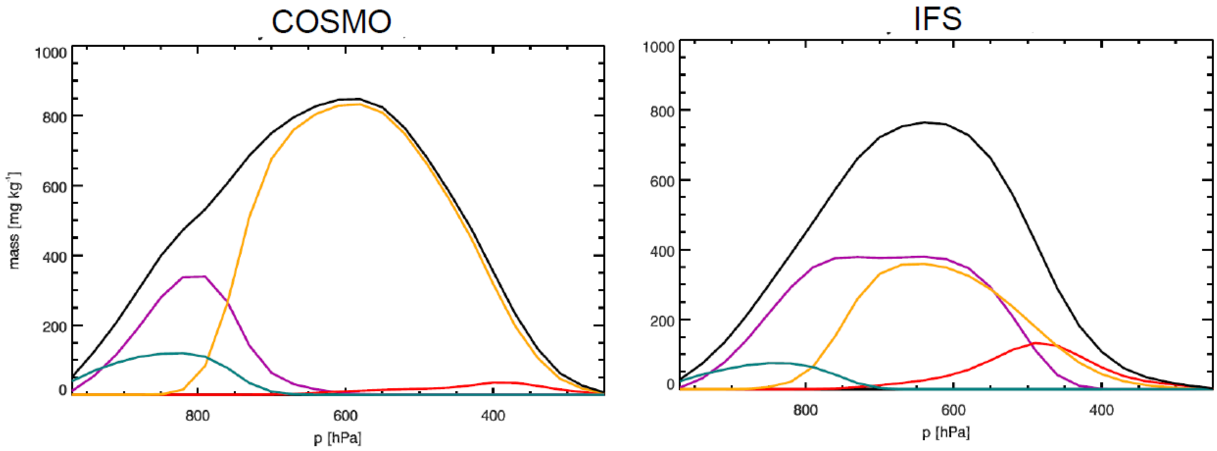
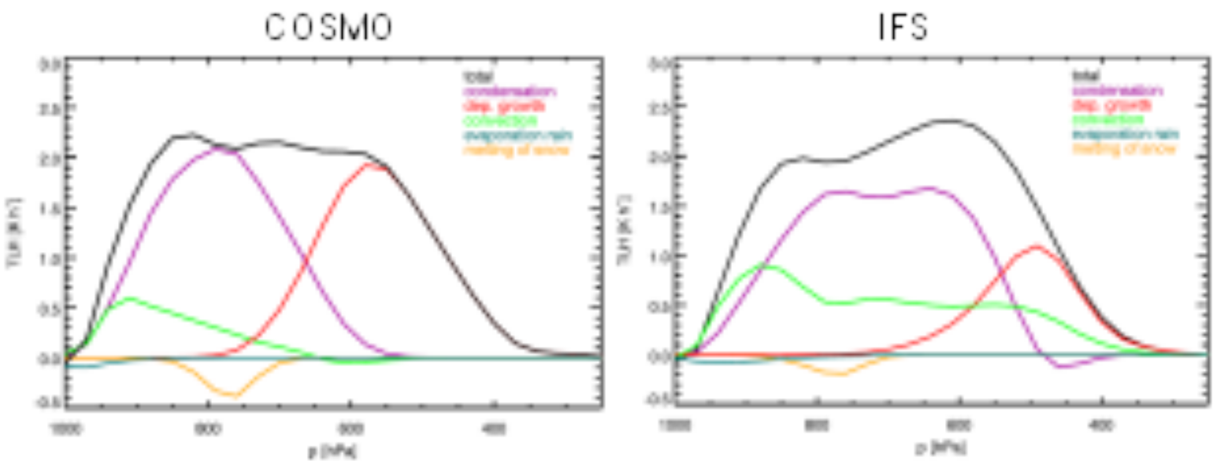


Fig 1: Evolution of the mean over all WCB trajectories of hydrometeor mass for COSMO (left) and IFS (right). Coloured lines denote the hydrometeor mass (mg/kg) of total condensate (black), cloud water (purple), snow (yellow), rain (turquoise) and cloud ice (red).

In both models, first a liquid cloud forms. In COSMO, the LWC decreases strongly above 800 hPa and the LWC equals zero above 600 hPa. At that height, the cloud in COSMO consists only of snow and ice with a small vertical extent of the mixed phase cloud with coexisting LWC and SWC between 850 and 600 hPa. In contrast, in the IFS, the LWC persists up to 400 hPa leading to a large area with supercooled liquid water and a mixed phase cloud reaching from 850-400 hPa. The differences in the partitioning between the different hydrometeor species lead to differences in the latent heat release caused by the formation of the hydrometeors (see Fig.2, upper row). Although the general pattern is again similar in both models (see black lines), pronounced differences occur in the contributions from the different microphysical conversion processes. Whereas in COSMO, the heating due to condensation of cloud liquid and depositional growth of snow contribute with a roughly same amount to the total heating, in the IFS the contribution from condensation to cloud liquid strongly dominates. This difference is then also reflected in the DPVRs which are associated with these heating rates (see Fig. 2, lower row). In both models, there is a positive total DPVR below 850 hPa with the largest contributions from condensation, convection and evaporation of rain. However, this strong positive DPVR in the lower troposphere is more pronounced in the IFS than in COSMO.



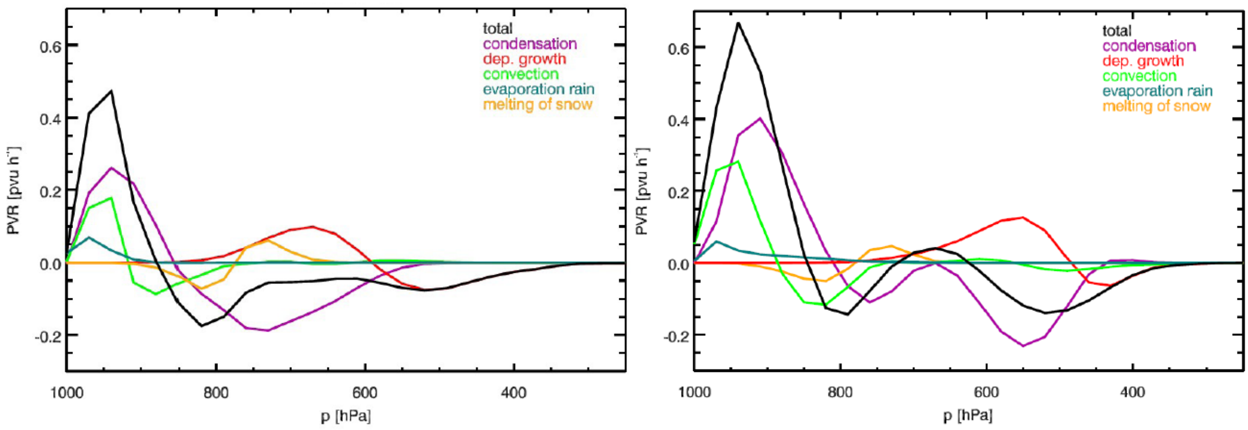


Fig 2: *Evolution of the mean over all WCB trajectories of DHRs (upper row) and DPVRs (lower row) for COSMO (left) and IFS (right). Coloured lines denote the DHR (K/h) (DPVR (pvu/h)) due to total latent heating (black), condensation of cloud liquid (purple), depositional growth of ice and snow (red), convection (light green), evaporation of rain (dark green) and melting of snow (yellow).*

In the mid troposphere around 700 hPa, in COSMO the total DPVR exhibits negative values whereas in the IFS, the DPVR gets slightly positive. In Fig.3, the total DPVR which is produced by the WCB as well as the PV averaged between 950 and 850 hPa is shown relative to the cyclone centre for COSMO and IFS. It can be nicely seen, that in COSMO the total DPVR caused by the WCB is much smaller than in IFS (see Fig. 3, upper row). In the IFS, the DPVR reaches values of more than 1.5 pvu/h along the cold front where the WCB ascents whereas in COSMO only values around 0.5 pvu/h occur. This has also an influence on the lower tropospheric PV pattern as can be seen in Fig.3, lower row. In the IFS, a strong positive PV anomaly with values up to 3 pvu develops along the cold front which in large parts overlaps with regions of high values of the DPVR. In contrast, the PV anomaly at the cold front in COSMO with values up to 1.5 pvu is much less pronounced which coincides well with the associated DPVR.
Finally, a vertical cross section through the cold front at 38°N is shown in Fig. 4 for both models. It can be clearly seen, that the positive PV anomaly in the lower troposphere is much weaker in COSMO. The green lines show the position of the WCB, which in large parts overlaps with the PV anomalies, demonstrating its importance for their formation. The wind speed associated with the PV anomalies exhibits much higher values to the East of the front, where values of 20 m/s are exceeded in IFS whereas in COSMO the northerly wind along the cold front is hardly above 10 m/s. The differences in the microphysics thus lead to different modifications of the low level wind field.

Summarized, these results emphasize the importance of details in microphysics for dynamics of extratropical cyclones and the need for detailed measurements.
However, in order to isolate the effect of microphysics on dynamics without influence from other parametrisations and the grid resolution, additional simulations with the same model where only the microphysics differ, is necessary. This next step has been done in the continuation of this special project ([2] and Future plans).

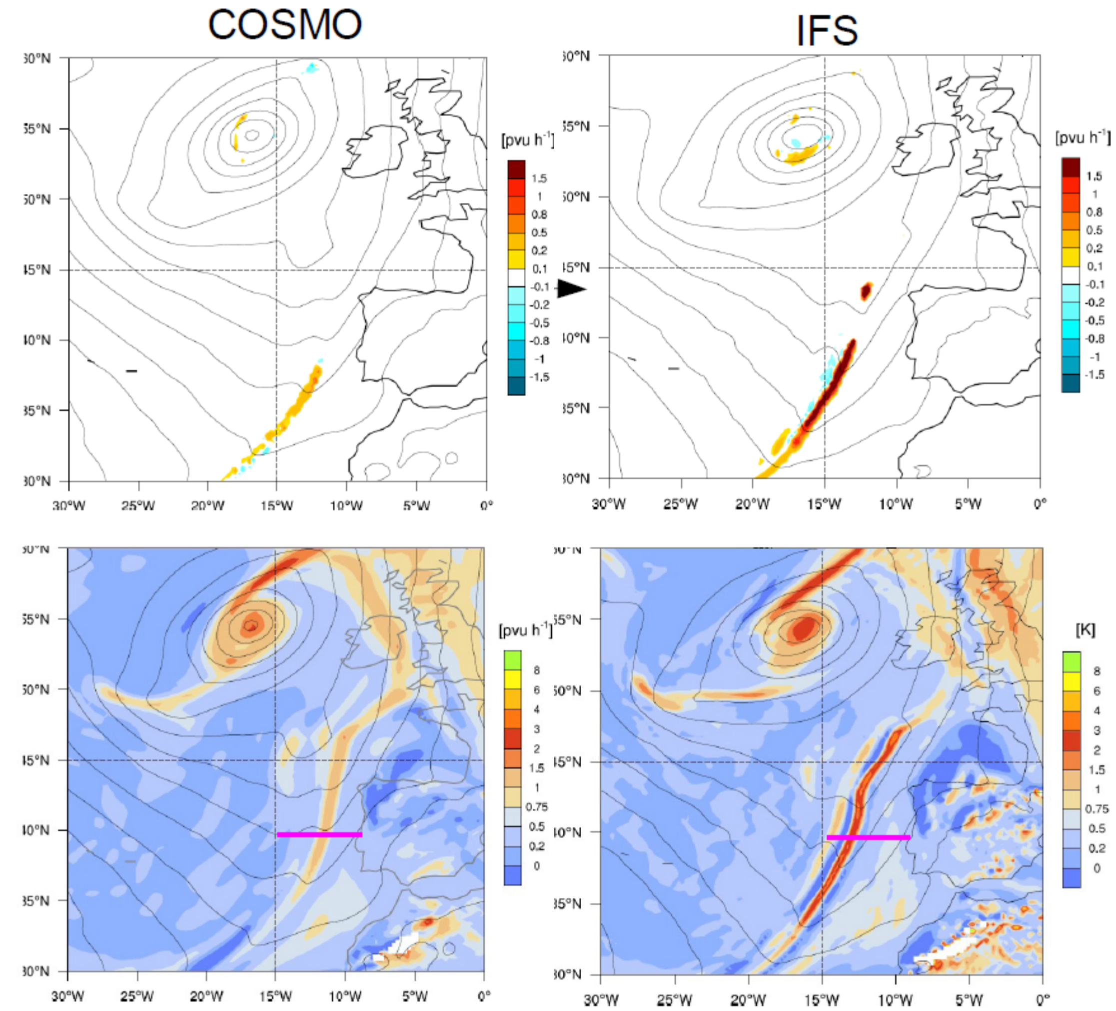


Fig 3: Total DPVR associated with the WCB (upper row) and PV (lower row) averaged between 950 hPa and 850 hPa for one specific time step for COSMO (left) and IFS (right). The pink line indicates the position of the cross section shown in Figure 4.

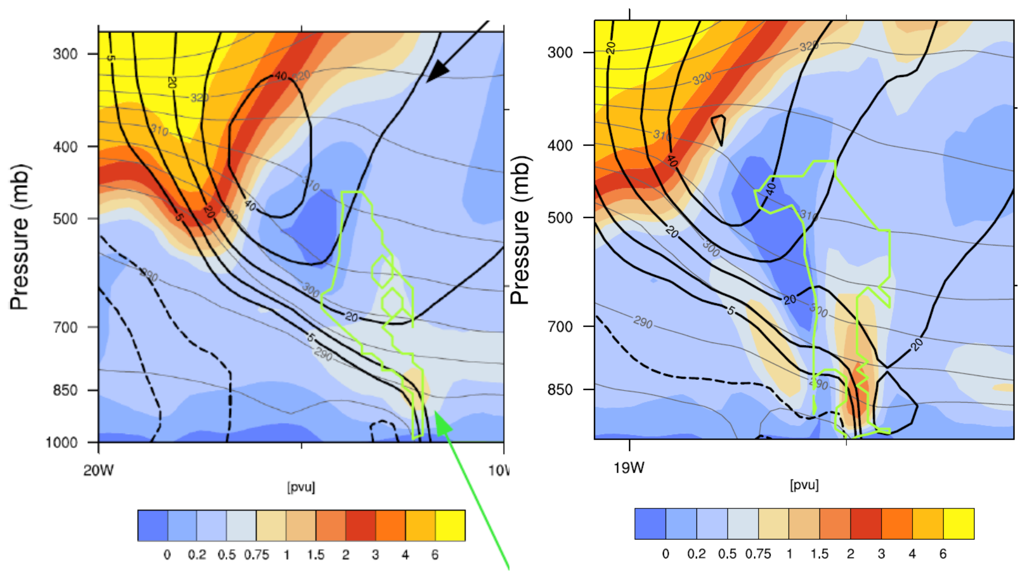


Fig 4: Vertical cross section at 38°N (along pink line shown in Fig. 3). Colour shading denotes the PV (pvu), grey lines the potential temperature (K), black lines the wind speed with solid (dashed) lines for northerly (southerly) wind directions and the green line shows the position of the WCB.

In an additional project, which started in autumn 2014 in the framework of a Master thesis by Daniel Steinfeld [3], the influence of microphysical processes on the potential vorticity in diabatic Rossby waves (DRW) is investigated. Therefore, an IFS simulation with a resolution of T799, L137 (CY40R1) has been performed for a DRW occurring in January 2013 in the North Atlantic. Again, the IFS version where all the diabatic heating rates (DHR) occurring due to microphysical processes, convection and radiation are output every hour, is used. Based on this model output it is investigated in detail, which microphysical processes contribute most to the production of the DRW's low level positive PV anomaly. Therefore, a Lagrangian procedure has been applied, where forward and backward trajectories are started from the DRW's PV anomaly and all DHRs and the associated DPVRs are traced along the trajectories. In Figure 5, left, the position of the DRW to the East of the American coast is shown by a well defined positive low level PV anomaly. The DRW is situated relatively far away from the tropopause (blue lines) and at the southern side of a baroclinic zone. In the following days, the DRW propagates to the east along the baroclinic zone and finally intensifies strongly when it starts to interact with an approaching upper level trough.

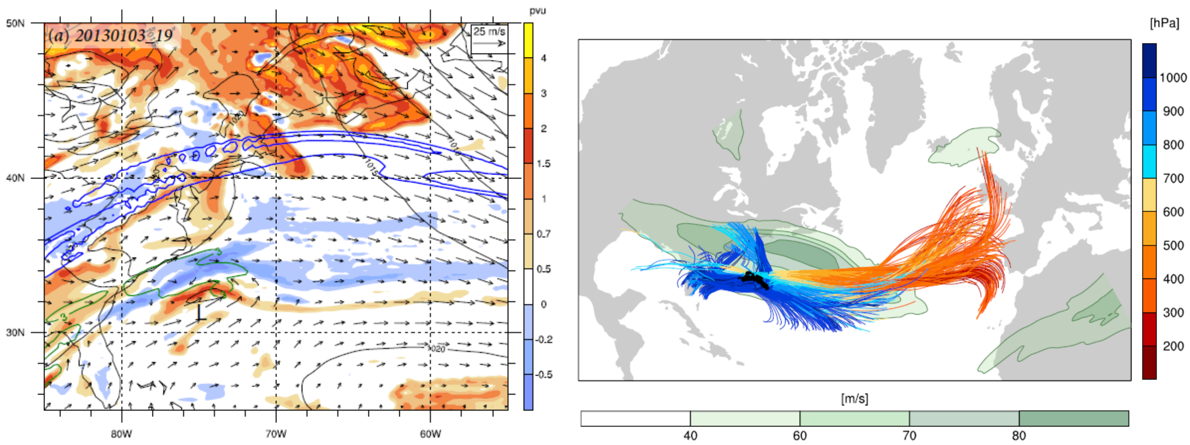
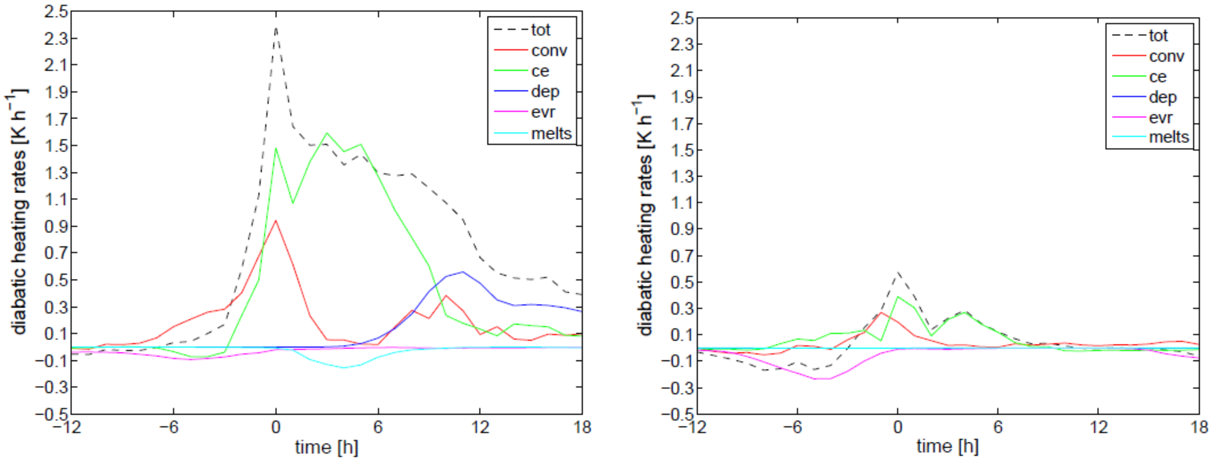


Fig 5: (Left) PV on 900 hPa (colour shading), sea level pressure (black lines), 3-hourly accumulated precipitation (green contour, 3 and 12 mm/3h) and PV on 250 hPa (blue lines, isolines for 1.5 and 2 pvu) indicating the dynamical tropopause. (Right) 48h backward and forward trajectories out of the DRW's positive PV anomaly (black dots), coloured with pressure and zonal wind velocity at 250 hPa (green shading).

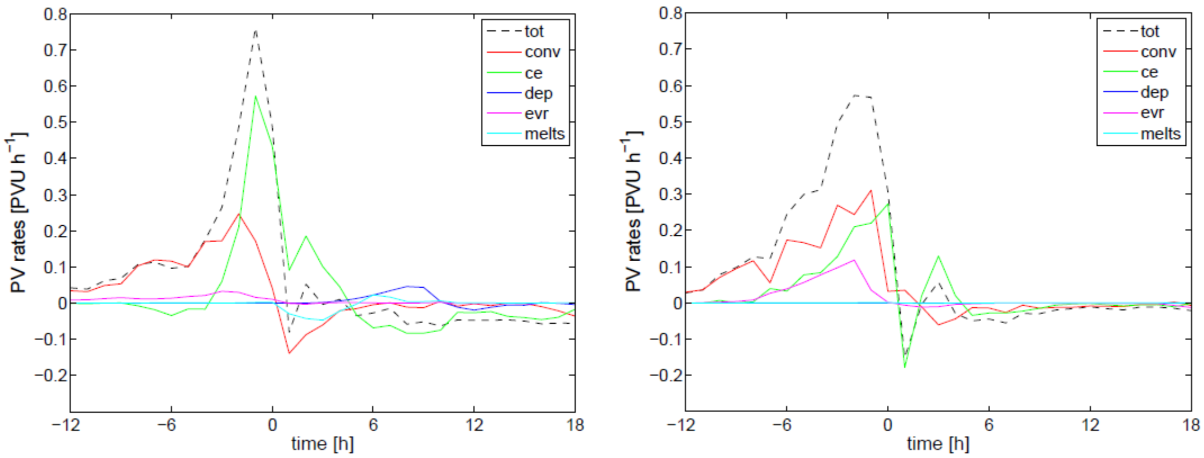
In Figure 5, right, the airstreams entering and leaving the DRW can be seen. The entering airstreams can be sub-divided in two parts. One airstream originates over the North American continent and enters the DRW from north west,whereas the other one originates in the subtropics and enters the DRW from south west. Both airstreams are located in the lower troposphere during the whole 48h before entering the DRW. The airstreams leaving the DRW can also be divided into two different branches, east of the system. One branch strongly ascends, similar to a WCB, whereas the other one stays close the surface.
In the following it is investigated how the PV of the different airstreams is modified by the different microphysical processes. In Figure 6, the temporal evolution of the most important DHRs is shown separately for the ascending and not ascending trajectories.



(a) ascending trajectories *(b) not-ascending trajectories*

Fig 6: Temporal evolution of DHRs (K/h) along ascending trajectories (a) and non-ascending trajectories (b). Lines denote the mean over all trajectories for total diabatic heating (black dashed line), convection (red), condensation/evaporation of cloud liquid (green), depositional growth of ice/snow (blue), evaporation of rain (pink), melting of snow (turquoise).

It can be seen that the ascending trajectories are hardly heated 12 hours before they enter the DRW. Only 3h before they reach the DRW, the airstreams are strongly heated by condensation of cloud liquid and convection whereas the total DHR reaches values up to 2.3 K/h. Due to the heating, the ascent of the trajectories along the sloped isentropes of the baroclinic zone is further increased. The airstreams are heated due to condensation up to 10 h after they left the DRW and due to depositional growth of ice/snow, starting 6 h after they left the DRW. For the non-ascending trajectories, a different evolution can be seen. The non-ascending trajectories are cooled due to evaporation of rain before they enter the DRW. Shortly prior and after entering the DRW they are only slightly heated due to condensation and convection. In Figure 7, the associated DPVRs are shown along the different airstreams.



(a) ascending trajectories *(b) not-ascending trajectories*

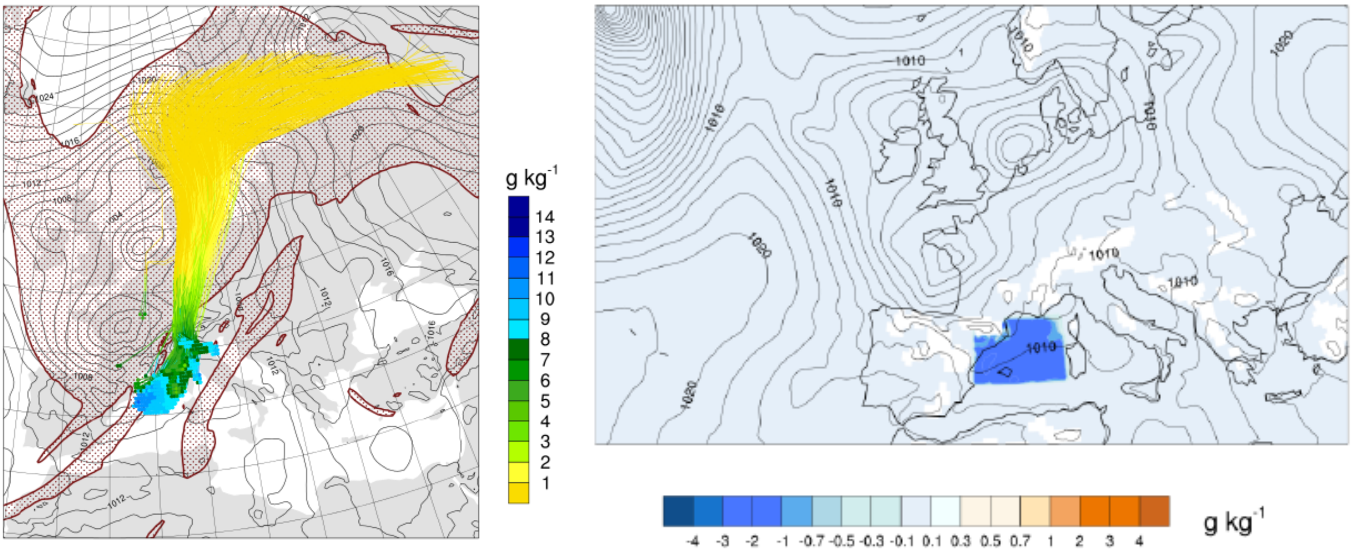
Fig 7: Temporal evolution of DPVRs (pvu/h) along ascending trajectories (a) and non-ascending trajectories (b). Lines denote the mean over all trajectories for total diabatic heating (black dashed line), convection (red), condensation/evaporation of cloud liquid (green), depositional growth of ice/snow (blue), evaporation of rain (pink), melting of snow (turquoise).

First of all it can be seen that the total DPVR (black dashed line) is stronger for the ascending than for the non-ascending trajectories. The processes which are mainly responsible for the PV production are in both branches the condensation and convection. However, in the non-ascending branch a relatively large contribution also comes from the evaporation of rain. Further analysis which is not shown here shows that the PV production in the non-ascending branch is partly caused by falling and evaporating/sublimating hydrometeors which are produced within the ascending

airstream. This coupling of the two airstreams due to sedimenting hydrometeors which can be quite important for the PV modification is an interesting feature which has to be investigated in more detail.
Thus, the results from this project also demonstrate the importance of details in the microphysics as the efficiency of precipitation formation, sedimentation velocity and below cloud evaporation/sublimation for the PV production in DRWs or extratropical weather systems in general.

In the 2nd part of the project, the sensitivity of the WCB for various amounts of humidity in the inflow is investigated. It is hypothesized that is variable is one of the important parameters to determine the WCB ascent. Concerning this variable, studies have been shown, that it is not always accurately represented in the IFS. To study the sensitivity of the WCB, experiments were performed where the specific humidity in the environment was disturbed artificially.

The first case study in the 2nd part of the project was on a WCB which had been sampled during the T-Nawdex-Falcon aircraft campaign in October 2012. The WCB started from the western Mediterranean and ascent over the Alps towards Scandinavia within 2 days (Fig. 8 a).

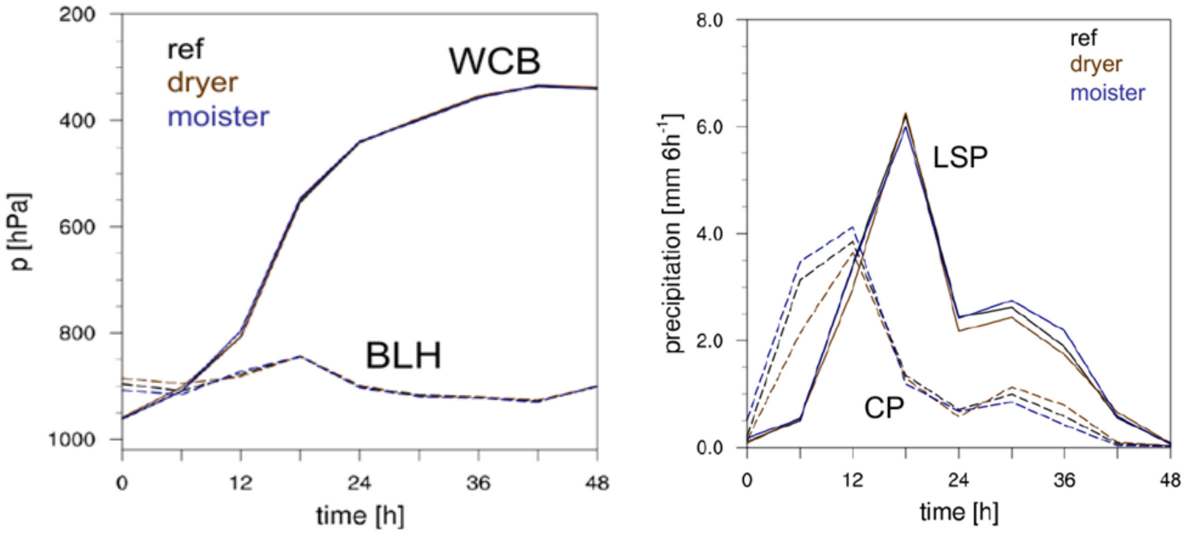


a) b)

Figure 8: Case study on a Mediterranean WCB started on 12 UTC 14 October 2012. a) WCB trajectories, colours correspond to specific humidity (g kg-^{1}), SLP (black contours) and PV at 250hPa (PV > 2pvu are shaded in red). b) Difference of low-level specific humidity (g kg^{-1}) from dry experiment and control forecast for the time step immediately after the artificial modification came into effect.

The investigations were performed with a combined model version which allows for additional heating rates output and artificial moisture modification. For the experiments, low-level specific humidity was modified artificially in a limited region within the boundary layer for one model time step, whereas the humidity was reduced or increased by 25% of the original value, respectively (Fig. 8 b). It was expected that for the dryer (moister) experiment, the number of WCB trajectories decreases (increases), the cloud processes weaken (enhance), and the altitude of the outflow lowers (rises).

Surprisingly, the overall appearance of the WCB in both experiments did not change (not shown). Further investigations revealed that neither the number nor the height of the outflow changed (solid lines in Fig. 9a). In addition, and related to the investigations in project part 1 the micropysical heating rates and the corresponding PV modification of this WCB has been analysed for the control run and experiments. As the WCB in total, the heating rates due to the single microphysical proccesses hardy changed. With this result, the reasons for this interesting and unexpected result were analysed.



a) b)

Fig. 9: Averaged variables over all trajectories along the WCB started at 40th October 2012: a) pressure (solid line) and boundary layer height (dashed) and b) large scale precipitation(solid line)and convective precipitation (dashed) for the control forecast (black), the dryer (brown) and the moister (blue) experiment.

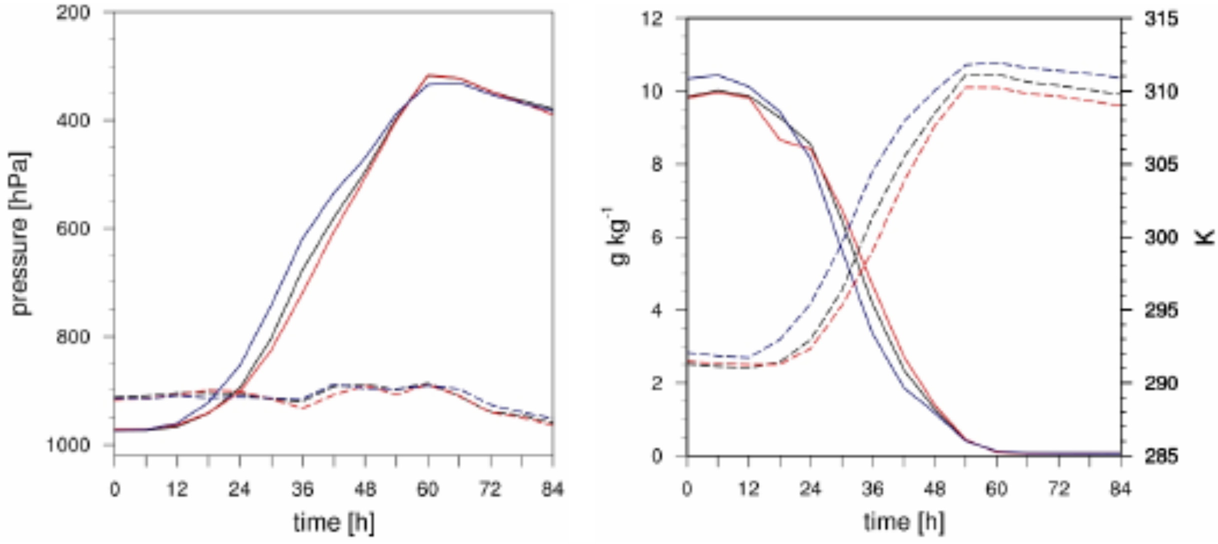
At first, due to the modifications in the lowest levels, the model increased (reduced) the surface evaporation in the dryer (moister) experiment (not shown). All in all, the activity within the boundary layer was increased (reduced) which led to a higher (lower) boundary layer height in the dryer (moister) experiment (dashed lines in Fig. 9a). The model reacted with enhanced (reduced) boundary layer processes to made up for the artificial removal of moisture.

A further expected reaction was to reducing (increase) precipitation in the dryer (moister) experiment (Fig. 9b), but only for the unresolved, convective part of the precipitation. The large scale precipitation remained nearly unchanged. This also shows that a certain amount of precipitation within this WCB was caused by convection although the ascent of WCBs is usually slantwise and dynamically driven instead of forced by vertical instability.

This study was presented at the cyclone workshop 2013 in Sainte-Adele, Canada [4]. Since these first experiments did not show the expected impact on the WCB, similar experiments were performed for a master student's project. In the following experiments the modified box remained in the boundary layer, but was shrunk in height and did not touch the surface any more.

In the master project, two WCBs were investigated whereas one showed a slow and slantwise ascent and the other one a strongly convective and quickly ascending share of trajectories [5]. The main focus of the investigations was on the ascending air masses and the outflow of the WCBs.

The number of trajectories did hardy change for the slowly ascending WCB case. Contrary to the expectations, the dryer experiment for the convective WCB case showed more and the moister less trajectories, respectively.
The slow and slantwise ascending WCB over the North Atlantic in February 2014 almost met the expectations: although more trajectories than expected, the moister experiment lead to slightly stronger moist-diabatic processes, a steeper ascent and a higher outflow in terms of pressure and potential temperature (Fig. 10). The moister experiment showed the opposite development. Admittedly, the overall pattern of the outflow did not change distinctively (not shown). The convective WCB case in February 2014 did not show a clear behaviour for the experiments.



a) b)

Fig. 10: Averaged variables over all trajectories along the WCB started at 18th February 2014 over the North Atlantic: a) pressure (solid) and boundary layer height (dashed) and b) specific moisture (solid) and potential temperature (dashed) for the control forecast (black), the dryer (red) and the moister (blue) experiment.

All results suggested that for an at least moderately instable and convective environment the IFS is compensating the artificial changes by enhanced ocean evaporation and boundary layer processes. The more stable WCB case better correspond to our hypotheses, although some reactions were inconsistent and the expected responses were rather small.

List of publications/reports from the project with complete references

1. Joos, H., Boettcher, M., Forbes, R. and Wernli, H.: Microphysical heating rates in a warm conveyor belt: Comparison of a COSMO and IFS simulation, ECMWF, Reading, UK, 2012
2. Joos, H., Boettcher, M., Forbes, R. and Wernli, H.: Microphysical heating rates and PV modification in a warm conveyor belt: Comparison of a COSMO and IFS simulation, WWOSC, Montreal, 2014
3. Steinfeld, D., Boettcher, M., Joos, H. and Romppainen, O.: The influence of microphysical processes on the potential vorticity in diabatic Rossby waves, PANDOWAE Final Symposium, Karlsruhe, 2015
4. Boettcher, M., Forbes, R., Joos, H. and Wernli, H.: Numerical study on the impact of low-level moisture modification on the warm conveyor belt, Cyclone Workshop, Sainte-Adele, Quebec, Canada, 2013.
5. Piquerez, A.: What determines the ascent of a Warm Conveyor Belt – Sensitivity experiments with the ECMWF global model, Master Thesis, ETH Zurich, 2015.

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.)

In the continuation project (SPCHBOJO), we did additional simulations with the IFS where only the parameterizations of autoconversion/accretion and rain evaporation differ. These simulations are now analysed in detail. A focus is put on the effect of these microphysical differences on the upper level PV pattern and down stream flow evolution. A paper is in preparation.
Furthermore, the project on DRWs continues. There is also a paper in preparation. For the 2nd phase of the project our general focus will be on the feedback of microphysical heating rates and dynamics (i) in various weather sytems and (ii) in model studies related to field campaigns.