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ICE CLOUDS IN EXTRATROPICAL CYCLONES

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1 INTRODUCTION

The aim of this work is to explore the role of the ice phase for the evolution and the structure of extratropical cyclones. The liquid phase or rather the thermodynamical processes associated with the condensation of water vapour are very important for the structure and evolution of cyclones and the processes are well known (e.g. Reed et al. 1992; Davis et al. 1993). In contrast the role of the formation and sublimation of ice and its influence on extratropical low-pressure systems is quite unknown. So far some case studies support the assumption that the sublimation may be important for the mesoscale structure of cyclones (Clough et al. 2000; Forbes and Clark 2003).
For the investigation of these issues the 3-dimensional cloud ice field from the ERA40 (ECMWF Re-Analysis) data set is used. To make sure that this field is a reliable basis for the analysis of ice clouds, a global verification has been made of the cloud top phase derived from the ERA40 data with satellite data from the POLDER1 - instrument (POLarization and Directionality of the Earth Reflectances). Some results of this verification are presented in section 2. More details can be found in Weidle (2005).

Section 3 contains preliminary results on the relationship between ice clouds and cyclones in the ERA40 data set.Additionally, some results of a Lagrangian trajectory calculation based on the ERA40 data are presented in section 4. Backward trajectories have been calculated from grid points where ice clouds occur in the model. These calculations are used to learn something about the history and formation of the ice clouds.

2 VALIDATION OF ERA40 ICE CLOUDS

The validation of the ERA40 ice cloud field is done with data from the POLDER1-instrument that was on board of the ADEOS1-satellite during the time period November 1996 to June 1997. POLDER determines cloud features such as the cloud top phase by measuring the bidirectional polarised reflectances of the clouds.

The data set provided covers among many others 2-dimensional fields of the cloud top phase, and of the pressure level between cloud top and cloud bottom on a global scale. Comparison with other independent observational data sets shows that the cloud top phase determined by POLDER is reliable (Riedi et al. 2000, 2001).
To compare the ERA40 data with the satellite data the 3-dimensional ERA40 cloud ice field must be converted into a 2-dimensional field that contains the cloud top phase of the ERA40 clouds. For that purpose a vertical scan algorithm has been developed to determine the cloud top phase in the following way:
Starting point is the POLDER cloud pressure level (Fig. 1, Polder pressure level). To make sure that the vertical scan in the ERA40 data starts above the cloud, the pressure is reduced by a specified value (here 150 hPa).
This pressure level is the start level for the scan in the ERA40 data. Now the ice water content IWC and the liquid water content LWC are integrated downward model-level by model-level until a defined threshold (0.001 g/kg for IWC and LWC as well) is exceeded (e.g. in Fig. 1 this is the case at pressure level p5). If the threshold for IWC is exceeded, the cloud is determined as an ice cloud. If the threshold for LWC is exceeded, the cloud is specified as liquid, and if both thresholds are reached at the same level the cloud is regarded as a mixed-phase cloud. In addition, there is a second pressure level defined by an increase of the POLDER pressure level in order to determine the end level of the ERA40 scan (cf. Fig. 1). If the integrated IWC/LWC between start and end levels is lower than the threshold, then the considered grid point is defined as cloud free in the ERA40 data set.
The model level, where the cloud top phase is determined, is defined as *cloud fix*. This level is always inside the model cloud (which was also detected by POLDER) and typically in the clouds' uppermost layers.
With this algorithm a global 2-dimensional field of the cloud top phase in the ERA40 data can be calculated every 6 hours and serves for a detailed comparison with the satellite data.
The validation is done every 6 hours by comparing the cloud top phase of both data sets gridpoint by gridpoint. For that purpose the ERA40 data as well as the POLDER data have been interpolated on a geographical grid with 1x1 degree horizontal resolution.

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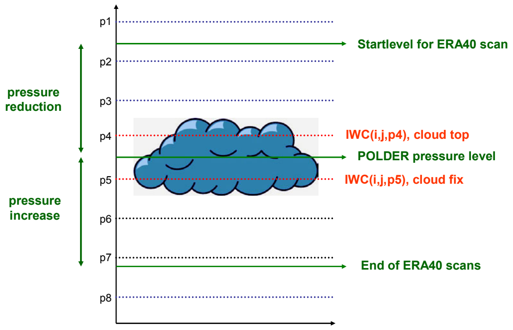

Figure 1: Schematic illustration of the algorithm to determine a 2-dimensional field of the cloud top phase from the ERA40 data set.

The validation is subdivided into two parts. The first one includes all grid points, where the POLDER-instrument observed an ice cloud during the time period the POLDER-instrument was in orbit. For these grid points and for every month, Fig. 2 shows the cloud top phase that was identified from the ERA40 data set. Nearly independent from the time of the year, the ERA40 data match the ice clouds observed by POLDER very well, with a probability of about 80% (black solid line in Fig. 2). For about 15% of the POLDER ice clouds our algorithm determines no clouds in the ERA40 data set (green line), while liquid and mixed clouds can be neglected. So if an ice cloud is measured by the POLDER-instrument, the ERA40 data match very well.

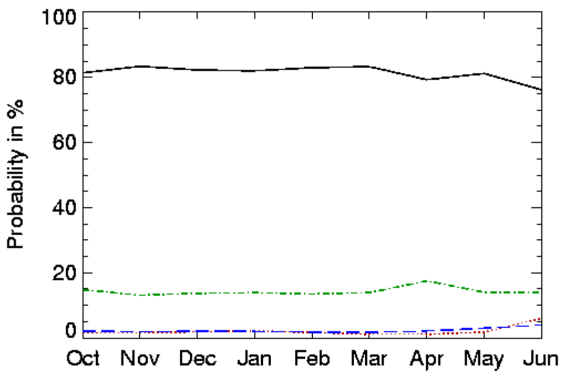

Figure 2: Probabilty that ERA40 data contains ice clouds (black solid line), liquid clouds (red dotted), mixed clouds (blue dashed) or no clouds (green dashed dotted) if the POLDER data set include ice clouds.

The second part (Fig. 3) analyses the situations where the ERA40 data show ice clouds. Here, the results from the comparison differ substantially from the first part of the validation.
The two data sets agree on ice clouds with a probability of only 23 to 30% (black solid line in Fig. 3).
The case that POLDER data contain liquid clouds when the ERA40 data show ice clouds occurs with the highest probability of up to 38% (red line).The two other cases (mixed or no clouds) appear with about the same probability of about 15 to 25%.

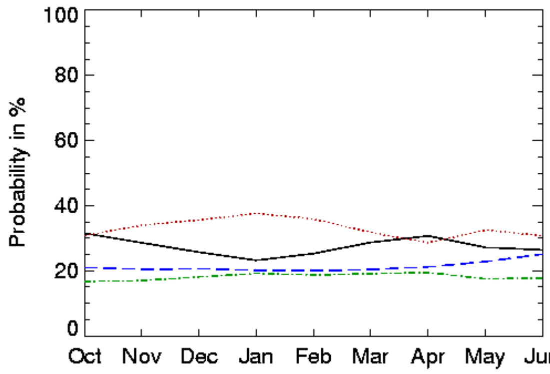

Figure 3: Probability that POLDER data contains ice (black solid), liquid (red dotted), mixed (blue dashed) or no clouds (green dashed dotted) if ice clouds have been identified in the ERA40 data set.

The reason for this relatively poor agreement in situations where ice clouds occur in the ERA40 data might be due to the phase parameterisation of the condensed water in the ECMWF model, which is done in a relatively simple way. For temperatures T>273.16K clouds are assumed to be liquid, for T<250.16K clouds are assumed to contain pure ice, and mixed clouds are parameterized in between. It seems that, compared to POLDER data, this parameterisation produces too much ice at relatively warm temperatures so that in our algorithm the threshold for integrated IWC is exceeded during the scan in the ERA40 data. To underline this assumption, Fig. 4 displays the cloud temperature for the mismatch cases, when ERA40 shows an ice cloud and POLDER observed a liquid cloud.

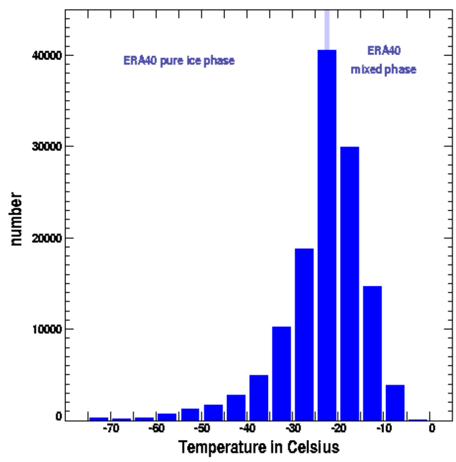

Figure 4: Temperatures when ERA40 indicates an ice cloud and POLDER observed a liquid cloud.

One can see that the mismatch appears very often at temperatures warmer than -25°C. Therefore the assumption in the ECMWF model that at temperatures below -23°C the whole condensed water is in the ice phase might be wrong. POLDER indicates liquid clouds with a remarkable frequency down to -40°C which is in agreement with in-situ measurements in the atmosphere.
The comparison of the two data sets was done for the other phases as well (cf. Weidle 2005).
Besides the mentioned mismatch caused by a not perfect parameterisation of the IWC/LWC at

relatively warm temperatures, the validation of the ERA40 data set gave satisfactory results.
So as a first conclusion one can say that the ERA40 ice cloud field seems to be reliable, in particular for cold ice clouds in the upper troposphere.

3 ICE WATER PATH (IWP) IN THE VICINITY OF THE CENTRE OF THE CYCLONES

As a first step to investigate the occurrence of ice clouds in extratropical cyclones, a preliminary analysis is made of the IWP in the vicinity of cyclones during one month (March 1997). Cyclones are identified from the ERA40 sea-level pressure field every 6 hours and a tracking algorithm (Wernli and Schwierz 2005) has been applied to determine the origin and track of individual cyclones.
The ice water path was calculated for all gridpoints within a distance of 300 km from the centre of the cyclone for every timestep of the cyclone's life-time.
One aim of this examination is to find out which cyclones produce a lot ice in their vicinity and which do not.
For that purpose, the sum of the IWP for all gridpoints within a 300 km distance from the cyclone centre and the sea-level pressure at the centre of the cyclone are displayed in Fig. 5.

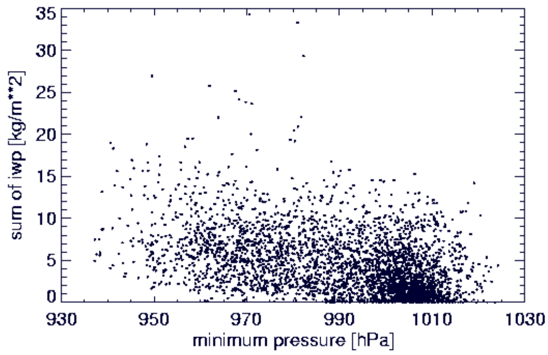

Figure 5: Scatterplot of the sum of IWP (sum of all gridpoints within 300 km around the sea-level pressure minimum) and sea-level pressure in the centre of the cyclone.

There seems to be a correlation between the minimum pressure in the low and the sum of the IWP in its vicinity. The lower the pressure, the higher are the domain-integrated IWP values. This indicates that during the growth of the cyclones IWC is produced in the model. It seems the maximum of IWC occurs near the time of minimum pressure. Further investigations are planned to analyse this finding more thoroughly, and to identify the typical locations of ice production and sublimation in the cyclones.
There also seems to exist a correlation between the geographical latitude of the cyclones, and the sum of the IWP in their vicinity. Typically, cyclones in high latitudes (in both hemispheres) produce more ice than the cyclones in low latitudes and even the tropical regions (see Fig. 6).

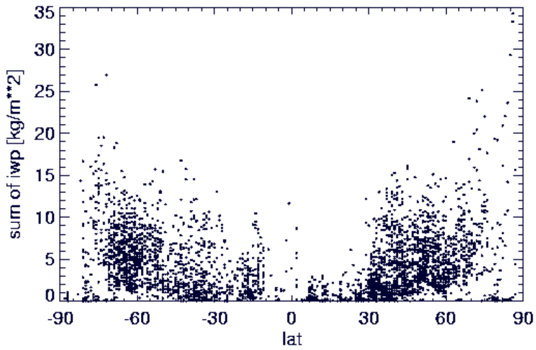

Figure 6: Scatterplot of the sum of IWP (sum of all gridpoints within 300 km around the centre of the cyclone) and the latitude of the cyclone.

This result indicates that the cyclones seem to play an important role for the ice clouds in the extratropical regions. In the tropical regions this is not the case. Whereas in these areas the highest values of IWP are obtained, this ice is not produced in the vicinity of cyclones. Most likely, deep convection is the most important process for the formation of ice in the tropical atmosphere.
These first results provide a good motivation for further analyses of the link between extratropical cyclones and the ice clouds in their vicinity.

4 TRAJECTORY CALCULATIONS

In this section we want to examine aspects of the life cycle of the ice clouds, e.g. their formation and life-time. For this purpose a Lagrangian trajectory model (Wernli and Davies 1997) and ERA40 data are used. Backward trajectories for a timeperiod of 96 hours are calculated from every gridpoint where an ice cloud occurs in the ERA40 data that was verified by the POLDER-observations. The trajectories were started at the cloud fix level (see section 2) that is located inside the cloud.
So far, the calculation of trajectories is done again just for one month (March 1997), and therefore the results have to be regarded as preliminary and not yet climatologically representative.
For a better understanding of the processes that lead to ice clouds in the extratropics, the calculated trajectories are subdivided in different classes. They are distinguished by the intensity of the vertical ascent: (i) more than 400 hPa within 24 hours, (ii) more than 400 hPa within 24-48 hours, (iii) more than 400 hPa within 48-72 hours and (iv) less than 400 hPa within 72 hours.
Fig. 7 displays the trajectories that belong to the first class. Every point marks the trajectory position at the end of the 24-hour ascent. The colours indicate the difference between the potential temperature of the air parcel after and before the vertical displacement phase. Another criteria that is fulfilled by these backward trajectories is that the air parcel's IWC is larger than 0.001 g/kg at their starting point.

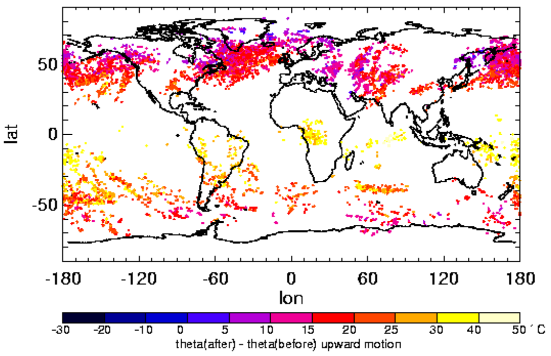

Figure 7: Positions at the end of the rapid ascent phase (more than 400 hPa within 24 hours) of air parcels that contain ice clouds at the starting time of the backward trajectory calculation. Colours show the difference between the potential temperature after and before the rapid vertical displacement.

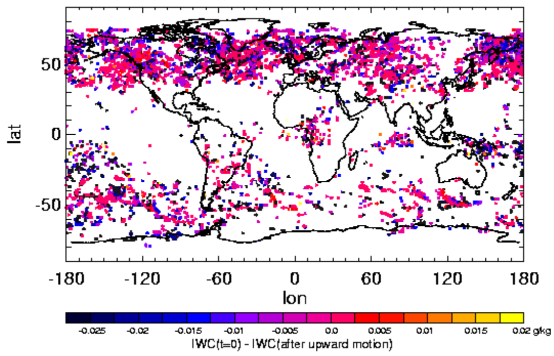

Figure 8: Coordinates of the starting point of the trajectories (with POLDER data validated ice clouds). Colours show the difference between IWC at start time of the backward trajectories and IWC after the upward motion.

One can see well-defined regions (especially in the northern extratropics) with an increased frequency of strong vertical displacement. In the northern extratropics most trajectories that meet the applied selection criteria are located in the late-winter storm tracks over the North Atlantic and Pacific oceans. They are part of the conveyor belts associated with the extratropical cyclones that transport warm and moist air polewards and upwards (Eckhardt et al. 2004). This vertical displacement is linked with an increase of potential temperature, or, in other words with (intense) diabatic heating due to condensation of water vapour of 5 to 20 K, the latter being a typical value for conveyor belts. In addition, Fig. 7 shows a distinct difference between extratropics and tropics. In the tropics the potential temperature increase is larger (about 30 to 50 K) than in the extratropics due to larger amounts of available moisture. In the southern extratropics there are no such preferred regions for strong vertical motion in the particular month considered.

In Fig. 8 the starting coordinates of the same backward trajectories are shown. These points mark the positions where the POLDER-instrument observed the ice cloud. Compared to Fig. 7 the distribution is more zonally symmetric. This indicates that extratropical ice clouds (i) are generated in well-defined regions, where strong vertical motion occurs due to synoptic-scale forcing (at least during the non-convectively dominated summer months), (ii) can be transported over long distances in the zonal direction and (iii) that they can have lifetimes of several days.

The colours in Fig. 8 indicate the difference of the air parcels' IWC at the starting time and the end time of the rapid ascent phase (more than 400 hPa within 24 hours).

Negative values indicate that IWC is lost (due to precipitation or sublimation) between the end of the upward motion and the time the ice cloud has been detected by POLDER. Most data points are near 0 g/kg and no geographical differences can be observed. The mostly low difference values occur

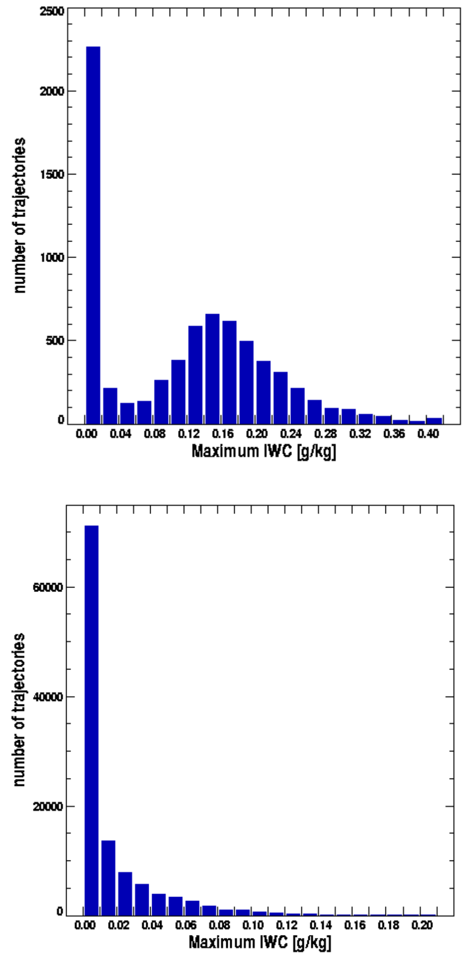

Figure 9: Upper panel: Maximum values of IWC along the trajectories that ascend more than 400 hPa in 24 hours. Lower panel: Same for trajectories with weaker ascent (less than 400 hPa in 72 hours).

either because the ascent just ended near the starting time of the backward trajectory, or the IWC at the end of the rapid vertical displacement was

quite low, such that there was not much IWC to lose further (the second case dominates, see Fig. 9).
It has to be mentioned that just a little fraction of the calculated trajectories fulfill the criteria of rising 400 hPa within 24 hours (about 5 %). The great majority (about 86%) of the trajectories feature much less vertical motion (< 400 hPa within 72 hours). The meteorological processes associated with these trajectories will be subject of further investigatons.
A significant difference occurs between these two categories of air parcels (strong rapid ascent vs. weak ascent) with respect to their maximum IWC. Figure 9 shows a histogram of the maximum values of IWC along the trajectories. One can see that the maximum IWC distribution of the two categories is different (note the different scaling of the x-axis). For clouds that form during a strong upward motion a secondary maximum can be observed at values of 0.12 to 0.20 g/kg maximum IWC, while for trajectories with little rising motion in the past 96 hours the most likely maximum IWC value is very low (less than 0.005 g/kg) of IWC. It seems that rapid vertical motion can lead quite frequently to the production of high IWC values. Nevertheless most of the considered ice clouds are characterized by fairly low values along their 4-day backward trajectories.

5 PRELIMINARY CONCLUSIONS

The 3-dimensional cloud ice field in the ERA40 data has been found to be relatively accurate and provides a comprehensive data set for the investigation of ice clouds and their interplay with atmospheric dynamics. The validation of this field with satellite data from the POLDER-instrument has been done by transforming the 3-dimensional field of IWC in a 2-dimensional field of the cloud top phase of the ERA40 clouds. The statistical evaluation shows that both data sets match fairly well. The ice clouds that are observed by the POLDER-instrument are reproduced by the ERA40 data with a probability of about 80%. But the parameterisation in the ERA40 data seems to produce IWC in too high concentrations at relative warm temperatures. While POLDER measured liquid clouds also at very low temperatures (down to -40°C) quite frequently, the applied algorithm to define the cloud top phase in the ERA40 data set mainly determines ice clouds for temperatures lower than -10°C.
First results of the investigation of cyclones in the ERA40 data and the IWC in their vicinity provides good motivation for further work. It was shown that there might be coherence between the minimum sea-level pressure in the cyclone centre and the total IWP in a certain radius. Deeper cyclones were associated with higher domain-integrated IWP values. Additionally, it was shown that the cyclones' total IWP reaches much higher levels in the extratropical regions than in the tropics. This indicates that in the extratropics cyclones play an important role for the production of ice in the atmosphere, while in the tropics they are not the dominant factor. It is expected that deep convection becomes the dominant process in the tropics. First evaluations with backward trajectories, calculated for ice clouds in the ERA40 data set, show some interesting results. The largest part of the trajectories show relatively little vertical motion (less than 400 hPa) in the last 72 hours before the ice cloud was detected by the POLDER-instrument. In a few cases (about 5%) there was strong ascent of the trajectories that led to the formation of the observed ice clouds. This ascent is reminiscent of warm conveyor belts and indicates the importance of this meteorological phenomenon also for the formation of ice clouds. In cases where the ice cloud air parcels experienced little ascent during the previous 4 days it might still be that much stronger vertical motion occurred just below the cloud. Such an event has been documented by Spichtinger et al. (2005).The maximum values of IWC along the trajectories for the weakly rising events are very low, so probably these clouds are quite thin. In contrast, the histogram of the maximum IWC-values for the trajectories that ascended more than 400 hPa within 24 hours (see Fig. 9) show a secondary maximum at values of about 0.15 g/kg. This is an indication for the assumption that conveyor belt-like upward motion can produce relativly high values of IWC.
The geographical distribution of the trajectories with fast upward motion shows that the ocean storm tracks are preferred regions for this kind of transport (especially in the northern extratropics), in agreement with earlier studies (e.g. Eckhardt et al. 2004). In the tropics there are some hot-spot regions where strong ascent occurs. They are related to deep convection, which results in a high difference between the potential temperature before and after the vertical displacement. It has also been shown that the ice clouds formed during upward motion can be transported over long distances. Although the upward motion occurs in preferred regions, the zonal distribution of ice clouds is zonally nearly uniform when they are observed by the POLDER-instrument. This is a first hint of the possibly long lifetime of extratropical ice clouds.

6 ACKNOWLEDGMENTS

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