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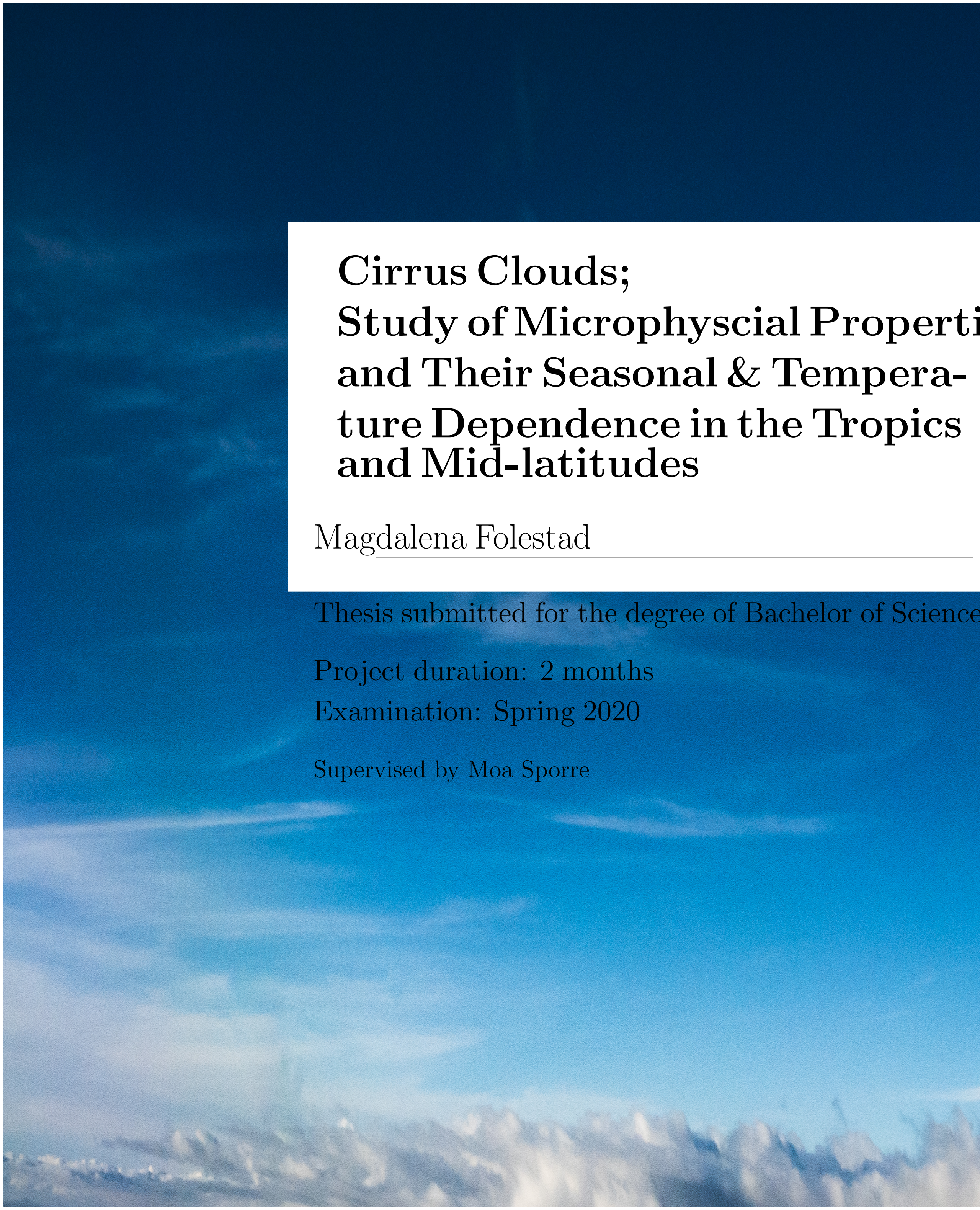

Cirrus Clouds; Study of Microphyscial Properties and Their Seasonal & Temperature Dependence in the Tropics and Mid-latitudes

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Contents

1 Abstract

Cirrus clouds are high-level ice clouds covering ≈ 30% of Earth's surface. The cirrus clouds ice crystals can be formed by heterogeneous or homogeneous nucleation, where temperatures for heterogeneous nucleation was set to -38 - -30 °C and for homogeneous nucleation below -42 °C. The study will focus on microphysical properties of cirrus clouds in the tropics, 0-30°, and the mid-latitudes, 30-60°, since different cirrus types dominate each respective region. The report is based on cirrus measurements from the satellites Cloudsat and CALIPSO. The dataset DARDAR (liDAR/raDAR) processes the satellite data, giving access to the microphysical parameters ice water content (IWC), ice crystal ICER (ICER) and ice crystal number concentration (ICNC). A cirrus filter, was applied to ensure solely cirrus clouds being studied and the data was averaged to monthly values. The data ranged from year 2008 to 2016.

The data revealed clear seasonal patterns for the vast majority of the microphysical parameters. In the tropics, ICER, ICNC 100 and IWC co-vary with temperature. ICNC 5 and 25 have opposite variations compared to temperature. An unexpected result in the Tropics was that the northern hemisphere (NH) and southern hemisphere (SH) had a similar seasonal variation in temperature, both with peaks during the NH summer. The mid-latitudes corresponded to lower values and warmer temperatures, compared to the tropics. In addition, the correlations with temperature were lower for the mid-latitudes. An unexpected finding in the mid-latitudes was that an increase in IWC did not correspond to a larger ICER. For ICNC 5 and 25 the values were higher for clouds classified as homogeneous than for those classified as heterogeneous, in contrast to the other parameters. Higher concentrations of smaller particles in homogeneous clouds is anticipated, since large crystals are expected in heterogeneous clouds. Overall, ICER showed the strongest temperature dependence followed by ICNC 100, particularly during boreal autumn season. IWC did not seem particularly temperature dependent. This study will aid the understanding of cirrus clouds, their structure and their climate effect. The study is part of a larger project investigating the effect of volcanic aerosols on cirrus clouds.

2 Introduction

2.1 Cirrus Clouds in General

Cirrus clouds cover around 30% of Earth's surface. They are part of the high-level clouds with a cloud base generally occurring above 5000m, belonging to the upper troposphere [Storelvmo and Herger, 2014]. In the sky, the cirrus clouds appear as feather-shaped or wispy trails as a result of evaporation in a vertical wind gradient of horizontal winds. The cirrus clouds obtained their name already in 1803 by Luke Howard [Lynch et al., 2002]. In clouds with a temperature below -38 °C all particles will be frozen and thereby deposition and growth of water droplets or water vapour can no longer occur [Heymsfield et al., 2016]. Additionally, the dry air at such altitudes, required for such cold temperatures, contributes to clouds consisting solely of ice crystals [Ahrens and Henson, 2017]. Clouds are originally primarily classified by morphology, hence based on their daytime visual appearance. Parameters like temperature, ice water content, altitude and optical depth are hence not part of the official definition, although highly important for classifying clouds [Lynch et al., 2002]. This is mainly due to that the characterising properties for clouds can vary greatly between clouds but also within a single cloud. This complicates a mathematical definition, although becoming more common.

2.2 Cirrus Clouds in Detail

The cirrus clouds are by Kärcher and Spichtinger [2009] classified into three categories, including in-situ cirrus, anvil cirrus and contrail cirrus. In Figure 1, in the left picture, contrail cirrus is seen as the streak cutting trough the picture. The white shades around the sun are the feather-shaped cirrus clouds. In the right picture, on the left hand side, anvil cirrus are spreading out from a convective Cumulonimbus cell. In-situ cirrus are formed by desublimation, water vapour directly freezing into ice crystals [Krämer et al., 2016] and can be present at all latitudes, at all times [Lynch et al., 2002]. In-situ is the most commonly used name but can also be defined as synoptic, lee wave, gravity wave or orographic cirrus [Krämer et al., 2016].

Figure 1: Left picture; a streak of contrail cirrus from an airplane cutting trough the image and cirrus clouds apperaing as white shades around the sun. Right picture; Cubulunibous cloud over ocean with anvil cirrus spreading out at the cloud top. Photographs by Bengt A.G. Nilsson 2019

The anvil cirrus arise from deep convective outflow, from the cumulonimbus (Cb) cloud outflow [Kärcher and Spichtinger, 2009]. Convective clouds are generated through the rise of warm air parcels. Due to uneven solar heating and different albedo of the Earth's surface, some areas become warmer compared to other areas [Ahrens and Henson, 2017]. In the warmer areas the air is heated and rises as an air parcel. If the parcel becomes saturated while lifted, condensation begins and a cloud begins to appear. Parts of the parcel continues to rise until the temperature of the parcel is cooler than the temperature of the surrounding environment, marking the cloud top. This often occurs when an inversion is present. An inversion is a point when temperature increases with height.

The Cb clouds have a great vertical extent and can reach all the way to the tropopause, where an inversion is always present. When reaching the tropopause the top of the Cb cloud is flattened and spread out, since not possible to rise further, creating an anvil. Due to the great vertical extent of the Cb cloud, usually the bottom part only includes water droplets. The strong updrafts in the cloud lift the water liquid droplets, that freezes and becomes glaciated, forming a mixed-phased cloud [Krämer et al., 2016]. When lifted high enough vertically, not allowing any water droplets or supercooled droplets, the change in characteristics now allows them to be a part of the cirrus clouds. Due to most favourable conditions for Cb clouds in the tropics the anvil cirrus are most widespread here. Along with the in-situ, the anvil cirrus have the strongest climate effect, being more widespread around the globe, compared to contrail cirrus.

Contrail cirrus is the visible cloud behind aircraft that results mainly from the water vapour emissions from the engines [Lynch et al., 2002]. Contrail cirrus are a visible sign of the human influence on the Earth's climate, though still less common than the natural occurring cirrus. During the later part of World War II, aircraft started flying into the cirrus clouds, discovering them. After this the study of cirrus became more serious [Lynch et al., 2002]. Overall, the contrail cirrus are the most studied; partly because of the environmental aspect and partly because they are easier to study than natural occurring cirrus. This is because the contrail cirrus appear during well defined and reproducible conditions [Lynch et al., 2002]. In addition, there are the frontal cirrus clouds associated with moving fronts, which have characteristics of both in-situ and anvil cirrus, hence not an own category.

2.3 Creation Mechanisms of Cirrus

Looking through the synoptic and mesoscale perspective, the appearance of cirrus clouds are mainly due to three different creation mechanisms. First is the Cb convection, mostly relevant in the area of the Intertropical Convergence Zone (ITCZ) [Kärcher and Spichtinger, 2009, Lynch et al., 2002]. The strong convection and updrafts inside the Cb cloud continuously provides the upper troposphere with water vapour and ice particles [Lynch et al., 2002]. Due to the high humidity in the upper troposphere in the tropics the cirrus have a longer lifetime without evaporating or precipitating as quickly. There is a greater latitudinal extent of cirrus clouds compared to the active Cb convective cells. This is possible due to the provision of moisture by the spreading of air from the Hadley cell [Lynch et al., 2002]. This results in the possibility of tropical cirrus to leave the origin of convection and travel towards the mid-latitudes [Lynch et al., 2002]. Second is the orographic lifting associated with orographic gravity waves [Kärcher and Spichtinger, 2009, Lynch et al., 2002]. Especially on the lee side of the mountain where the gravity waves mostly occur, the wave-like structure accounts for strong vertical velocities that allows for quick adiabatic cooling, and provided ice supersaturation, creating cirrus cloud [Joos et al., 2014]. Third are the cirrus created from baroclinic fronts and lows [Lynch et al., 2002].

Hence in the tropics, it is the strong convection with air parcels rising and hitting the tropopause, that is responsible for the creation of cirrus clouds. Thereby, in the tropics, the anvil cirrus are dominating. The high altitude of the tropopause in the tropics entails colder temperatures compared to the tropopause in the mid-latitudes, since occurring at lower altitude. In the mid-latitudes the cirrus formed by convection is limited to the summer season, when incoming solar radiation is strong enough to aid convention. Therefore, it is the frontal and in-situ cirrus that are mostly associated with the mid-latitudes. In union with the in-situ cirrus, the contrail cirrus can be visible around the whole globe due to the large extent of travels by aircraft. The ITCZ in the tropics have the highest frequency of cirrus clouds, and the mid-latitude storm-belts is the second most frequent location for cirrus to occur [Kärcher and Spichtinger, 2009, Lynch et al., 2002].

2.4 Homogeneous and Heterogeneous Nucleation

Scaling down to a microscale perspective, cirrus clouds can consist of heterogeneously formed ice crystals, homogeneously formed ice crystals or a combination. Homogeneous nucleation is the process of supercooled droplets freezing spontaneously, which is mainly dependent on temperature, and normally occurs at -38 °C. It can also occur upon saturation [Kärcher and Spichtinger, 2009]. For heterogeneous nucleation there is ice nuclei present, consisting of aerosol particles. The aerosols can be of mineral dust, metallic particles and soot [Cziczo et al., 2013] that lowers the saturation needed for activation of ice crystal growth. For a long period of time, the dominating mechanism of cirrus formation was considered to be the homogeneous nucleation [Jensen et al., 2010]. A more recent study have however shown heterogeneous nucleation to be dominant in Central- and North America, while a model study found heterogeneous nucleation to be dominant over the Artic, west coast of North America and central Asia [Barahona et al., 2014].

Determination of the nucleation mechanism for in-situ cirrus, anvil cirrus and contrail cirrus is highly difficult and no general conclusion or rules have yet been possible to make. When satellites measure the ice crystals, they measure them in their current state. Therefore, the satellites cannot determine if the crystals have initially been supercooled water droplets, freezing when traveled by strong updraft, or if the crystal has frozen in-situ. How the nucleation is distributed between homogeneous and heterogeneous in contrail, in-situ and anvil cirrus is yet not assuredly known.

2.5 Effect on Climate

The total albedo of clouds is about 60% [Ahrens and Henson, 2017]. The reflection of incoming shortwave solar radiation is greater than the absorption leading to a cooling of the climate. In addition, clouds emit longwave radiation partly into space and partly towards Earth, having a warming effect. The net effect of clouds depends on the cloud type, altitude and physical properties.

Cirrus clouds contribute with a negative effect, cooling, in the sense that they reflect incoming shortwave solar radiation back into space. However, this is not the dominating mechanism since cirrus clouds are efficient absorbers of longwave radiation and reemit longwave radiation back towards the surface of Earth, contributing with a positive warming effect [Friberg et al., Kärcher and Spichtinger, 2009]. The optical depth of the cirrus clouds greatly influences the net radiative effect. Optically thin cirrus clouds have low reflectance of shortwave radiation and transmit the majority of the solar radiation, warming the surface. In addition, due to the low temperatures of the clouds, the ratio of absorbed longwave radiation warming the surrounding atmosphere, is greater than the amount of longwave radiation emitted into space, giving a net warming effect of the climate [Ahrens and Henson, 2017]. With increasing optical depth the cloud albedo increases, leading to a greater cooling effect which is most efficient for small effective ice crystal radius [Kärcher and Spichtinger, 2009]. Except for optical depth, altitude, cloud cover and ice crystal size distribution influence the radiative response [Kärcher and Spichtinger, 2009]. Incoming solar radiation have seasonal, diurnal and spatial fluctuations which affect both the formation of cirrus clouds and the Earth's radiation balance.

Human impact on cirrus clouds can be in form of airplane emissions. Airplanes leading to the formation of contrail cirrus posses a direct effect on Earth's climate. They may also have an indirect effect through the emissions of aerosol particles that in a later time and location will affect the formation and properties of cirrus clouds [Lynch et al., 2002]. Considering both direct and indirect effects, predicting the exact climate effect of contrail cirrus contributed by humans is highly difficult.

For easier prediction of the climate effect of cirrus, including them in weather forecasts is essential. Clouds strong influence of the surface temperature, greatly affects the predicted temperature in weather forecasts. The main focus has been laid on the large convective and precipitating clouds since these have been seen to have the greatest effect on society [Lynch et al., 2002]. The cirrus clouds have unfortunately for this reason not been given as much attention in the models. The increase of studies of cirrus, revealing their possible climate effect has showed that accounting for the cirrus in weather forecast and climate models is most essential.

Even if it is essential to include the cirrus clouds in climate models, it can be problematic. Global weather models today usually have a resolution of 10-20 km [ECMWF, 2017] which is larger than the scale for where, for instance, convection and turbulence are acting. This results in clouds being overrepresented over some areas and underrepresented over other areas. The dynamic processes involving cirrus are weak and the creating and dissipating processes are significantly alike. This makes cirrus clouds one of the most difficult cloud types to numerically predict [Lynch et al., 2002].

2.6 Geoengineering and Seeding

In addition to including cirrus clouds in models, studies have been made to find approaches to decrease their warming effect on climate, to combat global warming. A presented solution is geoengineering. In general, this method implies seeding cirrus clouds with ice nuclei that potentially would reduce the high-level cloud cover and minimize the warming effect of cirrus [Storelvmo and Herger, 2014]. The injection of ice nuclei within the cloud would presumably result in solely having heterogeneous nucleation, growing few but large ice crystals, which would in turn decrease the cloud lifetime [Mitchell and Finnegan, 2009]. Nevertheless, the seeding must be implemented with greatest caution and the amount, chemical compound, time and location must be considered carefully for optimal effect.

Recent studies performed using data simulations have concluded multiple important results affecting the seeding outcome. In the tropics, seeding should be avoided since these cirrus clouds are mainly produced by convective flow where the added ice nuclei would have minimal impact [Storelvmo and Herger, 2014]. Secondly, summer hemisphere seeding results in less cooling effect compared to winter hemisphere. Lastly, nonuniform seeding of the globe have by model outputs resulted in equally efficient cooling as uniform seeding [Storelvmo and Herger, 2014].This gives an opportunity of reducing the total needed amount of seeding material and thereby also the costs, which is always a prevailing issue.

2.7 Observing Cirrus Clouds

Detecting cirrus clouds via visible satellite images is commonly rather difficult. However detection via infrared satellite images is more straightforward. Additionally, due to absorption characteristics in the infrared region, the cirrus clouds are easier to detect over sea than over land [Kärcher and Spichtinger, 2009]. Satellite instrument with higher sensitivity, like the lidar, detects more cirrus and more cloud cover in general, though also more sensitivity to noise [Delanoë and Hogan, 2008, Lynch et al., 2002].

Satellite observations is not the only method used when collecting data and gaining knowledge about cirrus and clouds in general. In many scientific articles radiosondes, aircraft, ships and ground based measurements are used. The methods can bring difficulties when investigating cirrus since, for instance, the altitudes where cirrus appear are difficult to approach by aircraft [Lynch et al., 2002]. Moreover, when taking ground based measurements low-level clouds can inhibit the emitted signals to reach the level of cirrus clouds, thereby not being detected.

2.8 Aim of The Study

The study will focus on microphysical properties of cirrus clouds. Hence it is the properties, of the cirrus clouds that will be looked at, while the amount of cloud coverage and global distribution is not investigated. Identifying and studying the seasonal variations will be done for the microphysical parameters ice water content (IWC), ice crystal ICER (ICER) and ice crystal number concentration (ICNC) above 5, 25 and 100 µm. In addition, the study includes looking at how the microphysical parameters depend on and are effected by temperature. This study is a part of a larger study, investigating the effect of sulfate aerosol particles on cirrus clouds. Specific latitude bands have been chosen for the studies of the microphysical variables. The latitude bands are the tropics, 0-30°, and the mid-latitudes, 30-60°. These two regions have been chosen since they are dominated by different types of cirrus clouds and where the creation mechanisms differ. The tropics are dominated by anvil cirrus from large convective cells, while the mid-latitudes are mainly dominated by frontal cirrus. Anvil cirrus can also occurs in the mid-latitudes, tough limited to the summer season. The polar region, latitudes 60-90°, are not included since they are not well covered by the satellites. Polar nights also complicates detection for the satellites and the occurrence of cirrus clouds is smaller than in the other latitude bands.

3 Method

3.1 Satellite Data

In this report, the cirrus clouds are studied by using satellite measurements from the A-train. The A-Train or so called afternoon constellation [ICARE Data and Services Center, 2020] is a setup of several measuring devises, where two will be used to study the cirrus clouds in this report. The devises are the CloudSat radar and the CALIPSO (Cloud-Aerosol and Infrared Pathfinder Satellite Observation) lidar. The measurements from the two, are combined in a project named DARDAR (raDAR/liDAR) that aims to retrieve cloud properties of the atmosphere. DARDAR has a vertical resolution of 60 m and a 1.7 km horizontal resolution [Sourdeval et al., 2018]. CALIPSO and CloudSat have been operating in the A-train since mid 2006. The A-train have an equatorial orbit at an altitude of approximately 705 km and crosses the equator around 1:30 am and 1:30 pm local solar time [Sourdeval et al., 2018]. The average delay between CALIPSO and CloudSat is 12.5 seconds which allows near-simultaneous observations [Dept. of Atmospheric Science

Colorado State University, 2016]. CloudSats mission is to provide liquid-water and IWC vertical profiles inside clouds as well as the clouds optical properties. The radar is a 94-GHz radar and is estimated to detect 90% of all ice clouds and 80% of all water clouds [United States., & Goddard Space Flight Center, 2006]. The CALIPSO lidar sends out light pulses with a wavelength of 1064 nm and 532 nm [United States., & Goddard Space Flight Center, 2006], providing vertical profiles of aerosols and clouds, and can detect thin cirrus that goes undetected by the radar [NASA, 2020].

Not all the microphysical parameters investigated in this study are direct products from the DARDAR data, from the satellites in the A-train. Directly received from DARADAR is the IWC and the ICER. The ICNC is a product of the DARDAR data, IWC and ICER, called DARDAR-Nice. The temperature data used in the retrievals and provided with the satellite data is a reanalyses from the European Centre for Medium-Range Weather Forecast [Sourdeval et al., 2018]. All data used in this study have been downloaded from DARDARs official website.

From the retrieved dataset, additional changes have been implemented. Data from year 2006 and 2007 have been removed from the study, as a result of a change in the off-nadir angle of CALIPSO. The initial off-nadir angle was set to 0.3 degrees, however changed to 3.0 degrees during some periods of 2006 and 2007 NASA [2016a]. In November 2007 the off-nadir angle was set permanently to 3 degrees which is thereby the angle used for this study. In addition, January 2016 has been excluded from the dataset, due to problems with the retrieval of ICER during this month, seen from graphs not displayed here.

The satellites Cloudsat and CALIPSO, used to retrieve the microphysical parameters, have also had some malfunctions. On the 17th of April 2011, Cloudsat stopped transmitting data due to a battery failure NASA [2016b]. 3rd of November 2011, Cloudsat was again functioning, however only for collection of daytime data, and on 19 of July 2012 Cloudsat was again reunited in the A-train constellation fully operating during daytime NASA [2016b]. As a result, no DARDAR data was produced for this period and, for this study the decision was made to solely include daytime data for the whole time period studied.

3.2 Cirrus Filter

From the DARDAR and DARDAR-Nice products of the cirrus clouds, collected from the devices in the A-train constellation, a cirrus filter was applied. The filter was applied to ensure that solely cirrus cloud was encountered for, and hence a couple of criteria had to be met;

- The height of the clouds should be above the tropopause level times 0.4 and above 5000 m, although still within 3 km from the tropopause level.
- Retrieval of data only from Cloudsat is not included since indicating that the clouds are to thick to count as cirrus. Hence detection of both the satellites or only CALIPSO is needed for the data to be included.
- The satellite needs to have made the assumption that the cloud is made of ice, and that the retrieval of data for ICNC is possible.
- All clouds included should have a temperature below -30 degrees Celsius.

The division between homogeneous and heterogeneous nucleation is accomplished trough temperature. The heterogeneous category corresponds to temperatures from -30 to -38 °C. The homogeneous category includes temperatures below -42 °C. The interval between -38 to -42 °Cis excluded to guarantee that the nucleation is solely homogeneous or heterogeneous. However in the category for all clouds, the interval is included.

The data is averaged to a resolution of 2 latitudes times 5 longitudes, with a vertical resolution of 60 m. 3D gridboxes with this resolution were created and each of the gridboxes are then monthly-averaged, by geometric averaging. For producing the graphs in this report, additional averaging was made over height and over latitudes and longitudes, producing a single value for each month and latitude band. A limit is set to constrain how many values each pixel must include for the pixel to be included. The limit of data coverage is set to 0.5, and hence a pixel with less data coverage will be excluded. The averaging is geometric, since it was best fitted. Previous studies of the distributions of the pixels, not part of this thesis, could conclude the geometric averaging as the best fit, and therefore used in this report. The errors provided for the satellite parameters were propagated through the averaging and calculated for each monthly average. Due to the large number of pixels included in the averaging, the errors for the monthly averages become very small (max 0.5 %). These errors will not be visible as error bars and therefore these are not displayed in the graphs.

3.3 Microphysical Parameters

In this report the following microphysical variables will be investigated: IWC, ICER and ICNC for the size ranges above 5, 25 and 100 µm. IWC is the amount of ice in mass per cubic metre of atmospheric air [g/m^3]. The ICER is defined as the volume distribution divided by surface distribution and is given in units of µm. ICNC is a product of ICER and IWC, aforementioned, and divided into size ranges above 5, above 25 or above 100 #/l. The unit for ICNC is given in amount of ice crystals per litre [#/l]. The values for the microphysical parameters are measurements taken inside the cirrus clouds and are hence only valid for the clouds, and not for the atmosphere in general.

4 Results

In the sections below, the results of this study will be presented and discussed. The section is structured by studying the latitude bands separately, starting with the tropics and with the mid-latitudes following. For each latitude band, the time plots for each microphysical parameter and temperature is shown and discussed. Subsequently the temperature dependence for each microphysical parameter is displayed and discussed. The parameters will be discussed in the following order: IWC, ICER, ICNC 5, ICNC 25, ICNC 100. After both latitude bands, there is a section with further discussion, and then lastly a summary and outlook is given.

4.1 Latitude 0-30°, Tropics

For the tropics, latitude band 0-30°, the microphysical parameters will first be looked at over time. Then the parameters will be studied against temperature. All parameters are studied individually, starting with IWC.

4.1.1 Time Variation of The Microphysical Parameters and Temperature Data

Figure 2 illustrates how the microphysical parameters and temperature vary with time from 2008 to 2016. For each parameter the values for the northern hemisphere, NH, and the southern hemisphere, SH, are shown separately.

No heterogeneous nuclei values are present in the tropical latitude band, and will hence not be analysed. One criteria in the selection of data is that the cirrus clouds must be within 3 km from the tropopause. In the tropics, this latitude band, this means very high altitudes and therefore also temperatures that are colder than set temperature range for heterogeneously formed crystals. In this study the temperature limits for heterogeneous nucleation is set between -30 to -38 °C. Homogeneous nucleation corresponds to temperatures below -42 °C. Included in the values for all clouds, are the homogeneous, heterogeneous, and the crystals between -38 and -42.

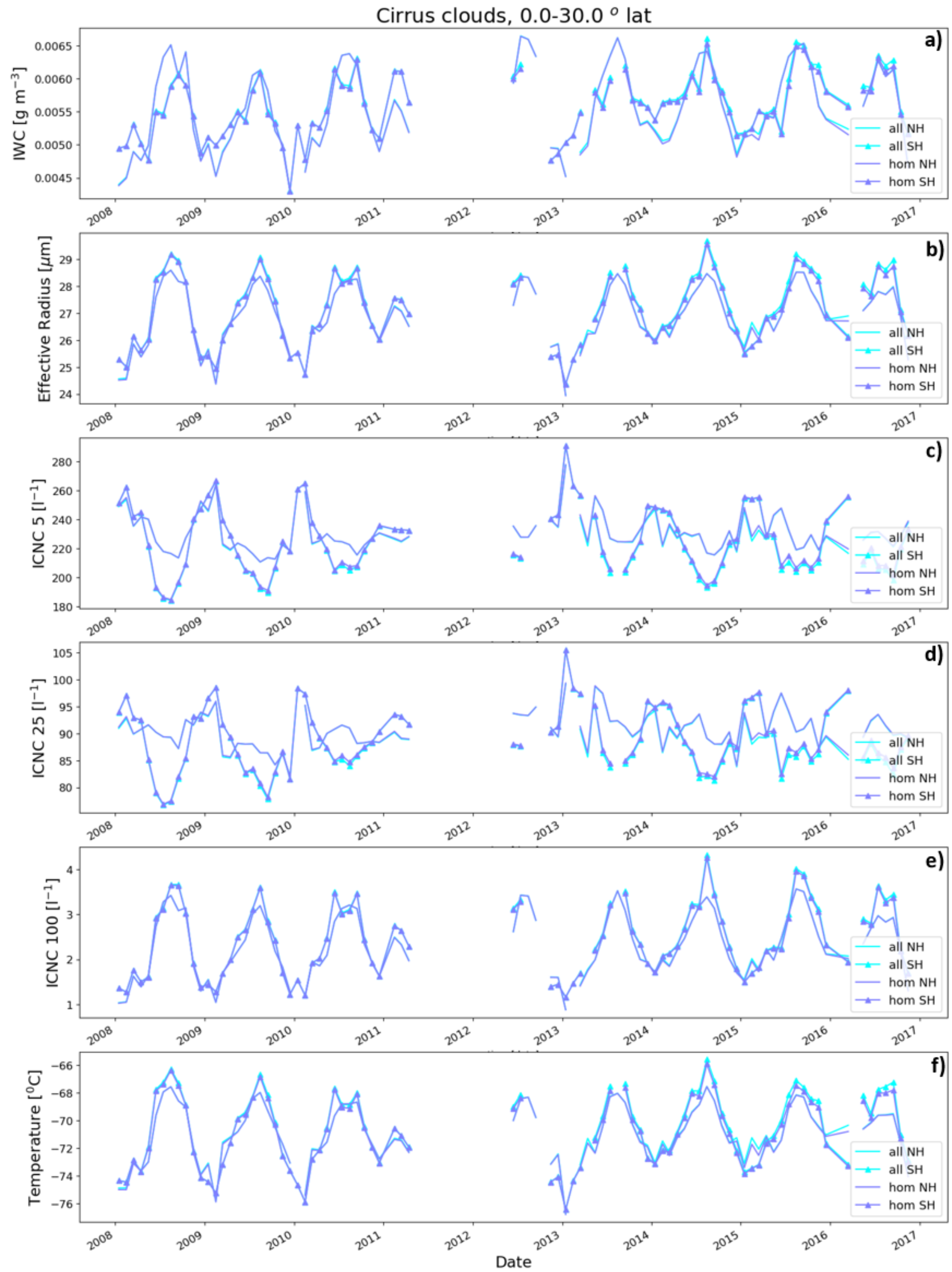

Figure 2: Time representation of the microphysical parameters a) IWC, b) ICER, c) ICNC 5, d) ICNC 25 and e) ICNC 100. Temperature is also represented in f). The illustration is for the tropics, between the latitudes 0 to 30°. Blue lines represents homogeneous values and turquoise values of all clouds. Regular lines are for the NH while SH has triangle markers.

IWC

The amount of ice inside the cirrus clouds displays a seasonal pattern for the NH and the SH. Both the hemispheres peaks during the boreal summer, having maximum values of 0.0066 g/m^3, and minimum values, of 0.0043 g/m^{3}during the boreal winter season. An overview, over all years, shows that the hemisphere with the highest peak alternates between the NH and the SH, and hence no clear pattern can be established. For the troughs, the majority are deeper for the NH.

The category for all cirrus clouds is similar to the homogeneous category although not exact. This applies for all variables in Figure 2. The reason for this is that the amount of homogeneously formed crystals are much greater than the heterogeneously formed, and hence the all category is most influenced by the homogeneous values. In the tropics where no heterogeneous values are shown, the all and homogeneous categories still differ, although the difference is small. The explanation is that there could be a few heterogeneous values included in the all category, although not enough data coverage to be included in the graphs. It can also be an effect from the temperature interval between -38 and -42 °C included in the all category, but not in the category for homogeneous or heterogeneous clouds.

ICER

The ICER is evidently dependent on temperature, showing an almost identical seasonal variation, see Figure 2 b) and f). The NH and the SH co-vary, although the SH peaks higher for all years. The greatest difference between peaks, in the two hemispheres, is of magnitude 1 µm and smaller for the minimums. Furthermore, the troughs are found during the boreal winter for both hemispheres, while the maximum values during the boreal summer season, in union with both IWC and temperature.

ICNC 5um

In contrast to the above microphysical properties, IWC and ICER, the smallest crystals peaks in amount during the boreal spring and are fewest during the boreal autumn. The variations in the hemispheres differs, where SH has a distinctly greater seasonal variation, seen from Figure 2c). The peaks of both hemispheres have alike values. The minimum values are lower for the SH, compare 180 #/l (SH) to 195 #/l for the NH. After year 2011, the general appearance is less clear, which also applies for ICNC 25#/l.

ICNC 25um

Similar to the smaller crystals, the SH has an evidently greater seasonal variation than the NH. The peaks occur during the spring season while the troughs occur during the autumn season. Anomalies to this pattern are for instance during the years 2009, 2010, 2013, 2014 and 2016 where the NH shows peaks during the summer/autumn period while the SH have minimum values during this season, see Figure 2d).

ICNC 100um

Focusing on the largest crystals, again a clear seasonal pattern is displayed that peaks during the summer season and have troughs during the winter season for both hemispheres. The pattern follows the temperature pattern closely , indicating that the largest crystals are dependent on temperature. Since this cannot be seen as strongly for the smaller crystals, a possible scenario is that the larger the crystals, the more dependent on temperature. A valid explanation for this plausible behaviour is not known. ICER is also a parameter that follows the ICNC 100 and temperature closely. The total amount of crystals is dominated by the smaller size ranges since the number is much larger. However, since the radius of the largest crystals is bigger, ICER is mostly influenced by largest crystals. This could partly explain their close relationship.

Furthermore, the ICNC 100 have higher peaks in the SH than the NH, while no obvious pattern can be distinguished for the minimum values. The minimum values, from year 2014 and forward, are less deep compared to the earlier period.

Temperature

The temperature of the cirrus clouds in the tropics are generally quite cold due to the high height of the tropopause. This can be seen in Figure 2 f) where the temperature varies between -77 °C to approximately -66 °C, corresponding to the highest peak and lowest trough. The strong co-variation of the NH and the SH is evident, see Figure 2f). This is also found for the other microphysical parameters in the tropics. However, for the temperature, the SH generally have higher peaks, warmer temperatures compared to NH. Overall, the seasonal pattern is clear with minimum temperatures during the boreal winter and warmest temperatures during the boreal summer, for both hemispheres. The seasonal patter hence follows the northern hemisphere's expected variation. The co-variation of temperature for both hemispheres in the tropics was not expected, yet similar behaviour, have also been found in other studies [Seidel et al., 2001]. From the year 2011, making an exception for 2013 which corresponds to the deepest trough, the minimum values appears to be warmer compared to the period 2007-2010. Since this has not been statistically tested, no conclusion can be made. Since ICNC 100 seems strongly dependent on temperature, the decrease in minimum temperatures could therefore also effect the parameter ICNC 100. Hence, this is probably the reason for the lower minimum values of ICNC 100 after year 2014.

4.1.2 Temperature Dependence of The Microphysical Parameters

In this section the impact of temperature on each of the microphysical parameters will be investigated, divided according to seasons. Equal to the time plots, the categories for all clouds, homogeneous and heterogeneous are viewd seperately. The NH and SH will be looked at individually. The yearly months are divided into four seasons according to;

- Boreal winter= December, January and February
- Boreal spring= March, April and May
- Boreal summer= June, July and August
- Boreal autumn= September, October and November.

Additionally, included in the plots are a linear regression for each season. The r-value corresponds to the correlation coefficient and the p-value is the statistical significance. The two sided p-values are calculated using a Wald Test with a t-distribution

IWC

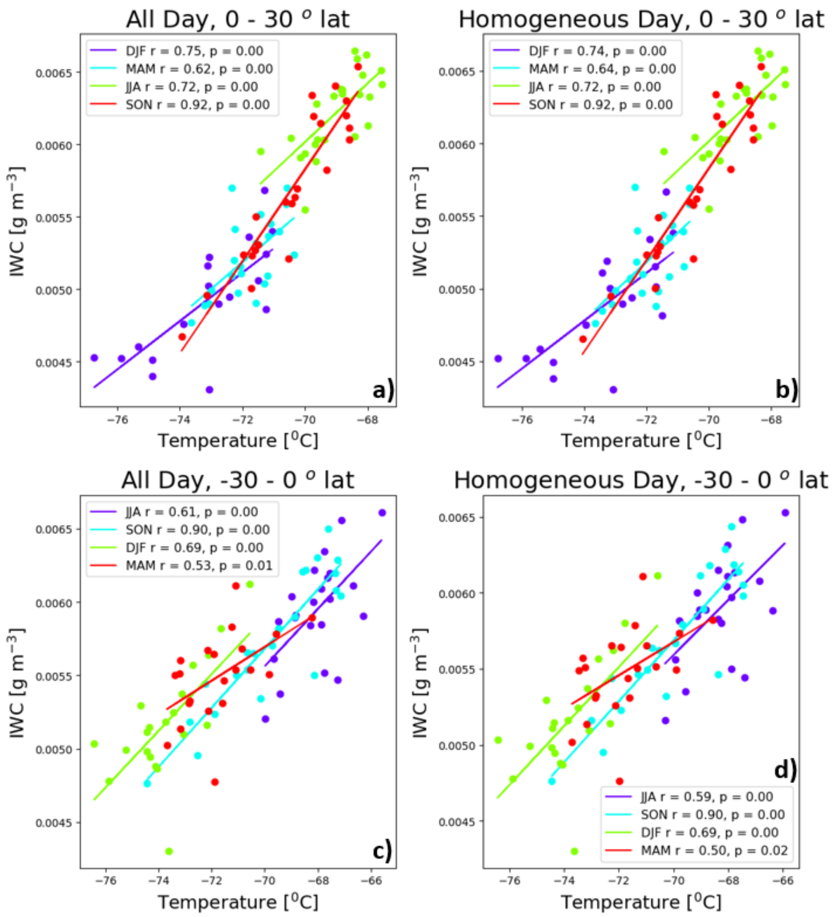

Figure 3: Illustration of the relation between IWC and temperature in the tropics, separated into winter, spring, summer and autumn season. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn. a) and b) corresponds to the NH, latitude 0-30°while c) and d) represents the SH, -30-0°. In addition, a) and c) shows values for all clouds, and b) and d) for homogeneously formed cloud crystals.

All seasons, categories and both hemispheres show a positive correlation for IWC with temperature. The boreal winter season corresponds to the coldest temperatures for both hemispheres, which was also seen for the tropical time-plot of temperature, Figure 2. Each respective season have a higher correlation coefficient (r-value) in the NH compared to SH. Otherwise the hemispheres display a similar appearance except for the seasons being inverted. Both hemispheres have one month, the boreal autumn, that stands out with a higher statistically significant correlation, r= 0.92 in NH and r=0.90 in SH.

ICER

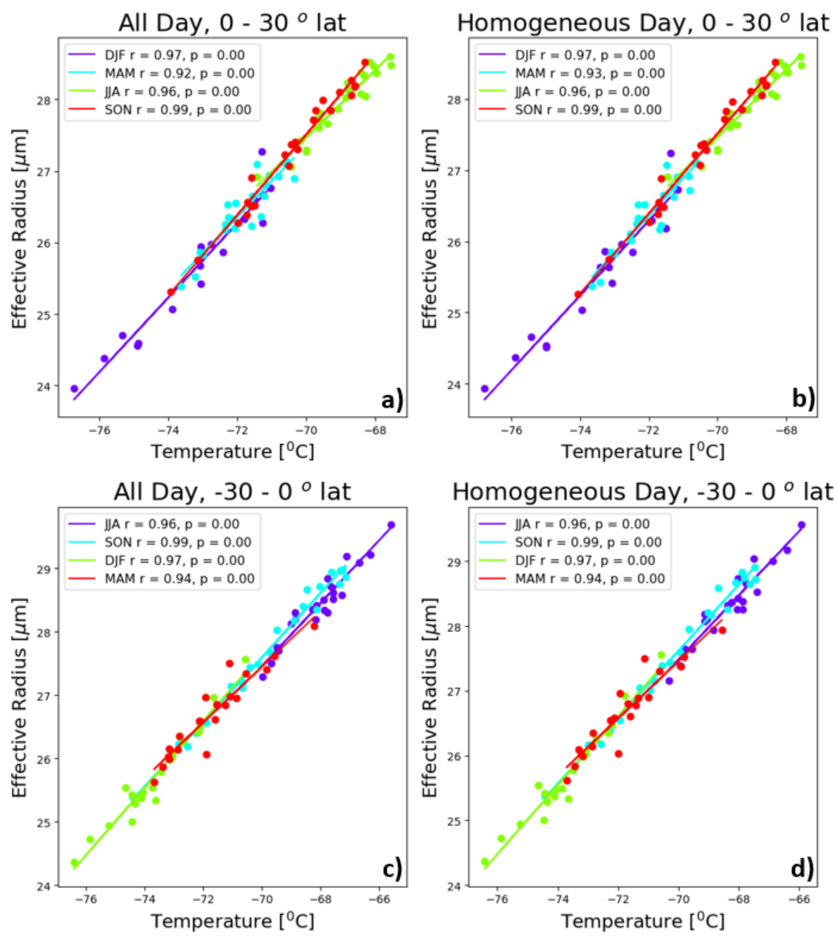

Figure 4: Illustration of the ICER-temperature dependence in the tropics, separated into winter, spring, summer and autumn season. Plot a) and b) corresponds to the NH, latitude 0-30°while c) and d) represents the SH, -30-0°. In addition, a) and c) shows values for all clouds, and b) and d) for homogeneously formed cloud crystals. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn.

In an overview of the ICER in Figure 4, it can be seen that ICER have a strong positive correlation with temperature. The correlation coefficient ranges from 0.92 to 0.99 and all cases are statistically significant. It is the boreal autumn season that coincide with the highest correlation coefficient for both hemispheres. However, the differences to the other seasons are minimal. The temperature range during the winter in the NH and the SH is large, possibly implying that the coldest temperature can vary substantially from year to year.

ICNC 5

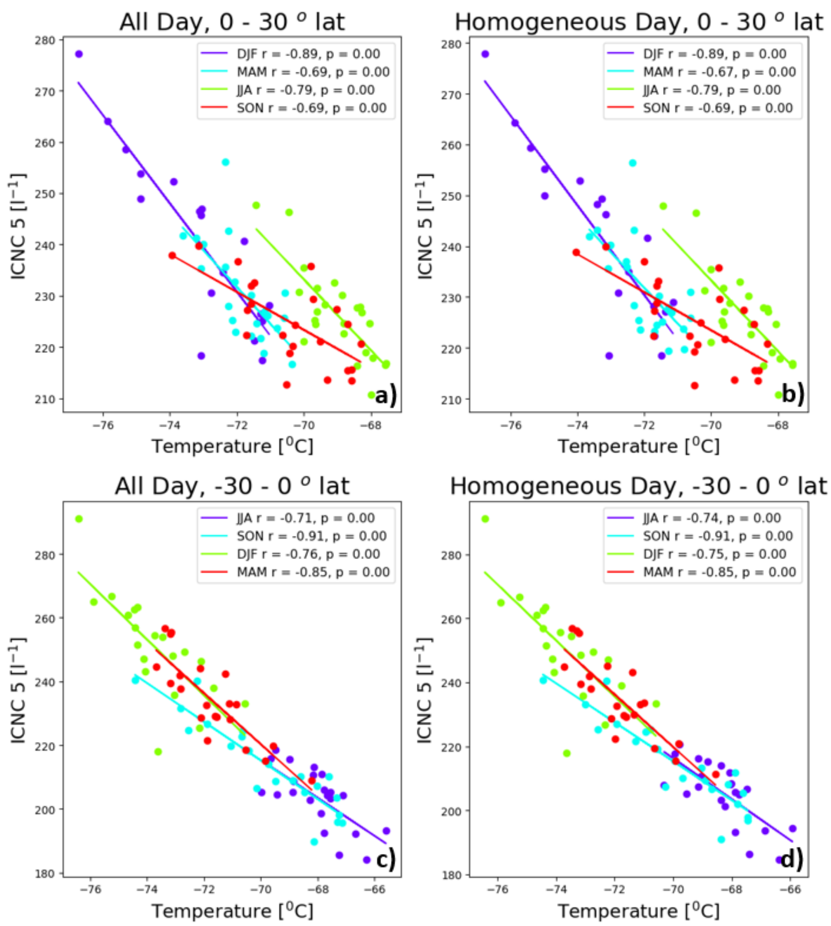

Figure 5: Illustration of the relation between ICNC 5 and temperature in the tropics, separated into winter, spring, summer and autumn season. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn. Plot a) and b) corresponds to the NH, latitude 0-30°while c) and d) represents the SH, -30-0°. In addition, a) and c) shows values for all clouds, and b) and d) for homogeneously formed cloud crystals.

The ice crystals above 5 µm display a negative correlation with temperature, that is marginally stronger for the SH. The colder the temperature hence indicates in a smaller amount of crystals. It is the spring season in the SH that has the highest significant correlation, while it is the winter season that has the strongest significant correlation with temperature in the NH, see Figure 5. The maximum correlation is hence offset by one season between the NH and SH.

ICNC 25

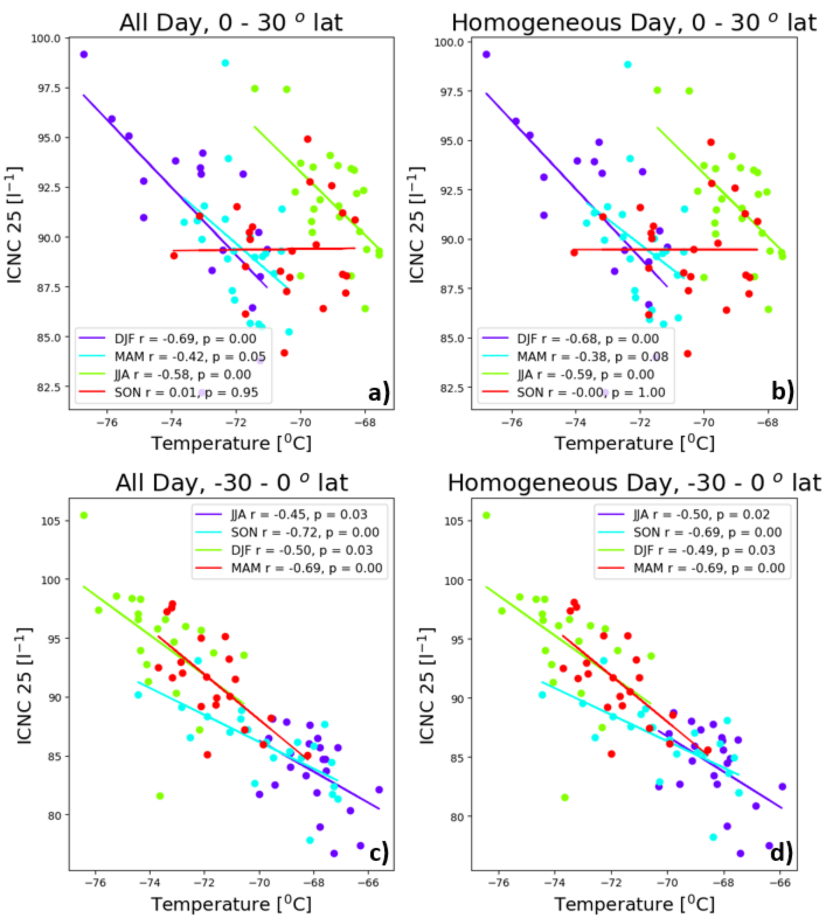

Figure 6: Figure shows the relation between ICNC 25 and temperature in the tropics, separated into the seasons winter, spring, summer and autumn. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn. Plot a) and b) corresponds to the NH, latitude 0-30°while c) and d) represents the SH, -30-0°. In addition, a) and c) shows values for all clouds, and b) and d) for homogeneously formed cloud crystals.

In union with the smaller ice crystals, ICNC 5, the crystals above 25 µm have a negative correlation with temperature, except from two cases. The two exception cases are the autumn season in the NH, with correlation coefficients of almost zero. These are hence not dependent on temperature.

The SH appears to be more temperature dependent than the NH. Otherwise looking at the seasonal pattern, it follows the same as for the smaller crystals. The coldest temperatures are found during the boreal winter and with the winter and autumn seasons having the strongest significant correlations for NH and SH respectively. The pattern for ICNC 5 and 25 are thereby very similar, although the crystals above 5 µm have somewhat higher correlation coefficients for all seasons.

ICNC 100

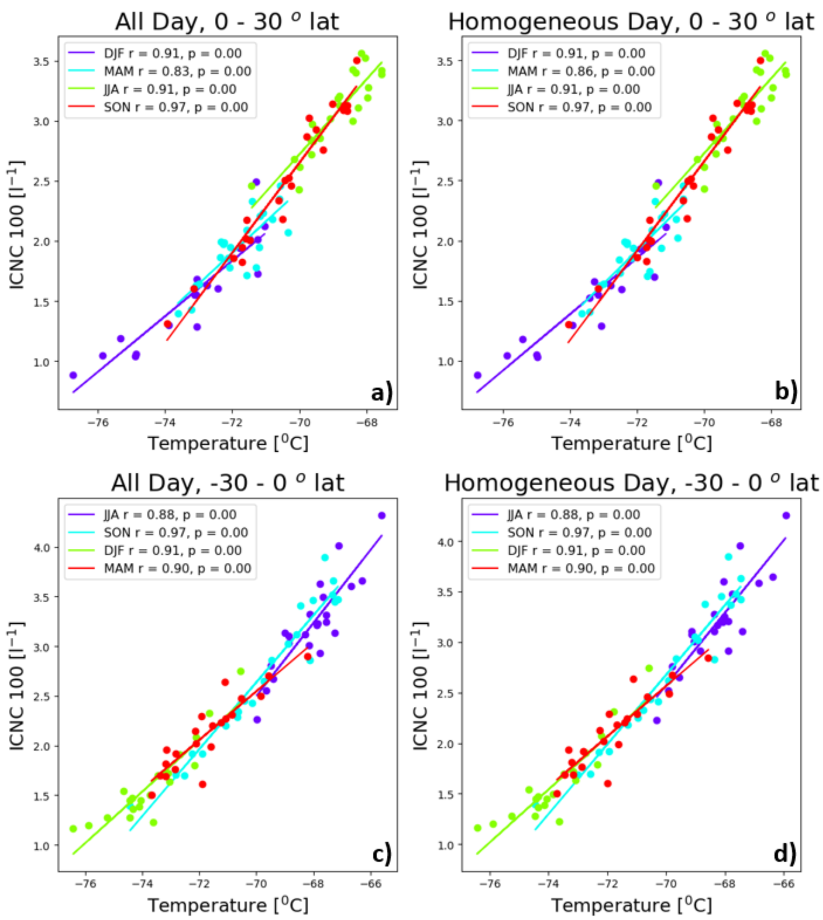

Figure 7: Illustration of the relation between ICNC 100 and temperature in the tropics, separated into winter, spring, summer and autumn season. Plot a) and b) corresponds to the NH, latitude 0-30°while c) and d) represents the SH, -30-0°. In addition, a) and c) shows values for all clouds, and b) and d) for homogeneously formed cloud crystals. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn.

Moving on to the largest crystals above 100 µm, they differ significantly compared to the smaller crystals, since the largest crystals all have a positive correlation with temperature. Warmer temperatures hence corresponds to a greater amount of large crystals. Along with the ICER, this microphysical parameter holds the strongest significant correlation with temperature. Seasonally, the highest correlation belongs to the boreal autumn season for the NH and the SH. The smallest correlation is found during the winter in SH and spring season in NH, not a similar pattern to the smaller crystals. Looking at all crystal sizes, it is seen that the amount of smaller crystals decreases with warmer temperatures while the largest crystals increases. Thereby it seems that when the temperature increases so does the crystal size. This agrees well with the results of ICER, that increases for warmer temperatures.

4.2 Latitude 30-60°, Mid-latitudes

The mid-latitude band is analysed similarly to the tropical region. The microphysical parameters IWC, ICER, ICNC 5, ICNC 25 and ICNC 100 are studied for the time period 2008 to 2016. The parameters are divided into values for the NH and the SH. All microphysical parameters will be studied and then investigated against temperature.

4.2.1 Time Variation of The Microphysical Parameters and Temperature Data

For the mid-latitudes the heterogeneous clouds are included and will be looked at together with the homogeneous and the values for all clouds. The NH and SH are viewed at separately.

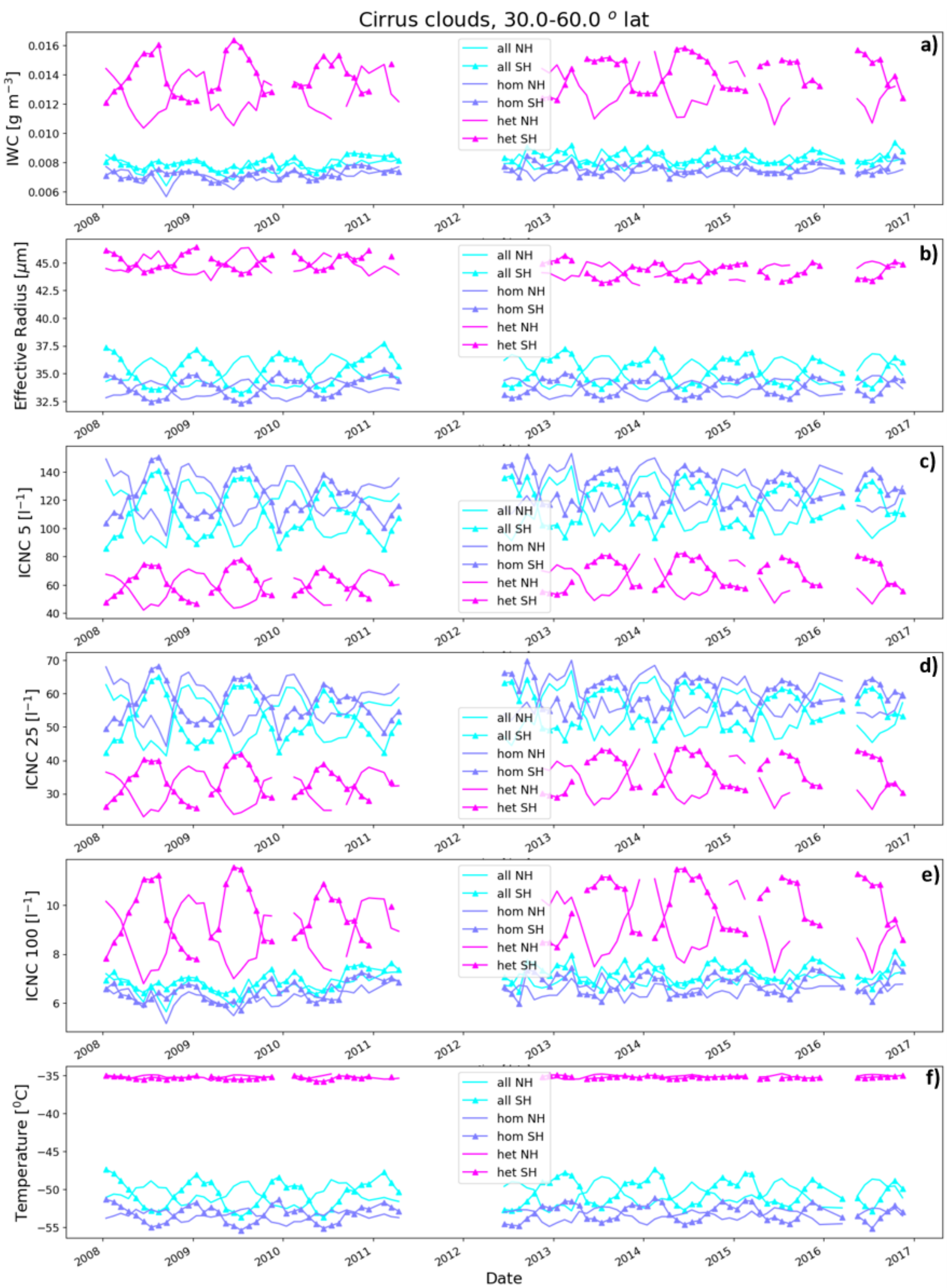

Figure 8: Time representation of the microphysical parameters a) IWC, b) ICER, c) ICNC 5, d) ICNC 25 and e) ICNC 100. Temperature is also represented in f). The illustration is for the mid-latitudes, between the latitudes 30 to 60°. Blue lines represents homogeneous values, pink heterogeneous and turquoise lines values of all clouds. Regular lines are for the NH while SH has triangle markers.

IWC

For the IWC, the heterogeneous values are approximately doubled the values of the homogeneous. IWC have a greater variation for the heterogeneous category compared to the homogeneous. The heterogeneous category has a larger seasonal variation in the SH compared to NH. Both hemispheres in the heterogeneous category peaks during their respective winter season. For the category all and homogeneous, a seasonal variation is not distinct. Although small peaks can be seen for the winter season in each respective hemisphere. This is in disagreement with the tropics, where the hemispheres both peaking during the boreal summer. After the malfunction of the satellite, after year 2012, there is a fair amount of data missing for the heterogeneous category, and the homogeneous category have in general obtained marginally greater values (by a close study of the appearance, not calculations).

ICER

ICER is greater during the summer season for both hemispheres and thereby has an opposite behaviour compared to the IWC. Similarly, there is a large difference between the heterogeneous and homogeneous values, ranging from about 43-46 µm for the heterogeneous category, compared to $\approx$ 32-35 µm for the homogeneous category. The seasonal variation for the homogeneous category is marginally greater in the SH, due to higher peaks than the NH. The troughs are of similar magnitude for both hemispheres. For the heterogeneous category, the seasonal variations are of same magnitude for both the NH and the SH. In total for the mid-latitudes, the variations of the heterogeneous and homogeneous categories are of equal magnitude, in contrast to the IWC. An interesting finding is that, for this latitude band, an increase of IWC does not imply a larger ICER. Rather the opposite applies, due to maximums in the summer for ICER and winter for IWC. It is easiest seen for the heterogeneous category. The increased convection and more anvil cirrus during the summer could be the reason for larger ICER during the summer. Colder temperatures during the winter does not allow the air to hold much water vapour, which could increase the amount that sublimates. This could be a possible explanation for IWC to be greater during winter. However, further investigation would be needed to make a definite conclusion. Comparing with the tropics, the pattern is not the same, since IWC and ICER peak during summer meaning that an increase in IWC affect the ICER in a positive direction.

ICNC 5um

For the smallest crystals, the pattern has now changed, and the homogeneous values are greater than the heterogeneous values, see figure 8c). This is an anticipated outcome, since it is expected to have larger and fewer crystals in heterogeneous clouds. The formation of ice crystals on aerosol particles means that more of the available moisture sublimate on a few crystals, compared to when many small droplets form through homogeneous nucleation and there is more competition for the moisture. The seasonal variation is larger for the homogeneous category. There is no significant difference in the seasonal variation between the NH and the SH. The highest concentrations of ICNC above 5 µm is for the winter season, and the lowest for the summer.

ICNC 25um

As for the tropics, this latitude band also has a similar seasonal variation for the ICNC 5 and ICNC 25. In the mid-latitudes, the amount of crystals above 25 µm is less compared to the tropics (around 20-70 #/l compared to 75-105 #/l for the tropics). The highest concentrations of ICNC 25 in the mid-latitudes are found during the winter and lowest during the summer season. The seasonal variations are larger for the homogeneous category than the heterogeneous. For the homogeneous category, the difference between NH and SH are minimal, while for the heterogeneous the SH consistently have higher peaks and the NH have deeper lows. For the year 2013 and forward, the homogeneous category have numerous small fluctuations causing the troughs to be less clear. The very alike characteristics of the ICNC 5 and ICNC 25 could indicate that the parameter ICNC 5 consists of few particles and mainly of crystals in the upper part of the size range, since ICNC 5 includes all crystals between 5 and 25 µm. This would result in ICNC 25 and crystals close to 25 µm dominating the appearance. The alike characteristics could also be due to that ice crystals below and above 25 µm have a similar pattern for their variations.

ICNC 100um

For the largest crystals, the heterogeneous category is again greater than the homogeneous (7-≈12 µm compared to about 5-7.5 µm). Moreover, the seasonal variation is larger for the heterogeneous category and the highest concentrations occur during winter. In the SH the heterogeneous category have higher maxima, while the NH have deeper minimums. For the homogeneous category, the NH and the SH are predominantly not co-variant, yet occasionally they are (see winter season in 2009 and 2011 in Figure 8e).

Temperature

The heterogeneous category appear at warm temperatures around -35 °C for both SH and NH. The variations in temperature are small, as expected, due to the narrow set range for the heterogeneously formed clouds in this study. The category for homogeneously formed clouds, occurs at colder temperatures and have a larger variation, largest for the SH varying between ≈-56 °C to -52 °C. NH varies from -55 °C to -53 °C. Overall the warmest temperatures are found during the summer season and lowest during winter, which is expected. Comparing the total magnitude of variation for the two latitude bands, including both hemispheres, the greatest variation is interestingly found in the tropics. In the tropics the temperature varies between -75 °C and -67 °C, compared to the mid-latitudes, varying between -55 °C and -52 °C.

4.2.2 Temperature Dependence of The Microphysical Parameters

For this latitude band, the mid-latitudes, the division of months have been done identical to the tropical latitude band. The Figures 9, 10, 11, 12 and 13 represents the temperature dependence of each microphysical parameter, sectioned into the four seasons.

IWC

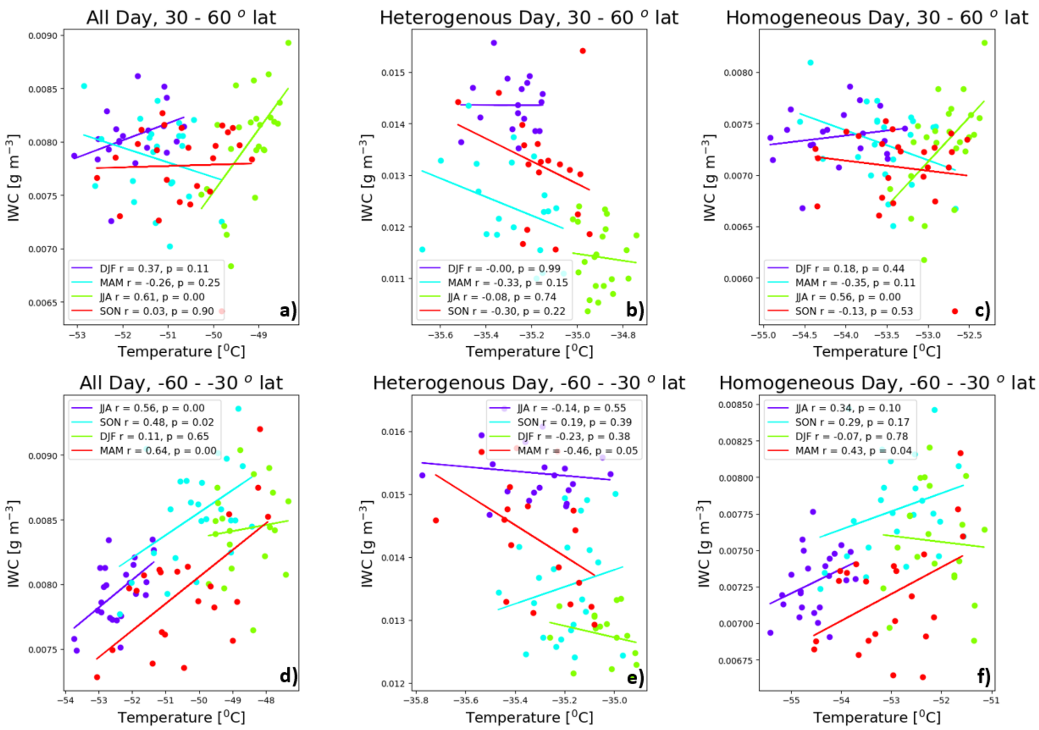

Figure 9: Figure of the IWC and temperature dependence in the mid-latitudes, for the yearly seasons: winter, spring, summer and autumn season. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn. Plot a), b) and c) corresponds to the NH, latitudes 30-60°while d), e) and f) represents the SH, -60- -30°. In addition, a) and d) shows the seasons for all clouds. B) and e) displays the seasons for homogeneously formed cloud crystals and c) and f) for the heterogeneously formed crystals.

An overview of the IWC at in the mid-latitudes reveals that the warmest temperatures are found during the summer season for both hemispheres, which is as expected. For the category all in the SH, nearly all seasons (not summer) have a statistical significant correlation with temperature, where an increase of IWC follows an increasing temperature, see Figure 9. For the NH on the other hand, a statistically significant positive correlation can only be seen for the summer season. The limited temperature dependence of IWC in the NH, compared to the SH, could partly depend on the sea-land distribution which means that in general the NH contains more aerosol particles at these altitudes. A higher levels of volcanic aerosol particles in the NH during these years could also be an explanation of the different results between the hemispheres for IWC. However, further investigation would be needed to determine the cause.

Moving to the heterogeneous seasons for both hemispheres, none are statistical significant and hence no temperature dependence can be established. The summer season for both hemispheres lies in the warmer part of the temperature range. The opposite cannot be seen for the winter season, which is widely spread out. A total overview of the IWC for both hemispheres, reveals that for the heterogeneous category this is a microphysical parameter not particularly dependent on temperature. The cause for this is a short temperature range for the category heterogeneously formed clouds. This means that the temperatures will not shift very much since colder cloud pixels are assigned to another category. The narrow temperature range is making it more difficult to find correlations and draw conclusions for the heterogeneous category, for all microphysical parameters.

ICER

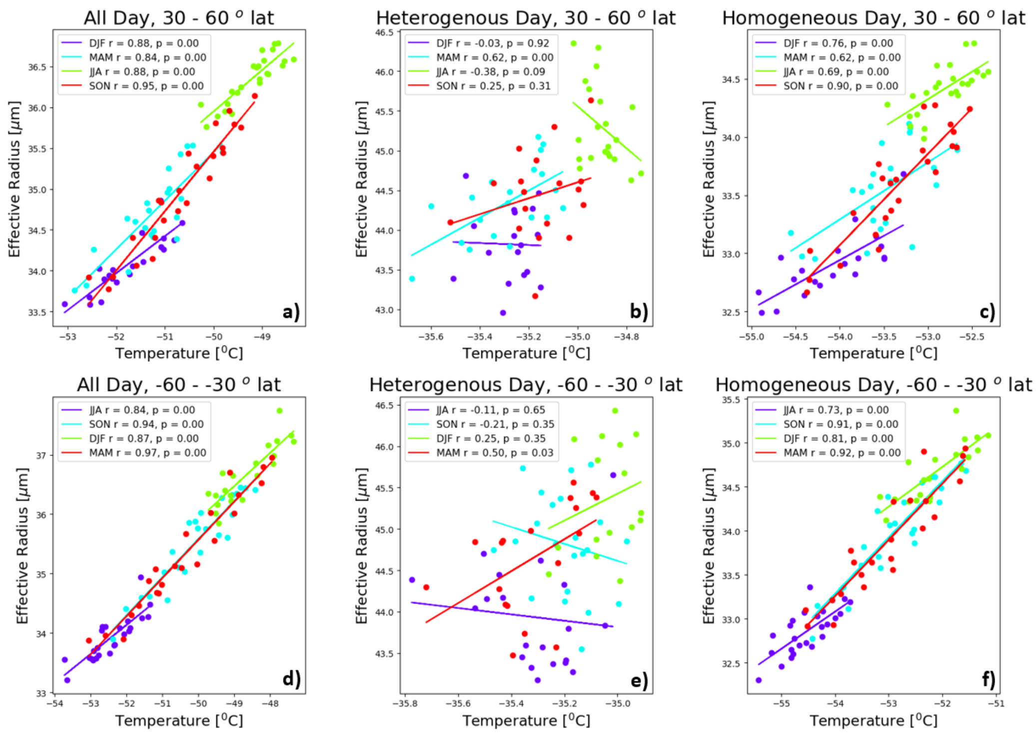

Figure 10: Illustration of the relation between ICER and temperature in the mid-latitudes, separated into winter, spring, summer and autumn season. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn. Plot a), b) and c) corresponds to the NH, latitudes 30-60°while d), e) and f) represents the SH, -60- -30°. In addition, a) and d) shows the seasons for all clouds. B) and e) displays the seasons for homogeneously formed cloud crystals and c) and f) for the heterogeneously formed crystals.

For the ICER in the mid-latitudes the warmest season is the summer season in both hemispheres. The categories for all and homogeneous clouds show a positive correlation, thus a warmer temperature increases the ICER. The coefficients are however lower than for the latitude band 0-30°. The strongest correlation for the NH and SH is found for the autumn season. Also for the heterogeneously formed crystals in the SH, the autumn season stick out for all seasons with the highest coefficient, see Figure 10. As discussed before and seen here the coefficients are smaller for the heterogeneous category compared to the homogeneous and all cloud values. Half of the seasons for the heterogeneous category have a negative correlation with temperature, winter and summer for NH, and winter and spring for SH. No clear overall pattern is seen. Due to the limited temperature range, -35.6 °C - -34.8 °C, a valid correlation with temperature is difficult to obtain. The categories for all and homogeneous have statistical significant correlations, while the vast majority of the heterogeneous seasons do not. Overall, the ICER is the one parameter that appears to be most dependent on temperature, increasing with increasing temperature, in both the tropics and in the mid-latitude band.

ICNC 5

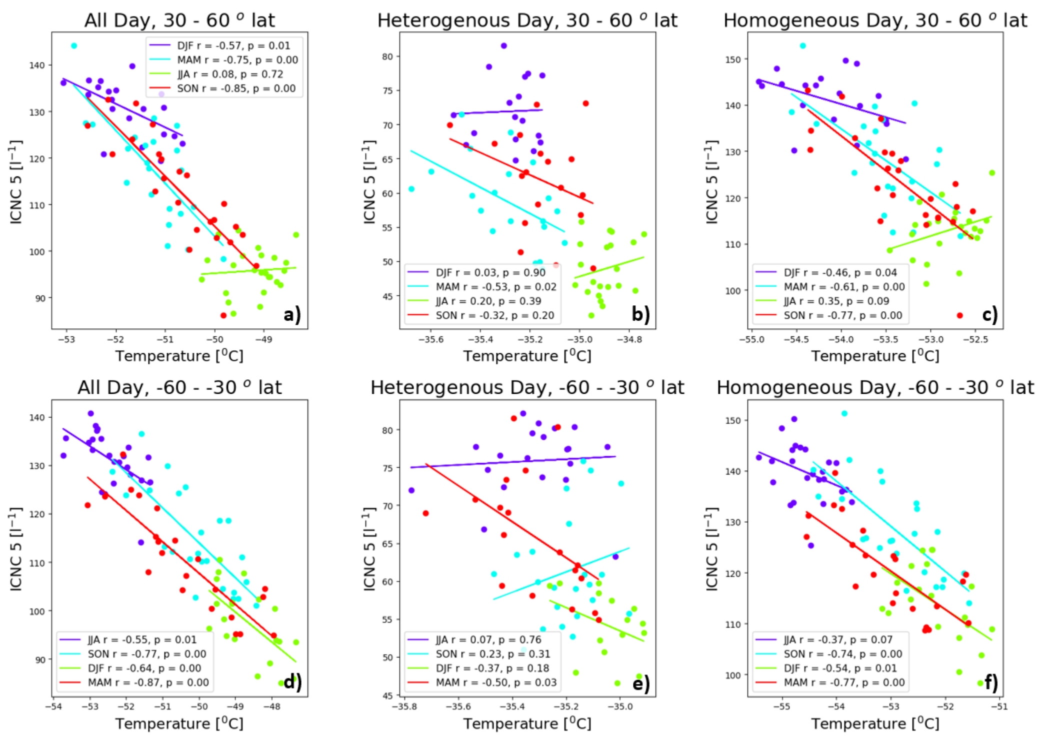

Figure 11: Figure showing the relation between ICNC 5 and temperature in the mid-latitudes, separated into winter, spring, summer and autumn season. Plot a), b) and c) corresponds to the NH, latitudes 30-60°while d), e) and f) represents the SH, -60- -30°. In addition, a) and d) shows the seasons for all clouds. B) and e) displays the seasons for homogeneously formed cloud crystals and c) and f) for the heterogeneously formed crystals. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn.

For the smallest crystals, the mid-latitudes values are lower compared to the tropics. The strongest correlation for all cloud and homogeneous clouds is seen for the autumn season for both NH and SH, not similar to the tropics. It is also the autumn and spring seasons that are most widespread, largest temperature range. Moving to the heterogeneous crystals, for both hemispheres, they alternate between a positive and a negative correlation. The heterogeneous category differs from the all and homogeneous categories. That the categories all and homogeneous have most similar pattern, can be seen for nearly all parameters. As aforementioned, this could partly be a result of the set temperature range for the heterogeneous category.

Evident is the summer season in the NH that have a positive correlation for all categories. This cannot be seen for the SH. The reason is possibly due to a greater amount of convection during the summer, than the other seasons. A greater amount of landmasses in the NH, creating more convection during the summer, could be the reason why the same behaviour is not seen for the SH. Otherwise, the all and homogeneous categories have a negative statistically significant correlation for both hemispheres, visible in Figure 11.

ICNC 25

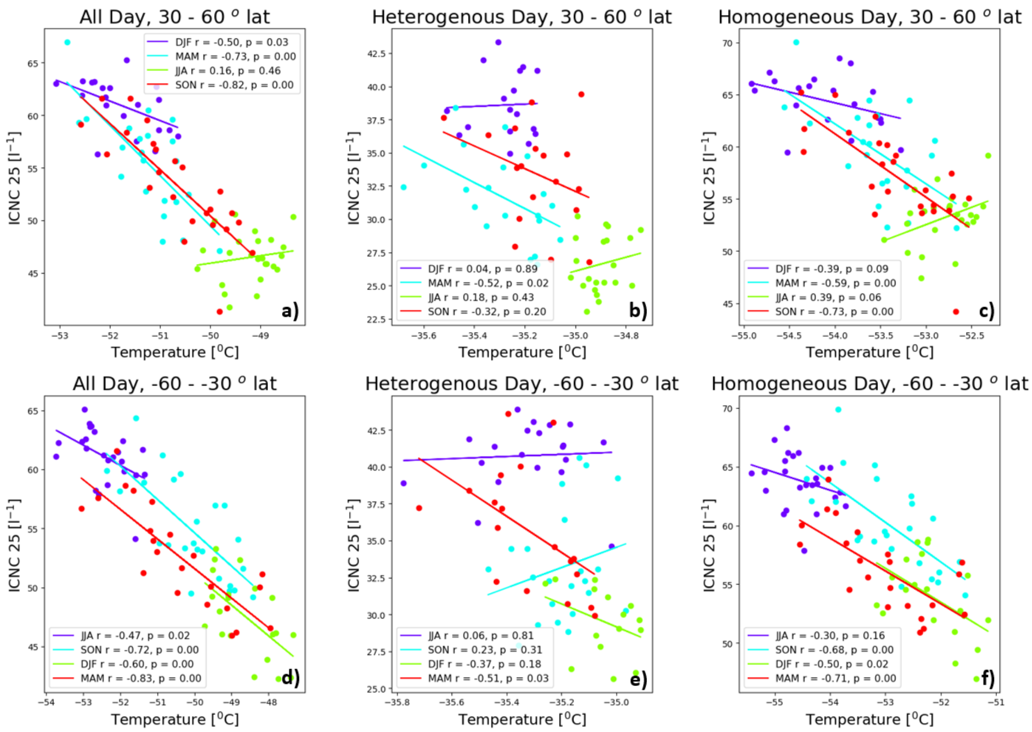

Figure 12: Illustration of the relation between ICNC 25 and temperature in the mid-latitudes, separated into winter, spring, summer and autumn season. Plot a), b) and c) corresponds to the NH, latitudes 30-60°while d), e) and f) represents the SH, -60- -30°. In addition, a) and d) shows the seasons for all clouds. B) and e) displays the seasons for homogeneously formed cloud crystals and c) and f) for the heterogeneously formed crystals. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn.

For ICNC 25, and in union with the ICNC 5 parameter, the correlations are generally lower for the mid-latitudes compared to the tropics, comparing Figures 12 and 6. Aforementioned is the deviation of the summer season in the NH, the wide temperature range of the spring and autumn season and the narrow temperature range for the heterogeneous category. For both crystal size ranges above 5µm and above 25 µm, a similar small negative correlation can be seen for the heterogeneous category in the autumn season in both hemispheres. However the correlation is not statistically significant.

An increase in the amount of ice crystals with decreasing temperature is seen for the values of all clouds and in the homogeneous values, for both ICNC 25 and ICNC 5. A similar negative correlation, yet not as distinct, can also be found in the tropics. This has also been found by Sourdeval et al. [2018], where colder temperatures increases the amount of ice crystals is explained as a result of orographic lifting or convection. This feature can however not be found for the largest crystals ICNC 100 in any of the latitude bands.

ICNC 100

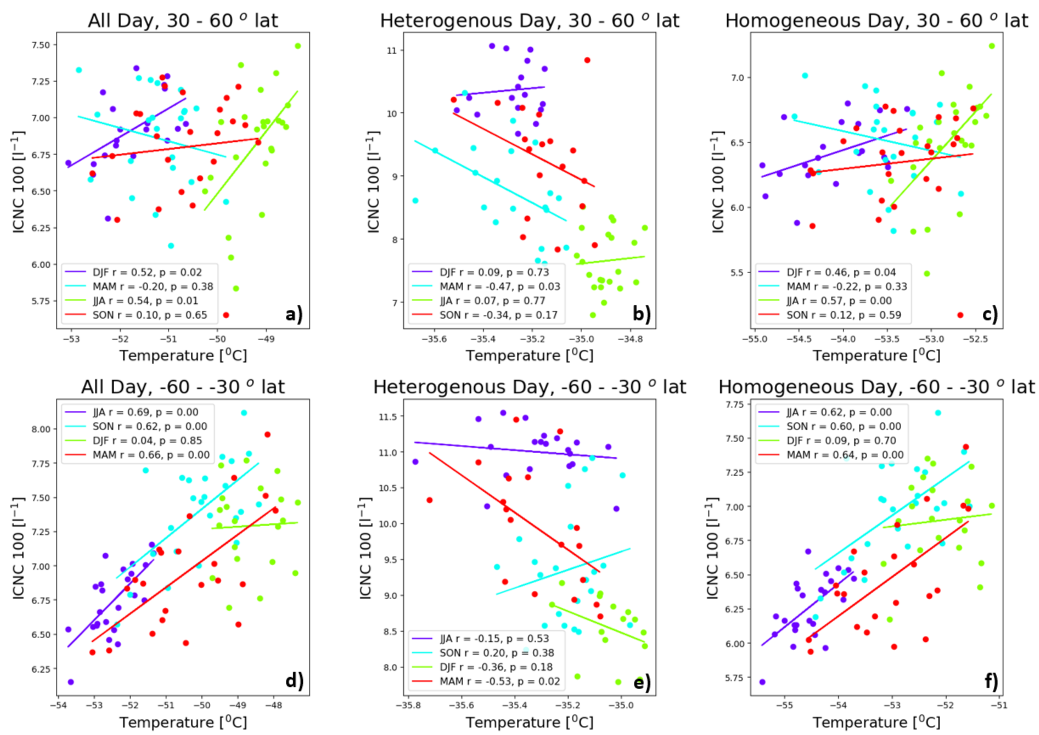

Figure 13: Demonstration of the relation between ICNC 100 and temperature in the mid-latitudes, separated into winter, spring, summer and autumn season. Plot a), b) and c) corresponds to the NH, latitudes 30-60°while d), e) and f) represents the SH, -60- -30°. Plot a) and d) also shows the seasons for all clouds. B) and e) displays the seasons for homogeneously formed cloud crystals and c) and f) for the heterogeneously formed crystals. The seasons are represented by lines in the colours dark blue for winter, light blue for spring, green for summer and red for autumn.

A clear differences of the crystals above 100 µm is seen between the two latitude bands. For the homogeneous and all category in the SH, all seasons follow a pattern with a strong positive correlation, except for the summer. For the NH the values are more widespread, compared to the SH, and the season with highest significant correlation is the summer season. Possibly there is a greater impact of aerosols in the NH for the largest crystals. For the heterogeneous values, no clear apparent behaviour can be seen in any of the hemispheres. The absolute vast majority of the heterogeneous seasons are not statistically significant. In the SH the all and homogeneous categories are statistically significant, while in the NH only half are significant.

5 Discussion

For a more general view of the results, a seasonal pattern can be observed in the absolute vast majority of the time plots. According to Kärcher and Spichtinger [2009], Lynch et al. [2002] and Stubenrauch et al. [2006], the existence of a seasonal variation for cirrus clouds in the tropics, is due to the strong convection and the movement of the ITCZ towards the summer hemisphere. In the mid-latitudes the seasonal variation is mostly due to variations in cirrus associated with frontal systems. The increased convection during the summer, in the mid-latitudes, also affect the seasonal variation. In addition, there is a trend of the seasonal variations being stronger in the tropics compared to the mid-latitudes, although in some cases it is difficult to decide. When looking at the occurrence of cirrus clouds, Kärcher and Spichtinger [2009] also found seasonal variations to be weaker in the mid-latitudes in comparison with the tropics.

Another result obtained from figure 8, covering the mid-latitudes, is that all microphysical parameters excluding the ICER have maximum values during the winter season. This is in agreement with findings by Stubenrauch et al. [2017] and is interpreted as the result of moving low-pressures during the winter. Furthermore, in the tropics four of the five (not IWC) microphysical parameters show a greater seasonal variation for the SH, compared to the NH, a highly interesting result (see Figure 2). This is possibly an effect of temperature since, in the tropics, the temperature variation in the SH is greater than in the NH. In the mid-latitude band, the same conclusion is more difficult to make due to smaller differences between the hemispheres, see Figure 8.

Additionally, noted from figures 8 and 2, is that the maximum and minimum values are not always single peaks, but two adjacent peaks. This is for instance visible for IWC in the tropics in the summer season of 2008 and the winter season of 2009, see Figure 2a). The variation in weather can vary greatly within a month or be more consistent. Regardless, this can lead to that the average weather of two months is similar which can result in several peaks for each season, also denoted internal variability. Furthermore, for the time period after the satellite malfunction of Cloudsat, many of the investigated microphysical parameters show less deep minimum values. The reason for this is probably related to the generally higher winter temperatures.

Moving to the measuring techniques and processing of data, there are always some weaknesses, and areas in need of improvement. As mentioned in the section cirrus filter, the errors resulted from monthly averaging are very small due to the large amount of pixels. Hence the major areas were errors can result, is in the processing of the DARDAR data, the algorithms producing the ICNC-values and in the operating satellites. Ice crystals can be in a wide range of shapes, were some limitations have been necessary for calculation of the particle size distribution. An overestimation of ICNC 25 and ICNC 5, less for ICNC 5, is found in the data for DARDAR-Nice, which is described as a result of the particle size distribution limitations and not because of instrumental sensitivity in the satellites [Sourdeval et al., 2018]. In this study the seasonal variations and temperature dependency is studied for the microphysical parameters. Since the study only look at variations, and not absolute values, the overestimation of ICNC 25 and 5 is not problematic for the results.

The dataset used in this study has been evaluated by preforming comparisons to ground-based measurements, aircraft measurements, and modelling algorithms, as described partly by Delanoë and Hogan [2008, 2010]. One important aspect to mention is that, although comparisons with ground-based and aircraft measurements have been made, comparisons are difficult. The cirrus clouds can be shadowed by lower level clouds not detectable by the ground-based devises and the airplanes might not be able to fly at the altitude of cirrus, especially in the topics where the tropopause level can reach up to almost 18km. Additionally, for a valid comparison most optimal is when the aircraft and ground-based measurements are taken aligned with the path of the A-train. Further and more detailed descriptions of the difficulties with the DARDAR/DARDAR-Nice datasets and data processing can be found in Delanoë and Hogan [2008, 2010] and Sourdeval et al. [2018].

6 Summary, Conclusion and Outlook

In this study, satellite data from CALIPSO and Cloudsat have been used to study microphysical parameters of cirrus clouds. The seasonal variation and temperature dependency of the microphysical properties in cirrus have been investigated.

The results revealed, a clear seasonal pattern for the vast majority of the microphysical parameters. For the temperature in the tropics there is a strong, unexpected, co-variation between the NH and SH, both following the seasonal variation for the NH. For the tropics, the microphysical parameters ICER, IWC and ICNC 100 follow the same seasonal variations as temperature, while ICNC 5 and 25 does not. ICER show the strongest temperature dependence, where an increase in temperature corresponds to an increase in ICER. Additionally, for the tropics, four of the five (not IWC) parameters show a greater seasonal variation for the SH, compared to the NH. In the mid-latitudes, the microphysical parameters generally have lower values and warmer temperatures compared to the tropics. The temperature in the mid-latitudes is highest for both hemispheres during their respectively summer season. For IWC, ICER and ICNC 100 the heterogeneous values are nearly doubled the homogeneous, where also the seasonal variation is larger for the heterogeneous. An interesting finding is that, IWC and ICER did not covary, hence more cloud ice did not result in larger crystals. ICNC 5 and 25 have higher homogeneous than heterogeneous values. It was an anticipated outcome since heterogeneous clouds generally have larger crystals. All parameters in the mid-latitudes except ICER have peaks during the winter and troughs during the summer.

For the temperature dependency, a positive correlation for all seasons is shown for ICER and IWC in the tropics. The ICNC 5 and 25 show a negative correlation for all seasons, expect for ICNC 25 during the autumn season in the NH which has no correlation. For the largest crystals, ICNC 100, the seasons are positive correlated with temperature, equal to a greater amount of crystals with warmer temperatures. Along with the ICER, ICNC 100 holds the strongest statistically significant correlation with temperature in the tropics.

In the mid-latitudes, heterogeneous clouds have also been studied. However the set temperature criteria have made it difficult to find any correlations between temperature and the microphysical parameters. A positive significant correlation is found for ICER and for half of the seasons for IWC. ICNC 25 and ICNC 5 both show a negative correlation with temperature. The largest crystals, ICNC 100, show a positive correlation for the SH. In the NH, the correlations alternates between positive and negative. The heterogeneous seasons for ICNC 5, 25 and 100 are only statistically significant for the boreal spring season. In general for ICNC, the SH have a higher ratio of statistically significant correlations. Overall ICER is the most temperature dependent parameter, while IWC does not seem particularly temperature dependent.

Looking forwards, this study is a part of larger project that studies the effect of volcanic aerosol particles on cirrus clouds and these results will be included in a future publication on this. Clouds are affected both by aerosol particles and meteorological parameters. Hence it is important to do research on both aspects to obtain most knowledge about the behaviors and general features of cirrus clouds. This report will aid the understanding of the volcanic aerosol effect on cirrus clouds, and the global climate.

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