Response to reviewer 1

: In the manuscript, a classification system for cirrus clouds that is based on re-analysis and satellite data is presented. Cirrus clouds are separated in four main types, differing by meteorological/dynamical situation and thus microphysical and radiative properties. The topic of the study is very interesting and timely and I recommend the paper for publishing in ACP. However, before final publication, I think that the manuscript should be revised taking into account the following points.

Reply: We thank the reviewer for their useful comments and address each of them in turn below. Line numbers related to the diff'ed version of the manuscript. A short section on the seasonal variation of the regimes has been added to demonstrate their utility and help better characterise them for future work.

1*: To my opinion, the study has more potential and relevance than currently elaborated. Though it is claimed to be a "technical note", the link or physical mechanisms, respectively, between cirrus classes (meteorology), updraft, microphysical property (IWC or OD) and radiative property (CRE) needs to be shown and discussed in more detail to make the study scientifically sound. The exciting is that with the applied method it seems that these links can be identified!*

- *In Fig. 4 the link between cirrus class and updraft is seen (the standard deviation of the respective updraft distribution could serve as measure for class specific updraft);*
- *Also, the mean CREs of the cirrus classes shown in Fig. 5 must be caused by a respective microphysical property (IWC, OD).*

Reply: This paper was originally pitched as a technical note, as it aimed primarily to describe the occurrence of the regimes and how they are defined. With the inclusion of the model output and CRE data it has become a bit more in-depth and so it has now been shifted so that it is listed as a research article. We have re-worded parts of the paper to make these links more explicit and have included information about the cloud optical depth in Fig. 6. However, We do not believe that we are yet able to account for the properties of the clouds within regimes. While this study shows that the convective and orographic regimes have a higher updraught than the synoptic regime, other properties, such as the aerosol environment remain uncertain, preventing an attribution of the differences in radiative and cloud properties to any particular factor. Further studies are planned to explore these differences in more detail.

2a*: The aim of the paper is to identify cirrus clouds by their formation mechanisms: orographic, frontal, convective, in-situ. The name "in-situ" does not match to the other names, which describe the meteorological situation - it should*

be renamed to "synoptic".
Reply: Thank you for this comment, "synoptic" is a better fit for this class and it has now been renamed.

2b*: The defined classes refers to meteorological (dynamical) situations, not to formation mechanisms (as stated in the abstract and elsewhere). Formation mechanisms are:*

- *homogeneous or heterogeneous ice nucleation for in-situ origin cirrus (here called ice origin cirrus, see comment 3 below) and*
- *heterogeneous or (sometimes) homogeneous drop freezing for liquid origin cirrus.*

So it should better be stated that cirrus clouds should be identified by the meteorological (dynamical) situation, which is what has been done in the paper.
Reply: Thank you for pointing out the potential confusion here. Following previous regime definitions, it is not clear that "dynamical regimes" should be used either, as it has previously been applied to regimes defined using only meteorological variables (e.g. Nam and Quaas, 2013; Zhang et al., 2016). We note that some previous studies (e.g. Heymsfield et al., 2017) refer to ice formation mechanisms (homogeneous and heterogeneous) somewhat separately from the mechanisms that create the cloud in the first place (processes creating the cloud updraught, radiative cooling). We have modified the text to refer to cirrus or cloud formation mechanisms where there is a potential for misunderstanding.

2c*: I also recommend to link the meteorological to the dynamical situation: synoptic (in-situ), frontal, orographic and convective cirrus are cirrus in increasing updraft regimes from low to high. To identify cirrus by their formation mechanism, I would recommend to define for example three updraft regimes (weak, middle, high) and assign the them to the meteorological types:*

- *synoptic (in-situ) - weak updraft,*
- *frontal - middle updraft,*
- *orographic/convective - high updraft.*

Then, the cirrus formation mechanisms can be identified (to a certain degree) by the updrafts

- *weak updraft: mostly heterogeneous freezing - low IWC/OD - low CRE ?*
- *Middle/high updrafts: increasing homogeneous ice formation - higher IWC/OD - higher CRE ?*

: This is true for "liquid origin" as well as for "ice origin" cirrus. As far as I can see, these links apparant in the paper and I would recommend to point that out in the paper.
Reply: We have added some more discussion on the updraughts within the

different regimes (e.g. P14L1), but we do not believe that there is enough information to add updraught information to the classification as it stands. The model results with ICON indicate that there is a link between the regime type and the cloud scale updraughts, but without more large scale measurement efforts, we do not believe it is possible to classify the regimes by updraught yet.

3*: "in-situ" : beside the previous comment on the term "in-situ" (2a), I also like to mention that "in-situ origin cirrus" is recently introduced (by Kraemer et al. (2016), ACP, Luebke et al. (2016) and Wernli et al (2016), GRL) for those cirrus that you name "ice origin cirrus". Though "ice origin" might be the better companion of "liquid origin", for consistency reasons I would recommend to keep the terms as they are now introduced.*

Reply: references to "ice-origin" have now been updated to "in-situ origin" in line with previous work.

4*: Cirrus formation mechanisms of in-situ origin and liquid origin cirrus and their link to cirrus properties and meteorological situations are also discussed in Kraemer et al. (2016), ACP, and Luebke et al. (2016), ACP. Also, cirrus clouds classification, formation and so on is summarized in the recent review article of Heymsfield et al. (2017), Meteorological Monographs (see http://journals.ametsoc.org/doi/pdf/10.1175/AMSM D-16-0010.1). These studies should be considered in your work. In more detail, Luebke et al. (2016) compared aircraft measurements in mid-latitude frontal liquid origin and in in-situ origin cirrus. They show the microphysical properties of the cirrus types and their distribution with temperature, which is quite similar to what is found in this study. This should be discussed, it is a good confirmation of the approach used here. Liquid and in-situ cirrus are classified by means of trajectory analysis, similar as in Wernli et al (2016)*

Reply: Thank you for bringing these studies to our attention, they are now included in the introduction.

5*: The CRE is shown for the various cirrus types in Fig. 5 c). The highest total CRE is for F and C, followed by O1 and O2, and around zero CRE is for the other types. This seems to be related to the optical thickness or IWC, respectively of the cirrus types, which in turn depend on the updraft. A plot showing this would greatly improve the paper. Also, it would be good to know if the cooling effect from F and C is because thick liquid origin cirrus constitute a large part of these cirrus types ? In general, it would be good to see the difference in microphysical and radiative properties between liquid origin and ice origin in more detail.*

Reply: A plot showing the COD for the regimes has been included in Fig. 6. The large negative CRE of the F and C classes is indeed due to their large COD, as they are the only regimes that have selection criteria based on their COD (mentioned P14L14). While it would make sense, unfortunately we do not have enough data to know if the liquid origin cirrus in the F and C regimes is the dominant cause of the strong negative CRE, as the liquid-ice origin classification only exists for a single year over the North Atlantic.

6*: Methods: The "Criteria for regime assignment" (please specify regime in Table 1, I guess the cirrus classes are meant) are not very clear. I strongly recommend to add two columns, one containing the range of updrafts for each class and one with their range of microphysical properties, IWC or optical depth.*
Reply: Information on the optical depth is now included in Fig. 6. The table currently contains the information necessary to reproduce the regime classification. We would prefer not to add information on the cirrus class properties at this point in the paper, as they are not used in the regime classification and are now covered in more detail later in the paper (e.g. Fig. 6)

7*: Abstract: Include not only the method but also the most important results! In the current form, the paper will not get much attention when potential readers look at the abstract which I think is a pity.*
Reply: Information on the results has now been included.

8*: Conclusions: The properties of the cirrus classes are described, but I miss explanations of physical mechanisms leading to the properties. Two examples:*

- *"The in-situ (synoptic) regimes in this classification are primarily composed of in-situ/ice-origin cirrus clouds, even to temperatures as warm as -20° C while the frontal and convective regimes contain a much higher proportion of liquid-origin cirrus to much colder temperatures." This is related to the updrafts, yes? The larger the updrafts, the higher the liquid origin cirrus can rise = colder temperatures.*

- *"The frontal and convective regimes have the strongest LW, SW and net negative CRE." This could again be related to the updrafts, yes? High updrafts → thick cirrus, many liquid origin → strong CRE, yes?*

This comment relates to comments 1 and 2.
Reply: This may be the case, but we do not feel that we have enough data to claim that this is purely an updraught effect. For example, it could be that the cloud bases are higher in the synoptic class (as indicated by the model results), rather than just a change in the cloud top height of clouds with lower bases. A comment related to the updraught has been added to the (new) section on the cloud optical depth (P13L3).

Specific comments

Page 1, line 15:*: Please delete "While"*
Reply: Done

Page 1, line 20-21:*: "... aerosol influence on ice clouds would likely modify ice nucleation processes, changing the ICNC, perhaps by orders of magnitude ..." - "orders of magnitude" is definitively too high, please scale back this statement. Also, aren't more recent publications available studying the effect of IN on cirrus properties ? Another point to think about is that the most prominent* *parameter influencing the radiative cirrus properties is the ice water content (IWC). Changing the ICNC by influencing the IN number does not necessarily means that the IWC is changed, since the available water vapor distributes on the present ICNC. The result are different sizes of the ICNC (but not IWC) and thus differing sedimenation behavior, which influences the further development of the cloud.*

Reply: This has been changed to "an order of magnitude", the maximum change observed in the Kärcher and Lohmann, (2003) paper. We agree that the IWC is a more important component of the cloud albedo and that a change in ICNC may not modify it. However, even at a constant IWC, a change in the ICNC would modify the radiative properties of the cloud, similar to the Twomey effect in liquid clouds. The IWC has been included in the first paragraph along with the ICNC (P1L21).

Page 1-2, lines 23-1*: "... ice crystals are formed either by heterogeneous nucleation from ice nucleating particles (INP) or freezing of liquid droplets by either INP or existing ice crystals." Do you mean either immersion freezing or contact freezing ? Please specify.*

Reply: This sentence was intended to provide a brief mention of the role of INP. It has been expanded to indicate that both contact and immersion freezing are possible.

Page 2, line 2:*: "..freezing of and remaining liquid droplets." Please remove "and".*

Reply: Done

Page 2, line 5:*: ".. (e.g. Krcher, 2017), .." Since this is the introductary part of the manuscript, I would recommend to cite some more basic studies on the influence of freezing mechanisms on cirrus microphysical properties, e.g. the work of P. Spichtinger, E. Jensen, M. Kraemer, A. Heymsfield. Include references.- Heymsfield 2017, review article.*

Reply: Thank you for pointing this out, we have now included the Heymsfield et al., 2017 review article here.

Page 2, line 6-7:*: Heterogenous freezing in cirrus is in most cases determined by the INP number. This should be mentioned here.*

Reply: Done

Page 2, line 8:*: "Convective clouds can contain liquid water to temperatures as low as -37°C ..." - This happens only in very strong updrafts, please explain.*

Reply: A clarification about the high updraught speeds is now included.

Page 2, line 10:*: ... importance of the origin of the ice in a cloud (liquid or ice) has recently been introduced and demonstrated by Krämer et al. (2016).*

Reply: Amended.

Page 2, lines 14-16:*: "However, information on the in-cloud updraught and the ice origin has a strong dependence on the microphysics and convection schemes*

used in a model and so may not be suitable for use as an observations-based constraint on cloud ice microphysics parametrisations in general circulation models (GCMs)." - To me this sentence is not very clear - can you reformulate what you mean ?
Reply: Replaced with "However, the cloud scale updraught and the ice origin are not often directly simulated in atmospheric models, being calculated through parametrisations. As such, reanalysis values of these quantities may not be suitable for use as a constraint on cloud ice microphysics parametrisations in general circulation models (GCMs)."

Page 2:: *Existing classifications - I highly recommend to cite here the recent overview article of Heymsfield et al. (2017)(see http://journals.ametsoc.org/doi/pdf/10.1175/AMSMONOGRAPHS-D-16-0010.1).*
Reply: This reference has now been included, although slightly earlier in the manuscript (P2L13) so that it provides a good reference for the introduction on cirrus in general.

Page 2, last paragraph:: *This paragraph reads clumsy*
Reply: This paragraph has been re-worded.

Page 3, lines 23-24:: *"..., irrespective of whether a cloud is observed such that a simpler comparison with models (which may produce sub-visible cirrus) can be made." ????*
Reply: This is simplified to "...irrespective of whether a cloud is observed. This ensures that every location is assigned to a regime, such that the regime occurrence is not biased by any satellite cloud detection threshold." We has also removed the "aim of classifying the uppermost layer" from later in this paragraph due to it's potential to confuse this issue.

Page 4, lines 1-3:: *What is the meaning of the "windspeed-height variation product" that defines O1 and O2?*
Reply: This has been changed to "windspeed-surface topography variation product" to better align with the terminology in the previous paragraph.

Page 9, lines 6-8:: *"In all the regimes, almost all clouds colder than -60° C are formed directly as ice and many of those warmer than -40° C are originally formed as liquid (Fig. 3, "Total" column). However, there is considerable variation between the regimes between these temperatures." This nice result should appear in the conclusions and maybe also in the abstract.*
Reply: The abstract has been re-worded to make a clearer link to the variations in ice origin between the regimes. The temperature dependence of the in-situ/liquid origin cirrus had previously been noted in the Wernli et al, 2017, paper describing the classification.

Page 14, lines 6-7:: *"The in-situ regimes in this classification are primarily composed of in-situ/ice-origin cirrus clouds, ..." I guess you mean liquid here.*
Reply: This sentence was intended to show that the liquid-origin cirrus is much

less common in the synoptic regime at warmer temperatures than in the frontal or convective regimes. The renaming of the in-situ regime to synoptic should make this clearer.

Page 14, line 16:: *“As seen in previous studies, the net cloud radiative forcing (CRE) is negative, ...” - Which previous studies ?*
Reply: This was intended to reference the overall mean CRE. This sentence has now been corrected to read “As seen in previous studies (e.g. Hartmann et al., 1992), the mean cloud radiative effect (CRE) is negative ...”

Response to reviewer 2

General Comments:

: This is a very innovative approach for classifying the various types of cirrus clouds in a way that provides qualitative knowledge about cloud updrafts and whether the cirrus ice crystals formed near -38° C from supercooled liquid cloud droplets advected into the T < -38° C zone, classified as "liquid origin cirrus", or from another ice nucleation process (e.g. immersion freezing, vapor deposition or homogeneous freezing), classified as "ice origin cirrus". As such it represents a potentially significant contribution to scientific progress within the scope of ACP.

Reply: We thank the reviewer for their comments, which are addressed in turn below. Line numbers related to the diff'ed version of the manuscript. A short section on the seasonal variation of the regimes has been added to demonstrate their utility and help better characterise them for future work.

: However, a key parameter not mentioned in the methodology for determining cirrus cloud regimes is temperature T. To begin with, the authors need to define what they mean by "cirrus cloud". Most investigators define cirrus as a pure ice cloud (i.e. no liquid water is present), and the best way to insure this is to require T < -38° C. Such a restriction was not applied in this study, making the proposed classification scheme ambiguous, especially in regards to cloud radiative properties. Unless I have not understood this classification scheme properly, this appears to be the main drawback.

Reply: We agree that this is an important factor of cirrus clouds. This classification is primarily intended to classify gridboxes, irrespective of the cloud that had actually formed there, similar to the dynamic regimes described in Medeiros and Stevens (2011). As noted here, this then leads to the issue observed in Fig. 6, where the CRE is a strong function of the underlying low-level cloud. Although we have not completely removed cloud properties from the regime classification, having a classification that is mostly independent of the cloud properties then allows global models to be assessed on their ability to form these regimes separately from their simulation of the cloud properties within them. This has been expanded upon in the methods section (P4L11) and noted at the end of the introduction (P4L5).

: It is evident from Fig. 3 that the classification scheme is applied for T < -20° C, and supercooled liquid water may exist between -20 and -38° C. Over this T range, the clouds should not be regarded as cirrus clouds. The differences between the cirrus categories in Fig. 3 become much more subtle if cirrus are defined as being colder than -40° C, but the cloud categories can be distinct for -40° C < T < -20° C. Perhaps this classification scheme could be improved if each class were divided into two T regimes; T < -40° C and -40° C < T < -20° C.

Reply: Following the previous point, classification according to the observed cloud phase would conflate the occurrence of the regimes with the occurrence of different cloud types within them. This also limits the possibility of splitting the regime by temperature vertically by cloud occurrence.

The liquid/in-situ origin dataset is derived from ERA-Interim, which contains a relatively simple ice parametrisation, lacking the impact of aerosols such that most clouds are glaciated by -20°C. This means that the occurrence of liquid-origin cirrus becomes very low even at temperatures warmer than -40°C, whilst this might not be the case in the atmosphere, where liquid drops can persist to colder temperatures (possibly allowing liquid origin cirrus a colder temperatures). This then suggests that the difference between the regimes might persist to higher altitudes in the atmosphere, even though it cannot be determined from this dataset. The methods section has been expanded to include this point (P7L8).

: Figure 4 introduces even more mixed phase ambiguity by applying the classification scheme to cloud temperatures between 0°C and -90°C.
Reply: See previous points

: Although I am familiar with the concepts of liquid origin and ice origin cirrus clouds, I felt that these complex concepts were not clearly explained in this paper, especially in regards to what kind of knowledge they impart to this classification scheme. More explanation should be given.
Reply: Extra explanation is included in the introduction (P2L19) and in the relevant results sections.

The paper is well organized and well written, with a sufficient number of quality figures to illustrate the main points. Many other important concerns are listed below. Given these concerns, I recommend major revisions.

Major Comments:

Page 2, line 18:: *In this section on "Existing Classifications", the authors might also want to mention the work of Tselioudis et al. (2013, J. Climate), who used cluster analysis to define 11 atmospheric weather states (WSs) based on optical depth and pressure level. While only one WS is primarily cirrus, other WSs contain cirrus contributions.*
Reply: Thank you for suggesting this, it has now been included.

Page 3, line 15:: *This is the 1st mention of the ICON model that is used extensively in this work. The full name of the model and/or a reference should be given here (along with acronym).*
Reply: The acronym and reference are now included here

Page 3, line 31:: *In some mountainous regions, 850 hPa may be below the surface. What is done when this occurs?*
Reply: Following the ERA-Interim extrapolation algorithm, this windspeed is replaced with the surface windspeed. This is now noted in the text.

Section 2 (Methods):: *Since MODIS was used to develop this classification scheme, it would be helpful to show in this paper a mean visible cloud optical depth (OD) associated with each cirrus cloud category, as well as the corresponding standard deviations. This would be helpful for understanding the net CRE of each category that is discussed later.*
Reply: This is now included towards the end of the results section (Fig. 6)

Section 2 (Methods):: *A temperature criteria of* $T < -38^\circ C$ *is not used to select cirrus in any of these cirrus categories, raising the possibility that some clouds classified as cirrus may actually be mixed phase clouds. Figures 3 and 4 suggest that this classification scheme was applied for* $T < -20^\circ C$ *and* $T < 0^\circ C$*, respectively. If either is correct, then mixed phase conditions are built into this classification scheme, and this should be made clear. Moreover, the word "cirrus" in the paper's title should be replaced by "ice cloud", and all references to "cirrus" in the paper should be replaced by "ice cloud".*
Reply: Thank you for pointing this out, we agree that the phase is ambiguous for some of these cloud, but as mentioned previously, we feel that adding cloud phase to the classification would reduce the separation between the meteorological state and the cloud formed due to it. While "ice cloud" or "cirriform" might be a broader term to cover this classification, we feel that the term "cirrus" is also a good way to indicate that this classification aims to separate out many different types of high cloud, from anvil cirrus through to the thinner synoptic cirrus varieties.

Page 9, lines 2-8:: *Since this classification scheme is for cirrus clouds, this implies only ice exists. But when classifying clouds between -20 and -40 C, what assurance is there that these clouds are "ice only" based on Wernli et al. (2016)? And even if the Wernli et al. analysis shows that the classified "cirrus" in Fig. 3 between - 20 and -40 C are ice only, the phase partitioning in cloud resolving models is not an exact science, is highly variable between models, and depends strongly on the parameterization scheme used. Thus it is difficult to understand just what exactly is being shown in Fig. 3 at warmer temperatures (e.g. are the clouds ice only or mixed phase?). Please address these concerns, clarifying all these issues. If the authors insist on using their classification scheme at these warmer temperatures, they need to be clear just what kind of cloud they are classifying (e.g. all-ice or mixed phase).*
Reply: Following the points made earlier, we have noted that the classification attempts to avoid basing the classification on the retrieved cloud properties (such as phase), to enable a clearer distinction between the meteorological state and the clouds it produces. Further notes on this have been included in the methods section (P4L11) and introduction to better justify this.

Figure 5c and associated discussion: : *Two questions come to mind here: (1) How much do mixed phase conditions contribute to these CRE values? Even if liquid water comprises only 10% of the total water content, it can still have a large impact on cloud radiative properties (e.g. Mitchell and d'Entremont, 2012, AMT; Shupe and Intrieri, 2004, J. Climate). Thus, a small liquid water*

fraction is likely to have a strong impact on the net CREs given in Fig. 5c, increasing the SW over the LW contribution.
Reply: It is likely that mixed-phase clouds play a role in the CRE of these regimes, especially given the importance of liquid water in these clouds. An investigation into this is beyond the scope of this work, which is mainly to provide a description and brief characterisation, but is definitely considered for the future.

Figure 5c*: And regarding the 2nd question (wrt Fig. 5c), CRE is evaluated from CERES SYN1deg daily data at 1:30 pm LST. At this time, SW CRE is near maximum, whereas LW CRE is much less variable over a 24 hr. daily cycle. This sampling time will negatively bias the net CRE, making it non-representative of the daily-mean net CRE associated with cirrus clouds having low-to-moderate ODs.*
Reply: The data is actually taken from the daily mean SYN product. This has been corrected in the text

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Fig. 5b and c:*: It is commendable that the authors have partly explained why all the in situ cirrus categories have more SW CRE than LW CRE (due to low clouds). These cirrus are typically having lower optical depth and thus lower SW and LW CRE (Fig. 5c), with TOA LW CRE > SW CRE (e.g. Fu, 2008, Fig. 4; Hong and Liu, 2015, J. Climate). But after removing the low clouds in Fig. 5c, in situ cirrus still have a net CRE < zero, whereas other studies infer positive values. For example, for cirrus OD < 3.6 and cloud top pressure <440 mb, the net CRE reported by Chen et al. (2000, J. Clim.) was positive, as was also true for Hartman et al. (1992, J. Clim.) for cirrus OD <9.4. Based on the ECHAM6 GCM, the global average net CRE of cirrus clouds is +5.7W/m2 (Gasparini and Lohmann, 2016, JGR). The proposed technical note appears to be at variance with the literature in regards to the overall sign of the net cirrus forcing, and this discrepancy should be addressed. Note that the calculations in Fu are for the equator during an equinox when the sun is highest in the sky, which maximizes the SW CRE.*
Reply: Thank you for drawing our attention to these studies. We have gone back to look at the CRE data again. The average net synoptic CRE is slightly positive, at around 3Wm^{-2} (similar to previous work), when removing any liquid clouds, which is more consistent with methods in previous work. The overall cirrus net CRE is still negative, but this is mostly due to the strong negative effect on the frontal and convective regimes. We suspect that the difference to previous work most probably comes come the different pressure levels used to separate out low cloud. Hartmann et al, 1992 used 440 hPa, whereas we have used 550 hPa. This results in a slightly less positive LW CRE, contributing to the overall smaller CRE. A clause has now been added noting that the net synoptic CRE is now positive (P17L25).

Page 14, line 16:*: "As seen in previous studies, the net cloud radiative forcing (CRE) is negative". Yes, but this paper is about cirrus clouds, and their net CRE is positive. Please cite these "previous studies" that pertain to cirrus*

clouds. One study by Chen et al. (2000, J. Clim.) was cited in the Introduction and could be cited again here. As noted above, Chen et al. (2000) and Hartman et al. (1992) found that for cirrus OD <3.6 or 9.4, respectively, their net CRE is positive.
Reply: This sentence was intended to point out that the total CRE is negative and has now been amended.

Minor Comments

Page 2, line 2:: *Remove "and" from this sentence.*
Reply: Done

Page 2, line 12:: *Comma not needed*
Reply: Amended

Page 2, line 18:: *"Existing Classifications" should be given a sub-header value of 3.1.*
Reply: Amended

Page 3, line 27:: *determines => determining?*
Reply: Amended

Figure 4:: *Please label all the panels as a, b and c. Also, what do the 3 horizontal lines indicate in the middle-regions of Fig. 4b and 4c?*
Reply: Amended. The caption now states that the grey lines are gridlines.

Page 12, line 15:: *Fig. 5a does not show RFO; please clarify. Also, "frontal convective regimes" => "frontal and convective regimes"? Based on Fig. 5b, frontal and convective regimes appear to account for slightly > 12%.*
Reply: Corrected to refer to Fig. 2, percentages and missing "and" amended.

Page 13, line 8:: *"once" => "until"?*
Reply: This sentence has been re-written for clarity.

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~~Technical note:~~ An automated cirrus classification

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Abstract. Cirrus clouds play an important role in determining the radiation budget of the earth, but many of their properties remain uncertain, particularly their response to aerosol variations and to warming. Part of the reason for this uncertainty is the dependence of cirrus ~~clouds on the mechanism of formation~~ cloud properties on the cloud formation mechanism, which itself is strongly dependent on the local meteorological conditions.

In this work, a classification system (Identification and Classification of Cirrus or IC-CIR) is introduced to identify cirrus clouds by ~~their formation mechanisms~~the cloud formation mechanism. Using re-analysis and satellite data, cirrus clouds are separated in four main types: orographic, frontal, convective and ~~in-situ~~synoptic. Through a comparison to convection-permitting model simulations and back-trajectory based analysis, it is shown that ~~the~~ these observation-based regimes can provide extra information on the ~~properties and origin of cirrus that could not be provided by the~~ cloud scale updraughts and the frequency of occurrence of liquid-origin ice, with the convective regime having higher updraughts and a greater occurrence of liquid-origin ice compared to the synoptic regimes. Despite having different cloud formation mechanisms, the radiative properties of the regimes are not distinct, indicating that retrieved cloud properties ~~or reanalysis data alone .~~ alone are insufficient to completely describe them.

This classification is designed to be easily implemented in GCMs, helping improve future model-observation comparisons and leading to improved parametrisations of cirrus cloud processes.

1 Introduction

High clouds are a key component of the Earth's energy budget, although there is still considerable uncertainty about ~~their~~ cloud formation mechanisms and their response to environmental changes, particularly in response to changes in the aerosol environment (Heyn et al., 2017) and to warming (Bony et al., 2016). ~~While thin~~ Thin cirrus clouds tend to have a positive cloud radiative effect (warming the atmosphere)(Chen et al., 2000)~~, their~~. Their radiative properties are strongly controlled by their altitude and water content in addition to their microphysical properties, particularly the ice water path (IWC), ice crystal number concentration (~~ICNC) and~~ N_i) and the crystal size distribution (Fu and Liou, 1993). Constraining the impact of cloud controlling factors on cirrus clouds is thus vital to improve the parametrisation of cirrus clouds and to constrain their response to aerosol and warming.

Similar to the effect of aerosols on liquid clouds, an aerosol influence on ice clouds would likely modify ice nucleation processes, changing the ~~ICNC~~N_i, perhaps by orders of magnitude ~~(Kärcher and Lohmann, 2003)~~ (Kärcher and Lohmann, 2003; Heymsfield et and impacting the cloud development. Ice nucleation mechanisms and rates are strongly temperature dependent. At temperatures warmer than about -37.5°C, ice crystals are formed either by heterogeneous nucleation from ice nucleating particles (INP) or through the freezing of liquid droplets ~~by either INP or existing ice crystals~~(via either immersion or contact freezing) with the INP concentration providing a strong constraint on $N_i$formed from heterogeneous nucleation. At temperatures colder than around -37.5°C, ice can also nucleate homogeneously (without an INP), through either the freezing of liquid aerosol or the freezing of ~~and~~ remaining liquid droplets. These processes are dependent on the supersaturation, with homogeneous nucleation being restricted to higher supersaturations than heterogeneous nucleation. The relative importance of these different processes is relevant for determining the ~~ICNC~~ N_i and the ice crystal size distribution ~~(e.g. Kärcher, 2017)~~ (e.g. Heymsfield et al., 2017; Kärcher, 2017), which can affect the reflectivity, extent and lifetime of a cirrus cloud.

The ice nucleation rate and the nucleating ability of INP is thus a strong function of temperature and of supersaturation (Hoose and Möhler, 2012), which is in turn related to the strength of the cloud-scale updraughts. These factors vary by cloud type. ~~Convective clouds~~ With very high updraught speeds, convective clouds can contain liquid water to temperatures as low as -37°C (Rosenfeld, 2000), suggesting an important role of liquid origin ice~~, whilst~~ . In contrast, tropical tropopause cirrus are more likely to contain ice formed in-situ (e.g. Jensen et al., 2010). The importance of the origin of the ice in a cloud (liquid or ~~ice~~in-situ) has recently been ~~demonstrated by Krämer et al. (2016)~~introduced and demonstrated by Krämer et al. (2016); Luebke et al. (2016), using in-situ observations to show that liquid origin cirrus typically have higher IWC and $N_i$than in-situ formed cirrus.

Understanding how cirrus clouds and the ~~ICNC~~ N_i in particular respond to these four factors (temperature, in-cloud updraught, liquid/~~ice~~ in-situ origin and aerosol environment) ~~,~~ is vital for improving cloud parametrisations in atmospheric models. Temperature and the aerosol environment can be determined from reanalysis data (Dee et al., 2011; Benedetti et al., 2009; Morcrette et al., 2009). However, ~~information on the in-cloud~~ the cloud scale updraught and the ice origin ~~has a strong dependence on the microphysics and convection schemes used in a model and so~~ are not often directly simulated in atmospheric models, being calculated through parametrisations. As such, reanalysis values of these quantities may not be suitable for use as ~~an observations-based~~ a constraint on cloud ice microphysics parametrisations in general circulation models (GCMs). Developing a classification for cirrus clouds that can provide information on the in-cloud updraught and the ice origin is the main focus of this work.

~~Existing classifications~~

1.1 Existing classifications

The most common classification of cirrus clouds is based on their surface observed properties, based on the work of Howard (1803) and formalised by the World Meteorological Organization (2017). Although this classification can be easily applied by surface observers, a lack of data availability in many regions of the globe (Woodruff et al., 2011) and the obscuring of cirrus from the surface by low cloud means that there are significant advantages to a satellite-based classification. The manual classifications that have been used in past studies (e.g. Sassen and Comstock, 2001) are labour intensive, making them difficult to apply to large satellite datasets. An automated classification based on satellite data and reanalysis data is thus a necessary step forward in order to provide observational constraints on cirrus cloud processes for large statistical analyses.

Existing automated cloud classifications can be grouped into two broad categories, although ~~the regimes produced by both~~ both categories are often mapped to the Howard (1803) classification. “Cloud regimes” are based on the observed properties of clouds. ~~These have been based on the brightness temperatures (Inoue, 1987)~~ As an example, Inoue (1987) determined a regimes classification based on satellite brightness temperatures allowing a separation of convective cloud cores from the anvils that surround them~~, but more recent studies define the regimes based on the satellite retrieved cloud properties . These methods often produce regimes that separate cirrus clouds of varying optical depths, ~~. More recent studies have used extra cloud properties in defining a regime classification (such as cloud optical depth), producing cirrus cloud regimes in addition to regimes describing low cloud properties ~~(e.g. Rossow et al., 2005; Gryspeerdt and Stier, 2012; Oreopoulos et al., 2016)~~ (e.g. Rossow et al., 2005; Gryspeerdt and Stier, 2012; Tselioudis et al., 2013; Oreopoulos et al., 2016). These methods require that the properties defining the cloud regimes vary strongly between the cloud types, but this also means that if the cloud properties used to define the regimes change (perhaps as a function of aerosol), this will change both the properties and the occurrence of the regimes (Williams and Webb, 2009; Gryspeerdt et al., 2014). Being based purely on the observed cloud properties, “cloud regimes” do not require assumptions about the impact of local meteorology on the regime occurrence.

Conversely, “dynamical regimes” are based on the meteorological situation, often using reanalysis data as a method of defining the regimes (e.g. Medeiros and Stevens, 2009; Muhlbauer et al., 2014). These regimes can often be related to specific cloud types, but they are not necessarily a good constraint on the cloud properties if the regimes are not defined using the correct parameters (Nam and Quaas, 2013; Leinonen et al., 2016). However, it is not required that these regimes map to the “Howard” classification. For example, Wernli et al. (2016) use reanalysis data to classify cirrus as either liquid or ~~ice~~ in-situ origin, depending on their meteorological history and the parametrised cloud phase within the reanalysis. “Dynamical regimes” require assumptions to be made about the important meteorological variables and may have to rely on the accuracy of reanalysis products. However, as a change in the properties of a cloud does not change the occurrence of a “dynamical regime”, using “dynamical regimes” can simplify analyses into the response of cloud parameters to meteorological parameters not used for defining the regimes.

In this work, elements of both the “cloud regime” and “dynamical regime” methods are combined to develop a source-based classification of cirrus and other high cloud, using satellite and reanalysis data. The aim of this classification is to provide

ID	Short name	Class	Definition
11	O2	Oro. 2	Highest sextile of orographic updraught
10	O1	Oro. 1	Second sextile of orographic updraught
9	F	~~Front~~ Frontal	Within ~~blob~~ “blob” of high cloud that intersects a reanalysis front
8	F2	~~Front~~ Frontal 2deg	Within 2° of ~~front~~frontal/~~class 9~~ F
7	F5	~~Front~~ Frontal 5deg	Within 5° of ~~front~~frontal/~~class 9~~ F
6	C	~~Conv~~ Convective	Within a blob ~~and in~~ intersecting a region of negative ω(500 hPa)
5	C2	Conv. 2deg	Within 2° of conv./~~class 6~~ C
4	C5	Conv. 5deg	Within 5° of conv./~~class 6~~ C
3	J	Jet	Windspeed(300 hPa) $>$ 30 ms^{-1}
2	~~Iu~~ Su	~~Insitu wu~~ Synoptic up	Negative ω(500 hPa)
1	~~Id~~ Sd	~~Insitu wd~~ Synoptic down	ω(500 hPa) $<$ 0.05 Pa s^{-1}
0	~~I~~ S	~~Insitu sd~~ Synoptic	None of the above

Table 1. ~~Criteria for regime assignment~~Classification criteria. Gridboxes are assigned the highest applicable class, regardless of if a cloud is detected.

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information on the cloud-scale updraughts and ice origin within cirrus clouds. The classification will be compared against the Wernli et al. (2016) classification and convection-permitting simulations from the ICON ~~model~~ (ICOsahedral Non-hydrostatic) model (Zängl et al., 2015) to examine how much information it provides on the ice origin and the cloud-scale updraughts. By separating frequency of occurrence of cloud-forming meteorological conditions from the properties of the clouds that form as a result (similar to “dynamical regimes”), this classification also aims to improve process-based observational comparisons with GCMs. This will enable future studies to combine the regimes defined here with reanalysis temperature and aerosol properties, along with additional observational data to investigate the controls on ice nucleation processes and cirrus cloud properties.

2 Methods

For this classification, the regimes are derived from four main sources of cirrus cloud: orographic uplift, frontal uplift, convective systems and ~~cirrus formed in-situ~~ synoptic cirrus formed through large scale rising motions. These are divided into the twelve cirrus cloud regimes specified in Tab. 1.

Each 1° × 1° gridbox globally is assigned to one of these regimes, irrespective of whether a cloud is observed~~such that a simpler comparison with models (which may produce sub-visible cirrus) can be made.~~ . This ensures that every location is assigned to a regime, such that the regime occurrence is not biased by any satellite cloud detection threshold. This also enables the occurrence of the meteorological conditions to be separated from the properties of the clouds that occur within each regime, making the classification more suitable for a process-based analysis of the cirrus clouds in GCMs.

As an aim of this work is to generate a classification that is applicable to GCMs, consideration is given to the data volume that would be required to generate the classification and availability of diagnostics and observational measurements. As such, only a two dimensional classification is created~~, with the aim of classifying the uppermost cloud layer~~. Gridboxes are ~~assigned using the following method~~classified in the following order, with the first set of criteria that are satisfied ~~determines~~ (Tab. 1) determining the regime.

1. Orographic clouds (O1, O2)

   Similar to parametrisations for in-cloud updraughts in orographic clouds (Lott, 1999; Joos et al., 2008), the in-cloud updraught for an orographic cloud is assumed to be proportional to the product of the ~~ERA-Interim (Dee et al., 2011)~~ windspeed at 850 hPa (or the surface if it is a higher altitude) and the surface topography variation (the difference between the mean and minimum altitude within each 1°×1° degree gridbox). The windspeed is from ERA-Interim (Dee et al., 2011) and the topographic data is from the United States Geological Survey GMTED2010 dataset gridded to 0.1°×0.1° resolution.

   Gridboxes falling into approximately the upper tercile of parametrised updraughts are assigned to orographic regimes. Those with a ~~windspeed-height~~ windspeed-surface topography variation product of greater than 880 $\mathrm{m^2s^{-1}}$ are assigned to the O1 regime (Tab. 1), with those with a ~~windspeed-height~~ windspeed-surface topography variation product larger than 1800 $\mathrm{m^2s^{-1}}$ forming the O2 regime. These constants were selected based on a year of data to give approximately equal relative frequencies of occurrence (RFO) for the O1 and O2 regimes. The orographic regime is defined first, given their dominant control over the in-cloud updraught in mountainous regions (Joos et al., 2008).

2. Frontal clouds (F, F2, F5)

   Points are assigned to the frontal regime based on their proximity to atmospheric fronts, located using reanalysis data. Fronts are determined using an objective front detection method based on (Hewson, 1998), using the wet bulb potential temperature (θ_w) at 850 hPa calculated from ERA-Interim reanalysis (Dee et al., 2011) at a 1°×1° resolution following the method from Davies-Jones (2009). The fronts are located using the criterion

$$\nabla \cdot |\nabla |\nabla \theta_w|| = 0 \tag{1}$$

   which was shown to provide similar results to a more sophisticated locator based on mean-axes (Hewson, 1998). A single field of fronts is created for a local solar time of 13:30, to align with the A-Train overpass. Fronts which exist for only a single six hour reanalysis timestep are removed, as are fronts that pass through less than ten 1°×1° gridboxes. The quasi-stationary fronts (front speed parameter of less than 1.5 ms^{-1}) identified by Berry et al. (2011) are also excluded, as these often occur in regions of tropical convection, where the convective regime is more appropriate.

To identify clouds that are part of a frontal system, cloud “blobs” are created ~~. These “blobs” are connected regions in the level 3, collection 6~~ using cloud data from the moderate resolution imaging spectroradiometer (MODIS) instrument on the Aqua satellite (Platnick et al., 2017) at 1° by 1° (MYD08_D3). The “blobs” are defined as contiguous connected regions where the cloud top pressure (CTP) is less than 550 hPa and the optical depth is greater than 5. “Blobs” are not allowed to exist where the orographic regimes have been assigned, nor in regions with topography over 1500 m (approximately 850 hPa), as fronts cannot be accurately determined in these regions. The primary effect of this restriction is to prevent frontal and convective clouds being classified over Greenland and East Antarctica.

These choices ensure that ~~related clouds~~ clouds from the same system are placed in the same “blob” while at the same time preventing the formation of a single, global “blob”. The requirement for a cloud optical depth retrieval limits these regime definitions to daylight, ~~usually~~ around 13:30 local solar time (the overpass time of the Aqua satellite on which MODIS is flown).

Clouds are then assigned to the frontal class if they are part of a blob that intersects a front (F). As this method is likely to miss thinner frontal clouds, regions of two (F2) and five (F5) degrees around the edge of the frontal clouds are created to include these clouds. The width of these “buffer” regimes is further considered in the results ~~of this work~~section.

3. Convective clouds (C, C2, C5)

   Cirrus from convective (non-frontal) clouds is determined using the same “blobs” that are used for the frontal cloud ~~detection~~classification. In this case, clouds in a blob that is not labelled as frontal are considered convective (C) if they intersect a region of large scale updraught (as defined by the ECMWF ERA-Interim grid-scale pressure vertical velocity at 500 hPa - ω_{500}). As with the frontal clouds, buffer “regimes” of two (C2) and five (C5) degrees are defined around each convective “blob” to include thinner clouds that are not included in the “blob”. The convective regime cirrus are defined after the frontal regimes as many frontal locations also satisfy the criteria for the convective regime.

4. Other classes

   From the remaining pixels, locations with a windspeed at 300 hPa greater than 30 ms^{-1} are classed as jet-stream cirrus (J). The remaining locations are ~~candidates for in-situ~~ considered as candidates for synoptic cirrus formation. These are separated into three further regimes using the ω_{500} to further limit the possibility of convective clouds contaminating the ~~in-situ~~ synoptic cirrus regime. Locations with a negative ω_{500} form the ~~in-situ~~ synoptic updraught regime (~~Iu~~Su), a positive ω_{500} less than 0.05 Pa s^{-1} the ~~in-situ~~ synoptic weak-updraught (~~Id~~Sd) and the remaining form the final ~~in-situ regime (I~~synoptic regime (S). The ~~in-situ~~ synoptic regimes are the residual regimes, assigned after the more clearly-defined classes.

Whilst these classes do not cover every ~~formation method of cirrus clouds~~cirrus formation mechanism, they are designed to cover the most globally significant sources of cirrus. Other classes or subdivisions could be added in future work.

To examine the ability of this classification for determining cirrus cloud origin, it is compared to the classification from Wernli et al. (2016) over the north Atlantic (30N-80N, 110W-40E) for the year of 2007. The Wernli et al. (2016) classification uses back trajectories in the ECMWF ERA-Interim re-analysis to determine if a cirrus cloud is formed directly in the ice phase, or if it formed through the freezing of liquid droplets. This back-trajectory technique is suitable for use in the regions of large-scale rising air associated with fronts, but the reliance on parametrised convection makes it less suitable to determining the origin in highly convective locations. For each regime, the probability of a trajectory being liquid or ~~ice~~ in-situ origin at each temperature is calculated, with the same regime assigned at all temperatures within each lat-lon gridbox. As it is based on the ERA-Interim phase parametrisation, it is likely to overestimate the fraction of in-situ origin cases, particularly at temperatures colder than -23°C. This misclassification would not be limited to temperatures warmer than -40°C, as these colder clouds may still be liquid origin cirrus. However, as liquid water is rare at temperatures below -23°C (Choi et al., 2010), the errors phase misclassification are likely small, such that the Wernli et al. (2016) classification is able to provide a useful first comparison for the regimes derived in this work.

Convective clouds are likely produce liquid-origin cirrus (Rosenfeld, 2000), such that the in-cloud updraught is a key parameter for these clouds. The convective regime should be able to identify regions with a higher in-cloud updraught if it is to correctly identify convective origin cirrus. As in-cloud updraughts are not currently retrieved by satellite, the cirrus regimes classification is also compared to output from a convection-permitting simulation using the ICON model (Zängl et al., 2015), performed at 2.5 km resolution over the tropical Atlantic (10S-20N, 68W-15E), with a nested domain at 1.25 km resolution over Barbados (4S-18N, 64W-42W) during August 2016 (see. Fig. 1b). The simulation was initialised each day at 0000 UTC using the ECMWF operational analysis of the atmospheric state and boundary conditions are provided three hourly from the ECMWF operational forecast. Output from the nearest hour to 1330 LST (the time of the Aqua satellite overpass) across the domain is used to compare with the regimes, corresponding to a period 12-16 hours after the start of the simulation on each day. As the simulation can resolve convection, the updraught velocities in the simulation show whether the cirrus classification is able to provide information on the convective updraught velocities.

To characterise the regimes and guide further studies, the cloud radiative effect (CRE) for each of the regimes are determined following Oreopoulos et al. (2016). Using the CERES SYN1deg daily product at 1°×1° resolution (Doelling et al., 2013), daily mean the solar (SW) and terrestrial (LW) CRE is calculated for each of the regimes for the ten year period 2003-2013 inclusive. As the classification is based on assigning high clouds but makes no requirement on any underlying low cloud, the CTP histogram in the MODIS level 3 MYD08_D3 product is used to select gridboxes that have more than 99% of retrieved CTPs higher than 550 hPa, allowing the CRE of the high cloud to be studied separately.

3 Results

3.1 Example classification

Fig. 1a shows a MODIS true-colour composite from the 12th of April, 2007, Fig. 1b shows the retrieved cloud top pressure for the same day, with the bands of high cloud in the mid latitude and convective systems in the tropics both clearly visible.

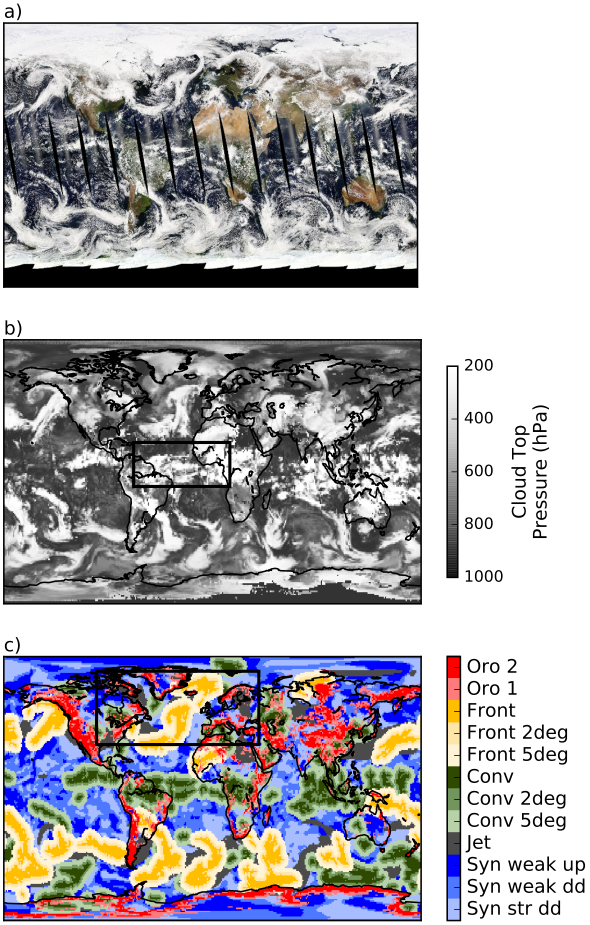

Figure 1. a) A MODIS Aqua true-colour image for the 12th of April, 2007. b) The MODIS daytime cloud top pressure, in-filled with the night-time CTP where no daytime retrieval exists. The box in the tropics shows the location of the regional ICON simulation. c) The classification presented in this work, derived from MODIS Aqua, ERA Interim and topographic data for the 12th of April, 2007. The colours denote the classified regime at each point for 13:30 local solar time. The box shows the region where the classification is compared to that from Wernli et al. (2016).

An examination of the classification (Fig. 1c) shows many of the features commonly seen with this classification method. The frontal cloud fields (F, F2, F5) are clearly visible in bands through the extratropics, although the front detection method does occasionally label frontal clouds in the tropics. The convective cloud regimes (C, C2, C5) occur primarily in the tropics, but can be occasionally seen in relation to frontal clouds. For example, the convection in the cold air outbreak behind the frontal in the southern ocean is clearly visible in Fig. 1. Orographic regimes (O1, O2) are found over land and although they are related to altitude, they are clearly distinct, with the east Antarctica plateau being classed as primarily ~~in-situ~~ synoptic cirrus, despite its altitude. This agrees with previous studies showing a low CF over east Antarctica (Bromwich et al., 2012). The jet stream regime (J) is visible in the extratropics, often linking frontal systems.

3.2 Relative frequency of occurrence

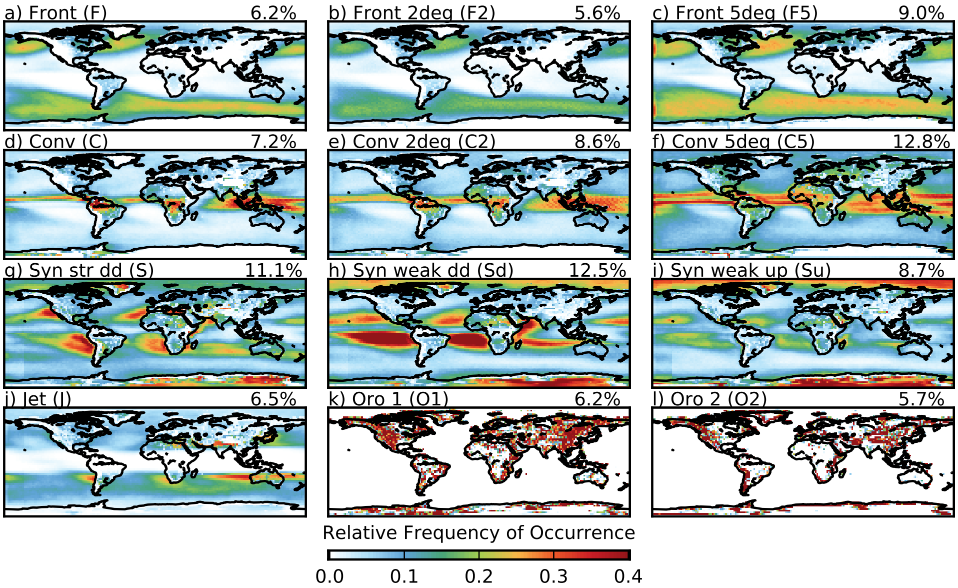

Figure 2. The relative frequency of occurrence of the different regimes over a ten year period (2003-2013). The frequencies are normalised so that they sum to one in each gridbox. The latitude weighted mean RFO for each regime is shown at the top right for each subplot.

The relative frequency of occurrence (RFO) of the regimes for a period of ten years (Fig. 2) behaves qualitatively similarly to the example day shown in Fig. 1. The RFO of the frontal regimes is highest in the stormtrack regions, with the misclassification in the tropics contributing a small amount to the total RFO of the frontal regime. Similarly, the two and five degree buffer regimes (F2, F5) also show the highest RFO in the extratropical stormtrack regions.

The convective regimes occur primarily in the tropics, although their extra-tropical RFO is not zero. The two and five degree buffer regimes (C2, C5) are more common than the convective regime itself and the five degree buffer regime starts to show a split around the equator.

Although the jet regime (J) is not excluded from the tropics by design, the RFO in this region is almost zero. It becomes more common in the southern ocean and also over some of the large scale descent regions, where the RFO of the frontal regime (which is assigned in preference to the jet-stream class) is much lower. The ~~in-situ~~ synoptic regimes are most common in the subtropical subsidence regions and the polar regions, where the RFO of the other regimes is small. However, there is also a significant RFO in other regions of the globe, demonstrating that even outside of the regions of large scale descent, it is still possible to find situations where cirrus cloud can form that is not clearly convective or frontal in origin.

3.3 Seasonal variation

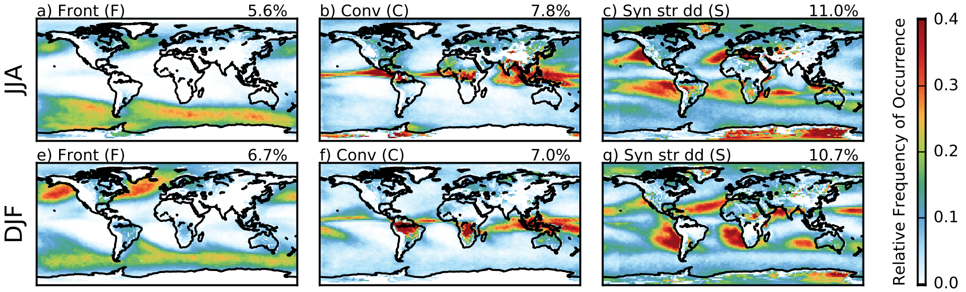

Figure 3. The relative frequency of occurrence for three of the regimes (frontal, convective and synoptic - strong downdraught) for the boreal summer (a,b,c) and winter (d,e,f) over a ten year period (2003-2013). The frequencies are normalised so that they sum to one in each gridbox. The latitude weighted mean RFO for each regime is shown at the top right for each subplot.

The global mean frequency of occurrence of the regimes is approximately constant between the seasons, but there is significant seasonal variability in the regime frequency of occurrence, particularly for the frontal, convective and synoptic regimes (Fig. 3). Although it is concentrated in the mid-latitudes, the frontal regime is significantly more common in the winter hemisphere, with occurrences of around 10 to 20% in the north Pacific summer, but over 40% in during DJF. Over land, there is a slight increase in the occurrence of the frontal regime in the summer months, but this may be due a mis-classification of convective clouds in the frontal regime.

The variation in the convective regime in the tropics roughly follows the variation in precipitation (Adler et al., 2003, e.g.) with maxima in the Amazon and Congo regions during the boreal winter. There are also strong increases in the occurrence of the convective regime around south Asia in the summer, consistent with the occurrence of the monsoon. However, these increases are less clear over land, where the mountainous terrain often leads to a an orographic classification (Fig. 2k,ll). A winter increase in the convective regime is also observed over the Weddell sea, perhaps due to vertical motion generated by the mountains of the Antarctic Peninsular.

As a residual regime, the synoptic regime also shows seasonal variations in occurrence. However, these variations are less clearly a function of the meteorological situation. Variations in the synoptic regime occurrence follow those of the frontal regime in the mid-latitudes, with a higher synoptic regime occurrence in the summer hemisphere over the sub-tropical subsidence regions (Fig. 3c,f). These seasonal variations demonstrate the important of a regime decomposition when considering annual mean datasets.

3.4 Regime origins

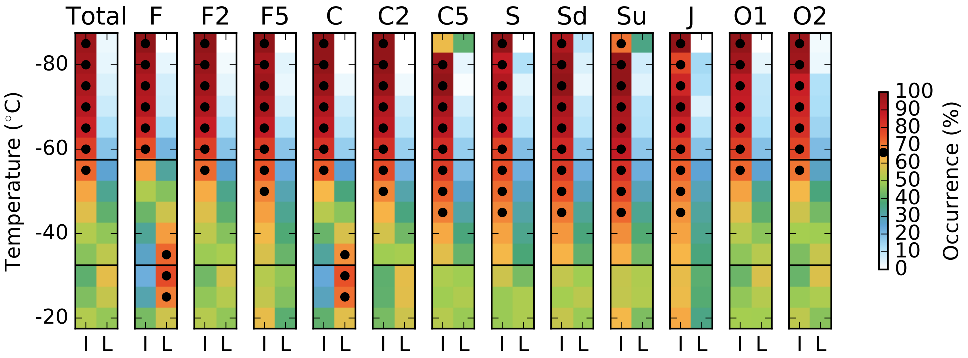

Figure 4. The probability of finding liquid or ice origin cirrus for each of the regimes over a north Atlantic region during 2007. The cirrus origin is from the dataset in Wernli et al. (2016), with “I” indicating “~~ice~~in-situ” origin and “L” indicating liquid origin. The plots are normalised such that the probabilities sum to one for each regime and temperature. The dots indicate more than two-thirds of clouds assigned to either liquid or ~~ice-origin~~ in-situ origin classes.

Although these regimes have not been created using explicit information about their origin (does the ice originate from liquid droplets, or was it formed directly), they can be compared with the classification of Wernli et al. (2016) over the north Atlantic to examine how skillfully they can determine the origin of different cirrus types. Fig. 4 shows the fraction of liquid and ~~ice~~ in-situ origin trajectories at each temperature level for each of the identified regimes during 2016 for the region depicted in Fig. 1c.

In all the regimes, almost all clouds colder than -60°C are formed directly as ice and many of those warmer than -40°C are originally formed as liquid (Fig. 4, “Total” column). However, there is considerable variation between the regimes between these temperatures.

The ~~in-situ regimes (I, Id, Iu~~synoptic regimes (S, Sd, Su) are composed of mostly ~~ice~~ in-situ origin cirrus, even at relatively warm temperatures (close to -30°C), providing evidence that the cirrus clouds in these ~~in-situ~~ synoptic regimes are really formed directly in the ice phase. In contrast, the frontal and convective regimes are much more commonly liquid origin cirrus at temperatures warmer than -40°C, and even at temperatures as cold as -50°C, the proportions of liquid and ~~ice~~ in-situ origin cirrus are almost equal. The frontal regimes show a slightly higher proportion of liquid origin cloud around -45°C than the convective regimes. This may be related to reduced effectiveness of the back-trajectories in regions where the parametrised convection is responsible for much of the vertical transport. The two and five degree buffer regions for both the frontal (F2, F5) and convective regimes (C2, C5) show more similarities to the ~~in-situ~~ synoptic regimes than the main regimes (C, F), suggesting that 5 degrees is a suitable buffering distance.

3.5 Updraught velocities

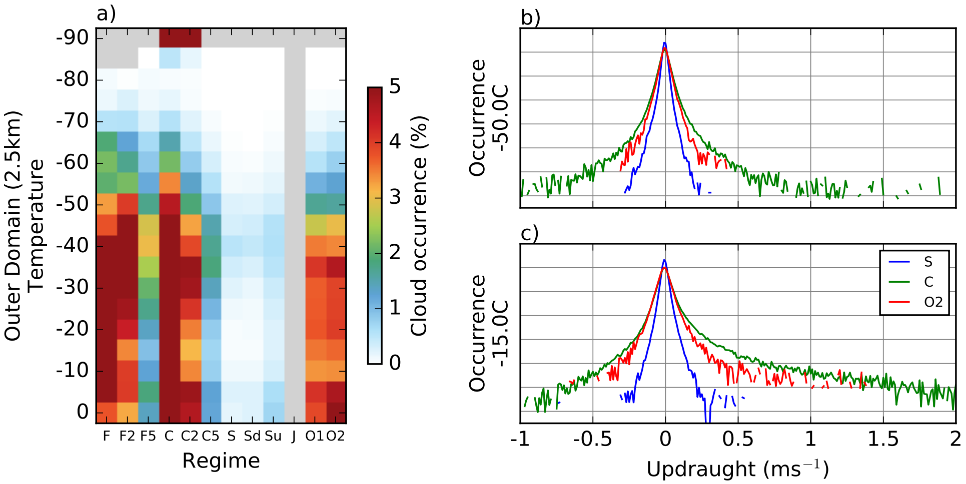

Figure 5. The properties of the observed regimes from within the one month ICON simulation, run in forecast mode. a) shows the vertical cloud occurrence fraction for each of the regimes. b) and c) show the updraught distributions for the ~~in-situ~~synoptic, convective and orographic regimes at -50C (b) and -15°C (c). The grey lines in b) and c) are gridlines.

The convection-permitting ICON simulations for the tropical Atlantic in August 2016 show many of the expected properties of the regimes. The cloud occurrence (Fig. 5a) is highest for the frontal and convective regimes, becoming lower for the buffer and the ~~in-situ~~ synoptic regimes. The orographic regimes also show an increased cloud fraction, although with lower cloud tops than the frontal and convective regimes. This demonstrates that the ICON simulation is able to adequately represent the meteorological situation, even when running in forecast mode and so can provide useful information on the properties of these regimes in the tropics.

There is a large variation in updraught velocity in the regimes (Figs. 5b,c), although this updraught variation is much more pronounced in the convective regime. The orographic regimes has a higher variability than the ~~in-situ~~ synoptic regime, but slightly lower than the convective regime, consistent with previous studies that have found high updraughts in orographic clouds. The convective regime has a long tail towards higher updraughts that is especially visible at lower levels in the atmosphere (Figs. 5b). This long tail results in the convective regime having a slightly larger mean in-cloud updraught than the ~~in-situ~~ synoptic regime (not shown). The difference in mean updraught velocity is minimised as clouds are rarer in the ~~in-situ~~ synoptic regimes, forming only at the highest available updraughts within the regime.

At higher altitudes, the updraught distributions become more symmetrical. While the variability of the distributions (especially in the convective regime) is reduced, the convective and orographic regimes still have a broader distribution than the ~~in-situ~~ synoptic regime. This shows that even at high altitudes, higher updraughts are still more common in the convective and orographic regimes than in the ~~in-situ~~ synoptic regime. The results demonstrate that the classification proposed here is able to provide useful information on the vertical velocity environment of the clouds that cannot be resolved using reanalysis data.

3.6 Cloud optical depth by regime

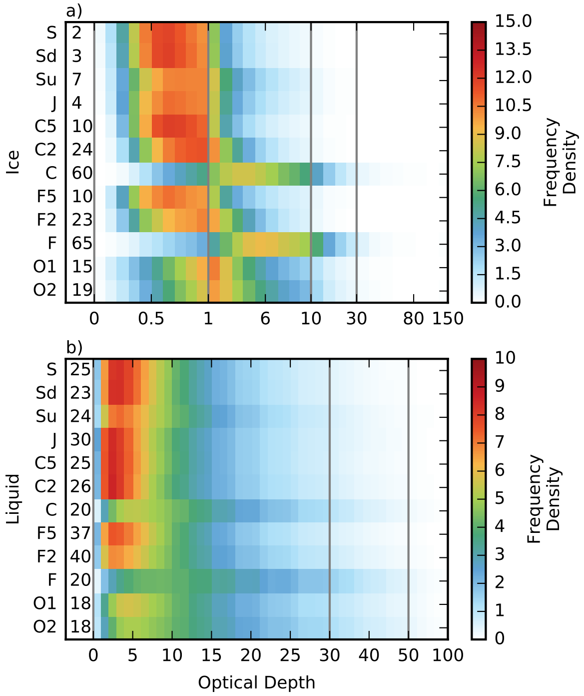

Figure 6. The mean normalised MODIS collection 6 cloud optical depth (COD) distribution for each of the regimes, showing clouds classified as a) ice-phase and b) liquid-phase separately. The bins are taken from the MODIS level 3 daily product, vertical lines indicate a change in bin width. The frequency density is normalised by the bin width and sums to one within each regime. The numbers along the right-hand edge of each plot show the percentage occurrence of valid retrievals within that regime (analogous to a cloud fraction). Note the different scale for the two plots.

There is not a strong distinction between cloud optical depths of most of the regimes. The ice optical depth frequency density is highest below an optical depth of 1 for the majority of the regimes. The main exceptions to this are the frontal (F) and convective (C) regimes, as these regimes are selected based on their mean ice cloud optical depth. These regimes also have a much higher occurrence of ice cloud than the other regimes with fractional occurrences of 65 and 60% respectively. While the 2 degree buffer regimes C2 and F2 are noticeably different from the synoptic regimes, the 5 degree regimes are have a very similar optical depth distribution, again suggesting that 5 degrees is a suitable buffer distance. The orographic regimes both show a larger average cloud optical depth, particularly in the O2 regime, suggesting that the increased in-cloud updraught in these and the convective regime (Fig. 5) has an important part to play in determining the cloud optical depth.

The liquid optical depths for the regimes are very similar between the regimes, with a maximum frequency density at an optical depth of about 5 for most regimes. Again, the F and C regimes have an optical depth distribution skewed towards larger values, but they have a lower fractional occurrence due to the overlying ice cloud. The similarities in the optical depth distributions of the regimes, despite the different updraught (Fig. 5) and ice origins (Fig. 4) of the regimes demonstrates how the retrieved cloud properties alone are insufficient for fully identifying the cirrus cloud formation mechanisms.

3.7 Cloud radiative effect by regime

The CRE for each of the regimes (Fig. 7a) makes it clear that although some of the regimes have similar properties and origins, the mean CRE of the regimes occur in different locations in CRE space. The 25 and 75% quantiles for each of the regimes indicate that the regimes are not as distinct radiatively as regimes defined using the cloud optical depth and CTP (Oreopoulos et al., 2016), with significant variation in CRE within the regimes.

Both the frontal and convective regimes have a strong negative SW and positive LW CRE, with the convective regime having a stronger LW and SW CRE than the frontal regime, although they both have very similar net CREs. This is due to the large optical depth of these regimes (Fig. 6). The two degree buffer regimes (C2, F2) fall between the main convective and frontal regimes and the rest of the cloud regimes, showing that the buffering is necessary to separate the ~~in-situ~~ synoptic regimes. The remainder of the regimes, including the five degree buffer regimes (C5, F5), have very similar CREs, suggesting that a five degree buffer region is sufficient to separate the ~~in-situ~~ synoptic regimes from the frontal and convective regimes. The jet stream cirrus regime (J) falls between F5 and the ~~in-situ~~ synoptic regimes, highlighting its composition as a hybrid between the frontal and the ~~in-situ~~ synoptic types. The ~~in-situ regimes (I, Iu and Id~~synoptic regimes (S, Su and Sd) occupy a separate cluster, with the ~~in-situ~~ synoptic regimes having a smaller LW CRE, indicating a differing albedo-cloud top temperature relationship for these cloud types.

Despite the strong CRE in the frontal and convective regimes, they do not dominate the global CRE in the same way (Fig. 7b), particularly in the SW, due to their low RFO of around 6% (Fig. ~~7a~~2). The frontal and convective regimes contribute around ~~12~~15% of the global mean CRE in both the SW and the LW, while the ~~in-situ~~ synoptic and orographic regimes both contribute between 5% and 10%. However, it should be noted that this CRE is calculated for all of the clouds that occur in the gridbox, not just for the high clouds. As such, the occurrence of low clouds may influence the CRE calculated for the regimes, especially where the high cloud is thin. Given the high RFO of the ~~in-situ~~ synoptic regimes in the subtropics, their large SW CRE contribution may be due to underlying stratocumulus clouds ~~.~~ with a significant liquid cloud optical depth (Fig. 6b).

The contribution of the underlying clouds can be seen by comparing the results using only gridboxes with more than 99% of the MODIS observed cloud top pressures less than 550 hPa (Fig. 7c). While this does not completely separate the CRE of the high clouds (especially for vertically extensive clouds), it provides an idea of the CRE of the overlying high clouds. This indicates that the majority of the regimes have a very small contribution to the net CRE, with the SW and LW components roughly offsetting each other. The convective and frontal regimes are the exception, both having a strong negative total CRE.

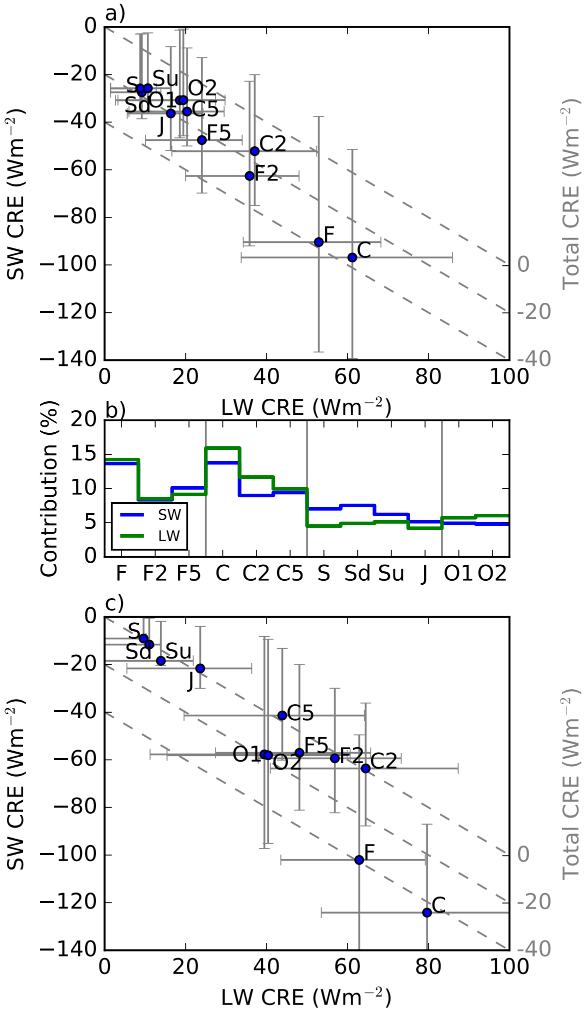

Figure 7. a) The daily, constant-meteorology mean cloud radiative effect (CRE) in the SW and LW for each of the regimes from CERES SYN1deg daily data. A negative value shows a cooling effect and the dashed grey lines are lines to constant net CRE. b) The contribution to the SW and LW global CRE from each regime. c) As (a), but using only pixels where 99% of the MODIS cloud top pressure retrievals are less than 550 hPa. The errorbars show the 25% and 75% quantiles for each regime.

One of the biggest changes is found in the ~~in-situ~~ synoptic regimes, where removing the low cloud has very little effect on the LW CRE, but a large reduction to the magnitude of the SW CRE, resulting in a slightly positive net CRE, similar to the results in previous work (Hartmann et al., 1992; Chen et al., 2000, e.g.)). This highlights the impact of the underlying low clouds in this regime and smaller effect of fractional cloud cover increases in the ~~in-situ~~ synoptic regime on the SW CRE due to this underlying low cloud. For the buffer regimes, the main effect of removing lower cloud is to increase the LW CRE. This is expected as it reduces the regime mean cloud top temperature, increasing the LW CRE. The small corresponding change in the SW CRE indicates that these regimes are not strongly affected by the presence of large amounts of low cloud.

4 Discussion

The results of the previous section show that by separating cirrus clouds according to their source, this classification provides information on the origin of the ice crystals in a cloud as well as the cloud-scale updraughts. This combination of satellite and reanalysis data provides extra information about the cloud properties that can be used to separate out cloud types and for future studies into cloud processes. However, there are still a number of improvements that could be made in future versions of the scheme.

One issue with this classification is that it is resolution dependent. This has a potential impact for defining the orographic regimes, where ~~a large scale vertical velocity would have to be used once~~ the ~~resolution increases to the extent that a large amount of the topography is~~ windspeed-surface topography variation product used to define these regimes becomes small once the topography is sufficiently resolved. Defining the regimes at a different spatial resolution would require a re-calibration of some of the constants used in the classification. Whilst this could potentially be an issue for very high resolution models, the output from these models could be used on a lower resolution grid (as is demonstrated in section 3.5 of this work).

Another area for improvement is the use of the MODIS satellite data “blobs” within the scheme. These “blobs” are used to define regions of cloud that are connected and that intersect the meteorological conditions necessary for the formation of the frontal and convective types of cirrus, but this use highlights our current uncertainty about the best way to assign clouds to these regimes. These “blobs” require subjective choices for the definition of a “blob” and limit the regimes to being determined at 13:30 LST (the satellite overpass time). Future improvements to this scheme could use cloudy regions determined from the reanalysis, which would allow the classification to be generated at night, although the subjective definitions of cloud “blobs” would remain.

Another significant issue is that the classification is instantaneous, in that it only takes into account the meteorological and retrieved cloud properties at the moment of classification. As the classification has been designed for use with data from the A-train, this does not present a problem for investigating the properties of these regimes, but cirrus clouds are known to travel a considerable distance from convective source regions (Luo and Rossow, 2004). Although the convective regimes does a good job of selecting high updraught clouds, there is clear scope for improvement. Possible methods include back-trajectories (e.g. Gehlot and Quaas, 2012) and cloud-object tracking, but until more information is available about the factors controlling cirrus cloud lifetime, conclusively linking an observed cirrus cloud to a convective event that took place days ago using reanalysis data continues to prove challenging. As many convective origin cirrus remain in the tropical region where the convective regime occurs, it is possible that they are already assigned to the convective (C) or buffer regimes (C2, C5), although future work will be undertaken to explore this possibility.

5 Conclusions

In this work, a method of classifying cirrus clouds based on their origin has been demonstrated. This method makes use of re-analysis data to determine likely locations for frontal and convective cirrus. Combining this with satellite cloud observations from MODIS, cirrus clouds are assigned to frontal or convective regimes over ocean or regimes based on the surface roughness over land. Any pixels that are not assigned to one of these classes are considered likely candidates for ~~in-situ~~ synoptic cirrus formation. The classification finds frontal regimes primarily in the extratropical storm-track regions (Fig. 2), with the convective regime occurring primarily in the tropics. Possible locations for ~~in-situ~~ synoptic clouds are found globally, particularly regions of large scale subsidence in the subtropics and polar regions. Orographic clouds are defined using a combination of the reanalysis windspeed and local sub-grid topography, similar to the parametrisations used in many GCMs. Significant seasonal variation is also observed in the occurrence of the frontal, convective and synoptic regimes (Fig. 3).

When compared to the classification from (Wernli et al., 2016, Fig.4), it is shown that the regimes presented here are able to provide useful information on the origin of cirrus clouds (liquid or ice). The ~~in-situ~~ synoptic regimes in this classification are primarily composed of in-situ ~~/ice-origin~~ origin cirrus clouds, even to temperatures as warm as -20°C, while the frontal and convective regimes contain a much higher proportion of liquid-origin cirrus to much colder temperatures. At temperatures below -60°C, almost all the observed clouds are ~~ice/~~in-situ origin cirrus.

Simulations with a high-resolution model show that the classification is also able to provide information on the updraught environment experienced by the clouds in each regime. In high-resolution simulations of the tropics, the convective regime has a significantly more variable updraught environment, with much more common strong updraughts and downdraughts than the ~~in-situ~~ synoptic regimes (Fig. 5). The convective regime also has a long tail of positive updraughts, leading to a higher mean in-cloud updraught than found in the ~~in-situ~~ synoptic regimes. These results demonstrate the ability of this classification to provide information on the ice origin and in-cloud updraught that are not easily obtained from re-analysis data.

As seen in previous studies ~~, the~~ (e.g. Hartmann et al., 1992), the mean net cloud radiative ~~forcing~~ effect (CRE) is negative, but with significant variation amongst the regimes (Fig. 7a). The frontal and convective regimes have the strongest LW, SW and net negative CRE. The CRE for the ~~in-situ~~ synoptic regimes is strongly affected by underlying low cloud. Although the regime has a negative net CRE overall, when low clouds are removed, the net CRE is ~~close to zero~~ slightly positive due to a large reduction in the SW CRE (Fig. 7c). When regions with cloud top pressures lower than 550 hPa are removed, the net CRE for all of the regimes other than the frontal and convective regimes is close to zero.

Although there are some shortcomings to this classification, future work is planned to improve the selectivity and specificity of the regimes. However, they currently show significant skill in separating different cirrus types and provide a suitable starting point for investigating the differences between the properties and lifecycle of different cirrus types.

Data access: Preliminary agreement has been received to place the regime classification online at the British Atmospheric Data Centre (BADC) with a doi being assigned once the classification is finalised.

Acknowledgements. The authors would like to thank Heini Wernli (ETH Zürich) for providing data and for his helpful comments on the manuscript. The MODIS data are from the NASA Goddard Space Flight Center. The CERES data are from the NASA Langley Research Center. The GMTED2010 data is available from the U.S. Geological Survey. This work was supported by funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement no. FP7-306284 (QUAERERE). EG was supported by an Imperial College Junior Research Fellowship. TG received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 703880. DK is supported by the Hans Ertel Center for Weather Research (HErZ), a German research network of universities, research institutions and the Deutscher Wetterdienst is funded by the BMVI (Federal Ministry of Transport and Digital Infrastructure).

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