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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, 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. Using re-analysis and satellite data, cirrus clouds are separated in four main types: orographic, frontal, convective and in-situ. Through a comparison to convection-permitting model simulations and back-trajectory based analysis, it is shown that the regimes can provide extra information on the properties and origin of cirrus that could not be provided by the retrieved cloud properties or reanalysis data alone. 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 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 cirrus clouds tend to have a positive cloud radiative effect (warming the atmosphere)(Chen et al., 2000), their radiative properties are strongly controlled by their altitude and water content in addition to their microphysical properties, particularly the ice crystal number concentration (ICNC) and 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, perhaps by orders of magnitude (Kärcher and Lohmann, 2003) 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. 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 and the ice crystal size distribution (e.g. 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 contain liquid water to temperatures as low as -37°C (Rosenfeld, 2000), suggesting an important role of liquid origin ice, whilst 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) has recently been demonstrated by Krämer et al. (2016).

Understanding how cirrus clouds and the ICNC in particular respond to these four factors (temperature, in-cloud updraught, liquid/ice 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 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). 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

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 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) 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, in addition to regimes describing low cloud properties (e.g. Rossow et al., 2005; Gryspeerdt and Stier, 2012; 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 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 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 to examine how much information it provides on the ice origin and the cloud-scale updraughts. 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 through large scale rising motions. These are divided into the twelve cirrus cloud regimes specified in Tab. 1. Each $1^\circ \times 1^\circ$ 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. 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, with the first set of criteria that are satisfied determines the regime.

1. Orographic clouds

   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 and the surface topography variation (the difference between the mean and minimum altitude within each $1^\circ \times 1^\circ$ degree gridbox). The topographic data is from the United States Geological Survey GMTED2010 dataset gridded to $0.1^\circ \times 0.1^\circ$ resolution.

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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	Within blob that intersects front
8	F2	Front 2deg	Within 2° of front/class 9
7	F5	Front 5deg	Within 5° of front/class 9
6	C	Conv	Within a blob and in a region of negative ω(500 hPa)
5	C2	Conv 2deg	Within 2° of conv/class 6
4	C5	Conv 5deg	Within 5° of conv/class 6
3	J	Jet	Windspeed(300 hPa) $> 30\,\mathrm{ms}^{-1}$
2	Iu	Insitu wu	Negative ω(500 hPa)
1	Id	Insitu wd	ω(500 hPa) $< 0.05\,\mathrm{Pa\,s}^{-1}$
0	I	Insitu sd	None of the above

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

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Gridboxes falling into approximately the upper tercile of updraughts are assigned to orographic regimes. Those with a windspeed-height variation product of greater than 880 $\mathrm{m^2s^{-1}}$ are assigned to the O1 regime (Tab. 1), with those with a windspeed-height 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

Fronts are determined using an objective front detection method based on (Hewson, 1998), using the wet bulb temperature (θ_w) at 850 hPa calculated from ERA-Interim reanalysis (Dee et al., 2011) at a $1^\circ \times 1^\circ$ resolution. 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

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a single six hour reanalysis timestep are removed, as are fronts that pass through less than ten $1° \times 1°$ 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 cloud data from the moderate resolution imaging spectroradiometer (MODIS) instrument on the Aqua satellite (Platnick et al., 2017) (MYD08_D3). The "blobs" are defined as contiguous 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 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.

3. Convective clouds

Cirrus from convective (non-frontal) clouds is determined using the same "blobs" that are used for the frontal cloud detection. 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 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 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 cirrus regime. Locations with a negative ω_{500} form the in-situ updraught regime (Iu), a positive ω_{500} less than 0.05 Pa s^{-1} the in-situ weak-updraught (Id) and the remaining form the final in-situ regime (I). The in-situ regimes are the residual regimes, assigned after the more clearly-defined classes.

Whilst these classes do not cover every formation method of cirrus clouds, 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 origin at each temperature is calculated, with the same regime assigned at all temperatures within each lat-lon gridbox.

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 $1^{\circ}\times1^{\circ}$ 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. 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

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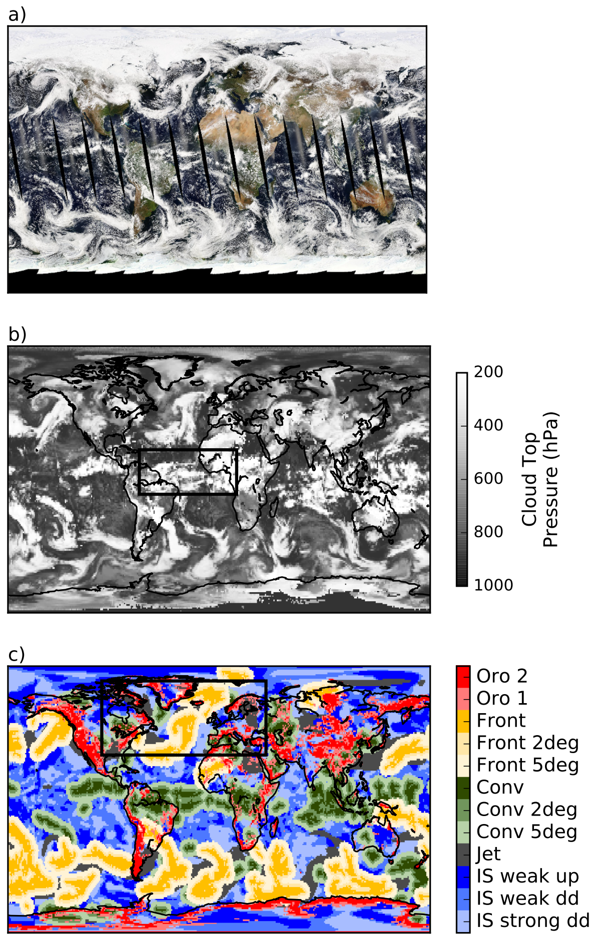

Figure 1. a) A MODIS Aqua true-colour image for the 12th of April, 2007. b) The MODIS daytime cloud top pressure, in-filled with the night-time CTP where no daytime retrieval exists. The box in the tropics shows the location of the regional ICON simulation. c) The classification presented in this work, 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).

altitude, they are clearly distinct, with the east Antarctica plateau being classed as primarily in-situ 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.

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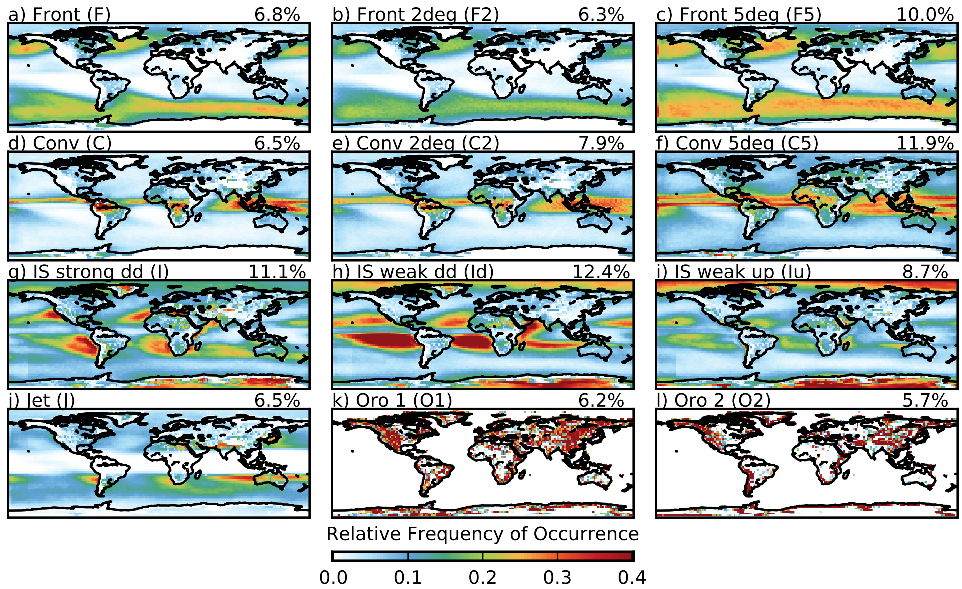

Figure 2. The relative frequency of occurrence of the different regimes over a ten year period (2003-2013). The frequencies are normalised so that they sum to one in each gridbox. The latitude weighted mean RFO for each regime is shown at the top right for each subplot.

3.2 Relative frequency of occurrence

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 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 Regime origins

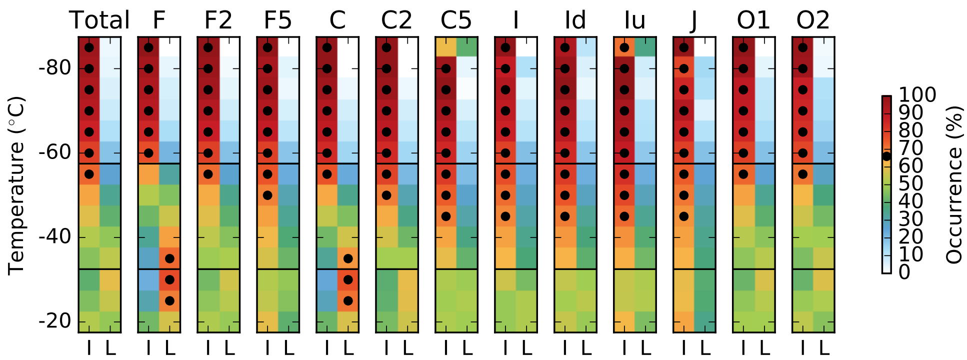

Figure 3. The probability of finding liquid or ice origin cirrus for each of the regimes over a north Atlantic region during 2007. The cirrus origin is from the dataset in Wernli et al. (2016), with "I" indicating "ice" origin and "L" indicating liquid origin. The plots are normalised such that the probabilities sum to one for each regime and temperature. The dots indicate more than two-thirds of clouds assigned to either liquid or ice-origin 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. 3 shows the fraction of liquid and ice 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. 3, "Total" column). However, there is considerable variation between the regimes between these temperatures.

The in-situ regimes (I, Id, Iu) are composed of mostly ice origin cirrus, even at relatively warm temperatures (close to -30°C), providing evidence that the cirrus clouds in these in-situ 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 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 regimes than the main regimes (C, F), suggesting that 5 degrees is a suitable buffering distance.

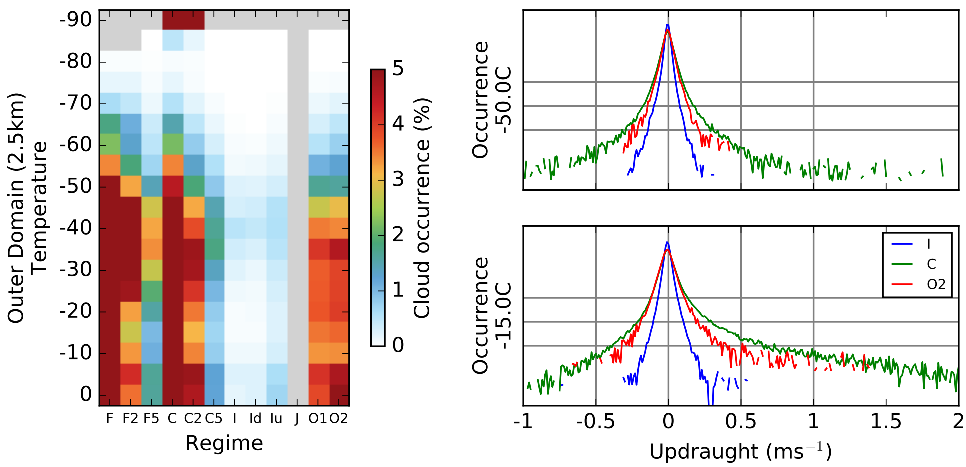

Figure 4. The properties of the observed regimes from within the one month ICON simulation, run in forecast mode. a) shows the vertical cloud occurrence fraction for each of the regimes. b) and c) show the updraught distributions for the in-situ, convective and orographic regimes at -50C (b) and -15°C (c).

3.4 Updraught velocities

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. 4a) is highest for the frontal and convective regimes, becoming lower for the buffer and the in-situ 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. 4b,c), although this updraught variation is much more pronounced in the convective regime. The orographic regimes has a higher variability than the in-situ 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. 4b). This long tail results in the convective regime having a slightly larger mean in-cloud updraught than the in-situ regime (not shown). The difference in mean updraught velocity is minimised as clouds are rarer in the in-situ 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 regime. This shows that even at high altitudes, higher updraughts are still more common in the convective and oro-

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graphic regimes than in the in-situ 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.

3.5 Cloud radiative effect by regime

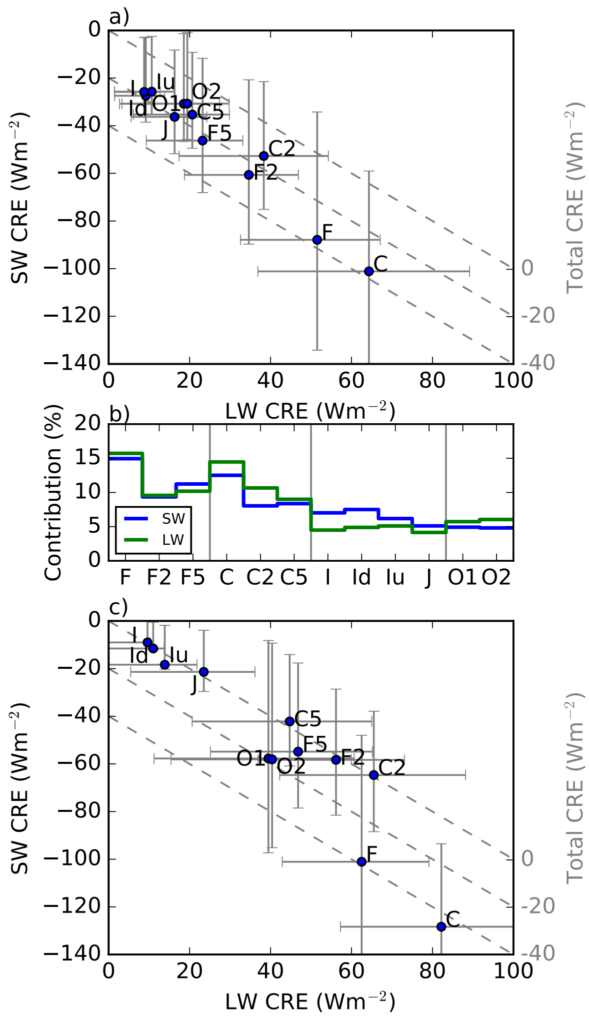

Figure 5. a) The daily, constant-meteorology mean cloud radiative effect (CRE) in the SW and LW for each of the regimes from CERES SYN1deg daily data. A negative value shows a cooling effect and the dashed grey lines are lines to constant net CRE. b) The contribution to the SW and LW global CRE from 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.

The CRE for each of the regimes (Fig. 5a) 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. 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 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 regimes from the frontal and convective regimes. The jet stream cirrus regime (J) falls between F5 and the in-situ regimes, highlighting its composition as a hybrid between the frontal and the in-situ types. The in-situ regimes (I, Iu and Id) occupy a separate cluster, with the in-situ 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. 5b), particularly in the SW, due to their low RFO (Fig. 5a). The frontal convective regimes contribute around 12% of the global mean CRE in both the SW and the LW, while the in-situ 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 regimes in the subtropics, their large SW CRE contribution may be due to underlying stratocumulus clouds.

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. 5c). 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.

One of the biggest changes is found in the in-situ 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. This highlights the impact of the underlying low clouds in this regime and smaller effect of fractional cloud cover increases in the in-situ 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.

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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 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 3.4 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 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 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.

When compared to the classification from (Wernli et al., 2016, Fig.3), 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 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. 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 regimes (Fig. 4). 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 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 net cloud radiative forcing (CRE) is negative, but with significant variation amongst the regimes (Fig. 5a). The frontal and convective regimes have the strongest LW, SW and net negative CRE. The CRE for the in-situ 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 due to a large reduction in the SW CRE (Fig. 5c). 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.

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