Investigating the Effect of Aerosol Height on Deep Convective Cloud Formation

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1 Abstract

This study aims to assess the use of the CloudSat (radar) and CALIPSO (lidar) satellite datasets to investigate the effect of differing vertical distributions of aerosols on the strength of convection in deep convective clouds. It is found that the method used in this study is not appropriate due to the strong effect of selection bias in its classification of the vertical distributions which, when combined with its inability in tracking individual clouds as they develop, mask any possible agreement with models in previous studies. Additionally, this study uses these datasets to try to confirm previous findings regarding the differing effects of aerosol type on the strength of convection in these clouds. However, the data analysed here does not appear to support previous conclusions. This is most evident polluted continental aerosols which are here found to have a strong inhibiting effect on convection where previously they were found to have a strong invigorating effect.

2 Introduction

The relationship between different aerosol types and the formation of deep convective clouds (DCCs) is not yet fully understood. There is evidence to suggest that, under differing conditions, aerosols can both invigorate convection and reduce it depending on the aerosol and its concentration in the area [1]. This alters how clouds form in the presence of aerosols and, given clouds contribute strongly to the global energy budget [2], studying these effects can help better understand the influence these varying aerosols can have on the climate and climate change.

Clouds form as lifted humid air from near the ground cools adiabatically enough to become supersaturated with water vapour [2]. At this point the vapour condenses into droplets or freezes into ice crystals. Introducing an aerosol that acts as cloud condensation nuclei effectively increases the ability of a supersaturated parcel of air to form water droplets or ice crystals because these act as nucleation points where this process can begin [2]. As the water vapour condenses, latent heat is released and this invigorates convection in the forming cloud. If that aerosol is present, latent heat could be released more rapidly and so the strength of convection is expected to be greater. Some aerosols might instead act against this process and thus inhibit convection within a forming cloud.

In previous studies (such as in Jiang et al. [1]), the optical depth of aerosol layers is used as a measure of aerosol concentration to compare against the height of the ice water content weighted centroid of deep convective clouds formed in those environments. This ice weighted centroid (IWC) is used to give an idea of the strength of convection in each cloud where the higher the altitude of the ice weighted centroid, the greater the assumed strength of convection. Its calculation is given by equation 1, where Z_{ice} is the IWC, I is the ice water content at height z between the cloud base z_{base} and top z_{top}.

$$Z_{ice} = \frac{\int_{z_{base}}^{z_{top}} I \cdot z \, dz}{\int_{z_{base}}^{z_{top}} I \, dz} \quad (1)$$

Optical depth is defined by the difference in the logarithm of the intensities of radiation between set start and end points on its path at a specific wavelength [3] (equation 2). Alternatively, it can be defined as the negative logarithm of the transmittance between those points, at that wavelength [3] (equation 3). Here the start and end points are the top and bottom of the atmosphere with the wavelength being 532 nm. The intuition for using this as a measure of concentration of aerosols is: given individual particles of these aerosols scatter, absorb and reflect radiation at 532 nm, their presence will reduce the transmittance of that radiation through a section of atmosphere. Additionally, the greater number of these particles in the given section, the greater their effect on the transmittance. Thus, where there is greater concentration of aerosols, optical depth will also be greater.

$$\tau = \ln[I_\lambda(s_1)] - \ln[I_\lambda(s_2)] \tag{2}$$

$$\tau = -\ln\,[t(s_1, s_2)] \tag{3}$$

In equations 2 and 3: τ is the optical depth, I_λ is the intensity at wavelength λ, and t is the transmittance between the points s_1 and s_2.

In this study, the heights of the aerosol layers will be taken into account. This is motivated by models which suggest that the relative heights of the aerosol layers compared to the cloud base should have an effect on the amount of that aerosol that gets into the cloud as it forms [4] and should thus have a different degree of effect on that formation. For example, if the aerosol provides cloud condensation nuclei, there will be a larger invigorating effect on convection for environments where the aerosol has a greater concentration within the cloud. One model, used in Zhang et al. [4], suggests that aerosol layers that overlap in height with a cloud's base will result in a larger volume of that aerosol entering the cloud than if the layer is separated in height above or below the cloud base.

3 Methodology

3.1 Sources of the Data

The cloud data used for this project come from CloudSat using the 2B-CLDCLASS-LIDAR [5] and 2C-ICE [6] datasets to get the locations, timestamps, cloud base heights, cloud top heights and ice water content distributions for each identified DCC. CloudSat was a satellite in the A-Train constellation of satellites and used radar to investigate the structure of clouds. The 2B-CLDCLASS-LIDAR data product uses a combination of the CloudSat and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) data to identify clouds with their classifications. CALIPSO being another satellite in the same constellation that uses lidar alongside passive infrared and visible sensors [7] to look at thin clouds and aerosols in the atmosphere. The 2C-ICE similarly uses a combination of CloudSat and CALIPSO data to estimate ice water content in vertical bins for each profile. CloudSat measurements for altitudes below ~1km are subject to ground contamination so cloud profiles that drop below this threshold were excluded from this study [8].

The aerosol data come from CALIPSO using the LID_L2_05kmALay-Standard-V4-51 [9] dataset to get the aerosol classification, distribution and optical depth data within a 55 km distance from the edges of the identified DCC. A 55 km distance is used to strike a balance between the number of profiles from which aerosol data can be taken and proximity to the cloud that those profiles are assumed to be able to affect. This data is used as CloudSat and CALIPSO were both part of the A-Train constellation for the duration relevant to this study and so gave well co-located profiles due to their proximity. Aerosol classification is given in profiles of varying degrees of horizontal averaging, the minimum of which being 5 km. Identified layers at altitudes below 0.5 km are excluded from this study to limit the effect of ground contamination.

For this study, an area over South America (0 to 30° S and 30 to 80° W) was chosen to investigate to allow for a simpler comparison with Jiang et al. [1] which uses the same area for their South America data. The data used also covers a period from January 2007 to December 2015, a longer time period than Jiang et al.

3.2 Process for Collating the Relevant Data

First, the profiles in the included CloudSat [5] data are filtered down to only those that contain DCCs and are grouped into individual clouds using a distance threshold between filtered profiles of 0.01° chosen to be smaller than the smallest horizontal averaging used for the aerosol data but also large enough to ensure that clouds containing a single misidentified profile would not be split in two. These individual clouds are then associated with their average cloud bases, tops and IWCs. In this calculation, it is assumed that the ice water content is constant in each vertical bin in the dataset [6]. This assumption produced results differing on the order of 10 m when compared to interpolating the ice water content data over the extent of each cloud from the given bin data. In comparison to the standard deviations in IWC which tend to be on the order of 1km, this assumption is considered to introduce only a small additional error to the IWC's that can be neglected.

Secondly, an area is defined by extending the edges of the identified DCCs by 55km in which the aerosol distribution and classifications are analysed to classify the environment surrounding each DCC with an aerosol type. This is done by defining any environments where no aerosols are present as clean and then by any aerosol that takes up a >0.75 fraction of all the aerosol layers within the area. The rest of the profiles are not included. This 0.75 fraction is used such that areas where not many aerosols are detected are not underrepresented in this study whilst also ensuring that only areas where the aerosols detected are dominated by one type are classified under that type.

Thirdly, the vertical distributions of the aerosols are separated into 4 categories: above the cloud top, within the extent of the cloud, at the base of the cloud, and below the cloud base. An aerosol layer is defined to be at the base of the cloud if any of its vertical extent overlaps with the height of the base of the cloud plus or minus the standard error on the cloud base. In the same way that the aerosol environments were classified, a cloud's vertical environment is defined when a fraction of >0.75 of the aerosol layers sit in the same vertical category.

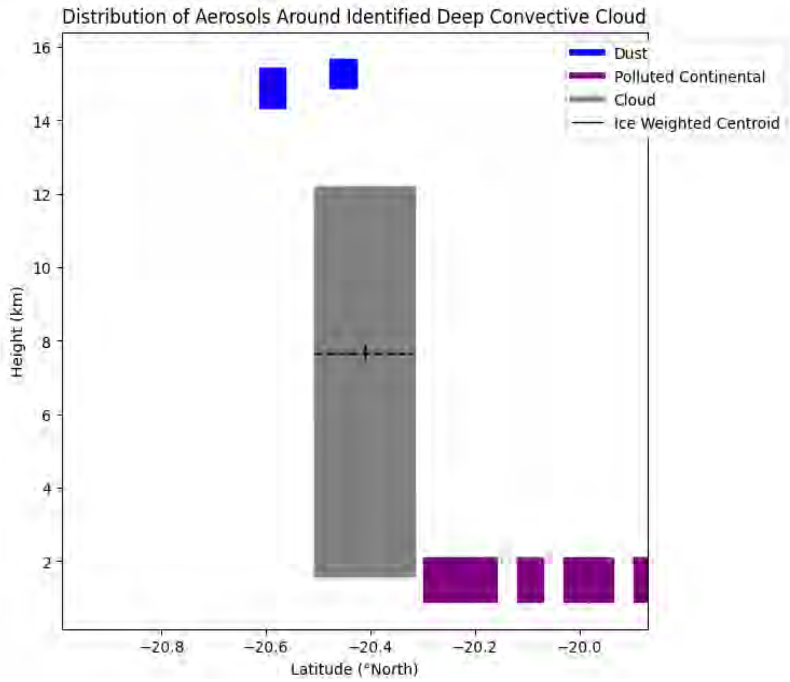

Figure 1: An example plot to illustrate an aerosol environment around a DCC. The identified aerosol layers are directly plotted from the CALIPSO dataset used while the cloud is plotted from its calculated mean base and top heights. This is an example that would be classfied as a 'polluted continental' environment due to its dominance compared to the number of dust profiles. Additionally, the aerosol is taken to be at the base of the cloud.

4 Results

4.1 Effect of Aerosol Type Alone

Figure 2 plots average differences in IWC of DCCs in 4 different aerosol environments from the clean environment average. The vertical distributions of the aerosols are not yet considered. Additionally, these average differences are taken for each month of all the years together to limit the effect that seasonal differences might have on the data. For example, if the winter had a higher general humidity than other seasons but saw a reduced volume of polluted continental aerosols in the area, taking an overall average difference would be skewed to a reduced IWC in DCCs in polluted continental aerosol dominated environments compared to the clean environment.

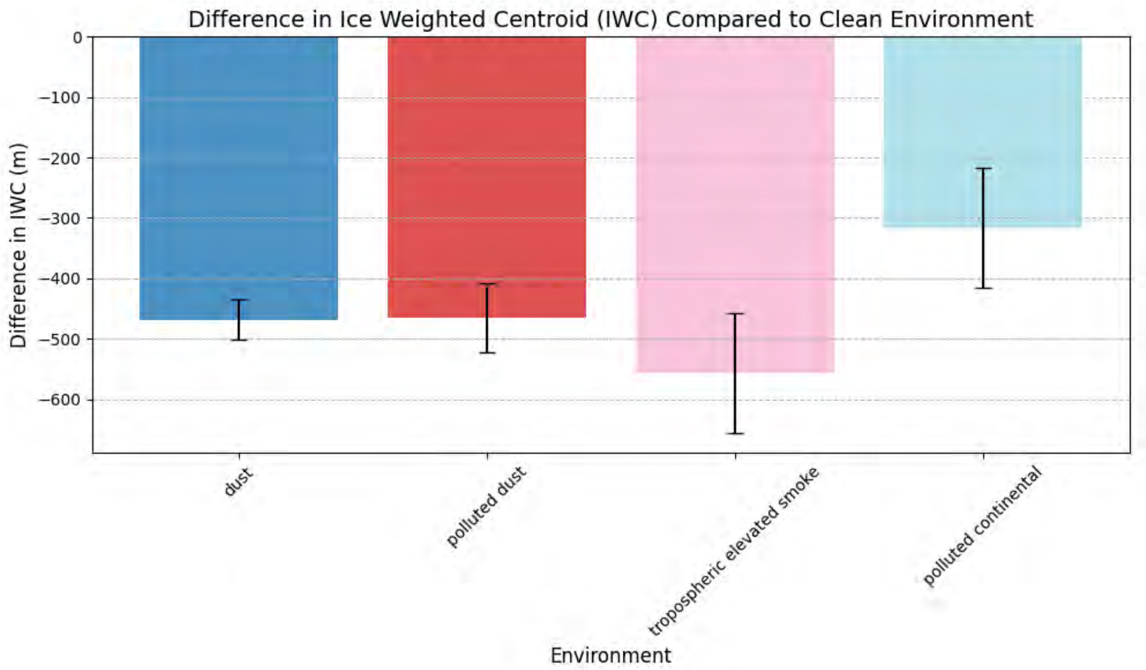

Figure 2: A bar chart showing the difference in the average IWCs from the clean environment average of each month (across all years) for DCCs in 4 categories of environments defined by the dominant aerosol for each. The errors shown represent the standard errors for the calculated average differences. Chart only includes environments for which at least 100 datapoints were available. The number of available datapoints for each are as follows: clean – 8479, dust – 2569, polluted dust – 799, elevated smoke – 312, and polluted continental – 305.

While figure 2 does demonstrate that different aerosol types have differing effects on the strength of convection in DCCs in agreement with the existing literature, it does not agree with previous studies such as Jiang et al. [1] on the exact nature of these effects. Most clearly, in that previous study it is shown that polluted continental aerosols have a strong invigorating effect on convection for both this area over South America and over Southeast Asia; while over South Africa there is a smaller but still positive effect. In direct contrast, this study finds that all 4 of the studied aerosols have an inhibiting effect on the strength of convection. This is unexpected since Jiang et al used very similar datasets to this study - differing only by the version number - and covered a timeframe from June 2006 to December 2010 which overlaps with the timeframe of this study. While there are some differences in the processing of the data (for example, Jiang et al. interpolates ice water content into new vertical bins from which it then calculates the IWC of each cloud), these do not explain the discrepancies.

Additionally, the newer versions of the datasets are not expected to have made such a large difference. For CALIPSO, the changes for the newer version addresses: stratospheric aerosol classification; above cloud smoke layer accuracy; particulate optical depths above opaque water clouds or from ocean surface returns; and a correction to some clouds being misidentified as aerosols in single-shot detection [10]. Stratospheric aerosols did not dominate enough environments in the study to be included; the smoke layer correction only effects a low number of smoke layers in the studied area; the relevant differences in particulate optical depths are attributed to the smoke layer corrections; and the cloud misidentification affects ~3% of layers clustered around smoke and desert dust [10]. For CloudSat, the main relevant change for the newest version is that 'some extensive shallow precipitating clouds were classified as the deep convective clouds' [11] previously although, the extent to which this occurred is unclear.

Making a similar comparison with the same study for the response to varying aerosol concentrations (figure 3), most of the data still does not seem to agree.

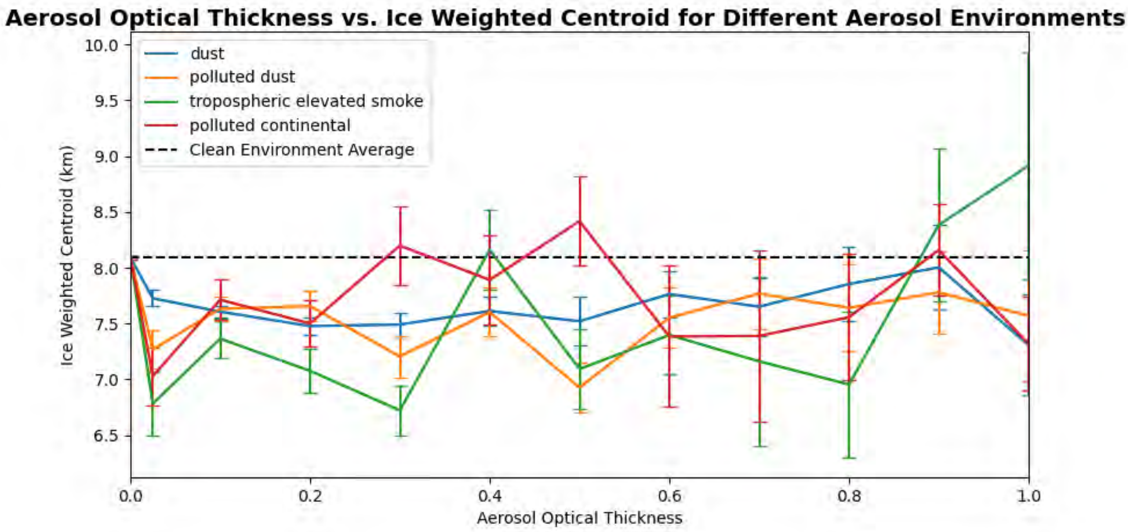

Figure 3: A plot of IWC against aerosol optical thickness for DCCs in environments dominated by different aerosol types. The errors shown represent the standard error for each bin.

The only data which appears to have some agreement with Jiang et al [1] is the shape of the curve for dust dominated environments. Whilst not seen in the previous study's data for South America, the other two plots of IWC against aerosol loading for dust in that study do have an initial drop in IWC for low loading followed by a steady increase as the optical thickness increases further. However, in this study, the IWC for dust dominated environments does not recover past the clean environment average, but Jiang et al finds that there begins to be an invigorating effect on convection for high dust concentrations which is not represented here. As before, these discrepancies are unexpected and cannot be simply explained by the differences in the processing of the datasets between the two studies.

4.2 Effect of the Relative Height of Aerosols to the Cloud Bases

Figure 4 again uses month based average differences in IWC for dust dominated environments compared to the clean environment IWC for the same reason as in the previous section: to reduce the impact of seasonal variations on the findings in this study.

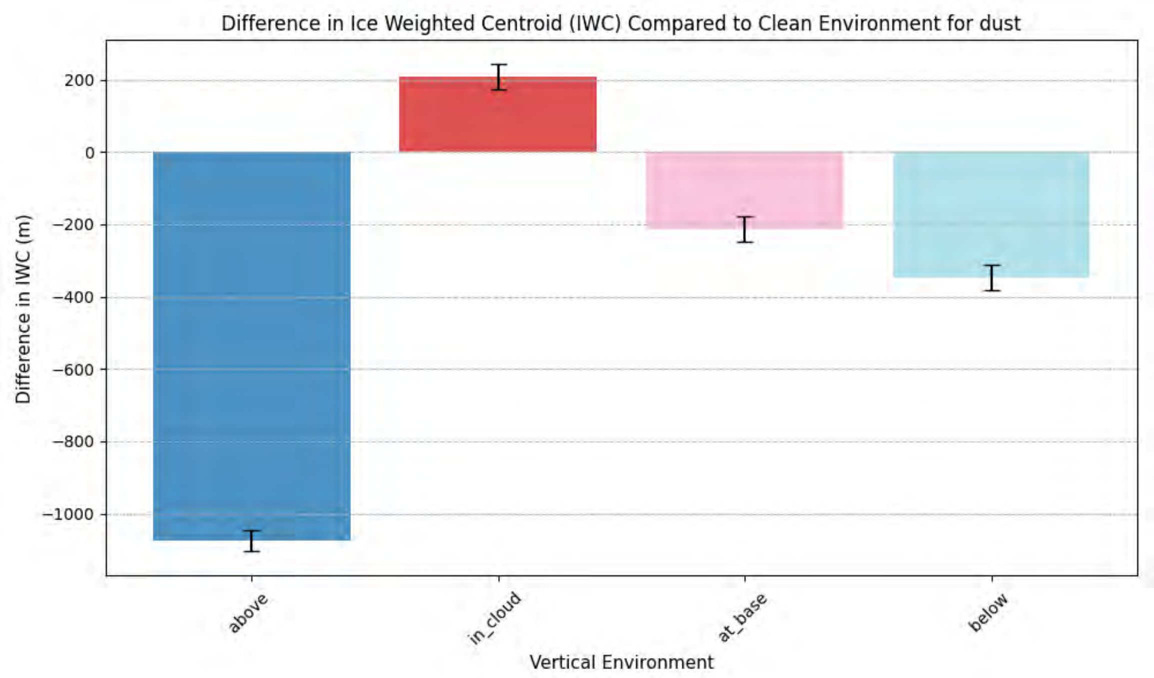

Figure 4: A bar chart showing the difference in the average IWCs from the clean environment average of each month (across all years) for DCCs in dust dominated environments where the majority of the dust lays above the cloud, within the vertical extent of the cloud, at the base height of the cloud or below the cloud. The errors shown represent the standard errors for the calculated average differences. The number of available datapoints for each are as follows: above – 1006, in_cloud - 754, at_base – 236, and below – 44.

Figure 4 shows the findings for DCCs in dust dominated environments and does not demonstrate the expected effects from studies such as Zhang et al [4]. The data representing DCCs where the dust is mostly at the cloud base shows one of the smallest effects on the average IWC which is directly contrary to the findings in Zhang et al where an aerosol layer achieves the greatest concentration within the cloud if it sits at the cloud base during formation.

Looking only at the data for where the dust lays within the vertical extent of the cloud, there is better agreement with Jiang et al [1] where dust in South America was found to have an invigoration effect on convection. However, the general disagreement between this study and Jiang et al. would suggest that this specific point of apparent agreement is not convincing.

Additionally, the number of datapoints (44) for dust that sits mostly below the DCCs is very small and makes the findings derived from them untrustworthy. This low count is somewhat due to the exclusion of detected aerosol layers from CALIPSO [9] that sat below 0.5km from the ground.

It is also noted that aerosols above the vertical extent of the clouds are expected to have a weaker effect on the strength of convection in the cloud but the data in this study, on first inspection, suggests a strongly inhibiting effect which cannot be true. Selection bias is believed to be the main cause of this discrepancy since DCCs that have lower cloud tops due to any factor – such as being at an earlier stage in their development – will be more likely to have dust above those cloud tops where it would be seen to be within the vertical extent of the same cloud if it were further along in its development when the measurement was made. This bias also affects the data for DCCs where the dust is mostly within the vertical extent of the cloud, but in the other direction (seemingly invigorating convection rather than inhibiting). The degree of this effect is smaller.

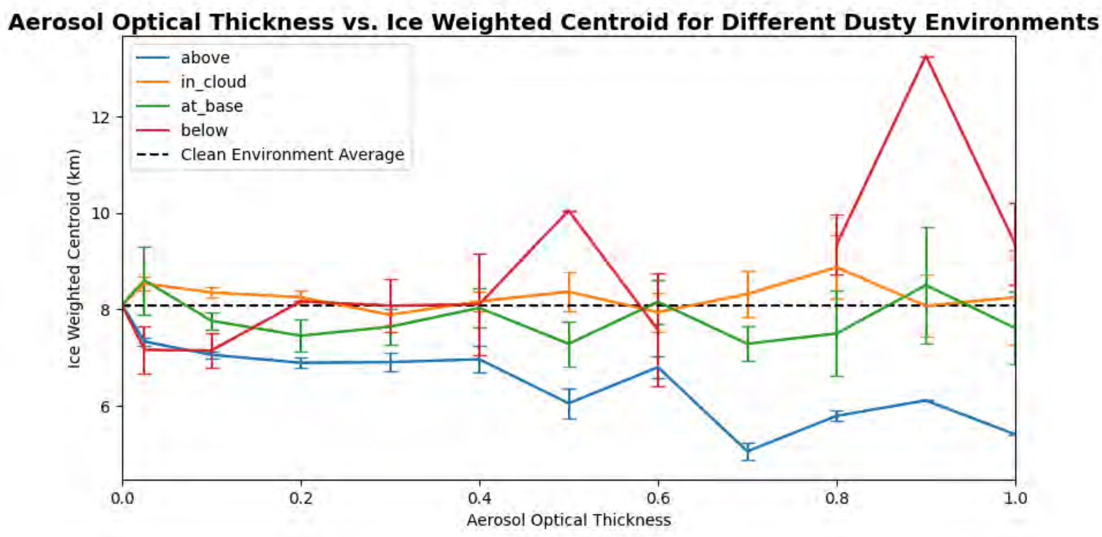

Figure 5: a plot of IWC against aerosol optical thickness for DCCs in environments dominated by dust sitting at different relative vertical positions to each DCC. The errors shown represent the standard error for each bin and, where the error shown is 0, the bin contains only 1 datapoint.

Figure 5 is included for completeness and demonstrates a lack of obvious structure in most of the data. The exception being the curve for dust above the clouds but, as discussed, this data is greatly affected by selection bias.

Similar charts to figure 4 for the other aerosol dominated environments are included in only the appendices because they contain bars with very few datapoints and so do not reliably demonstrate anything relevant to this study.

5 Conclusion

This study does not find evidence to support the findings of previous studies regarding the effects of dust, polluted continental aerosols and elevated smoke on the strength of convection in deep convective clouds. Here, all three are found to have an inhibiting effect on convection whereas polluted continental aerosols (for example) are found by Jiang et al. [1] to have a strongly invigorating effect. This discrepancy is unexpected and is not explained by differences in data processing nor by differences in the datasets used.

Additionally, this study concludes that the method used here for classifying and subsequently investigating the effect of differing vertical aerosol distributions is limited in usefulness due to the effects of selection bias in that classification process and the inability to determine how far the DCCs have reached in their lifetime. It is suggested that future studies utilise methods that allow for the tracking of individual cloud formation or for the direct measurements of aerosol concentrations within clouds for each of the studied scenarios.

6 Bibliography

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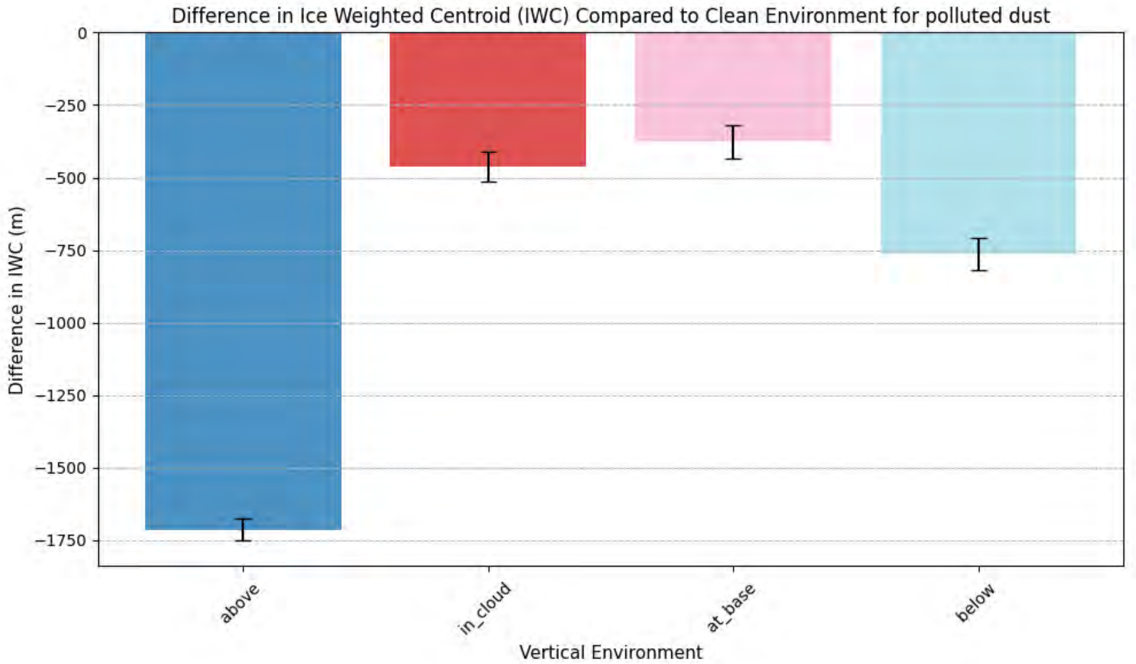
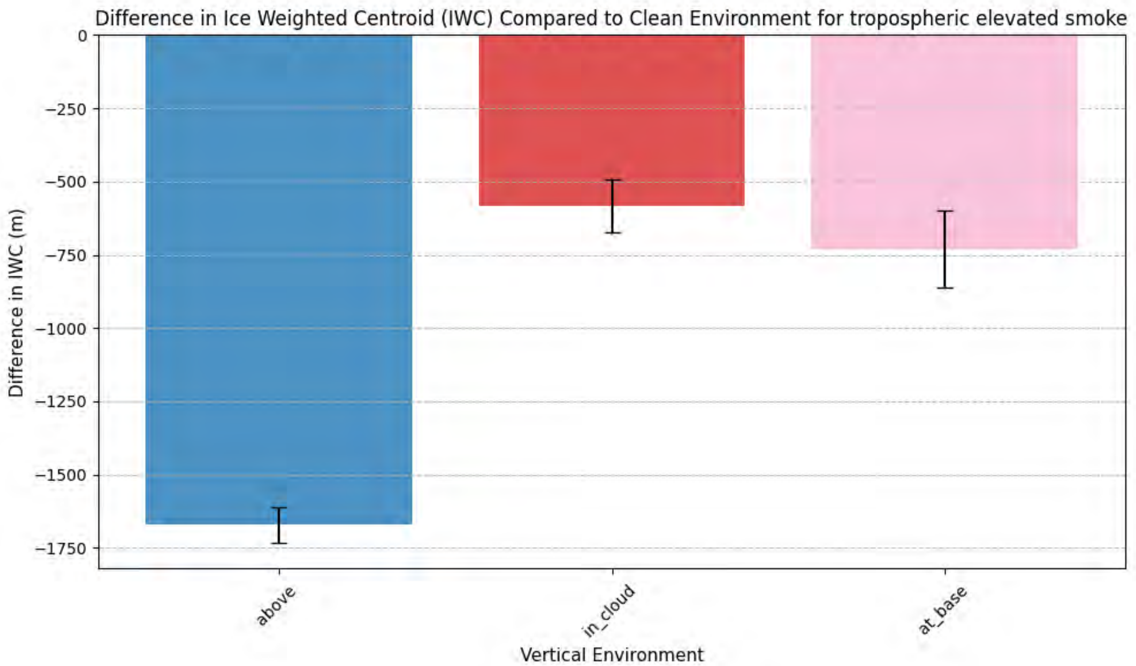
7 Appendices

7.1 Bar charts referenced in section 4.2



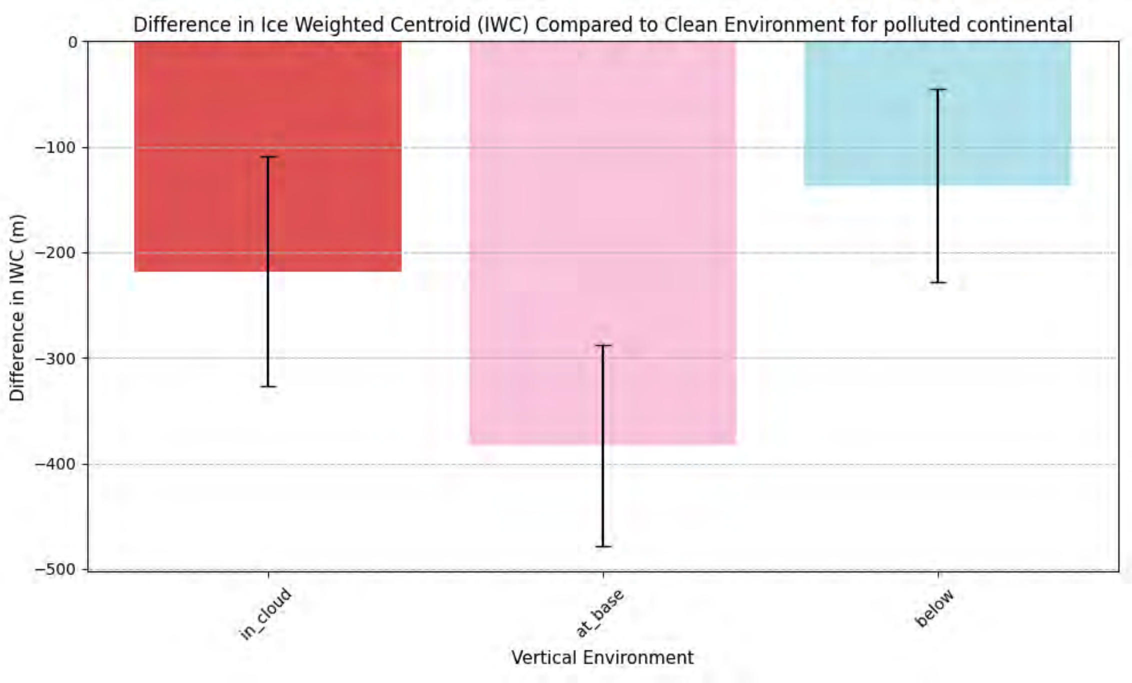
Number of datapoints for each bar for polluted dust dominated environments:

- above: 27
- in_cloud : 267
- at_base : 316
- below : 69



Number of datapoints for each bar elevated smoke dominated environments:

- above : 8
- in_cloud : 232
- at_base : 44
- below : 0



Number of datapoints for each bar polluted continental aerosol dominated environments:

- above : 0
- in_cloud : 5
- at_base : 236
- below : 41