Reviewer's comments in black, replies in blue.

Comments from Reviewer 1:

This paper provides a valuable contribution since there is not a huge amount of updraft information of this type in the literature. The results are valuable for a variety of reasons such as for providing better realism for numerical models on convection vertical motion scales and magnitudes. The results are also very useful for microphysical studies such as rain/snow growth mechanisms that require a vertical motions as a key input. The authors provide a good summary of past work and the manuscript in general is well written except for numerous typographical errors and some poorly worded sentences. The technical details are sufficient for the material presented. There is too much detail in some sections, and only the key points should be included (e.g., section 4.3).

Answer:

We appreciate the reviewer's comment. Actually, the Editor had pointed out the typographical errors after we submitted the original manuscript, then we sent the manuscript out for editorial service and submitted a revised version. However, when dealing with the technical comments, we found many typographical errors do exit in the old version, but have been corrected in the revised version. Maybe the reviewers were reading the old version. The revised version can be downloaded on http://www.atmos-chem-phys-discuss.net/acp-2015-1021/#discussion . Nevertheless, the sciences are the same. We have addressed the comments raised by the reviewer, the sample issue and limitations of aircraft measurements have been highlighted. Sections with too much detail are simplified. A discussion section has been added to show the complicated interactions among vertical velocity, entrainment/detrainment and microphysics. We have changed the manuscript title to "Characteristics of Vertical Air Motion in Isolated Convective Clouds" to highlight that this study deals with isolated convections rather than mesoscale convective systems.

The paper deals with what shallow to moderate convection. The authors need to add some discussion in the abstract and conclusions on the fact that the measurements presented are still a biased sample of convection. Are the measurements truly representative of all convection in the three regions presented, or did for example the planes used stay away from stronger, and/or deeper convection, or ones with higher reflectivity. What the paper points out is that there are some similarities between the regions, but that there is really a wide variety of convective types over the globe. This is a good point to make in the paper that there are few measurements of this sort so they are greatly needed, but they represent specific regions and types of convection, more from other regions are needed, and one should not interpret the results that these results can be generalized globally. A few summary sentences (abstract, intro, and conclusions) on this point would make the paper better.

Answer:

We appreciate the comment. We totally agree that this study only deals with a biased sample of convective clouds. Only three field campaigns are analyzed and MCSs were not sampled. The results cannot be generalized globally. We have pointed this out in the revised manuscript, included in abstract, introduction, datasets description and conclusion. We also changed the manuscript title to “Characteristics of Vertical Air Motion in Isolated Convective Clouds” to highlight that this study deals with isolated convections rather than mesoscale convective systems.

In addition, we have added more text to point out the limitations of aircraft measurements. First, aircraft cannot provide 3-D information of the cloud, so the air mass flux is derived from measurements in single-line penetrations. Second, aircraft might not penetrate through the strongest part of drafts due to safety issues. Moreover, in-situ measurements only provide data from single-line penetrations, but the vertical velocities are very different at different heights in a cloud. For example, many penetrations in COPE are near cloud top, while in HiCu and ICE-T there are many penetrations far below cloud top. Therefore, readers need to be aware of the limitations of aircraft measurements when using the results in this study.

While I find the paper quite interesting, there could be more connection between the convection dynamics and microphysics. Processes such as mixing are barely mentioned in the text. It would be interesting for example to make connections between the updraft characteristics such as mass fluxes, diameters, and entrainment.

Answer:

We appreciate the comment. We have tried to explore the interactions between dynamics and microphysics, but the physical processes are very complicated and there are many limitations of aircraft instruments (e.g. resolution, time response and uncertainty) and sample issues. An example is given in Fig. R1. In the figure, we plot the mean vertical velocity (a and b), normalized relative humidity (c and d), normalized FSSP concentration and normalized King LWC (e and f) as a function of normalized scale from cloud edge to location of the maximum vertical velocity in the updraft closest to the cloud edge. On the x-axis, 0 indicates the cloud edge, 1 indicates the location of maximum vertical velocity in the updraft closest to the cloud edge, where is less affected by entrainment. As shown in the figure, weaker updraft associates with lower relative humidity, droplet concentration and LWC, and stronger updraft associates with higher relative humidity, droplet concentration and LWC. This maybe partly due to entrainment/detrainment mixing. This figure is from ICE-T only because in HiCu and COPE we do not have fast-response instrument to measure RH. The droplet concentration and LWC may have large uncertainty because FSSP often has shattering issues and King probe cannot detect large drops (> 50um).

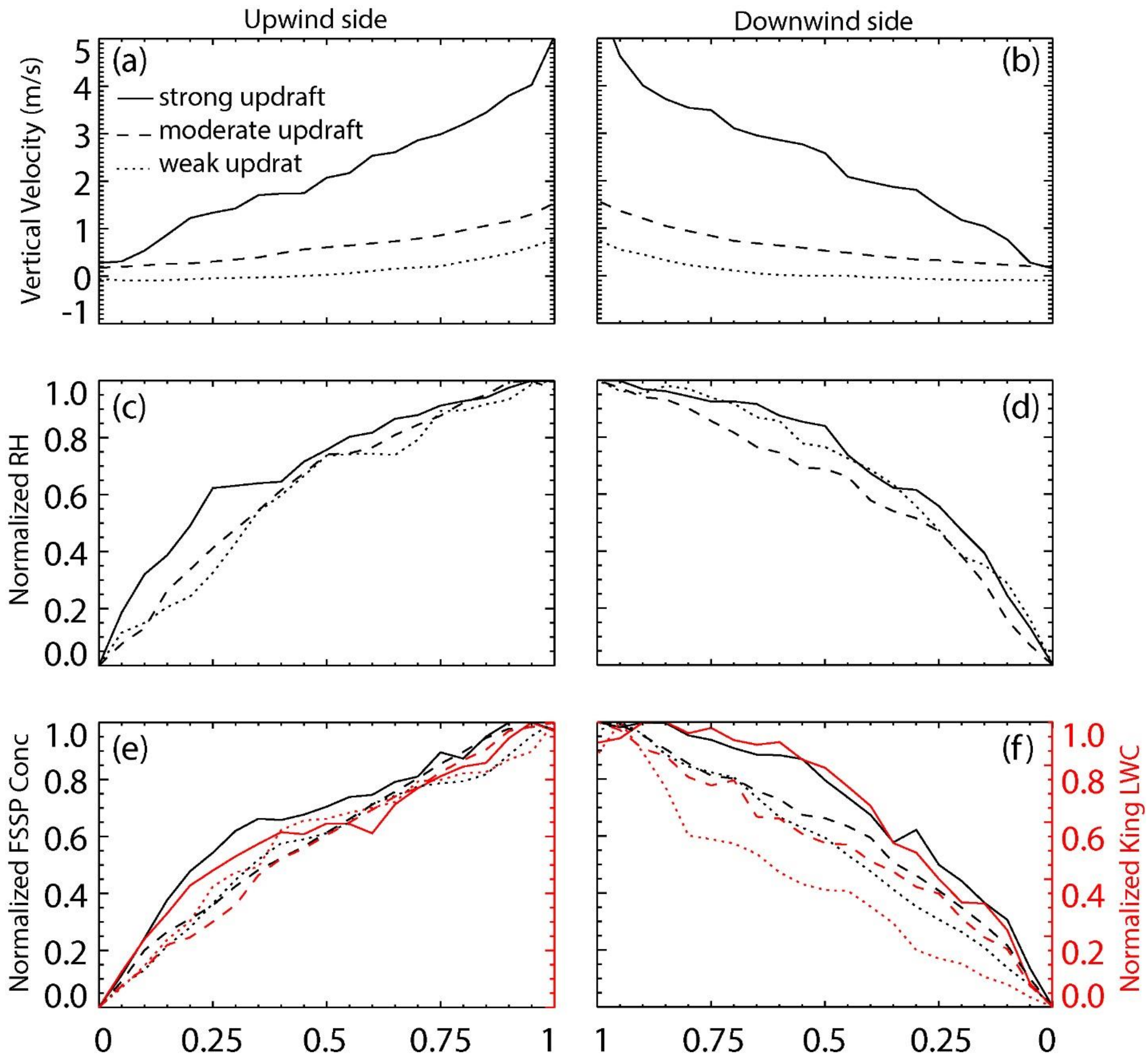

Fig. R1: Mean vertical velocity (a and b), normalized relative humidity (c and d), normalized FSSP concentration and normalized King LWC (e and f) as a function of normalized scale from cloud edge to updraft closest to the edge. 0 on the x-axis indicates the cloud edge, 1 on the x-axis indicates the location of maximum vertical velocity in the updraft closest to the cloud edge.

We also tried to use indirect ways to explore the impacts of entrainment on vertical velocity. Fig. R2 shows the PDF of vertical velocity in downdrafts near cloud edge and inside cloud. In HiCu and COPE the downdrafts near cloud edge are stronger than those inside clouds, maybe because of the strong evaporation-cooling effect induced by entrainment, while in ICE-T the downdrafts are similar near cloud edge and inside cloud. This only partly explains the stronger downdraft in HiCu and COPE than ICE-T, because the downdrafts inside clouds are also stronger in HiCu and COPE than ICE-T.

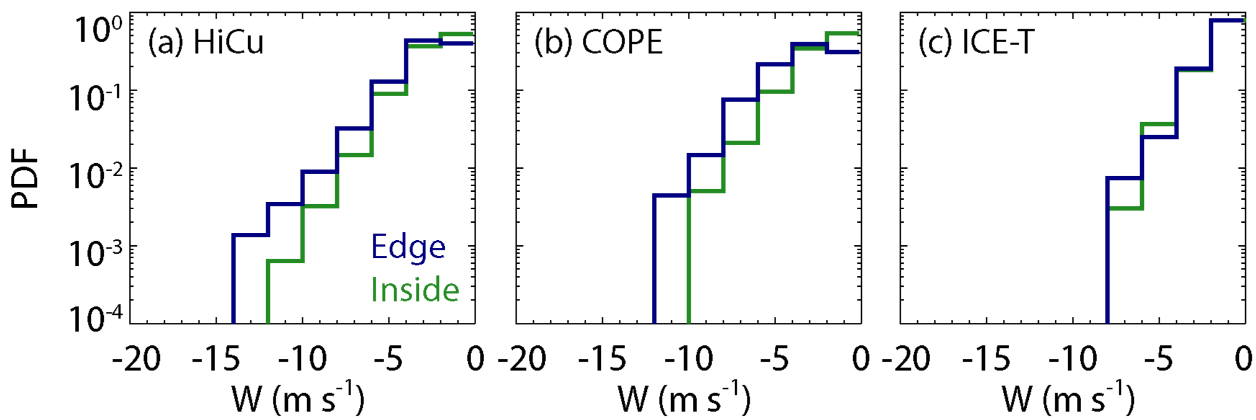

Fig. R2: PDFs of vertical velocity in downdrafts near cloud edge and inside cloud.

Due to the complexity of dynamics-microphysics interactions and the limitations of aircraft measurements, it is better to address this problem in detail in other papers. We have written a separated paper and discussed the interaction between vertical velocity and liquid-ice mass partitioning (Yang et al. manuscript submitted to JAS), in which an algorithms is developed to partitioning liquid and ice mass using multiple in-situ instruments. An example is given in Fig. R3, the figure shows in developing cloud the LWC and IWC are higher in stronger updraft, but the liquid fraction has no obvious correlation with vertical velocity. In mature clouds, LWC is higher in stronger updrafts, but IWC is similar in weak and strong updrafts. Between -3 C and -8 C, the liquid fraction is smaller in weaker updrafts, maybe because secondary ice production (e.g. H-M process) is more significant in weaker updraft (Heymsfield and Willis 2014). Only ICE-T is used in that paper because in COPE and HiCu we do not have the appropriate instruments to provide sufficient measurements.

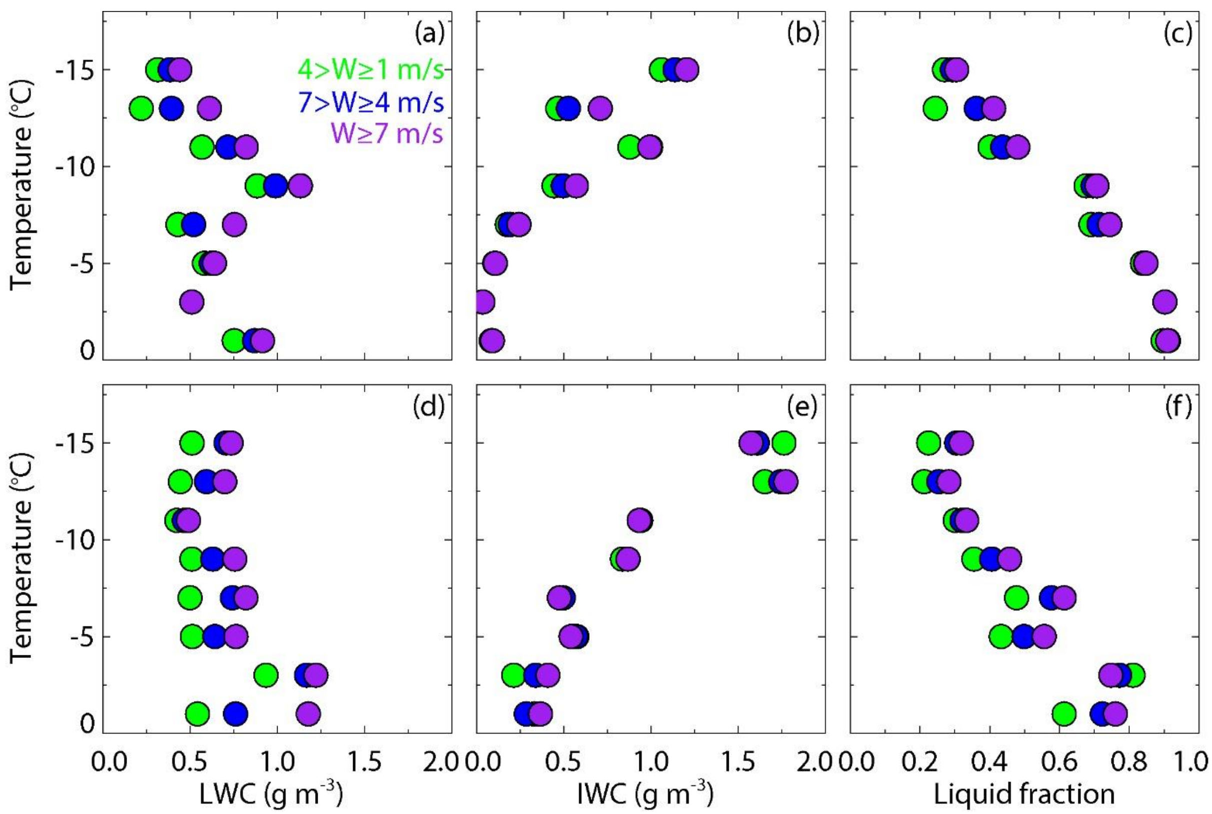

Fig. R3: The mean profiles of LWC, the IWC, and the liquid fraction as a function of temperature for the (a-c) young turrets and (d-f) mature turrets with vertical velocities of 1 m s^{-1} – 4 m s^{-1} (green), 4 m s^{-1} – 7 m s^{-1} (blue) and greater than 7 m s^{-1} (purple).

In the revised manuscript, we decide to add a discussion section to highlight the importance of the interactions between dynamics and microphysics, and discuss the possible impacts of entrainment and microphysics on vertical velocity.

Technical and other details:

Lines 128-138: What are typical reflectivity in the convection. I know this will be from the W-band radar but this information would still be useful.

Answer:

The reflectivity depends on the stage of the clouds. The reflectivity in convective core is typically 10-20 dBZ in ICE-T, 5-20 dBZ in COPE, and 0-15 dBZ in HiCu. These reflectivity values may not reveal the maximum reflectivity in convective cores due to sampling issue. We've added this information in the text.

Lines 171: Define strong updrafts since these are still relatively weak compared to deeper convection.

Answer: We have changed “strong updrafts” to “relatively strong updrafts”. And have added *"These drafts maybe strong for isolated convections, but not necessary strong compared to MSCs".*

Line 189: This accuracy (0.2 m/s) is quite good. Is there any chance there are biases rather than random errors on the vertical velocity?

Answer: There are no other instruments as references to provide systematic errors on vertical velocity. In the three datasets we do not see unrealistic values of vertical velocity (except a few cases in which the instrument was not working, which have been excluded in the study). Generally, the 0.2 m/s could be seen as the systematic error, random error could be larger than 0.2 m/s.

Line 209: Footnote. This is roughly the sensitivity of CloudSat. Is this the reason -30 dBZ was chosen since there will be cloud at lower reflectivities?

Answer: We choose this threshold by plotting the reflectivity near flight level in cloud free air. As shown in Fig. 2 in the manuscript, the reflectivity near flight levels is about -30 dBZ in cloud free air due to WCR signal noise. At levels far above or below flight level, the noise level is higher. In this study we mainly use in-situ measurement, so we only consider the reflectivity near flight level. Clouds with reflectivity lower than the noise level cannot be identified by WCR, and are excluded in this study, most of them maybe not convective clouds.

Lines 233-235: How do you know the 2D symmetry of the updraft since you might not fly through the peak up and downdrafts? Both the W-band radar and in situ measurements will not tell you this.

Answer: Here we want to show whirling penetrations and penetrations with significant turns have been rejected, so the cloud scale will not be significantly overestimated. We have modified this sentence to make it clear.

Line 236: “there is no” should be “there are no”

Answer: The comment has been addressed in the revised manuscript.

Line 238: Excluding MCS biases the results. This comes down to emphasis in this paper on small to moderate convection rather than deep convection in MCSs. Might mention this to keep the scope of your study in perspective.

Answer: We have pointed out the sample issue in the revised manuscript, including abstract, introduction, datasets description and conclusion. We also changed the manuscript title to “Characteristics of Vertical Air Motion in Isolated Convective Clouds” to highlight that this study deals with isolated convections rather than mesoscale convective systems.

Figure 4: need labels for field experiment associated with each color.

Answer: Labels have been added.

Lines 264-268: It might be useful to plot one example of a trace through one of the updraft/downdraft penetrations. This would be helpful to understand some of the averaging performed.

Answer:

Good suggestion. But the clouds were randomly sampled in the three field campaigns, we do not have continuous penetrations in one updraft/downdraft. More data are needed in the future. In addition, in-situ data itself is not enough to resolve the fine structure, in Fig. 2 in the manuscript, we can see many fine structures from the Doppler velocity measured by WCR, in-situ measurements can capture the details at single levels.

Line 268: “turbulences” to “turbulence”

Answer: “turbulences” has been changed to “turbulence” in the revised manuscript.

Line 300: “convections” to “convection”

Answer: “convections” has been changed to “convection” in the revised manuscript.

Line 294: “strong draft” – I would again put this in perspective since it is strong in your study, but not necessarily strong with respect to MCS updrafts for example.

Answer: We have add a sentence to indicate the definition of “strong” is only for this study, but not necessarily strong with respect to other convections (e.g. MCS): *“The definition of “weak”, “moderate” and “strong” only apply for this study. Other convections (e.g. MCS) could have much stronger updrafts.”*

Line 323-324: Again, this point should be more prominent in the paper.

Answer: We have highlighted that the definition of “weak”, “moderate” and “strong” only apply for this study.

Lines 386-387: This statement should be in the summary/conclusions since these measurements are important but we need a lot more.

Answer: We have added this statement in the conclusion.

Line 397: “results” to “result”

Answer: “results” has been changed to “result” in the revised manuscript.

Line 403: “relatively” to “relative”

Answer: “relatively” has been changed to “relative” in the revised manuscript.

Figure 10 and similar plots: I find these plots a little complicated and confusing but probably acceptable for publication. I can’t think of an alternative but possibly there is a better way to plot.

Answer: We tried to improve the figures but haven’t found a better way, because there are a lot of information in the figure. We have modified the text to better describe this figure.

Line 422: Some of the statements in this section should go in a summary and conclusions section. Points like lines 468-473 are important summary statements. You should consider pulling some of the summary points like this and putting them in the conclusions.

Answer: Statements with key points have been added in the conclusion.

Line 469: “pervious” to “previous”

Answer: “pervious” has been changed to “previous” in the revised manuscript.

Lines 509-510: “While in this study” should be something like “In contrast, this study shows the strongest. . ..”

Answer: The sentence has been changed to *"In contrast, this study shows the strongest updrafts and downdrafts were observed at higher levels"*.

Line 522: "When exclude" to "When we exclude" Line 536: "convective cloud" to "convective clouds"

Answer: The comment has been addressed in the revised manuscript.

Lines 539-540: Can you say anything about the two-dimensionality of drafts from the remote sensing data?

Answer: We have added the following sentence in the text: "for example, airborne radar with slant and zenith/nadir viewing beams can provide two-dimensional wind structure in convective clouds".

Line 553: "with expectation" to "expected"

Answer: "with expectation" has been changed to "expected" in the revised manuscript.

Line 564: "Since . . ..to better". This is an obvious fact. May want to just say that the aircraft just provides a line of data through drafts, and not vertical information unless the plane makes multiple passes through the same cell.

Answer: We have changed to sentence to *"Since the aircraft just provides a line of data through drafts, and not vertical information unless the plane makes multiple passes through the same cell, more data, including remote sensing measurements are needed to better understand the evolution of the vertical velocity in convective clouds at different stages."*

Line 568: in the Summary section, you should reiterate the criteria for considering up/downdrafts, i.e., >xx m/s.

Answer: The criteria for considering up/downdrafts is reiterated.

Line 596: Flux calculations assume two-dimensionality of drafts and this might not be the case. Should mention this as a weakness in the study, i.e., using a single line penetration through drafts to make flux calculations.

Answer: We have highlighted that due to the limitation of aircraft measurements, the air mass flux is calculated using the data from single line penetrations. This may not fully capture the real air mass flux in the clouds and is a weakness of this study.

Comments from Reviewer 2:

I always like to see an in-depth study of vertical motions in the atmosphere because, as the authors point out, understanding these is vital to improving our understanding of (and hence modeling capabilities) many processes influenced by vertical motions. First, before I get to the science, this document was not ready for submission in any form. It is riddled with typographical errors making it very difficult to get to the science. I started to list them but, frankly, this is the job of an editorial service, something I recommend the author take advantage of. For example: "The COPE project was conducted from 03 July to 21 August, 2013". This is not English.. "The COPE project was conducted from the 3rd of July to the 21st August, 2013".. Write in English not in code. I have two broad areas of concern with this manuscript:

Answer:

We appreciate the reviewer's comment and sorry for the typographical errors. Actually, the Editor had pointed out the typographical errors after we submitted the original manuscript, then we sent the manuscript out for editorial service and submitted a revised version. However, when dealing with the technical comments raised by Reviewer 1, we found that many typographical errors pointed out by the Reviewer 1 exit in the old version, but have been corrected in the revised version. Maybe the reviewers were reading the old version. The revised version can be downloaded on http://www.atmos-chem-phys-discuss.net/acp-2015-1021/#discussion . In this round of revision, we have corrected a few more typographical errors.

I have two broad areas of concern with this manuscript:

1) The authors do not address the idea of sample size or sample bias OR more importantly geometric issues of sampling, in a line, a 2/3D object (being an updraft core). See Giangrande et al 2013 for a discussion of issues with profiler systems and angle of attack. Basically if you dissect an updraft core how do you know if you hit the strongest part of the updraft? Furthermore, up until the end, the idea of selection bias is not addressed. Even the C-130 will avoid the strongest cores. You can not build a PDF out to the tail from aircraft measurements. You can, as the paper did somewhat, look at intrinsic updraft properties. But you can not look at the distribution. I am somewhat disappointed , given the brief reference to microphysical measurements, that the authors did not relate vertical motions to microphysical properties of the updraft cores. This is something in-situ platforms are uniquely capable of doing. Also, in the literature review of methodologies for measuring vertical motions the authors neglect scanning radar measurements such as those shown in Collis et al 2013 and Nicol et al 2015 (not to mention a raft of airborne radar measurements from the NOAA p3 (look for papers from Jorgensen) and other aircraft that use the vertical plus 45 degree tilt methods.

Answer:

We totally agree with the reviewer that there are many limitations in aircraft measurements. First, aircraft might not penetrate through the strongest part of drafts due to safety issues. In addition, aircraft cannot provide 3-D information of the cloud, and the air mass flux is derived from measurements in single-line penetrations. Moreover, this study only deals with isolated convective clouds. Only three field campaigns are analyzed and MCSs are excluded in this study. The results cannot be generalized globally. We have pointed out these weaknesses in the revised manuscript, including abstract, introduction, datasets description and conclusion. We also changed the manuscript title to “Characteristics of Vertical Air Motion in Isolated Convective Clouds” to highlight that this study deals with isolated convections rather than mesoscale convective systems (MCSs).

For the PDF distributions, we think it will be good to keep them the paper even though there are potential sampling issues. First, modelers do need the aircraft measurements to provide PDF distributions of vertical velocities (personal communications: Guangjun Zhang, Xiaohong Liu and Sungsu Park). Second, due to the relative small sizes of isolated convective clouds, the sampling bias associated with where to penetrate clouds is not as large as sampling MCSs. During the sampling of isolated convective clouds, we typically aligned the central part of cloud to penetrate at the flight height. During ICE-T and COPE, we have penetrations in updrafts stronger than 20 m/s (please note this is just for isolated convections, in which the updrafts are weaker than MCSs), and previous studies based on in-situ data rarely reported such relatively strong updrafts. Actually, this is one of our motivations to make this study. The PDFs can also be used to evaluate and improve remote sensing retrievals because in-situ measurements are more accurate than remote sensing, especially in mixed-phase convective clouds. Then remote sensing can provide PDFs out to the tail. Therefore, the PDFs in the paper still provide valuable information, but readers do need to be aware of the weaknesses and limitations of aircraft measurements.

We tried to explore the interactions between microphysics and vertical velocity, but the physical processes are very complicated, and there are many limitation of aircraft instruments in measuring the microphysics in mixed-phase convective clouds. For example, FSSP has the shattering issue, hot-wire probes often underestimates the LWC because there are many large drops which cannot be directly sampled by these probes. Due to the complexity of dynamics-microphysics interactions and the limitations of aircraft measurements, it is better to address this problem in detail in other papers. We have written a separated paper and discussed the interaction between vertical velocity and liquid-ice mass partition in the mixed-phase cloud region within convective clouds (Yang et al. manuscript submitted to JAS), in which an algorithms is developed to partitioning liquid and ice mass using multiple in-situ instruments. An example is given in Fig. R3 (please find Fig. R3 in the response to Reviewer 1), the figure shows in developing cloud the LWC and IWC are higher in stronger updraft, but the liquid fraction has no obvious correlation with vertical velocity. In mature clouds, LWC is higher in stronger updrafts, but IWC is similar in weak and strong updrafts. Between -3 C and -8 C, the liquid fraction is smaller in weaker updrafts, maybe because secondary ice production is more significant in weaker updraft (Heymsfield and Willis 2014), results in relatively larger fraction of IWC. Such in-depth analyses only can be applied to ICE-T measurements in that paper because in COPE and HiCu we do not have the appropriate instruments to provide sufficient measurements.

Other than the interactions between vertical velocity and microphysics, entrainment/detrainment mixing also have impact on vertical velocity. But due to the complexity of the physical processes and the limitations of aircraft instruments, we think it is better to address this problem in detail in separated paper as well. (Please see the reply to Reviewer 1's comments).

In the revised manuscript, we add a discussion section to highlight the importance of the interactions between dynamics and microphysics, and discuss the possible impacts of entrainment and microphysics on vertical velocity.

In the revised manuscript, we have added the literatures about ground-based and airborne volumetric radar measurements in Introduction. For example, "*Collis et al. (2013) provides statistics of updraft velocities for difference convective cases near Darwin, Australia using retrievals from ground-based scanning Doppler radars and a multifrequency profiler". "Airborne volumetric Doppler radars have also been used to study the dynamic structure of convective clouds (e.g. Jorgensen and Smull 1993; Hildebrand et al. 1996; Jorgensen et al. 2000)". "Remote sensing has the advantage of being able to measure the vertically velocity at different heights simultaneously (Tonttila et al., 2011), and some of the techniques can detect the strongest updraft cores in convective clouds (Heymsfield et al. 2010; Collis et al. 2013)". "Volumetric radars can provide three-dimensional (3D) structure of air motion in convective clouds (Collis et al. 2013; Nicol et al. 2015; Jorgensen et al. 2000)".*

2) This comment relates to a specific question asked by the Journal in its review criteria "Are substantial conclusions reached?". I am deeply concerned by the authors attempt to relate the three field programs and say something about maritime versus continental convection. For one, the author did not put the cases into context. What was the CAPE for various cases? etc.. A selection of clouds at each campaign a climatology does not make. While the author caveats his comparison even the attempt to contrast the different regime is dangerous. For one, as mentioned, the strongest cores in the region of HiCu would all but destroy even the C-130 (See the various

photos associated with the Byers et al study of hail damage). To attempt to make a comparison, then state it goes contrary to common conception (Continental » Maritime) and then turn around and say "we did not sample the strongest updrafts in the continental case" is disingenuous.

So negatives out of the way, one of the things that redeem the paper is the focus on updraft shape and how that varies with height. Personally I find this very interesting as not only does the mass flux of a plume influence transport but the vertical velocity within determines many microphysical aspects. ie a plume that starts thin and then expand for the same mass flux would have lower vertical velocities aloft influencing processes like Hallett-Mossop splintering etc.. (and associated latent feedbacks).. The paper should focus more on this and the *intrinsic* differences. Things that are co-varying and less susceptible to sampling and decision bias.

Answer:

We appreciate the reviewer's comments. We have pointed out the weaknesses of aircraft measurements in the revised manuscript, including abstract, introduction, datasets description and conclusion, as well as the title.

Due to the limitation of aircraft measurement, we have deleted some results which are sensitive to the sampling issue. For example, "the vertical velocity in HiCu is weaker than that in COPE and ICE-T". In addition, in this paper we plot the vertical velocity PDFs and profiles as a function of height MSL (Fig. 8 and 10), so at the same height, the vertical velocity maybe weaker in HiCu. However, the updrafts were strengthening with height, and some updrafts could be close to 20 m/s at > 6 km MSL (Fig. 8) in HiCu. Maybe at higher levels the updrafts in HiCu were stronger than COPE and ICE-T, but we do not have more data. If we plot the updraft PDFs and profiles as a function of height above cloud base, the results in HiCu maybe closer to that in COPE and ICE-T. However, cloud base heights are variable and we do not have data to calculate the cloud base heights.

In the revised paper, we have added some text to describe the ambient conditions which many affect the vertical air motion. For example, *"the convective available potential energy (CAPE) in ICE-T is greater than 2000 J kg^{-1}. The CAPE in COPE is typically a few hundred J kg^{-1}. No soundings are available for HiCu, so we have to use aircraft measurements to estimate the CAPE. In some cases, the full CAPE cannot be calculated since the aircraft only flew at low levels (< 10 km MSL). The aircraft measurements suggest the CAPE in HiCu ranges from less than 100 J kg^{-1} to more than 500 J kg^{-1}".*

As suggested by the reviewer, we have added more discussion about the *intrinsic* differences among the three field campaigns. For example, the downdrafts in HiCu and COPE are obviously stronger than that in ICE-T, maybe partly due to the evaporation-cooling effect induced by entrainment (please see the reply to Reviewer 1). We also changed Fig. 11 to Fig. R2 as follows to show how the draft shape changes with height. Actually, the evolution of draft with height is very complicated. Based on our datasets, there could be different possibilities: 1) an updraft expands and the vertical velocity weakens with height, 2) an updraft expands and the vertical velocity strengthens with height, 3) an updraft splits to multiple updrafts and downdrafts, 4) two updrafts merged and become one updrafts. Since we do not have continuous penetrations in a single cloud, we have to statistically analyze the evolution of draft shape. In Fig. R4, we can see that the normalized shape do not have significantly change with height, the peak vertical velocity is strengthening with height. Connecting this figure to diameter (Fig. 4), vertical velocity (Fig. 8) and air mass flux (Fig. 9), the results show statistically, the drafts were expanding (Fig. 4) and the vertical velocity was strengthening (Fig. R2 and 8), but the air mass flux was not increasing (Fig. 9). This reveals the complicated physical processes (e.g. entrainment, water loading and the possibilities described above). The interaction between vertical velocity evolution and microphysics is even more complicated and needs to be analyzed in detail in separated papers (please see the reply to the first comment above).

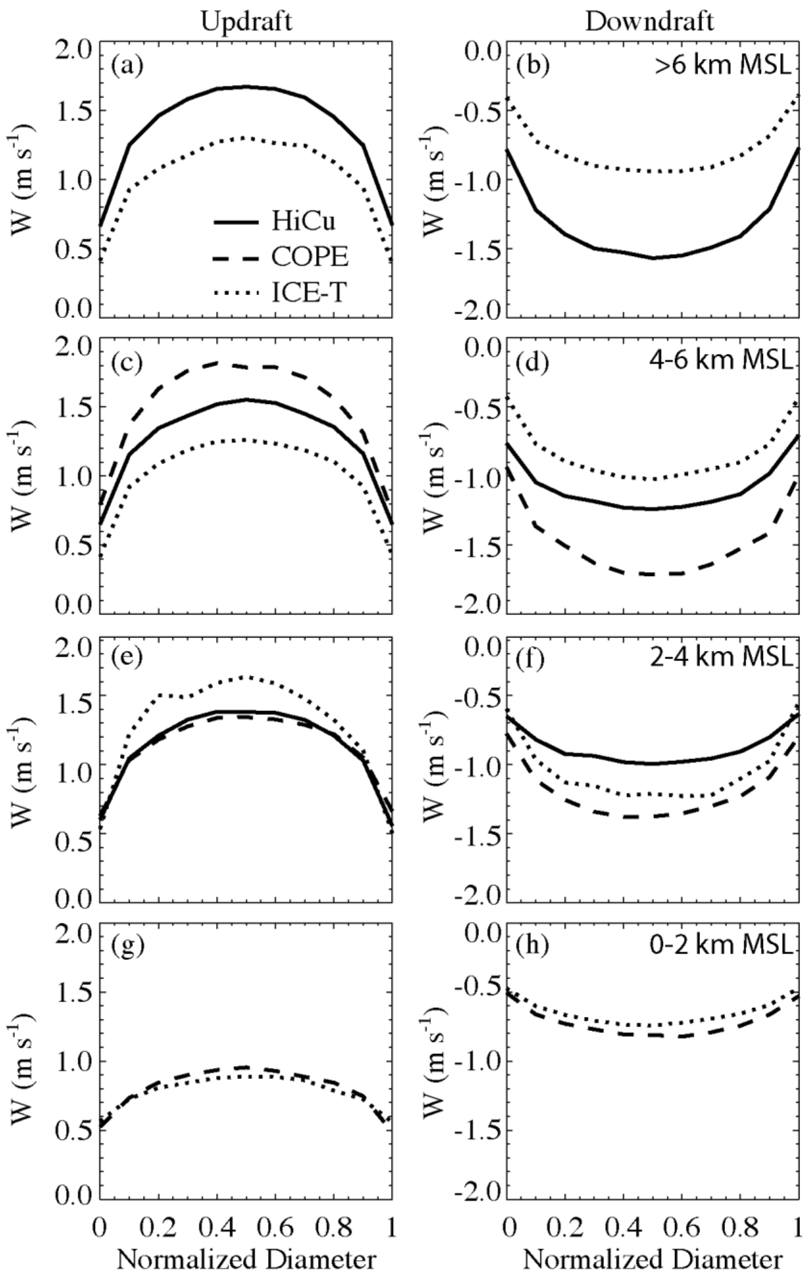

Fig. R4: Composite structure of the vertical velocity as a function of the normalized diameter for the updrafts and downdrafts with air mass flux ≥ 10 kg m^{-1} s^{-1} in magnitude. The 0 and 1 coordinates on the x-axis indicate the upwind and downwind sides of the draft.

Finally, we want to say this paper is just a part of the whole picture. The physical processes in mixed-phase convective clouds (e.g. interaction between dynamics and microphysics) are very complicated, and need to be further explored in the future with more experimental data, especially with more advanced measurements. The contributions of this paper are 1) provides statistical results of vertical air motion in isolated convective clouds using in-situ data in recent field campaigns, which could be used to evaluate remote sensing retrievals and model simulations. 2) In-situ measurements of vertical velocity stronger than 20 m/s in isolated convective clouds are provided. Previous studies using in-situ measurement rarely had penetrations in such relatively strong updrafts. 3) This paper highlights the importance of small drafts using high-resolution in-situ data, which is not shown in previous studies. 4) Some ‘intrinsic’ differences and similarities of vertical air motions among the three field campaigns are discussed. Aircraft measurements do have many limitations and this paper only deals with isolated convections, we have highlighted them in the revised paper.

Characteristics of Vertical Air Motion in Isolated Convective Clouds

Jing Yang[1], Zhien Wang[1], Andrew J. Heymsfield[2] and Jeffrey R. French[1]

[1] {Department of Atmospheric Science, University of Wyoming, Laramie, WY}

[2] {National Center for Atmospheric Research, Boulder, CO}

Correspondence to: Zhien Wang (zwang@uwyo.edu)

Abstract

The vertical velocity and air mass flux in isolated convective clouds are statistically analyzed using aircraft in-situ data collected from three field campaigns: High-Plains Cumulus (HiCu) conducted over the mid-latitude High Plains, COnvective Precipitation Experiment (COPE) conducted in a mid-latitude coastal area, and Ice in Clouds Experiment-Tropical (ICE-T), conducted over a tropical ocean. This study yields the following results. (1) Small-scale updrafts and downdrafts (< 500 m in diameter) are frequently observed in the three field campaigns, and they make important contributions to the total air mass flux. (2) The probability density functions (PDFs) and profiles of the vertical velocity are provided. The PDFs are exponentially distributed. The updrafts generally strengthen with height. Relatively strong updrafts (> 20 m s^{-1}) were sampled in COPE and ICE-T. ~~For updrafts, the PDFs of the vertical velocity are broader in ICE-~~

~~T and COPE than in HiCu; for downdrafts, the PDFs of the vertical velocity are broader in HiCu and COPE than in ICE-T. (3) Vertical velocity profiles show that updrafts are stronger in ICE-T and COPE than in HiCu, and~~ The downdrafts are stronger in HiCu and COPE than in ICE-T. (4) The PDFs of the air mass flux are exponentially distributed as well. The maximum air mass flux in updrafts is of the order 10^4 kg m^{-1} s^{-1}. The air mass flux in the downdrafts is typically a few times smaller in magnitude than that in the updrafts. Since this study only deals with ~~a biased sample of~~ isolated convective clouds, and there are many limitations and sampling issues in aircraft in-situ measurements, more observations and simulations are needed to better explore the vertical air motion in convective clouds.

1. Introduction

Convective clouds are an important component of the global energy balance and water cycle because they dynamically couple the planetary boundary layer to the free troposphere through vertical heat, moisture and mass transport (Arakawa, 2004; Heymsfield et al., 2010; Wang and Geerts, 2013). The vertical velocity determines the vertical transport of cloud condensate, the cloud top height and the detrainment into anvils, which further impact the radiative balance (Del Genio et al., 2005). Vertical velocity also has significant impact on the aerosol activation, droplet condensation and ice nucleation in convective clouds, which control the cloud life cycle and precipitation efficiency.

In order to reasonably simulate convective clouds, the vertical air velocity must be parameterized reliably in numerical weather prediction models (NWPMs) and global circulation models (GCMs) (Donner et al., 2001; Tonttila et al., 2011; Wang and Zhang, 2014). However, the complexity of the vertical velocity structure in convective clouds makes the parameterization non-straightforward (Wang and Zhang, 2014). Observations show that in most of the convective clouds the vertical velocity is highly variable, and consequently the detailed structure of convection cannot be resolved in many models (Kollias et al., 2001; Tonttila et al., 2011). Additionally, using the same parameterization of vertical velocity for different grid resolutions may result in different cloud and precipitation properties (Khairoutdinov et al., 2009). Furthermore, poorly parameterized vertical velocity may result in large uncertainties in the microphysics; for instance, the cloud droplet concentration may be underestimated due to unresolved vertical velocity (Ivanova and Leighton, 2008). Vertical velocity simulated by models with horizontal resolutions down to a few hundred meters may be more realistic (e.g. Wu et al., 2009), but more observations are needed to evaluate this suggestion.

Aircraft in-situ measurement has been the most reliable tool enabling us to understand the vertical velocity in convective clouds and to develop the parameterizations for models. Early studies (e.g. Byers and Braham, 1949; Schmeter, 1969) observed strong updrafts and downdrafts in convective clouds; however, their results have a large uncertainty, because the aircrafts were not equipped with inertial navigation systems (LeMone and Zipser, 1980). In 1974, the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) was conducted off the west coast of Africa, focusing on tropical maritime convections (Houze, 1981). A series of findings based on the aircraft data collected from the project was reported. For example, the accumulated probability density functions (PDFs) of vertical velocity and diameter of the convective cores are lognormal distributed. The updrafts and downdrafts in GATE (tropical maritime clouds) were only one half to one third as strong as those observed in the Thunderstorm Project (continental clouds) (LeMone and Zipser, 1980; Houze, 1981). These findings stimulated later statistical studies of the vertical velocity in convective clouds. Jorgensen et al. (1985) found that the accumulated PDFs of vertical velocity in intense hurricanes were also lognormal distributed and the strength was similar to that in GATE, but the diameter of the convective region was larger. Studies of the convective clouds over Taiwan (Jorgensen and LeMone, 1989) and Australia (Lucas et al., 1994) showed a magnitude of vertical velocity similar to that in GATE. Although the results from the Thunderstorm Project are suspect, the significantly stronger drafts reveal the possible difference between continental and tropical maritime convective clouds. Lucas et al. (1994) suggested that the water loading and entrainment strongly reduce the strength of updrafts in maritime convections. However, this underestimation of the updraft intensity may be also due to the sampling issues, e.g. penetrations were made outside the strongest cores (Heymsfield et al., 2010).

There are a few more recent aircraft measurements (e.g. Igau et al, 1999; Anderson et al., 2005), but the data are still inadequate to fully characterize the vertical velocity in convective clouds. In most of these earlier papers, the defined draft or draft core required a diameter no smaller than 500 m; this threshold excluded many narrow drafts with strong vertical velocity and air mass flux. In addition, the earlier studies used 1-Hz resolution data, which can resolve only the vertical velocity structures larger than a few hundred meters, but the narrow drafts may be important to the total air mass flux exchange and cloud evolution. Furthermore, previous aircraft observations for continental convective clouds were based only on the Thunderstorm Project; thus, new data are needed to study the difference between continental and maritime convections.

Remote sensing by means of, for example, wind profilers and radars is another technique which has often been used in recent years for studying the vertical velocity in convective clouds (e.g. Kollias et al., 2001; Hogan et al., 2009; Giangrande et al., 2013; Schumacher et al., 2015). Using profiler data, May and Rajopadhyaya (1999) analyzed the vertical velocity in deep convections near Darwin, Australia. They observed that the updraft intensified with height and that the maximum vertical velocity was greater than 15 m s^{-1}. Heymsfield et al. (2010) studied the vertical velocity in deep convections using an airborne nadir-viewing radar. Strong updrafts were observed over both continental and ocean areas, with the peak vertical velocity exceeding 15 m s^{-1} in most of the cases and exceeding 30 m s^{-1} in a few cases. Zipser et al. (2006) used satellite measurements to find the most intense thunderstorms around the world; they applied a threshold updraft velocity greater than 25 m s^{-1} to identify intense convection. Collis et al. (2013) provides statistics of updraft velocities for different convective cases near Darwin, Australia using retrievals from scanning Doppler radars and a multifrequency profiler. Airborne volumetric Doppler radars have also been used to study the dynamic structure of convective clouds (e.g. Jorgensen and Smull 1993; Hildebrand et al. 1996; Jorgensen et al. 2000). Remote sensing has the advantage of being able to measure the vertically velocity at different heights simultaneously (Tonttila et al., 2011), and some of the techniques can detect the strongest updraft core in convective clouds (Heymsfield et al. 2010; Collis et al. 2013). Volumetric radars can also provide three-dimensional structure of air motion in convective clouds (Collis et al. 2013; Nicol et al. 2015; Jorgensen et al. 2000). However, remote sensing measurements are not as accurate as aircraft measurements, because many assumptions are needed to account for the contribution of hydrometeor fall speed in the observed Doppler velocity in order to ultimately estimate air velocity. In addition, ground-based radars can rarely provide good measurements over oceans, and airborne cloud radars often suffer from the attenuation and non-Rayleigh scattering in convective clouds. Therefore, in-situ measurements are still necessary in order to characterize the dynamics in convective clouds and to develop parameterizations for models.

The present study provides aircraft data analysis of the updrafts and downdrafts in mid-latitude continental, mid-latitude coastal and tropical maritime convective clouds using the fast-response in-situ measurements collected from three field campaigns: the High-Plains Cumulus (HiCu), the COnvective Precipitation Experiment (COPE) and the Ice in Clouds Experiment-Tropical (ICE-T). All the clouds formed in isolation, but some of them merged as they evolved. Statistics of the vertical velocity and air mass flux are provided. The Wyoming Cloud Radar (WCR), onboard the aircraft, is used to identify the cloud top height, and high frequency (25-Hz) in-situ measurements of vertical velocity are used to generate the statistics. The major limitations of aircraft in-situ measurements are the aircraft maybe not able to sample the strongest part of convections due to safety concern, and it only provides the information of vertical air motion at single levels. These weaknesses need to be kept in mind in the following analyses. Section 2 describes the datasets and wind measuring systems. Section 3 presents the analysis method. Section 4 shows the results. Section 5 discusses the possible factors those interact with vertical air motions, and conclusions are given in Section ~~5~~6.

2. Dataset and instruments

2.1 Dataset

The data used in the present study were collected from three field campaigns: HiCu, COPE and ICE-T. Vigorous convective clouds were penetrated during the three field campaigns, including mid-latitude continental, mid-latitude coastal, and tropical maritime convective clouds. These penetrations provide good quality measurements for studying the microphysics and dynamics in the convective clouds, as well as the interactions between the clouds and the ambient air. The locations of the three field campaigns are shown in Fig. 1. Information regarding the penetrations used in this study is summarized in Table 1.

The HiCu project was conducted mainly in Arizona and Wyoming (Fig. 1) from the 18th of July to the ~~0~~5th of August, 2002, and from the ~~0~~7th of July to the 31st of August, 2003 to investigate the microphysics and dynamics in convective clouds over mid-latitude High Plains. The University of Wyoming King Air (UWKA) was operated as the platform. In 2002 and 2003, 10 and 30 research flights were made, respectively. In this study, the 2002 HiCu and 2003 HiCu are analyzed together because they were both conducted over the High Plains and the sample size of 2002 HiCu is relatively small. Fast-response in-situ instruments and the Wyoming Cloud Radar (WCR, Wang et al., 2012) were operated during the field campaign to measure the ambient environment, cloud dynamics and microphysics as well as two-dimensional (2D) cloud structure. As shown in Table 1, penetrations in HiCu were made between 2 km and 10 km MSL. The sample size is relatively good below 8 km and relatively small above 8 km. The aircraft flew about 2000 km in clouds. In-situ measurements and WCR worked well in these flights; however, the upward-pointing radar was operated in less than half of the research flights, and thus only a sub-set of the cloud tops can be estimated. Fig. 2a(1–3) shows an example of the clouds sampled in HiCu, including WCR reflectivity, Doppler velocity and 25-Hz in-situ measurement of the vertical velocity. In HiCu, both developing and mature convective clouds were penetrated; some penetrations were near cloud top, while most of them were more than 1 km below cloud top. The typical WCR reflectivity is 0-15 dBZ in the convective cores due to strong Mie scattering at the WCR wavelength. From the Doppler velocity and the in-situ vertical velocity, we can see that, in both the developing and mature cloud, relatively strong updrafts and downdrafts were observed, and multiple updrafts and downdrafts existed in the same cloud. These drafts maybe strong for isolated convections, but not necessary strong compared to the strongest updrafts in mesoscale connective systems (MCSs). No soundings are available to measure the ambient environment in HiCu, so we have to use aircraft measurements to estimate the convective available potential energy (CAPE). In some cases, the full CAPE cannot be calculated since the aircraft only flew at low levels (< 10 km MSL). The aircraft measurements suggest the CAPE in HiCu ranges from less than 100 J kg^{-1} to more than 500 J kg^{-1}.

The COPE project was conducted from the 03rd of July to the 21st of August, 2013 in Southwest England (Fig. 1). The UWKA was used to study the microphysics and entrainment in mid-latitude coastal convective clouds (Leon et al., 2015). Seventeen research flights were conducted; penetrations focused on regions near cloud top, which is verified based on the radar reflectivity from the onboard WCR. Since COPE was conducted in a coastal area, the convection initiation mechanism is different from that over a purely continental or ocean area. In addition, although the ambient air mainly came from the ocean, continental aerosols might be brought into clouds, since many of the convective clouds formed within the boundary layer, which further affects the microphysics and dynamics in the clouds. The measurements made in COPE include temperature, vertical velocity, liquid water content, and particle concentration and size distributions. The WCR provided excellent measurements of reflectivity and Doppler velocity. The downward Wyoming Cloud Lidar (WCL) was operated to investigate the liquid (or ice) dominated clouds. The typical WCR reflectivity is 5-20 dBZ in the convective cores. Between 0 km and 6 km, about 800 penetrations were made. Flight distance in cloud totaled about 1000 km. The sample sizes are relatively good between 2 km and 6 km, but relatively small between 0 km and 2 km. Examples of the penetrations are given in Fig. 2b(1–3). COPE has fewer penetrations than HiCu, and most of the penetrations are near the cloud top. Fig. 2b(2) reveals relatively simple structures of the updrafts and downdrafts in COPE compared to HiCu, but as shown by the 25-Hz in-situ vertical velocity measurement in Fig. 2b(3), there are still many complicated fine structures in the vertical velocity distribution. The typical CAPE estimated from soundings in COPE was a few hundred J kg^{-1}.

The ICE-T project was conducted from the 1^{st} of JulyJuly 1 to the 30^{th} of July 30, 2011 near St. Croix, U.S. Virgin Islands (Fig. 1), with state-of-the-art airborne in situ and remote sensing instrumentations, with the aim of studying the role of ice generation in tropical maritime convective clouds. The NSF/NCAR C-130 aircraft was used during ICE-T to penetrate convective clouds over the Caribbean Sea. Thirteen C-130 research flights were conducted during the field campaign, with vigorous convective clouds penetrated. In-situ measurements from ICE-T include the liquid and total condensed water contents, temperatures, vertical velocities, and cloud and precipitating particle concentrations and size distributions. The WCR was operated on seven research flights to measure the 2D reflectivity and Doppler velocity fields. The typical WCR reflectivity in the convective cores is 10-20 dBZ. The aircraft flew more than 1500 km in clouds, and more than 650 cloud penetrations were made between 0 km and 8 km. The sample sizes are good except between 2 km and 4 km (Table 1). Examples of the penetrations are shown in Fig. 2c(1–3). During ICE-T, clouds in different stages were penetrated, including developing, mature and dissipating, some near cloud top and some considerably below cloud top. Relatively sStrong Updrafts up to 25 m s^{-1} updrafts were observed in the developing and mature clouds, but the downdrafts in ICE-T are typically weaker than those in HiCu and COPE. The vertical velocity structures are complicated, as confirmed by both the Doppler velocity and the 25-Hz in-situ measurement. Weak updrafts and downdrafts were also observed in the dissipating clouds. The typical CAPE in ICE-T was greater than 2000 J kg^{-1}, which is larger than that in HiCu and COPE.

During the sampling of isolated convective clouds in the three field campaigns, we typically aligned the central part of cloud to penetrate at the flight height, but still, the aircrafts might not penetrate through the strongest part of convective core due to safety concern. ~~In all the three field campaigns~~In addition, aircraft in-situ measurements only provide the information of vertical air motion at single levels. Moreover, the clouds sampled are isolated convective clouds, MCSs were not sampled. ~~Therefore, the results cannot be generalized globally~~. These limitations need to be kept in mind in interpreting results from the following analysis. ~~In addition, the aircrafts might not penetrate through the strongest part of convective core due to safety concern, e during the sampling of isolated convective clouds, we typically aligned the central part of cloud to penetrate at the flight height, and they only provide data at single levels. So the statistic shown in this study is just a part of the complete picture.~~

2.2 Wind measuring system

On both C-130 and UWKA, A Radome Five-Hole Gust Probe is installed for three-dimensional (3D) wind measurement**.** A Radome Five-Hole Gust Probe is an aircraft radome probe with five pressure ports installed in a “cross” pattern. Relative wind components (e.g. true air speed and flow angles) are sensed by a combination of differential pressure sensors attached to the five holes (Wendisch and Brenguier, 2013). Detailed calculation of relative wind components is described in Kroonenberg et al. (2008) and Wendisch and Brenguier (2013). The time response and the accuracy of the pressure sensors is about 25 Hz and 0.1 mb. The 3D wind vectors can be derived by taking out the aircraft motions from the relative wind measurement. On both C-130 and UWKA, the aircraft motion is monitored by a Honeywell ~~Laseref~~ LASEREF SM Inertial Reference System (IRS), with an accuracy of 0.15 m s^{-1} for vertical motion. Global Positioning System (GPS) was applied to remove the drift errors in the IRS position in all the three field campaigns (Khelif et al., 1998). The final vertical wind velocity product has an accuracy of about ±0.2 m s^{-1}, and a time response of 25 Hz. This uncertainty (±0.2 m s^{-1}) is a mean bias. For each output, the uncertainty is related to the true air speed, aircraft pitch angle, roll angle and ambient conditions. Therefore, the random error varies and could be larger than the mean bias. More information about the wind measurement on C-130 and UWKA can be found on the C-130 Investigator Handbook (available on https://www.eol.ucar.edu/content/c-130-investigator-handbook) and UWKA Investigator Handbook (available on http://www.atmos.uwyo.edu/uwka/users/KA_InstList.pdf)

3. Analysis method

3.1 Identifying cloud using in-situ measurements

The Particle Measuring Systems (PMS) Two-Dimensional Cloud (2D-C) Probe and the Forward Scattering Spectrometer Probe (FSSP) are often used to characterize cloud microphysics (e.g. Anderson et al., 2004), although different thresholds of 2D-C and FSSP concentrations are usually used to identify the edge of a cloud. In this paper, we also use FSSP and 2D-C probes to find the cloud edges. In order to find a reasonable threshold for identifying cloudy air, we first use the WCR reflectivity to identify the clouds and the cloud-free atmosphere; for those regions we then plot the particle concentrations measured by FSSP and 2D-C in order to determine the reasonable thresholds, and we apply the thresholds of particle concentrations to all the research flights without WCR.

To identify clouds using WCR, the six effective range gates nearest to the flight level (three above and three below) are chosen in each beam. Any beam in which the minimum reflectivity at the six gates exceeds the noise level -30 dBZ[1] is identified as in cloud.

Fig. 3 shows the occurrence distribution as a function of the particle concentrations measured by FSSP versus the concentrations of the particles ≥ 50 μm in diameter measured by 2D-C in the clouds identified by WCR reflectivity. From the figure, we can see that the FSSP concentration ranges from 0.01 cm^{-3} to 1000 cm^{-3}, and the 2D-C concentration ranges from 0.1 L^{-1} to 10000 L^{-1}. Generally, shallow clouds have relatively higher concentrations of small particles and lower concentration of particles larger than 50 μm. In deeper convective clouds, high concentrations can be seen for both small and large particles. The FSSP concentrations in cloud-free air are found to be 2 cm^{-3} at most, and the FSSP concentrations measured below the lifting condensation level (LCL), where precipitating particles dominated, are lower than 2 cm^{-3}, as well. Therefore, 2 cm^{-3} is selected as the concentration threshold to identify clouds based on the FSSP measurements, as shown by the dashed line in Fig. 3. However, in some clouds (e.g. pure ice clouds), the FSSP concentration could be lower than 2 cm^{-3}, and 2D-C concentrations are needed to identify these cold clouds. We chose a 1 L^{-1} 2D-C concentration for particles ≥ 50 μm as the second threshold to identify cloud, as shown by the dotted line in Fig. 3. In order to avoid precipitating regions (below the LCL calculated from soundings), the second threshold is only

[1] Based on the reflectivity measured in cloud-free air, the noise level of WCR reflectivity is -32 dBZ at a range of 500 m and -28 dBZ at a range of 1000 m. In this study, we choose -30 dBZ as the threshold to identify cloud. This threshold (-30 dBZ) is examined for all three field campaigns.

applied to penetrations at temperatures colder than 0 ºC; thus the cloud is defined as FSSP concentration ≥ 2 cm^{-3} or 2D-C concentration ≥ 1 L^{-1}. At temperatures warmer than 0 ºC, the FSSP concentrations in most of the convective clouds are higher than 2 cm^{-3}, so only the first threshold is used.

Once a cloud is identified, the penetration details can be calculated, including the flight length, the flight height, the cloud top height if WCR is available, and the penetration diameter. The penetration diameter is calculated as the distance between the entrance and exit of a penetration. In order to reject whirling penetrations and penetrations with significant turns, we require that the diameter of a penetration be at least 90% of the flight length,~~. –~~ so the cloud scale will not be significantly overestimated.~~The penetration diameter can generally reveal the scale of a cloud~~, ~~but s~~Since the aircraft ~~may~~ might not penetrate exactly through the center of a cloud, the actual cloud diameter may be larger than the penetration diameter. Based on WCR reflectivity images, there are no isolated convective clouds sampled larger than 20 km in diameter. There are a few penetrations longer than 20 km, but these clouds are more like part of ~~mesoscale convective systems (~~MCSs~~)~~, and so they are excluded from this study.

3.2 Defining updraft and downdraft

In previous studies of the vertical velocity based on in-situ measurements, the updraft and downdraft are often defined as an ascending or subsiding air parcel with the vertical velocity continuously ≥ 0 m s^{-1} in magnitude and ≥ 500 m in diameter (e.g. LeMone and Zipser, 1980; Jorgensen and LeMone, 1989; Lucas et al., 1994; Igau et al., 1999). In this study, we use a vertical velocity threshold of 0.2 m s^{-1}, that is, the draft has a vertical velocity continuously ≥ 0.2

m s^{-1} in magnitude, because ±0.2 m s^{-1} is the accuracy of the instrument. Any very narrow and weak portion (diameter < 10 m and maximum vertical velocity < 0.2 m s^{-1} in magnitude) between two relatively strong portions is ignored, and the two strong portions are considered as one draft.

The diameter threshold (500 m) is not used in this paper, because drafts narrower than 500 m frequently occur and they make important contributions to the total air mass flux in the atmosphere and therefore they are necessarily to be considered in model simulations. Fig. 4 shows the PDFs of the diameters of all the updrafts and downdrafts sampled in HiCu, COPE and ICE-T. In all the panels, the diameters are exponentially distributed, the PDFs can be fitted using

$$f = \alpha \cdot |x|^{\beta} \cdot \exp(\gamma |x|) \qquad (1)$$

where *f* is the frequency and *x* is the diameter. The coefficients *α*, *β* and *γ* for each PDF is shown in each panel. This function will also be used to fit the PDFs of vertical velocity and air mass flux in the following analyses. Generally, as seen in Fig 4, the PDFs broaden with height increases for the three field campaigns; this is consistent with previous findings (LeMone and Zipser, 1980). The diameters of the updrafts are smaller in COPE compared to those sampled in HiCu and ICE-T, possibly because most of the penetrations are near cloud top. ~~The diameters of the downdrafts are relatively small in HiCu. ICE-T has the most drafts with diameters exceeding 100 m, and the average diameters in ICE-T for both updrafts and downdrafts are the largest.~~ As shown in Fig. 4, many narrow drafts are observed. More than 85%, 90% and 74% of the updrafts are narrower than 500 m (dotted lines) in HiCu, COPE and ICE-T, respectively, and more than 90% of the downdrafts in all three field campaigns are narrower than 500 m. A threshold of 500 m in diameter would exclude many small-scale drafts, therefore, in this study all the drafts broader than 50 m (dashed lines) are included. The drafts narrower than 50 m are excluded because most of them are turbulences and they can hardly be resolved in models.

Fig. 5a shows the occurrence distributions as a function of the mean vertical velocity versus the diameter of the drafts with the vertical velocity continuously ≥ 0.2 m s^{-1} in magnitude. From the figure, it is noted that many drafts narrower than 500 m have quite strong vertical velocities. The maximum mean vertical velocity of these narrow drafts can reach 8 m s^{-1}, and the minimum mean vertical velocity in the downdrafts is –6 m s^{-1}. With such strong mean vertical velocity, narrow drafts could contribute noticeably to the total air mass flux. Fig. 5b presents the occurrence distributions as a function of the air mass flux versus the diameter of the drafts. The air mass flux is calculated as $\bar{\rho}\bar{w}D$ (LeMone and Zipser, 1980), where $\bar{\rho}$ is the mean air density at the measurement temperature, $\bar{w}$ is the mean vertical velocity and D is the diameter of each draft. Due to the limitation of aircraft measurements, the air mass flux is calculated using the data from single line penetrations. This may not fully capture introduce additional uncertainties in the real air mass flux estimations infor these clouds and is a weakness of this study using aircraft data. Fig. 5b shows that the air mass flux in many drafts narrower than 500 m is actually larger than that in some of the broader drafts. The maximum value for these narrow updrafts reaches 4000 kg m^{-1} s^{-1}, and the minimum value for the downdrafts reaches –3000 kg m^{-1} s^{-1}. The normalized accumulated flux (red curves) reveals that the drafts narrower than 500 m (dotted horizontal lines) make very significant contributions to the total air mass flux. Calculations indicate that the updrafts narrower than 500 m contribute 20%–35% of the total upward flux, and that the downdrafts narrower than 500 m contribute 50%–65% of the total downward air mass flux. Drafts narrower than 50 m (dashed horizontal lines), which are excluded in this paper, contributes less than 5% of the total air mass flux.

In this study, we delineate three different groups of updraft and downdraft using three thresholds of air mass flux: 10 kg m^{-1} s^{-1}, 100 kg m^{-1} s^{-1} and 500 kg m^{-1} s^{-1} in magnitude. The air mass flux is used here to delineate the draft intensity because (1) air mass flux contains the information of both vertical velocity and draft size; (2) air mass flux can reveal the vertical mass transport through convection~~s~~; and (3) air mass flux is an important component in cumulus and convection parameterizations (e.g. Tiedtke, 1989; Bechtold et al., 2001). The first designated group, the "weak draft," with air mass flux 10–100 kg m^{-1} s^{-1} in magnitude, contributes 10% of the total upward air mass flux and 10% of the total downward air mass flux. The "moderate draft," with air mass flux 100–500 kg m^{-1} s^{-1} in magnitude, contributes 25% of the total upward air mass flux and 40% of the total downward air mass flux. The "strong draft," where the air mass flux ≥ 500 kg m^{-1} s^{-1} in magnitude contributes 60% of the total upward air mass flux and 20% of the total downward air mass flux. The definitions of "weak", "moderate" and "strong" only apply for the isolated convective clouds analyzed in this study, and are not necessarily appropriate for other convections (e.g. MCS). Drafts weaker than 10 kg m^{-1} s^{-1} are not analyzed because they are too weak and most of them are very narrow ~~and can hardly be resolved in models~~ (Fig. 5b). The numbers of weak, moderate and strong updrafts and downdrafts sampled at 0–2 km, 2–4 km, 4–6 km, 6–8 km and 8–10 km MSL are shown in Table 2. Generally, weak and moderate drafts are more often observed than strong drafts. At most of the height ranges, more updrafts are observed than downdrafts.

Some researchers have defined a "draft core" by selecting the strongest portion in a draft. For example, LeMone and Zipser (1980) define an updraft core as an ascending air motion with vertical velocity continuously ≥ 1 m s^{-1} and diameter ≥ 500 m. This definition of a "draft core" is followed in a few more recent studies (e.g. Jorgensen and LeMone, 1989; Lucas et al., 1994;

Igau et al., 1999). We too analyzed the vertical air motion characteristics in the stronger portion of the drafts considered here. However, we found that in many updrafts the strong portion where the vertical velocity is continuously ≥ 1 m s^{-1} dominates and contributes 80% of the total air mass flux, so the statistics of the vertical air motion characteristics in the stronger portion are very similar to those in the draft as a whole. Therefore, the present study focuses on "drafts" in which both weak and strong portions are included.

4. Results

4.1 Significance of drafts in different strengths

From the analysis above, we note that relatively small and weak updrafts are frequently observed in convective clouds. In this section, we provide further evidence to show the importance of the relatively weak updrafts in terms of air mass flux.

Fig. 6a shows the average number of updrafts as a function air mass flux observed in the three field campaigns. The solid, dashed and dotted lines represent the penetrations with different diameters. As shown in Fig. 6a, weak and moderate updrafts are more often observed than strong updrafts, and the numbers of updrafts are higher in longer penetrations. Since this is an average result, the number of updrafts could be smaller than 1 (e.g. many narrow penetrations do not have strong updrafts). Fig. 6b is similar to Fig. 6a but shows the occurrence frequency of updrafts with different air mass fluxes (i.e. the vertical axis in Fig. 6a is normalized). For the penetrations < 1 km, many of the clouds only have weak or moderate updrafts, and relatively strong updrafts are rarely observed. For penetrations of 1–10 km, the frequency of strong updrafts increases and the frequency of weak and moderate updrafts decreases. For even longer penetrations (>10 km), however, the frequency of weak updrafts increases again, indicating the increasing importance of weak updrafts.

Fig. 7 shows the average percentile contributions to the total upward air mass flux by the three different groups of updrafts as a function of penetration diameter. In Fig. 7a, all the penetrations are included. Since many narrow clouds have no strong updrafts in terms of air mass flux, the total air mass flux in these narrow clouds is mostly contributed by weak (red bar) and moderate (green bar) drafts. These narrow clouds may have a high vertical velocity but small air mass flux. As the diameter increases to 4 km, the contributions to total air mass flux from relatively weak updrafts (red bar) decrease, while those from stronger updrafts (blue bar) increase. For a penetration of 4 km, 80%–90% of the total upward mass flux is contributed by the strong updrafts with air mass flux $\geq$ 500 kg m^{-1} s^{-1}. However, for the penetrations with diameter larger than 4 km, the contribution from relatively weak updrafts increases, probably because more weak updrafts exist in wider clouds (Fig. 6). This is more obvious in Fig. 7b, in which only the penetrations with at least one strong updraft are included. As the diameter increases from 400 m to 20 km, the contribution from the weak and moderate updrafts (red bars and green bars) increases from 2% to 20%. This suggests that as the cloud evolves and becomes broader (e.g. mature or dissipating stage), the weak and moderate updrafts are also important and therefore necessary to be considered in model simulations.

4.2 PDFs of vertical velocity and air mass flux

Fig. 8 shows the PDFs of the vertical velocity in the drafts sampled at 0–2 km, 2–4 km, 4–6 km and higher than 6 km in the three field campaigns. Columns (a), (b) and (c) represent the drafts with air mass flux ≥ 10 kg m^{-1} s^{-1}, ≥ 100 kg m^{-1} s^{-1} and ≥ 500 kg m^{-1} s^{-1} in magnitude, respectively; in other words, column (a) includes all the weak, moderate and strong of drafts, column (b) includes moderate and strong updrafts, and column (c) includes strong updrafts only. For statistical analysis, it is better to analyze different drafts together rather than separately. Since the aircraft might ~~not~~under sampled the strongest updraft cores, the tails of PDFs ~~cannot be plotted out to the tail~~could biased low, but these PDFs~~y~~ still provide ~~some useful~~ valuable information. In all the panels, the vertical velocities are exponentially distributed for both updrafts and downdrafts; the PDFs can be fitted using Eq. (1). From Fig. 8 we can see that at 0–2 km, the PDFs for both COPE and ICE-T are narrow~~; the updrafts in COPE are slightly stronger than those in ICE-T, while the downdrafts are relatively weaker~~. At 2–4 km, stronger updrafts and broader PDFs are observed in both COPE and ICE-T compared to those at 0–2 km; the maximum vertical velocity is about 15 m s^{-1}. In COPE, the downdrafts are stronger than those in ICE-T, with the minimum vertical velocity as low as –10 m s^{-1}. For HiCu, the PDFs of the vertical velocity at 2–4 km are narrow, because the HiCu was conducted in the High Plains and the cloud bases are relatively high. At 4–6 km, the updrafts become stronger and the PDFs become broader in all the three field campaigns compared to those at lower levels, especially for COPE and ICE-T. Above 6 km, the PDFs for the updraft become broader in HiCu while they slightly narrow in ICE-T compared to those at 4–6 km. For the downdrafts, the PDFs broaden with height for all the three field campaigns. Generally, the PDFs of the vertical velocity are similar for the three columns. The main difference is found in the first bins of the vertical velocity (0–2 m s^{-1} and – 2–0 m s^{-1}): highest for column (a), which includes all the drafts with air mass flux ≥ 10 kg m^{-1} s^{-1} in magnitude, lowest for column (c), which only includes the strong drafts with air mass flux ≥ 500 kg m^{-1} s^{-1} in magnitude.

Generally, In Fig. 8, the updrafts are relatively stronger in ICE-T or COPE (maritime or coastal convective clouds) than in HiCu (pure continental convective clouds). But notice the aircrafts might not sampleunder sample the strongest part of the convective cores. In addition, the PDFs are plotted as a function of MSL height MSL, the relatively narrow PDFs in HiCu compared to COPE and ICE-T at the same height are possibly because of the higher cloud base in HiCu. Other than the sample issues, the convention triggering mechanism is also important to the updraft strength. The clouds sampled in the three field campaigns are all isolated convective clouds, the CAPE in HiCu was smaller than in COPE and ICE-T. Previous studies (e.g. LeMone and Zipser 1980; Heymsfield et al. 2010) suggest that for deeper convections (e.g. MCSs) the updrafts were stronger in continental clouds than in maritime clouds., an observation that differs from earlier studies (e.g. LeMone and Zipser 1980), in which stronger drafts were observed in continental clouds. This is probably because in the previous field campaigns over ocean (e.g. GATE), the aircraft did not penetrate the strongest cores due to safety concerns. Compared to GATE project, in which the clouds were also sampled over tropical ocean, the PDFs of the vertical velocity in ICE-T has a similar vertical dependence, broadening with height,. but But the PDFs are broader in ICE-T than those in GATE, and the maximum vertical velocity (25 m s^{-1}) in ICE-T is greater than that observed in GATE (15 m s^{-1}). Notice in GATE, the in-situ measurements also have sampling issues. In addition, convections in continental areas other than the High Plains (e.g. Great Plains) may be different from those in HiCu. Recently, Heymsfield et al. (2010) observed strong updrafts in both maritime and continental convective clouds: most exceed 15 m s^{-1} and some exceed 30 m s^{-1}, but the measurements were made for mature deep convection using airborne Doppler radar. More in-situ measurements are needed to further evaluate the difference between maritime and continental convective clouds, including both developing and mature stages.

the convective available potential energy (CAPE) is larger in ICE-T than that in HiCu. Typically, the CAPE in ICE-T is greater than 2000 J kg^{-1}, and the CAPE in HiCu was less than 100 J kg^{-1}. However, CAPE in COPE is also low (typically less than 100 J kg^{-1}), which cannot explain the relatively strong vertical velocity. There are a few possible explanations for the stronger updrafts observed in ICE-T and COPE compared to those observed in HiCu. For example, the convective available potential energy (CAPE) is larger in ICE-T than that in HiCu. Typically, the CAPE in ICE-T is greater than 2000 J kg^{-1}, and the CAPE in HiCu was less than 100 J kg^{-1}. However, CAPE in COPE is also low (typically less than 100 J kg^{-1}), which cannot explain the relatively strong vertical velocity. The strong vertical velocity in ICE-T and COPE maybe also be related to ice initiation. There are many more millimeter drops in the convective clouds observed in ICE-T (Lawson et al., 2015) and COPE (Leon et al., 2015) than that in HiCu; the millimeter drops can result in fast ice initiation (Lawson et al., 2015), and the significant latent heat released during the ice initiation process can strengthen the vertical velocity. In addition, high concentrations of millimeter drops in ICE-T and COPE can result in the quick formation of graupel and frozen rain drops. The falling graupel and frozen rain drops can strongly enhance the ice generation through ice multiplication processes (Heymsfield and Willis, 2014) and possibly strengthen the updraft. Another difference among the three field campaigns is found in the downdrafts. The downdrafts in HiCu and COPE, which are sampled in mid-latitude convective clouds, are obviously stronger than those in ICE-T, which was conducted over tropical ocean. This may be because the ambient relative humidity is low in HiCu and COPE compared to ICE-

~~T, resulting in a faster evaporation of cloud drops and a stronger cooling effect when ambient air mixes with cloud parcels through lateral entrainment (Heymsfield et al., 1978). But since the diameters of the downdrafts in ICE-T are relatively broader (Fig. 4), the air mass fluxes of the downdrafts are not obviously smaller than that in HiCu and COPE.~~

Fig. 9 shows the PDFs of the air mass flux for all the drafts sampled at 0–2 km, 2–4 km, 4–6 km and higher than 6 km. The PDFs are exponentially distributed for the three field campaigns at different heights, which can be fitted using Eq. (1). The coefficients for the fitted function are shown in each panel. ~~At 0–2 km, the PDF of the air mass flux in the updrafts is relatively narrow in ICE-T compared to that in COPE. For the downdraft, the PDF is broader in ICE-T than those in COPE. As height increases up to 6 km, more updrafts with larger air mass flux are observed in ICE-T and the PDFs broadens, but in COPE the PDFs remain similar. In HiCu, the PDFs for updrafts broadens from 2–6 km then remain similar at altitudes higher than 6 km. For downdrafts, the PDFs are similar at different heights for all the three field campaigns. Among the three field campaigns, the differences of the PDFs are small for the weak and moderate drafts and are larger for the strong drafts.~~In the three field campaigns, the PDFs of air mass flux have no obvious trend with height, although the PDFs of diameter and vertical velocity are broadening with height. The differences among the three field campaigns are small for weak and moderate drafts, and become slightly larger for relatively strong updrafts, ~~but again notice there are~~which could be resulted from the sampling issues.

4.3 Profiles of vertical velocity and air mass flux

Fig. 10 is a Whisker-Box plot showing the profiles of the vertical velocity (a-c) and air mass flux (d-f) in the drafts based on the three defined thresholds of air mass flux. The solid box includes all the three different groups of drafts, the dashed boxes excludes the weak drafts, and the dotted boxes includes strong drafts only. The minimum, 10%, 50%, 90% and the maximum values are shown in each box. ~~Notice that the vertical velocity and air mass flux in the downdraft is negative, so the minimum value represents the strongest subsiding parcel, the 10% value represents the strongest 10^{th} percentile subsiding parcel, and the 90% value represents the weakest 10^{th} percentile subsiding parcel. This is opposite to the updraft.~~ In each panel, the absolute values of the vertical velocities and air mass flux (except the minimum and maximum ones) are relatively small for the solid boxes.

In Fig. 10a-c, the three definitions of drafts show different intensities in the vertical velocities. Typically, the 10%, 50% and 90% values in the dotted boxes are 1–2 times larger in magnitude than those in the solid boxes. However, the profiles of the three definitions of drafts vary similarly with height for each field campaign. In the updrafts sampled during HiCu (Fig. 10a), the maximum vertical velocity increases ~~from about 10 m s^{-1} to 18 m s^{-1}~~ with height up to 8 km, then decreases with height; the 90% vertical velocity in the solid boxes increases from 4 m s^{-1} to 8 m s^{-1} between 0–10 km. The 10% and 50% vertical velocities in the solid boxes remain similar between 2–8 km then slightly increase at 8–10 km. ~~The magnitudes of the 10% and 50% vertical velocities in the solid boxes are about 0.5–0.6 m s^{-1} and 1.8–2.5 m s^{-1}.~~ In the downdrafts, the minimum vertical velocity decreases from –7 m s^{-1} to –12 m s^{-1} up to 8 km and increases to –9 m s^{-1} at 8–10 km. The 10%, 50 % and 90% values all slightly decrease with height. In the updrafts sampled during COPE (Fig. 10b), the maximum ~~vertical velocities increase from 8 m s^{-1} to 23 m s^{-1} between 0–6 km, the~~ 10%, 50% and 90% vertical velocities increase ~~up to 6 km~~with height, the maximum value is 23 m s^{-1} ~~The magnitudes are 0.35–0.45 m s^{-1}, 1–1.6 m s^{-1}, and 2.6–6 m s^{-1} in the solid boxes, respectively~~. The minimum vertical velocity in the downdrafts intensifies from –5 to –10 m s^{-1} with height up to 4 km, then remains similar at 4–6 km. In the updrafts sampled during ICE-T (Fig. 10c), the maximum vertical velocities increase with height from 5.5 m s^{-1} to 25 m s^{-1} up to 6 km, then slightly decreases at 6–8 km. The 90% value increases from 2 to 6 m s^{-1} between 0~~–~~–4 km, then remains similar at higher levels. The 10% and 50% values~~, which are about 0.32–0.6 m s^{-1} and 0.8–1.8 m s^{-1} in the solid boxes, respectively,~~ do not show an obvious trend with height. In the downdrafts the minimum vertical velocity remains similar below ~~increases from –6 m s^{-1} to –5 m s^{-1} between 0 km and~~ 4 km, and decreases ~~from –5 m s^{-1}~~ to –18 m s^{-1} between 4 km and 8 km. The 10%, 50% and 90% values tend to decrease or remain similar at first and then increase with height. The peak (~25 m s^{-1}) and the minimum (~-18 m s^{-1}) vertical velocities are observed at 4–6 km and 6–8 km, respectively.

To summarize, vertical velocity in the drafts varies differently with height in the three field campaigns. ~~Generally, the maximum and 90% vertical velocities in the updrafts are greater in COPE or ICE-T than in HiCu, while the median vertical velocities are the greatest in HiCu and weakest in ICE-T.~~ Stronger downdrafts are often observed in HiCu and COPE compared to those in ICE-T. The weak, moderate and strong drafts have similar variations ~~of the vertical velocity~~ with height, but the magnitudes are the smallest when including all the drafts and become larger if the weak drafts are excluded. The 10%, 50% and 90% vertical velocities in updrafts and downdrafts over tropical ocean (ICE-T) observed in this study generally have similar magnitudes to those shown in previous studies (e.g. LeMone and Zipser, 1980; Lucus and Zipser, 1994). But strong updrafts (downdrafts) in excess of 20 m s^{-1} (–10 m s^{-1}) are also observed in this study, which are ~~not~~ rarely ~~shown~~ reported in previous aircraft observations. This finding is consistent with recent remote sensing observations (e.g. Heymsfield et al., 2009). The updrafts and downdrafts in convective clouds over land shown in this study (HiCu) are weaker than those shown by Byers and Braham (1949) and Heymsfield et al. (2009), possibly because the clouds sampled in HiCu were isolated convective clouds over high plains, which could be different than deeper convective clouds from low elevations.of the sampling issues, different convection mechanisms and the relatively small CAPE in HiCu.HiCu was conducted over the High Plains.

Fig. 10d-f shows the profiles the air mass flux statistics for the drafts sampled during the three field campaigns. As expected, the absolute values of the air mass flux are relatively small if all the drafts are included (dotted boxes), and become larger if the drafts with small air mass flux are excluded. However, the variations of the air mass flux with height are similar for the three different definitions in each panel. As determined by the three thresholds, the minimum absolute values in the solid boxes are about 10 times smaller than those in the dashed boxes and about 50 times smaller than those in the dotted boxed; for the 10%, 50%, 90% and the maximum absolute values, the differences among the three type of boxes become smaller. tThe air mass flux varies with height differently for the three field campaigns and do not have obvious trend with height. For updraft, the maximum air mass flux is of the order of 10^4 kg m^{-1} s^{-1}, and the median values for the three different types of boxes are typically ~100 kg m^{-1} s^{-1}, ~200 kg m^{-1} s^{-1} and ~1000 kg m^{-1} s^{-1}, respectively. The air mass flux in the downdrafts is a few times smaller in magnitude than those in the updrafts, but extreme strong downdraft on the order of 10^4 kg m^{-1} s^{-1} maycould be observed in some specific cases. Compared to previous studies, the air mass flux in this study shows similar magnitudes, but the vertical dependences are different. Lucas and Zipser (1994) show that the convection off tropical Australia intensifies with height from 0 to 3 km, then weakens with height in terms of air mass flux. Anderson et al. (2005) shows that updrafts and downdrafts over the tropical Pacific Ocean intensify with height up to 4 km, then weaken at higher levels. In contrast, this study shows the strongest updrafts and downdrafts in terms of air mass flux were observed at higher levels~~In the present study, the strongest updrafts and downdrafts are observed at higher levels for all the three field campaigns.~~

~~In HiCu, the air mass flux does not show an obvious trend with height. In the updraft, the 10%, 50% and 90% values remain similar at different height ranges. The maximum air mass flux increases from 2–6 km, then decreases with height. The peak value is about 1.3×10^{4} kg m^{-1} s^{-1}, found at 4–6 km. The air mass flux in the downdrafts has relatively larger variability, especially for the minimum values. The strongest downdraft in terms of air mass flux (about -1.2×10^{4} kg m^{-1} s^{-1}) is found at 4–6 km, but this is probably due to a specific case since the 50% and 90% values are similar to those at the other height ranges. In COPE, the 90% and the maximum air mass flux in the updraft tend to increase with height, while the 10% and 50% values are similar at different height ranges. For the downdraft, the minimum air mass flux decreases between 0–2 km and remains similar at 4-6 km. The 10%, 50% and 90% values are similar at different height ranges. The strongest updrafts and downdrafts in terms of air mass flux are observed at 4–6 km and 2–4 km, about 1.8×10^{4} kg m^{-1} s^{-1} and -2.8×10^{3} kg m^{-1} s^{-1}. In ICE-T, the maximum air mass flux in the updraft increases with height up to 6 km, then decreases at 6–8 km. The 10%, 50% and 90% values in the updraft and downdraft intensify from 0-4 km and decrease or remain similar at higher levels. The strongest updraft (3×10^{4} kg m^{-1} s^{-1}) and downdraft (-3.5×10^{3} kg m^{-1} s^{-1}) are observed at 4–6 km and 0–2 km, respectively. The minimum value is probably due to a specific case because the 10%, 50% and 90% values at 0–2 km are larger or similar to those at the other heights.~~

To summarize, the air mass flux varies with height differently for the three field campaigns. For updraft, the maximum air mass flux is of the order of 10^4 kg m^{-1} s^{-1}, and the median values for the three different types of boxes are typically ~100 kg m^{-1} s^{-1}, ~200 kg m^{-1} s^{-1} and ~1000 kg m^{-1} s^{-1}, respectively. The air mass flux in the downdrafts is a few times smaller in magnitude than those in the updrafts, but extreme strong downdraft on the order of 10^4 kg m^{-1} s^{-1} may be observed in some specific cases. Compared to previous studies, the air mass flux in this study shows similar magnitudes, but the vertical dependences are different. Lucas and Zipser (1994) show that the convection off tropical Australia intensifies with height from 0 to 3 km, then weakens with height in terms of air mass flux. Anderson et al. (2005) shows that updrafts and downdrafts over the tropical Pacific Ocean intensify with height up to 4 km, then weaken at higher levels in terms of air mass flux. In the present study, the strongest updrafts and downdrafts are observed at higher levels for all the three field campaigns.

4.4 Composite structure of vertical velocity

Fig. 11- shows the composite structure for the updrafts and downdrafts with air mass flux ≥ 10 kg m^{-1} s^{-1} as a function of normalized scale. The 0 and 1 coordinates on the x-axis indicate the upwind and downwind sides of the draft. Since we do not have continuous penetrations in a single cloud, we have to statistically analyze the evolution of the draft structure. In Fig. 11, we can see the normalized shape do not have significant change with height, the peak vertical velocity is strengthening with height for all the three field campaigns. If the magnitude of the vertical velocity is normalized, the structures of the updraft and downdraft at different heights will be very similar. Connecting this figure to the PDFs of diameter (Fig. 4) and air mass flux

(Fig. 9), the results show statistically that , the drafts were expanding (Fig. 4) and the vertical velocity was strengthening (Fig. 11), but the air mass flux was not increasing with height (Fig. 9). This reveals the complexity of the evolution of the drafts. Based on our datasets, there could be different possibilities of the updraft evolution: 1) an updraft expands and the vertical velocity weakens with height, 2) an updraft expands and the vertical velocity strengthens with height, 3) an updraft splits to multiple updrafts and downdrafts, 4) two updrafts merged and become one updrafts. In addition, entrainment/detrainment and water loading also have important impacts on the evolution of drafts in convective clouds.shows the composite structure of the vertical velocity as a function of the normalized diameter for the updrafts and downdrafts with air mass flux ≥ 10 kg m^{-1} s^{-1}, 100 kg m^{-1} s^{-1} and 500 kg m^{-1} s^{-1} in magnitude. As expected, the draft as a whole is weaker if all the drafts are included in the calculation and becomes stronger if the drafts with small air mass flux are excluded. In HiCu, when all weak, moderate and strong updrafts are included (red curves), the vertical velocity near the center is about 1.7 m s^{-1}. When only moderate and strong updrafts are included (green curves), the vertical velocity near the center is ~2.4 m s^{-1}. When all the updrafts with air mass flux smaller than 500 kg m^{-1} s^{-1} in magnitude are excluded, the absolute values of the vertical velocity near the center increase to ~3.4 m s^{-1}. The vertical velocity in downdrafts is about 0.2 m s^{-1} smaller in magnitude than that in updrafts. The structures of the vertical velocity in COPE are quite similar to those in HiCu, in both shape and magnitude, especially for the red and green curves. The blue curves have relatively larger variations due to the small sample size. These variations reveal the complicated structure in some drafts. In ICE-T, the shapes of the vertical velocity structures are similar to those in HiCu and COPE, but the magnitudes are smaller, which suggests that statistically more weak drafts are found in ICE-T, although the peak vertical velocity is observed in ICE-T. This is consistent with

~~Fig. 10. In Fig. 11, if the magnitude of the vertical velocity is normalized, the structures of the three defined classes of updraft and downdraft among the three field campaigns will be very similar.~~

In this composite analysis based on in-situ measurements, the penetration direction has no obvious impact on the vertical velocity structure, whether the aircraft penetrates along or across the horizontal wind (not shown). For convective cloud, wind shear has a large impact on the cloud evolution (Weisman and Klemp 1982); however, aircraft data are insufficient to reveal the wind shear impact, because each penetration is made at a single level and the aircraft does not always penetrate through the center of the draft. Remote sensing data can be helpful to study the two-dimensional or three-dimensional structures of the vertical velocity in convective clouds. For example, airborne radar with slant and zenith/nadir viewing beams can provide two-dimensional wind structure in convective clouds (e.g. Wang and Geerts, 2013). Volumetric radar (e.g. Collis et al. 2013, Jorgensen et al. 2000) can provide three-dimensional structure of air (or hydrometeor) motion. Thus, in-situ measurements as well as remote sensing measurements are needed to further analyze the wind shear impact.

4.5 Vertical air motion characteristics as clouds evolve

Fig. 12 shows the profiles of the vertical velocity (a-c) and the air mass flux (d-f) for the updraft and downdraft in the convective clouds with different cloud top heights (CTH). Here, all weak, moderate and strong updrafts are included. Different colors represent the clouds with different CTHs. These profiles can generally reveal the change of vertical velocity and air mass flux as the clouds evolve. The key point presented in Fig. 12a-c is that the peak vertical velocity ~~and air~~

~~mass flux~~ is observed at higher levels as the clouds evolve. For clouds with CTHs lower than 4 km (red boxes), the maximum vertical velocity is observed at 2–4 km. When the cloud become deeper, the vertical velocity and air mass flux are stronger at higher levels. This is to be expected, because all the data analyzed in this paper are collected from isolated convective clouds, so the convective bubbles keep ascending as the clouds evolve. MCSs may have different characteristics of vertical air motion because there is continuous low level convective source.

The maximum vertical velocity is observed within 2 km below cloud top; this is consistent with Doppler velocity images measured by WCR (e.g. Fig. 2b), which show the typical strongest updraft is observed 1–1.5 km below cloud top. The strongest downdrafts are sometimes observed more than 2 km below cloud top. The 10% and 50% values do not have obvious trend as the clouds evolve, ~~especially in HiCu and ICE-T,~~ possibly because of the increasing contribution from moderate and weak drafts as the clouds become deeper and broader (Fig. 6 and 7). The air mass flux (Fig. 12d-f) has no obvious trend as the clouds evolve, again suggesting multiple factors (e.g. entrainment/detainment, microphysics) have impact on the evolution of the drafts.

~~Generally, in HiCu and ICE-T the drafts intensify as the clouds evolve, but this is not found in COPE, maybe because most of the penetrations were made near the cloud top, rather than in the strongest portion of a draft.~~ Since the aircraft just provides a line of data through drafts, and not vertical information unless the plane makes multiple passes through the same cell, more data, including remote sensing measurements are needed to better understand the evolution of the vertical velocity in convective clouds at different stages.~~Since the vertical resolution of aircraft in-situ data is poor, more data, including remote sensing measurements, are needed to better understand the evolution of the vertical velocity in convective clouds as they go through the different stages..~~

5. Discussion

In this study, we provide the statistics of vertical air motion in isolated convective clouds using in-situ measurements from three field campaigns. The statistical results suggest vertical air motions in convective clouds are very complicated and could be affected by many factors.

Microphysics strongly interacts with vertical velocity through different processes, for example, droplet condensation/evaporation, ice nucleation/sublimation, water loading, etc. Yang et al. (2016) shows the LWC and IWC are both higher in stronger updrafts in developing convective clouds, while the liquid fraction has no obvious correlation with vertical velocity. In mature convective clouds the LWC is also higher in stronger updrafts, but the IWC is similar in relatively weak and strong updrafts, the liquid fraction is correlated to the vertical velocity between -3 C and -8 C, possibly because Hallet-Mossop process is more significant in weaker updrafts (Heymsfield and Willis, 2014). Lawson et al. (2015) shows the existence of millimeter drops in the convective clouds ~~drops~~ can result in fast ice initiation, and the significant latent heat released during the ice initiation process can strengthen the updrafts. In ~~in~~ ICE-T and COPE, we do observe many millimeter drops, which may strongly interact with vertical velocity through fast ice generation. However, in some cases, the existence of millimeter drops can result in strong warm rain process (Yang et al. 2016; Leon et al. 2016), which may weaken the updrafts and make the clouds dissipate quickly.

Entrainment/detrainment also has strong interaction with the vertical velocity. In the analysis above, we see the downdrafts in HiCu and COPE are obviously stronger than those in ICE-T. This maybe partly because the ambient relative humidity is low in HiCu and COPE compared to

ICE-T, resulting in a strong evaporation-cooling effect when ambient air mixes with cloud parcels through lateral entrainment/detrainment (Heymsfield et al., 1978). Entrainment has impact on updrafts as well. Recent study using in-situ measurement and model simulation suggests stronger entrainment may result in weaker updrafts (Lu et al., 2016). In ICE-T, we also find the weaker updrafts are associated with stronger entrainment/detrainment using in-situ measurements of relative humidity, equivalent potential temperature, droplet concentration and LWC (not shown). In COPE and HiCu, we do not have the appropriate instruments to do similar analyses. Previous studies (e.g. Heymsfield et al., 1978; Wang et al., 2013) suggest updraft cores unaffected by entrainment may exist in some convective clouds.

A~~Here we a~~gain it is important to be aware of~~highlight there are many~~ limitations ~~and sampling issues~~ of using aircraft in-situ measurements for this kind of study. More observations (in situ and remote sensing) as well as model simulations are needed to better characterize the vertical air motion in convective clouds and its interactions with microphysics and entrainment/detrainment mixing.

~~5.~~6. Conclusions

The vertical velocity and air mass flux in isolated convective clouds are statistically analyzed in this study using aircraft data collected from three field campaigns, HiCu, COPE and ICE-T, conducted over mid-latitude High Plains, mid-latitude coastal area and tropical ocean. Three thresholds of air mass flux are selected to delineate weak, moderate and strong draft: 10 kg m^{-1} s^{-1}, 100 kg m^{-1} s^{-1} and 500 kg m^{-1} s^{-1} in magnitude. These definitions only apply for the isolated convective cloud in this study and are not necessarily appropriate for other convections (e.g. MCSs). The main findings are as follows.

1) Small-scale updrafts and downdrafts in convective clouds are often observed in the three field campaigns. More than 85%, 90% and 74% of the updrafts are narrower than 500 m in HiCu, COPE and ICE-T, respectively, and more than 90 % of the downdrafts are narrower than 500 m in the three field campaigns combined. These small scale drafts make significant contributions to the total air mass flux. Updrafts narrower than 500 m contribute 20%–35% of the total upward flux, and downdrafts narrower than 500 m contribute 50%–65% of the total downward air mass flux.

2) In terms of the air mass flux, the weak and moderate drafts make an important contribution to the total air mas flux exchange. Generally, the number of drafts increases with cloud diameter. For many narrow clouds, the weak and moderate drafts dominate and contribute most of the total air mass flux. For broader clouds, the stronger updrafts contribute most of the total air mass flux, but the contribution from weak and moderate drafts increases as the cloud evolves.

3) PDFs and profiles of the vertical velocity are provided for the ~~three defined types of~~ drafts. In all the height ranges, the PDFs are roughly exponentially distributed~~. At the lowest level, the PDFs of the vertical velocity~~ and ~~are relatively narrow, and~~ broaden with height. ~~For the updrafts, the PDFs of the vertical velocity are broader in ICE-T and COPE, while for the downdrafts the PDFs of the vertical velocity are broader in HiCu and COPE. The profiles show that updrafts are stronger in ICE-T and COPE than in HiCu, and d~~The downdrafts are stronger in HiCu and COPE compared to ICE-T. Relatively strong updrafts (> 20 m s^{-1}) were sampled

during ICE-T and COPE. The updrafts in HiCu are weaker than previous studies of deeper continental convections, possibly because the clouds sampled in HiCu were isolated convective clouds over high plains, which could be different than deeper convective clouds from low elevations.

4) PDFs and profiles of the air mass flux are provided for the drafts. The PDFs are similarly exponentially distributed at different heights, and have no obvious trend with height~~. For updrafts, the PDFs are broader in ICE-T than in HiCu and COPE, but for downdrafts the PDFs are broader in HiCu and COPE than in ICE-T~~. In the updrafts, the maximum air mass flux has an order of 10^4 kg m^{-1} s^{-1}. The air mass flux in the downdrafts are typically a few times smaller in magnitude than those in the updrafts.

5) The composite structures of the vertical velocity in the updrafts and downdrafts have similar normalized shapes for the three field campaigns: the vertical velocity is the strongest near the center, and weakens towards the edges. ~~On average, the updrafts have similar intensity across the three field campaigns, while for downdrafts the vertical velocity is the weakest in ICE-T and stronger in HiCu and COPE~~Statistically, the vertical velocity and diameter were increasing with height, but the air mass flux does not has obvious trend with height, ~~suggesting entrainment~~suggesting entrainment/detrainment, water loading and other complicated processes have impacts on the evolution of the drafts.~~.~~

6) The change of vertical air motion characteristics as the cloud evolves are briefly discussed. Generally, the strongest portion of a draft ascends with height as the cloud evolves. The maximum vertical velocity is observed within 2 km below cloud top; the downdrafts are sometimes stronger at levels more than 2 km below cloud top.

The vertical air motion in convective clouds is very complicated, and is affected by many factors, such as convection mechanisms, entrainment/detrainment and microphysics. ~~Based on the aircraft observations from three field campaigns, this study provides quantitative analyses of the vertical air motion characteristics in isolated convective clouds, compares the differences of vertical velocity and air mass flux among the different field campaigns, and shows the importance of small-scale updrafts and downdrafts. The results are useful to evaluate model simulations and improve parameterizations in models.~~ This study only deals with ~~a biased sample of~~isolated convective clouds and there are ~~many~~several limitations associated with using ~~of~~ aircraft in-situ measurements. More data, including in-situ and remote sensing measurements, are needed ~~To~~ to better understand the ~~differences of the vertical air motions among different convective clouds and the evolution of the updrafts and downdrafts in~~vertical air motion in convective clouds~~ more data are needed~~.

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Table 1. Number of penetrations, time in clouds and flight length in clouds sampled at 0–2 km, 2–4 km, 4–6 km, 6–8 km and 8–10 km MSL in HiCu, COPE and ICE-T.

Height (km MSL)	HiCu			COPE			ICE-T		
	Number of penetrations	Time in clouds (min)	Length in clouds (km)	Number of penetrations	Time in clouds (min)	Length in clouds (km)	Number of penetrations	Time in clouds (min)	Length in clouds (km)
8–10	43	12	79						
6–8	565	122	789				132	52	423
4–6	596	104	653	207	39	244	299	116	895
2–4	373	50	274	378	86	486	34	10	73
0–2				219	40	211	197	27	167

Table 2. Number of updrafts and downdrafts sampled at 0-2 km, 2-4 km, 4-6 km, 6-8 km and 8-10 km in HiCu, COPE and ICE-T. Three numbers are given for the updraft and downdraft at each level, respectively, according to the three different definitions: weak, moderate and strong.

Height (km)		HiCu		COPE		ICE-T	
		Updraft	Downdraft	Updraft	Downdraft	Updraft	Downdraft
8-10	weak	66	100				
	moderate	52	44				
	strong	44	17				
6-8	weak	818	763			382	372
	moderate	559	540			175	136
	strong	287	130			102	23
4-6	weak	748	668	290	184	858	671
	moderate	522	389	232	193	425	329
	strong	343	48	135	51	266	73
2-4	weak	311	235	568	424	49	47
	moderate	271	84	467	434	51	51
	strong	149	7	188	101	32	10
0-2	weak			368	192	319	205
	moderate			266	90	234	104
	strong			96	9	60	7

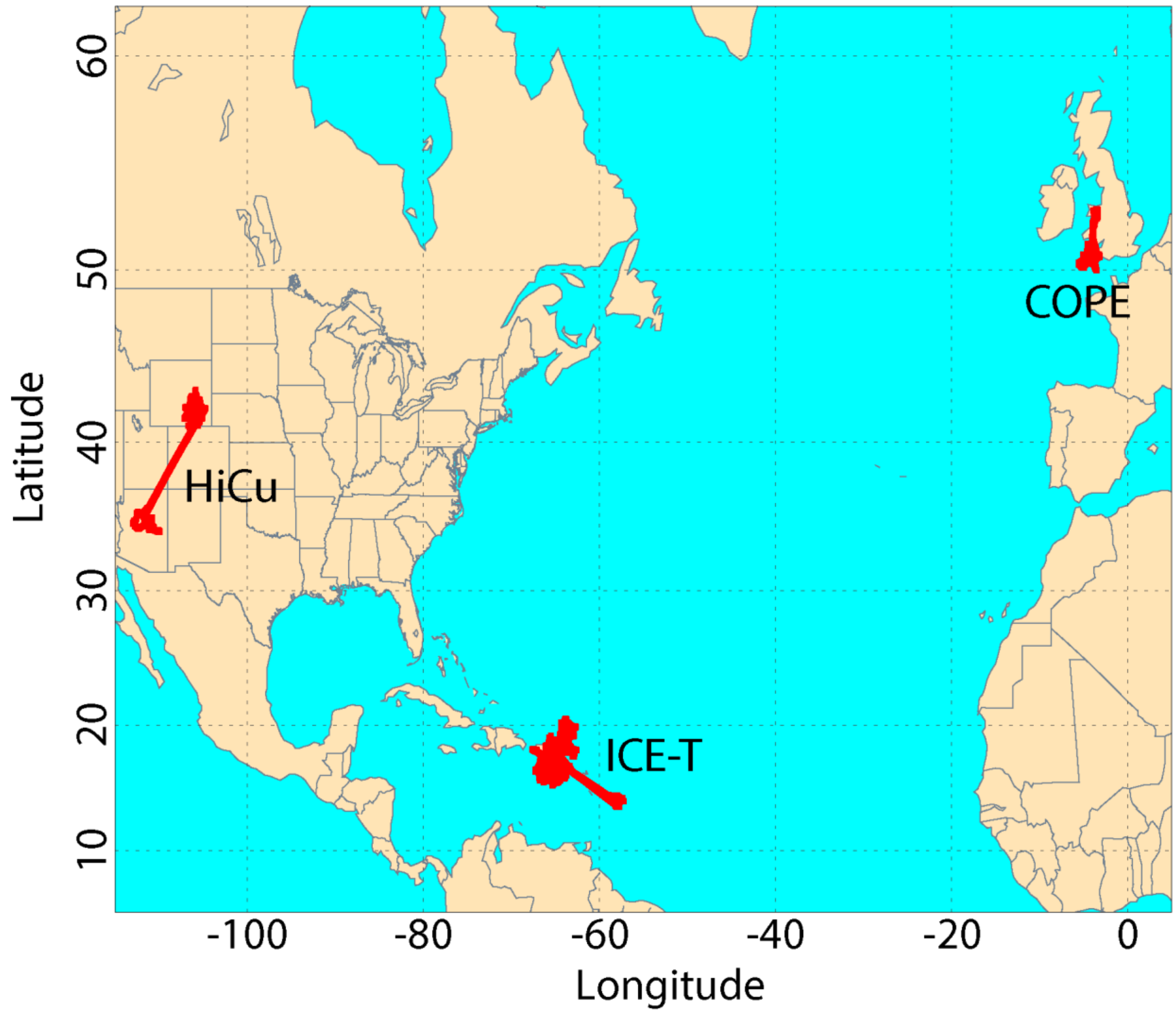

Figure 1. Flight tracks for the three field campaigns: HiCu, COPE and ICE-T.

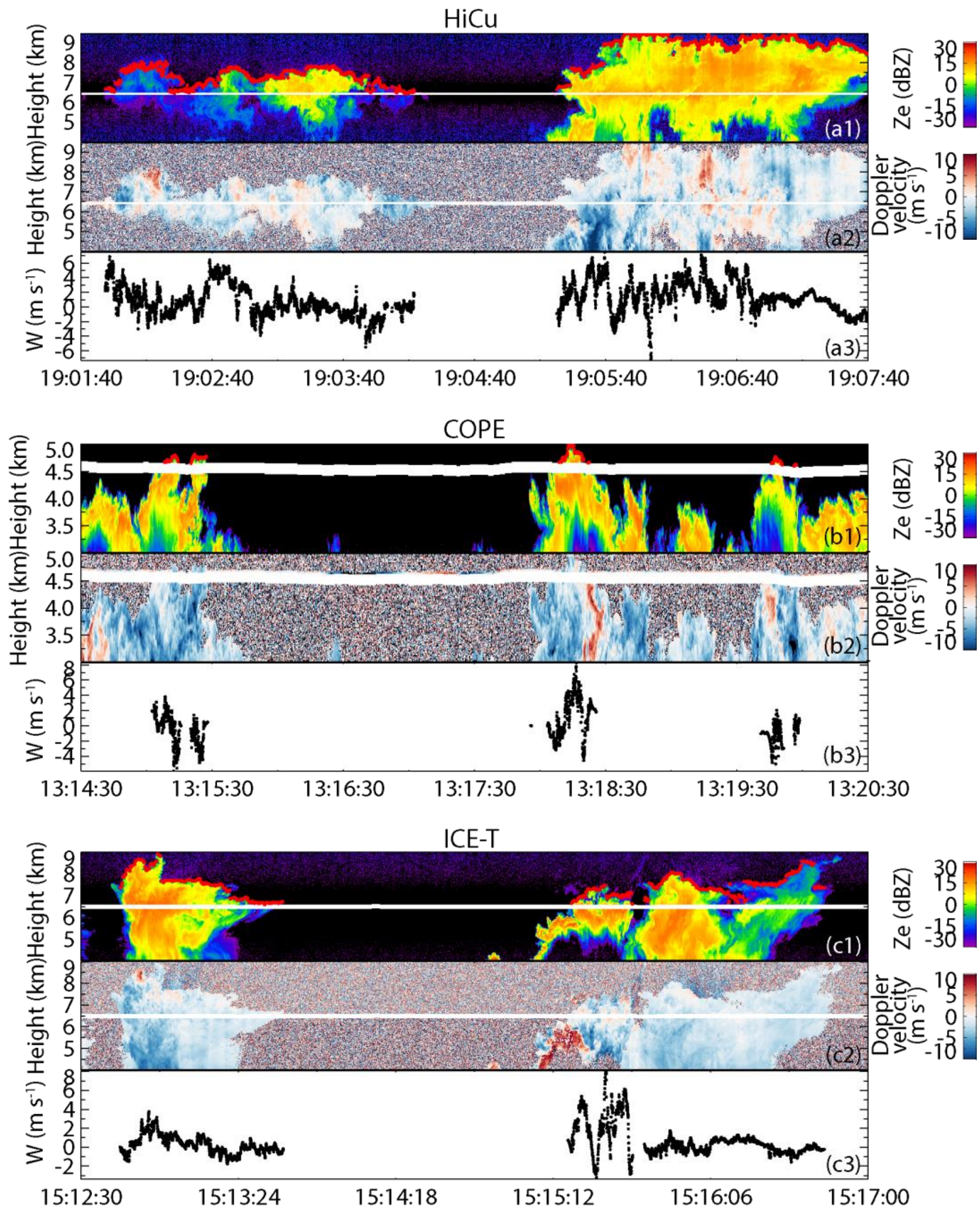

Figure 2. Examples of radar reflectivity, Doppler velocity and 25-Hz in-situ vertical velocity measurements for the convective clouds sampled in HiCu, COPE and ICE-T. The red dots in (a1), (b1) and (c1) are the cloud tops estimated by WCR.

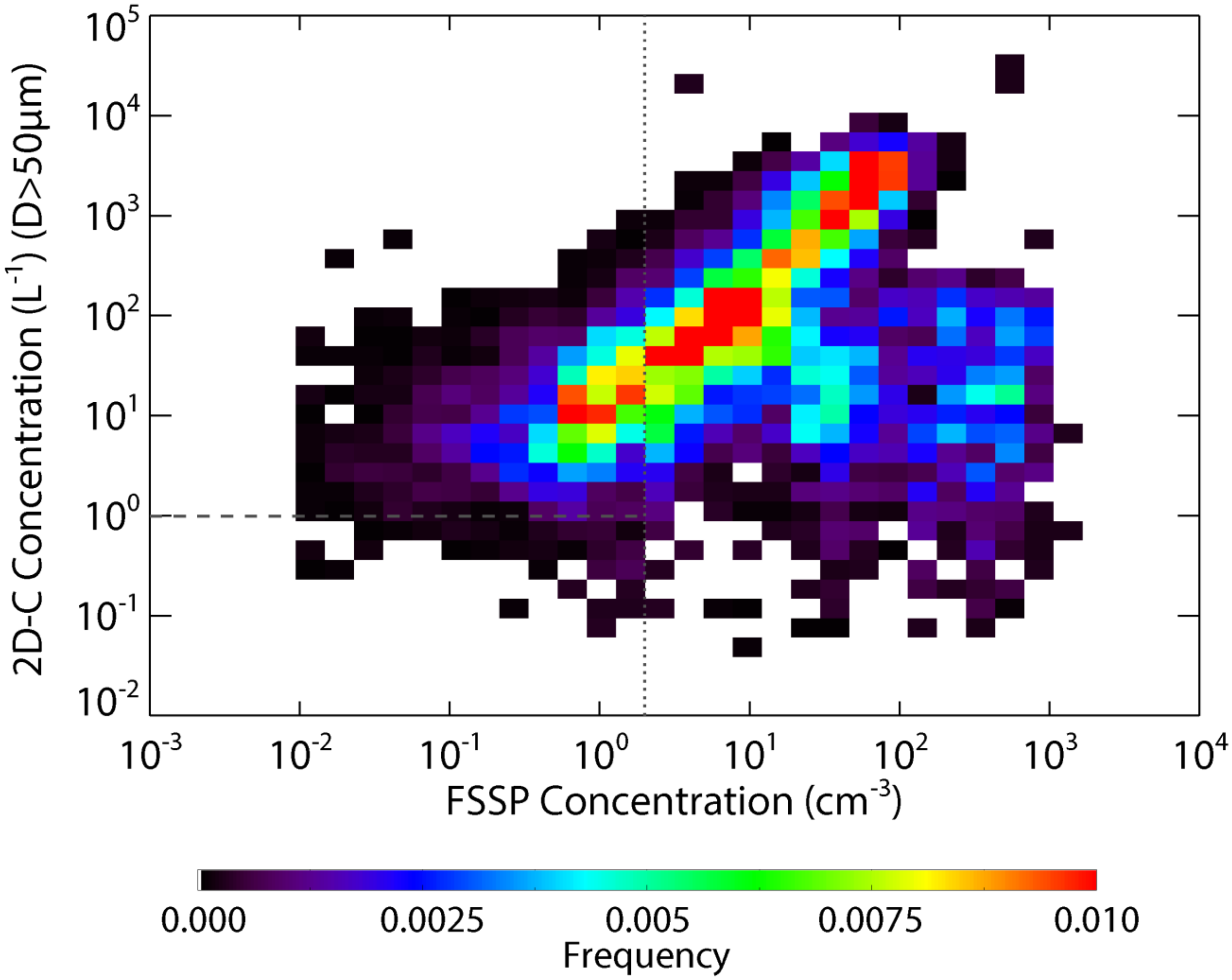

Figure 3. Occurrence distributions as a function of the particle concentrations measured by FSSP versus the concentrations of the particles ≥ 50 μm in diameter measured by 2D-C in the clouds identified by WCR reflectivity. The dashed and dotted lines indicate the FSSP concentration equal 2 cm^{-3} and the 2D-C concentration equal 1 L^{-1}, respectively.

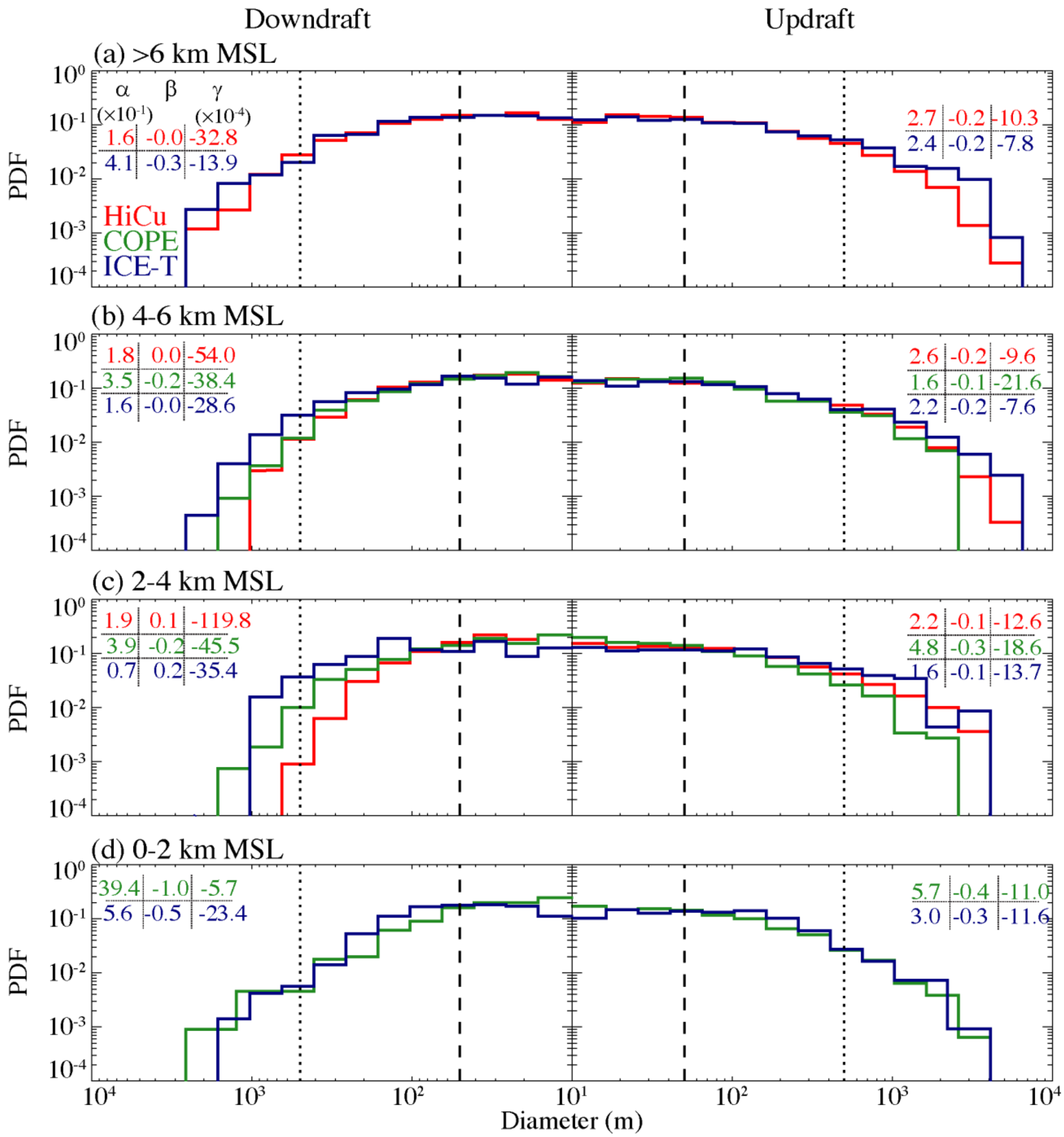

Figure 4. PDFs of the diameters for the updrafts and downdrafts sampled at 0–2 km, 2–4 km, 4–6 km and higher than 6 km. The numbers shown in each panel are the coefficients of the fitted exponential function (Eq. 1).

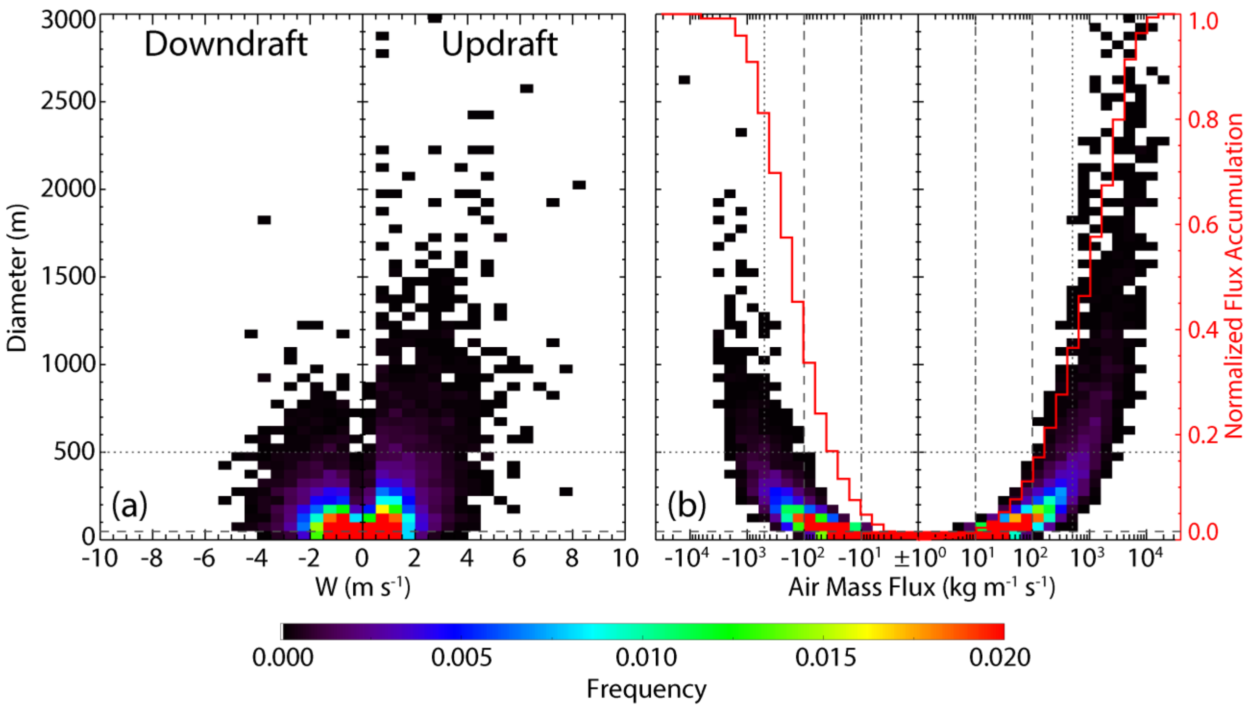

Figure 5. Occurrence distributions as (a) a function of diameter and mean vertical velocity, and (b) a function of diameter and air mass flux for all updrafts and downdrafts. The normalized accumulation flux is also shown by the red curves. The horizontal dotted and dashed lines in (a) and (b) indicate the draft diameter equal 500 m and 50 m, which are used as the diameter thresholds to identify a "draft" in previous studies and in this study, respectively. The vertical dash-dotted, dashed and dotted lines in (b) indicate air mass flux equal 10 kg m^{-1} s^{-1}, 100 kg m^{-1} s^{-1} and 500 kg m^{-1} s^{-1} in magnitude, respectively, which are the thresholds used to delineate the three different groups of draft.

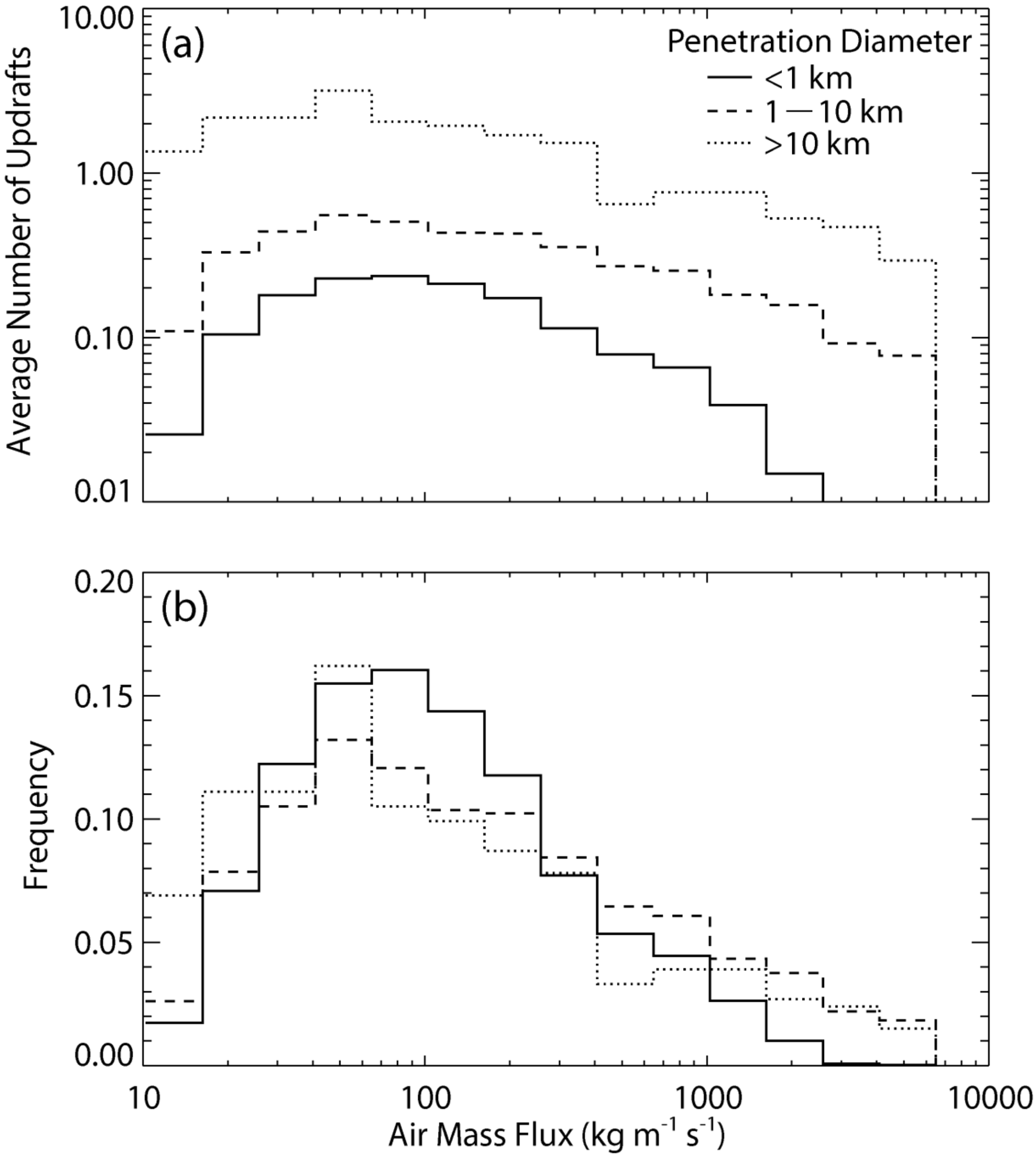

Figure 6. (a) Average number and (b) occurrence frequency of updrafts as a function of air mass flux observed in penetrations with length < 1 km (solid), 1-10 km (dashed) and >10 km (dotted). The result is a composite of HiCu, COPE and ICE-T.

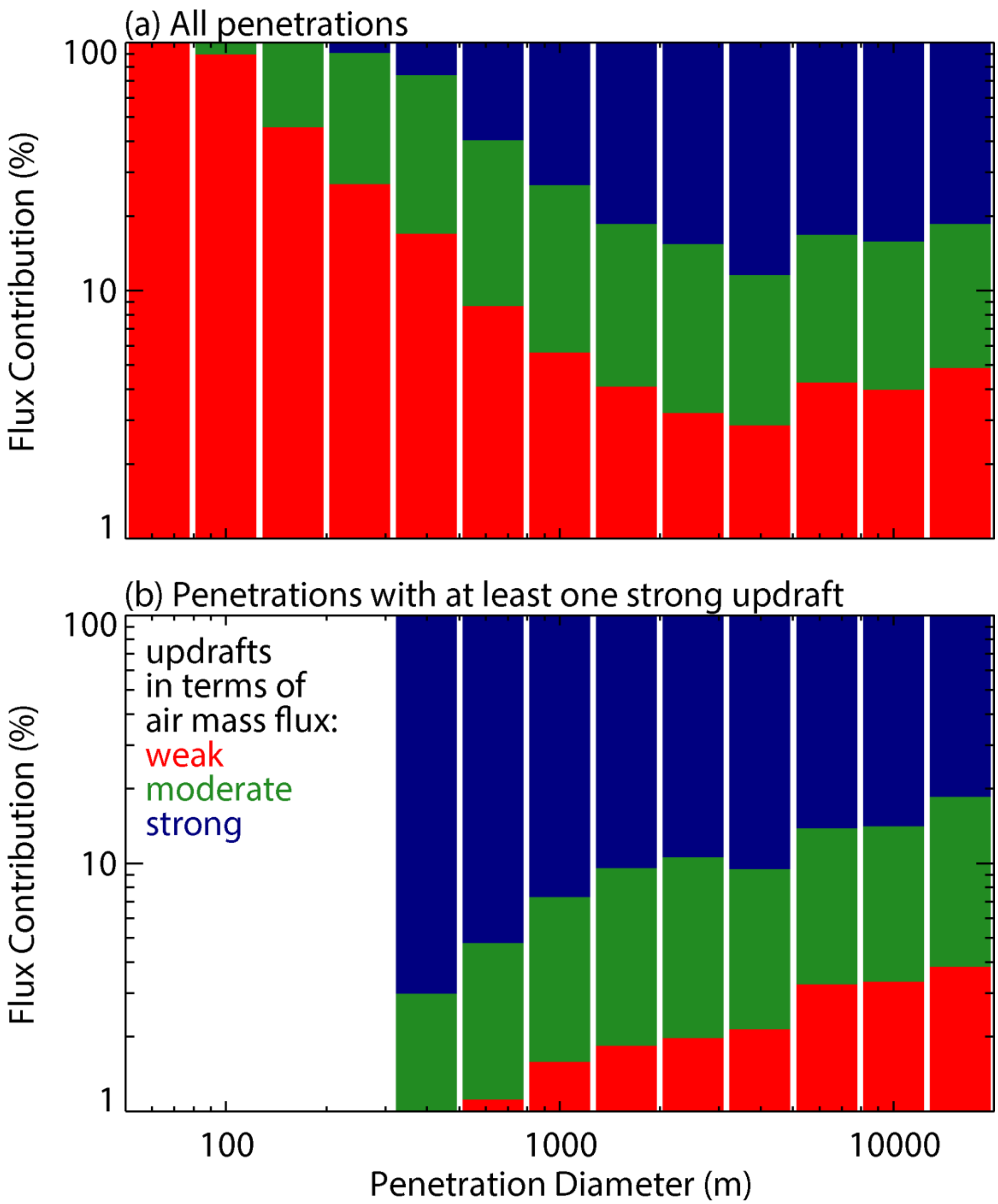

Figure 7. Average percentile contribution to total upward air mass flux by the weak (red), moderate (green) and strong (blue) updrafts delineated in this study. The result is a composite of HiCu, COPE and ICE-T.

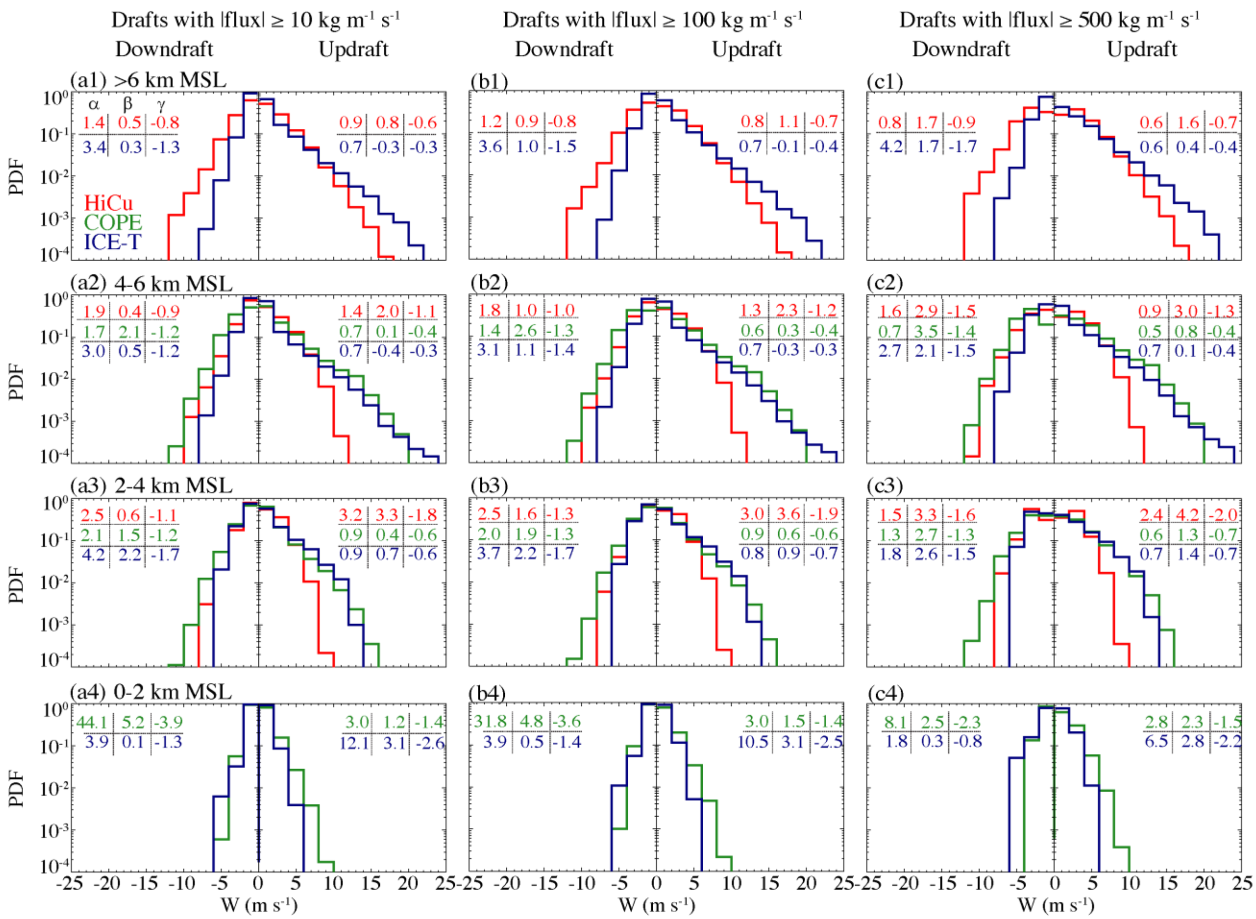

Figure 8. PDFs of the 25-Hz vertical velocity for the updrafts and downdrafts with air mass flux ≥ (a) 10 kg m^{-1} s^{-1}, (b) 100 kg m^{-1} s^{-1} and (c) 500 kg m^{-1} s^{-1} in magnitude, sampled at 0–2 km, 2–4 km, 4–6 km and higher than 6 km. The numbers shown in each panel are the coefficients of the fitted exponential function (Eq. 1).

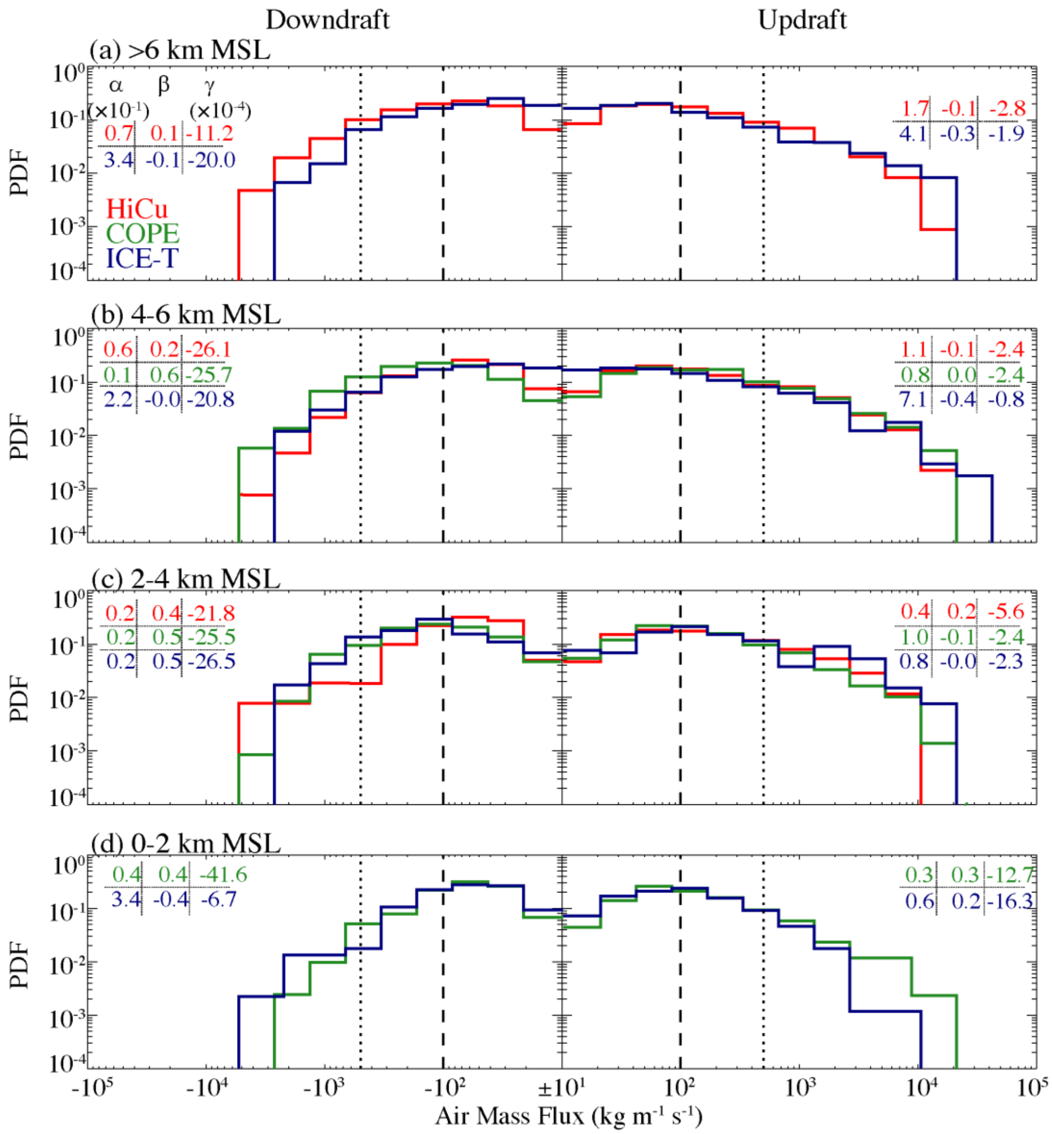

Figure 9. PDFs of the air mass flux for the updrafts and downdrafts sampled at 0–2 km, 2–4 km, 4–6 km and higher than 6 km. The three thresholds of the air mass flux (±10 kg m^{-1} s^{-1}, ±100 kg m^{-1} s^{-1} and ±500 kg m^{-1} s^{-1}) are shown by the solid (overlaps with the central y-axis in each panel), dashed and dotted lines. The numbers shown in each panel are the coefficients of the fitted exponential function (Eq. 1).

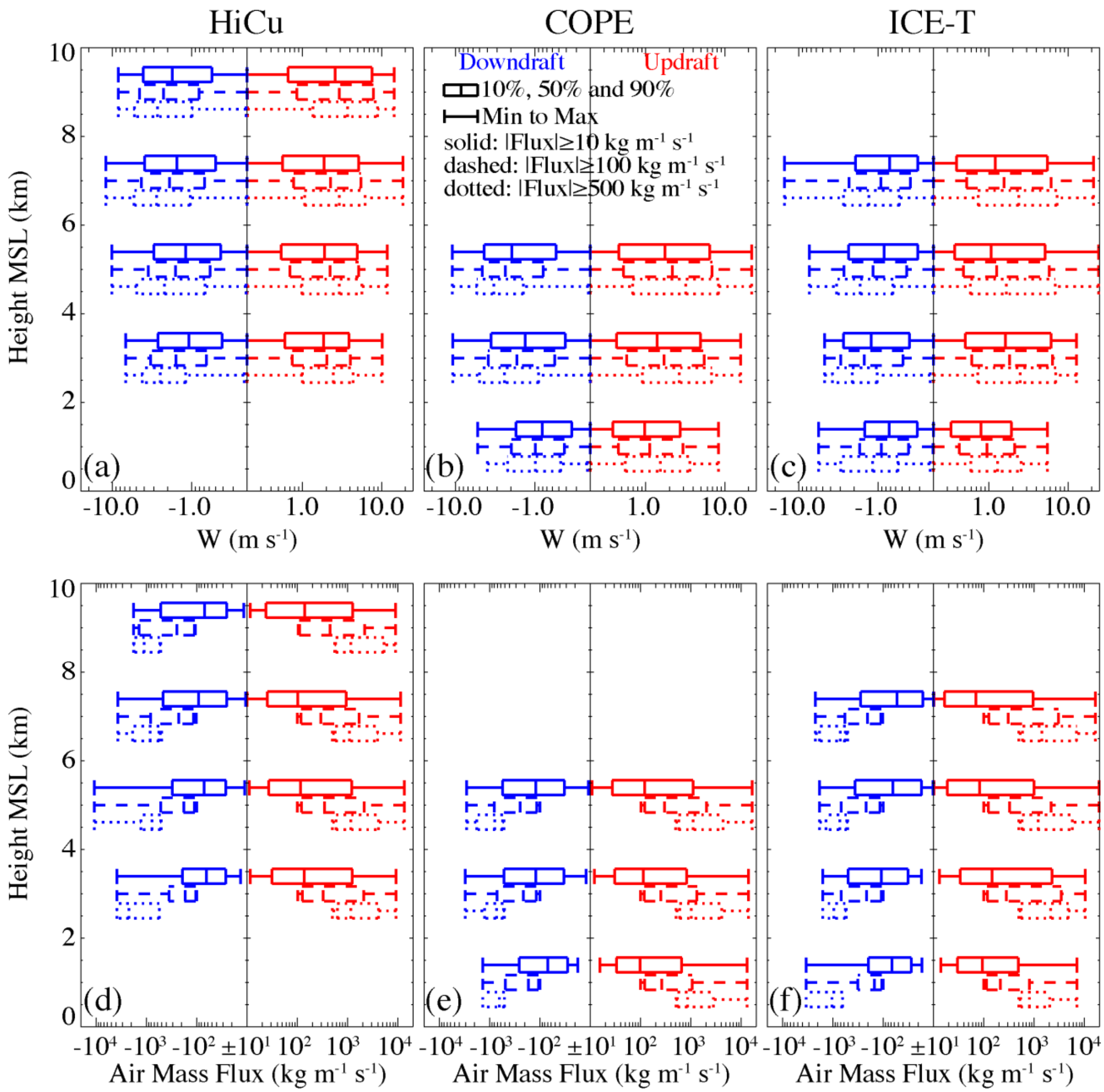

Figure 10. Profiles of (a-c) the vertical velocity and (d-f) air mass flux for all the updrafts and downdrafts sampled at 0–2 km, 2–4 km, 4–6 km, 6–8 km and 8–10 km. The dotted, dashed and solid boxes represent for the drafts with air mass flux ≥ 10 kg m^{-1} s^{-1}, 100 kg m^{-1} s^{-1} and 500 kg m^{-1} s^{-1} in magnitude, respectively.

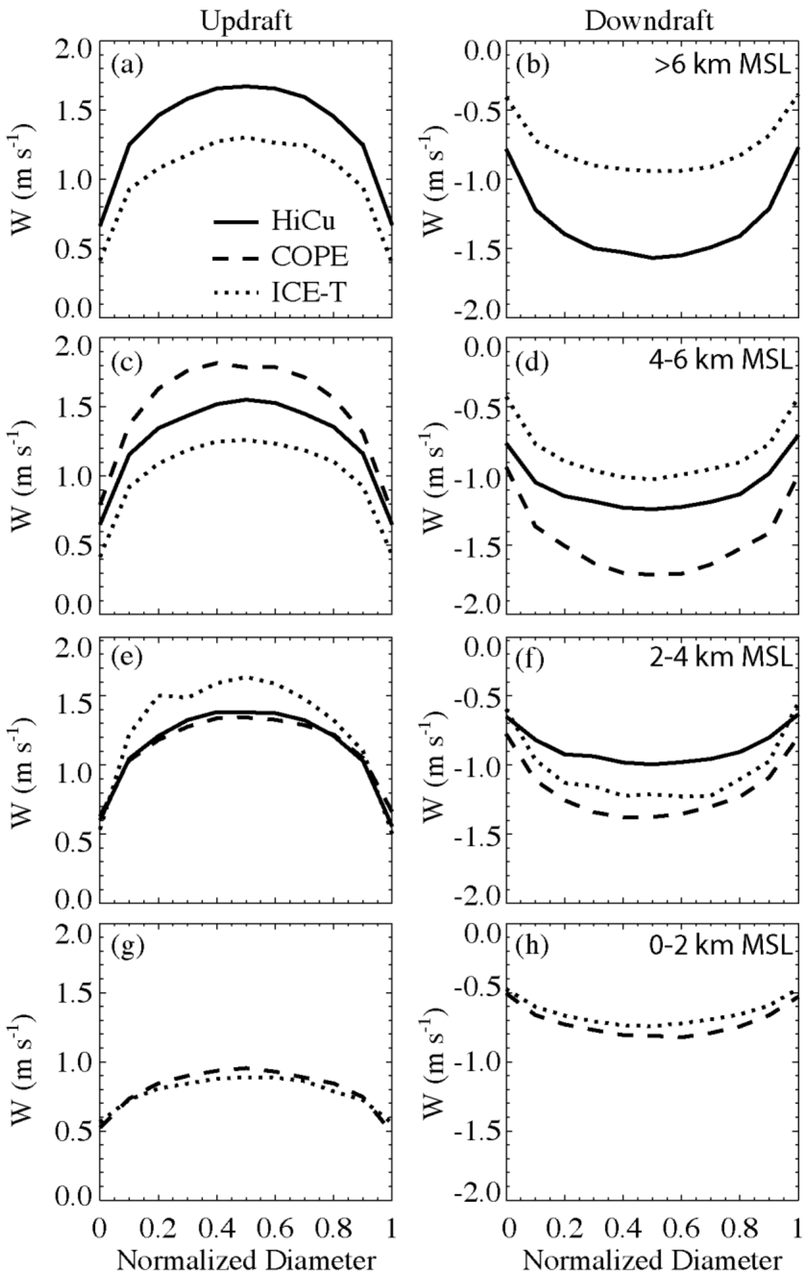

Figure 11. Composite structure of the vertical velocity as a function of the normalized diameter for the updrafts and downdrafts with air mass flux ≥ 10 kg m^{-1} s^{-1} in magnitude. The 0 and 1 coordinates on the x-axis indicate the upwind and downwind sides of the draft.

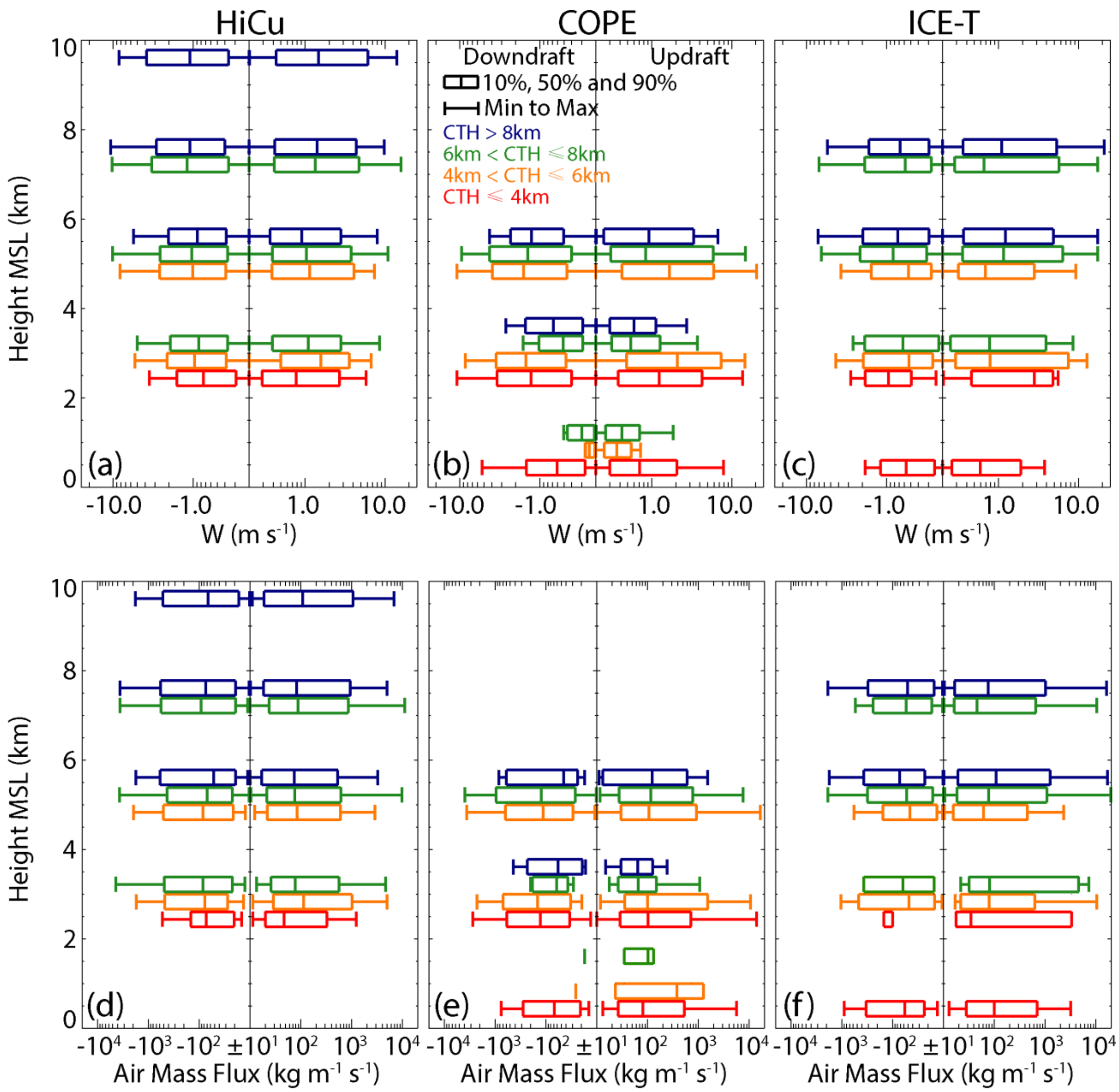

Figure 12. Profiles of (a-c) the vertical velocity and (d-f) the air mass flux for the updraft and downdraft with air mass flux ≥ 10 kg m^{-1} s^{-1} in magnitude. The red, orange, green and blue boxes represent clouds with cloud top heights of 0-4 km, 4-6 km, 6-8 km and higher than 8 km.