Reviewer 1:

Thanks for the review and for recommending minor revisions. Below we respond point by point to the comments and suggestions.

I would like to see the authors address the following:

1. I think there needs to be a more careful discussion of uncertainty. A close look at the figures suggests that there is a distribution of retrievals at each height with a fairly strong peak. The distribution is particularly noticeable in the 20-24 plots on the top row of Figure 3. Is each of these points a reasonable retrieval or is the distribution caused by noise in the retrievals?

This is an important point. As explained in the second and third paragraphs of section 3, the main limitation of these comparisons with radiosondes is that an unknown part of the differences is the temporal and spatial variability of the wind components (including internal cloud dynamics at small scale), the other part being the error of the retrieval. One way to get a sense of this spatial and temporal variability is to plot the two successive radiosonde profiles, which span about four hours from the time of launch of the first one to the arrival time of the second in the upper troposphere. Then, for each of these four-hour time intervals, we have produced the distribution of wind retrievals. Our qualitative indication of a "good agreement" is essentially when the distribution of retrievals at each height is bounded by the two radiosonde measurements. When writing this paper, we initially thought that further disentangling those two sources of differences was not possible. However, as it turns out, radiosondes from this experiment usually did not get further away from the ship by more than about 10 km, and from the new quantitative analysis we have conducted (see new version of the manuscript) we have now been able to characterize the errors more quantitatively. To do so, we have binned all comparisons with the time and spatial difference between observations and retrievals. We believe this provides the best possible quantitative assessment of our retrievals given the independent measurements we have.

Is part of the error budget the precision in the Doppler velocity measurement itself, does the noise arise from the pointing, etc? The congestus highlights the instantaneous aspects of the retrievals whereas the stratiform cases as depicted represent many hours of data yet the same level of noise seems to be present in both.

What is referred to as "noise" by the reviewer is actually not noise, it is the variability of the retrieval over four hours, which ideally should be bounded by the two radiosonde profiles, noting that inside the four hours there may be more variability than what has been measured with only two radiosondes. Precision of Doppler measurements is indeed part of the error, but not expected to be the main one by far, as we do pulse pair over 2048 samples to describe a Nyquist velocity interval of about 10 ms^{-1}, resulting in a Doppler spectral accuracy of 0.6 cms^{-1}.

There does seem to be some rather odd spikes in Vy in the congestus example on the sides of the cloud and at the top that do not show up in the vertical or eastward components. Are these real or outliers?

Well spotted. Those areas on the edges of clouds are where the detection limits of the instrument are reached, so what we see could be a contamination of the retrieval at very low signal-to-noise ratio. However we cannot discard the possibility of local turbulent structures on the edges of the clouds responsible for entrainment and detrainment on these edges. Difficult to tell for sure.

A short discussion regarding these issues would demonstrate how accurate you expect the single retrievals to be and how much averaging is expected to be necessary to converge on a useful solution. It would be interesting to show an actual updraft if such an example is available.

The new quantitative analysis of errors presented in the new version of the manuscript fully addresses this question of individual retrieval accuracy. Our new results show that virtually unbiased wind components are produced (bias less than 0.2 ms^{-1}) with a standard deviation of about 2.5 ms^{-1} on the horizontal wind components.

2. It would be nice to include plots of the radar reflectivity in the figures.

As radar scientists we can only agree that reflectivity would provide a nice context to the Doppler observations and wind retrievals, however, we feel those plots are not fully needed to discuss the wind retrievals and would result in large four-panel figures in the paper. As a result, unless there is an important reason we have overlooked, we have not added them in the new version of the manuscript.

The only typographical issue I see is on line 28 where it should read Plan Position Indicator not Plane.

This has been corrected, thanks.

Reviewer 2:

We would like to thank Reviewer 2 for his comments on the paper, which ultimately guided us to produce a revised version of the manuscript. We must admit we felt a bit puzzled by the main criticism raised in this review, because we felt we had fully disclosed and tried hard to address the limitations stated by the reviewer. However, a more quantitative analysis presented in the new version of the manuscript proved that our initial assumption that we could not produce a quantitative estimate of the errors was wrong. We have addressed the other comments thoroughly in our revised version and hope the reviewer will now be satisfied with the quality of our study.

As we explained in the initial manuscript, the reason why we thought we could not do a full quantitative estimation of the errors of our retrievals is that the radiosondes drift away quickly from the ship location with time as it ascends. So, differences between retrievals and independent measurements cannot be attributed to errors of the retrieval alone. It can be due to the unknown spatial and temporal variability of the 3D wind components (including the internal cloud dynamics). As a result, although we were as frustrated as the reviewer about the inability to fully quantify errors in our retrievals, we didn't think the measurements we have allowed for such quantification. The rule we came up with to make best use of our observations and label a comparison a "good agreement" was to use (as we try to explain more clearly in section 3) sets of two radiosonde launches bounding periods of horizontal wind retrieval profiles, and to produce height-dependent PDFs of horizontal wind retrievals between those two times, then to compare this spread of the retrievals with that measured by the two radiosondes. If the 4-hour PDFs of horizontal wind retrieval fell between the two radiosonde measurements, we labelled the comparison as a good agreement, because the retrievals are within the natural variability as captured by the two soundings.

These four-hour case studies did not provide a quantitative evaluation of the retrieved horizontal winds, which is the main criticism of the reviewer. As explained earlier, the main challenge of these comparisons with soundings is that differences include two components: the errors from the retrieval, which is what we would like to characterize, and the spatial and temporal variability of the true horizontal wind components captured by the soundings as the balloons drift away from the ship location during the hour it takes from the balloon to go from ground to the tropopause. Despite these challenges, the second term should vanish when the spatial distance and the time difference between the retrieved and measured horizontal winds is minimal. In order to investigate these effects and quantify errors in our horizontal wind estimates as accurately as possible, all comparison points have been binned as a function of distance (every 0.5 km from 0 to 10 km) and absolute time difference (every 2 minutes from 0 to 60 minutes) between sounding and retrievals. It turned out to be much more informative than what we initially assumed, and we now think that we have produced a quantitative estimate of the retrieval errors using the shortest distance and absolute time differences. These results, presented in new figures 8 and 9, are now fully presented and described in the new version of the manuscript. More specifically, the following text has been written :

" The case studies presented previously do not provide a quantitative evaluation of the retrieved horizontal winds. As explained earlier, the main challenge of these comparisons with soundings is that differences include two components: the errors from the retrieval, which is what we would like to characterize, and the spatial and temporal variability of the true horizontal wind components captured by the soundings as the balloons drift away from the ship location during the hour it takes from the balloon to go from ground to the tropopause. Despite these challenges, the second term should vanish when the spatial distance and the time difference between the retrieved and measured horizontal winds is minimal. In order to investigate these effects and quantify errors in our horizontal wind estimates as accurately as possible, all comparison points are binned as a function of distance (every 0.5 km from 0 to 10 km) and absolute time difference (every 2 minutes from 0 to 60 minutes) between sounding and retrievals. The statistical frequency distribution of errors (normalized to 100% in each bin), bias, and standard deviation of the differences are presented in Fig. 8 for distance and Fig. 9 for absolute time difference. Fig. 8 indicates that quantitative comparisons can be made between soundings and retrievals up to about 7 km distance (with fluctuations of the bias and standard deviation of about 1 and 1.5 ms^{-1}, respectively). However, it appears clearly that the frequency distribution of errors is more peaked for distances below 1km, showing as expected some impact at relatively short distance of the spatial variability on the accuracy of our error estimates. The statistical analysis of all comparison points at distances less than 0.5 km (6.4% of all points), which is our best estimate of the retrieval errors since they include the smallest possible contribution from the true spatial variability, indicate that virtually unbiased (less than 0.2 ms^{-1}) estimates of the two horizontal wind components are obtained, with a standard deviation of the error of 2.4 ms^{-1}.

Reorganizing the comparison points using bins of absolute time difference between soundings and retrieval points (Fig. 9) yield similar results to those obtained when binning using distance. From the samples used to produce Fig. 9, we obtain that the temporal evolution of the horizontal wind components has a large impact on our error estimates beyond time differences of 30 minutes, but a reasonably small effect on our error estimates for absolute time differences up to about 15-20 minutes (about 1 ms^{-1} for the bias and standard deviation of the error), with the distribution of errors getting broader for absolute time differences greater than about 15-20 minutes. As was observed for the analysis as a function of distance, the frequency distribution of errors is much more peaked for times less than about 6 minutes, which is therefore where we expect minimal contamination of our error estimates due to temporal variability. It is interesting to see that the frequency distribution for small distances is much more peaked than that for short time differences. This suggests that the temporal variability of the horizontal wind components has some impact on our error estimates than the spatial variability. The statistical analysis of all comparison points with less than 2 minutes of absolute time difference (8.5% of all points) confirms the small bias of the two horizontal wind components (less than 0.4 ms^{-1}) that was obtained using distances smaller than 0.5 km, and a similar but slightly higher standard deviation of the error (2.9 ms^{-1}). Using both distances less than 0.5 km and absolute time differences less than 2 minutes (3% of all comparison points) results in a bias less than 0.2 ms^{-1} and a standard deviation less than 2.5 ms^{-1} for both horizontal wind components, which we will consider as the final best estimates of the errors of our wind retrieval technique."

This response above covers most of the comments raised by the reviewer, and the new quantification of errors presented fully addresses this reviewer's concerns. However, below, we provide a point-by point response with more details when appropriate.

To understand the quality of this manuscript, the reader only needs to read this one sentence of the paper on p. 6.

"The purpose of the remaining figures of this study is to demonstrate that this good agreement for the stratiform precipitation case holds true for different types of cloud cover, including a cumulus congestus case characterized by high vertical wind shear (Figs. 4 and 5), an altostratus case in a very light wind environment (Figs. 6 and 7), and a tropical cirrus case embedded in a north-westerly jet (Figs. 6 and 7). " More than half of the figures in the text are explained in this one sentence with the conclusion that these figures represent "good agreement". No further explanation is provided. No quantitative assessment is provided in the text. The reader is expected to examine the figures for herself and then be convinced that this is good agreement. In short, high-quality scientific writing is not like this.

That is because, as we explained, we had established a rule to label a good agreement (see main response above) and felt there was not much more that could be said from these figures. The wind component PDFs are or are not within the variability measured by the radiosondes. The most important point we address visually with these plots is whether the retrieval behaves sensibly in very different types of clouds. However, we agree that this was a bit dry, and there were a few more things that needed to be highlighted on these figures, so, in order to address this comment, we have added the following text :
" Comparisons with ship-level weather stations and with the radiosondes bounding the congestus case (Figs. 4 and 5) indicate that the near-surface winds are well reproduced and the strong vertical wind shear in the low levels (about 5 10^{-3} s^{-1} in the 0-3 km layer) is accurately captured by the retrieval. We note some large differences with the radiosonde on the V_Y component at cloud top, which does not necessarily mean that the retrieval has failed, as tops of congestus clouds are notoriously turbulent. Therefore, these differences could be due to the internal convective-scale dynamics not captured by soundings obtained in clear-air. The altocumulus and cirrus cases are characterized by a much lower temporal variability of the wind components (see for instance the small difference between estimates from the two soundings for the cirrus case, Fig. 7). Accordingly, the distributions of retrieved horizontal winds over four hours is much narrower than within the other cases, and the peaks of the distributions align well with the radiosonde measurements for those two cases."

Although the authors are clearly working on an important and relevant problem that is appropriate for AMT, weaknesses in the presentation of the paper similar to the issue above detract from what could have been a quality submission.

1. Examine the abstract. There is no quantitative information about the comparison. There is no information about how many soundings are used. The sentences are vague and lack quantification when they should be clearly quantified: "small component of the Doppler velocity in most cases", "Statistical comparisons.... demonstrate that accurate 3D wind profiles can be obtained." There is no information about how much data is evaluated. What about the errors? How is accuracy defined? These are not quantified. How is the comparison performed? What metrics are used? This information is not provided. Thus, the abstract does not serve its role as a concise summary of the manuscript. There is no information about how much data is evaluated. What about the errors? How is accuracy defined? These are not quantified. How is the comparison performed? What metrics are used?

See main response above. This is now comprehensively done in the abstract, section 3, and conclusion.

2. Paragraphs are not indented, making it difficult to read this manuscript.

Thanks for pointing that out. We have now indented the paragraphs throughout.

3. Line 26: "very little has been done so far": Does this mean that there have been zero studies? If so, say so. If there have been some research, please discuss.

It was indeed a vague statement, so we have reworded as " The next challenge to better understand these interactions between dynamics and cloud microphysics is to characterize the dynamical context of these cloud microphysical

observations, including horizontal winds, vertical wind shear, and entrainment processes within and at the boundaries of clouds."

4. The data and code availability statement "upon request to [author]" does not presently adhere to the AMT standards for the data policy: https://www.atmosphericmeasurement- techniques.net/about/data_policy.html

Thanks for pointing that out.

Regarding code availability, we are only "encouraged" to deposit software, but I don't plan to do that due to protection of the Bureau IP on this (a version of this wind retrieval technique is currently being used to develop operational products that are planned to be sold commercially), so I rephrased as : "Code developed as part of this study is not available publicly as it is intellectual property of the Bureau of Meteorology."

I just looked at the data policy and searched "CSIRO data access portal" in the r3data.org, and it is there. The datasets used in this study are now posted on the CSIRO DAP, so I wrote this in the section :" All data and wind retrievals used in this study are publicly available on the CSIRO Data Access Portal (https://data.csiro.au/dap/)."

5. Line 175: Why four hours? Is this because of radiosonde travel time? If so, please state that to be more clear.

This information has been added. From the release time of the first radiosonde and the arrival time of the second radiosonde there are indeed about four hours, which is why we use this time span for each comparison.

6. I am curious as to why v_x and v_y are analyzed separately. Wouldn't this analysis be sensitive to small errors in the wind direction? You may have better agreement showing wind direction and speed instead.

There is value in using either the two wind components or the wind and direction, we agree. Using the two wind components avoids issues with 360 degrees flips of the wind direction, so we have kept the option of using the two horizontal wind components. Besides, this is formally what is retrieved.

7. I am not sure whether this paper may be of use to you, but I offer it in case you find it useful. Trapp, R.J. and C.A. Doswell, 2000: Radar Data Objective Analysis. J. Atmos. Oceanic Technol., 17, 105–120.

This very interesting paper (which is a very important one for radar scientists like us) is not relevant for this study, as we are not interpolating volumetric radar observations onto a Cartesian grid at all.

8. Even with the analysis of Figs. 1–3 at lines 158–182, I feel that not enough is said about the quantitative metrics of the comparison in Fig. 2. How good is it? When combined with Figs. 5 and 7, what are the main results? Is there a mean error that can be quantified? I'm really hoping the authors can provide more quantitative measurements of the quality of the comparisons. Not doing so makes this contribution quite weak scientifically. Yes, you may not have sampled the large number of cases that you had hoped, but more needs to be said about the statistics of the cases you did analyze. Readers of a technical journal such as AMT should expect this information at a minimum.

See detailed response above. Also, at the time our problem was never about the number of cases, it was about the limitations of the potential validation datasets, as explained. We hope we have now convinced the reviewer about this important point. New results included also fully addressed this comment.

Other minor concerns:

1. The authors tend to use "which" when they should use "that". Lines 23, 113, 13 1https://www.grammarly.com/blog/which-vs-that/

Thanks for the link. We have reviewed our use of "which" versus "that" using these explanations. We made use of the term "which" 13 times in the initial manuscript. Of these 13 times, we indeed used "which" 4 times in defining clauses. This has been corrected.

2. The authors need to be more careful in the proofreading with the correct use of hyphens versus en dashes. When using an en dash to connect two numbers ("2–4 km" in LaTeX), do not include spaces on either side.

This has been corrected.

3. Better proofreading is needed. I noticed some examples where commas were omitted.

We have carefully proof-read the new version of the manuscript, with attention paid to omitted commas.

4. Should the word "resolution" be changed to "data interval" (or similar). If there are data every 15 seconds, you can't resolve features that are 15 seconds. You need 5–8 time steps to resolve a feature.

We agree that this is formally an improper use of the word "resolution". We worked around this as follows: " The selected time interval of 15 seconds is a trade-off to make sure that we are collecting data from all four radar modes, which takes 12 seconds, for each pointing direction while still retaining a small time interval (1 minute) between retrieved 3D wind profiles."

5. Line 30: Should "in" be "of"?

I think both are acceptable in this context but we will go with your suggestion.

6. Line 45-46 repeats earlier text.

We have removed the first part of this short paragraph to still provide a short introduction to the section.

7. Lines 95–96: The parentheses aren't italicized.

Maybe they don't appear as italicized in the PDF conversion, but they are italicized in our Word version, we've double checked.

8. Line 99: Insert a comma after "sampling".

Done.

9. Lines 106 and 111: "Where" and "With" should not be capitalized., They are continuing from the previous equation. They are not starting new sentences.

Corrected.

10. Line 111: Change "which need" -> "needed".

This has been rewritten as " matched to the observed Doppler velocities $\boldsymbol{V_R}\ (\boldsymbol{i}, \boldsymbol{k})$ as part of the minimization process"

11. Line 122: Change "since" -> "because".

Corrected.

12. Line 158: "Figs." should be "Figures" because it starts the sentence.

Corrected.

13. Equation 1: I didn’t see that i and k were defined. My apologies if I missed it.

They are just the indices in the summations used in Equation 1 and because they go from 0 and nt and 0 and nz respectively, it is clear that these indices refer to summations over the times and range bins. I don't think it is customary to define the indices in this case (?).

14. I kept wondering if the soundings were released from the ship. Could you provide a more clear explanation? If I missed that information in the manuscript, I apologize.

Sorry, we thought it was obvious. We added "from the ship" in four different locations to make sure there is no ambiguity about that.

Marked-up revised version of the new manuscript below.

Three-dimensional wind profiles using a stabilized shipborne cloud radar in wind profiler mode

Alain Protat[1], Ian McRobert[2]

[1] Australian Bureau of Meteorology, Melbourne, Victoria, Australia
[2] Engineering and Technology Program, CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia

Correspondence to: Alain Protat (alain.protat@bom.gov.au)

Abstract.

In this study, a shipborne 95 GHz Doppler cloud radar mounted on a stabilized platform is used to retrieve vertical profiles of three-dimensional (3D) winds by sequentially pointing the stabilized platform in different directions. A specific challenge is that the maximum angle off zenith is 8°, which implies that the projection of the horizontal wind components onto the radar beam directions is a small component of Doppler velocity in most cases. A variational 3D wind retrieval technique is then described, allowing for 1-minute 3D wind profiles to be retrieved. Statistical comparisons with 3-hourly radiosonde launches from the ship indicate that horizontal wind profiles can be obtained from such cloud radar observations at small off-zenith angles with biases less than 0.2 ms^{-1} and standard deviations of differences with radiosonde winds less than 2.5 ms^{-1}.

1 Introduction

Vertically-pointing Doppler cloud radars provide unique observations to better understand the interactions between dynamics and microphysics in clouds and light precipitation and cloud radiative forcing. Doppler cloud radars are also extensively used to evaluate satellite products and the representation of cloud and precipitation properties in models. The focus of studies has been on retrieving the microphysical properties of clouds from cloud radars (e.g., Matrosov et al. 2002; Mace et al. 2002; Delanoë et al. 2007), lidars (e.g., Heymsfield et al. 2005), or cloud radar – lidar combination (Wang and Sassen 2002; Okamoto et al. 2003; Tinel et al. 2005; Delanoë and Hogan 2008, Deng et al. 2010). The next challenge to better understand the interactions between dynamics and cloud microphysics is to characterize the dynamical context of these cloud microphysical observations, including horizontal winds, vertical wind shear, and entrainment processes within and at the boundaries of clouds.

Scanning cloud radars were recently developed to describe clouds in three dimensions (3D) from ground-based observatories. However, scanning strategies need to be adapted to characterize 3D wind profiles at high vertical resolution within clouds using such measurements, as typical scanning strategies currently focus on describing the morphological structure using Plan Position Indicator (PPI, scanning in azimuth at successive constant elevations) or Range Height Indicator

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(RHI, scanning different elevations at constant azimuth) scanning sequences, which does not allow for the 3D wind profiles to be retrieved without stringent assumptions (e.g., linearity of the wind components). UHF and VHF profilers provide such 3D wind profiles in clear-air and precipitation from Bragg and Rayleigh scattering, respectively, using the so-called "profiler mode", that consists of alternating vertical pointing with off-zenith pointing by about 15-20° in two perpendicular directions (North and East for instance). The only issue with UHF and VHF wind profilers is that they lack the sensitivity to detect thin non-precipitating clouds.

In this study, we report on a pilot study using a shipborne cloud radar on a stabilized platform to derive high-resolution vertical profiles of 3D wind. The idea is to use the stabilized platform to point the cloud radar in a series of different directions. However, when the cloud radar is used on the Marine National Facility (MNF) Research Vessel (RV) *Investigator*, the maximum angle off zenith that can be pointed safely at with the stabilized platform is ±8° in pitch and roll directions due to the size of the aperture on the container roof. This is smaller than typical angles of ±15-20° used for wind profilers. The main objective of this pilot study is to assess whether high-quality 3D winds can be retrieved from such small angles off zenith. As this study was conducted during a major field experiment, the Years of the Maritime Continent – Australia (YMCA), radiosondes were launched every three hours from the ship, allowing for a quantitative evaluation of the retrieved cloud radar horizontal wind profiles. In section 2, we briefly describe the cloud radar, the stabilized platform and implemented scanning sequences. In section 3, we illustrate the retrieval with case studies and conduct a statistical evaluation of the cloud radar horizontal winds against radiosonde measurements. Conclusions are finally given in section 4.

2 Description of the pilot study

In this section we briefly describe the cloud radar, the stabilized platform and implemented sampling strategies, and the 3D wind retrieval technique.

2.1 The BASTA Doppler cloud radar

The research-grade BASTA Doppler cloud radar is described in detail in Delanoë et al. (2016). It is a frequency-modulated continuous wave (FMCW) radar operating at a frequency of 95 GHz. The radar uses two Cassegrain dishes (60 cm in diameter) and all the electronic components are installed in a pressurized and insulated box. The data acquisition and processing are done using a field-programmable gate array (FPGA). This cloud radar uses a low-power solid-state transmitter (0.5W) and estimates both reflectivity and Doppler velocity using the pulse-pair processing technique with 2048 samples, allowing for high Doppler measurement accuracy (better than 1 cms^{-1} Doppler spectral accuracy). During the YMCA field experiment, a 12 seconds sequence split into four successive modes (each mode with an acquisition and processing time of 3 seconds) was designed to capture both low-level clouds and light precipitation with high vertical resolution and tropical cirrus clouds with high sensitivity. The respective vertical resolutions of these four modes are 12.5m, 25m, 100m (moderate sensitivity), and 100m (higher sensitivity but shorter Nyquist velocity). The approximate minimum detectable signal of these

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four modes is -28, -34, -40, and -43 dBZ at 1 km range, respectively. This sensitivity is lower than that reported in Delanoë et al. (2016), due to current issues with the antenna alignment. This lower sensitivity is not detrimental to our pilot study.

2.2 The *RV Investigator* stabilized platform and sampling strategies

When used on *RV Investigator*, the BASTA cloud radar is mounted on a stabilized platform inside an air-conditioned container, ensuring resilient operations in harsh environments such as the Southern Ocean, Antarctica and the Tropics. The stabilized platform design is described in detail in Filisetti et al. (2017) and follows the design from Moran et al. (2012). It has been recently demonstrated that vertical stabilization to better than 0.2° can be achieved with this platform for sea states up to 6. In this shipborne configuration, the plexiglass dome of the BASTA cloud radar is removed and replaced by a bigger one mounted directly on the container roof. Due to the size of the aperture made on the container roof and the requirement to minimize contaminations of the signal by multiple reflections on the metallic structure inside the container, the top of the cloud radar is lifted very close to the dome. This configuration limits the possible rotation in pitch and roll directions to about 12° from the vertical of the container. Our experience from the Southern Ocean high seas is that with the anti-roll system of *RV Investigator* this value of 12° has been exceeded less than 1% of the time.

The baseline operating mode in earlier deployments was the "vertical mode", where the instrument is stabilized to point vertically all the time. For this pilot study we have developed an additional mode, referred to as the "profiler mode" in the following, which consists of a 120 seconds sequence with 15 seconds spent at the following 8 pointing angles: vertical, +8° pitch, vertical, +8° roll, vertical, -8° pitch, vertical, -8° roll. With such a sequence, we still retain a high temporal resolution for the vertical observations while being able to retrieve 1-minute 3D wind profiles from any of four successive pointing angles. The rationale for using positive and negative pointing angles is to assess whether the same 3D wind profiles can be derived from these different combinations of angles. Note that the time (about 1.5s) required to move from one angle to the next is included in the 15 seconds. The selected time interval of 15 seconds is a trade-off to make sure that we are collecting data from all four radar modes, which takes 12 seconds, for each pointing direction while still retaining a small time interval (1 minute) between retrieved 3D wind profiles. The 8° angle selected for this mode is also a trade-off between allowing enough projection of the horizontal wind components onto the radar beams off zenith, and the need to stabilize the instrument in that direction accurately. Using 8° means that we can only stabilize the instrument for motions less than about 4°. Although this will present a challenge in rough seas such as over the Southern Ocean, such motion was never encountered during the YMCA experiment.

2.3 The 3D wind retrieval technique

When operating in vertical mode, Doppler velocities are simply corrected for heave rates (the vertical component of ship speed) using the 10 Hz ship positioning system data (same as in Moran et al. 2012). When operating in modes with off zenith pointing, Doppler velocities need to be corrected for both heave rates and ship horizontal speed. During YMCA, we mostly stayed on station and heave was very low. As a result, Doppler corrections very rarely exceeded absolute values of 0.2

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ms^{-1} (not shown). However, it will not be the case for future deployments. Therefore, below we develop the full set of equations for the 3D wind retrieval including all corrections.

A variational 3D wind retrieval has been adapted for the profiler mode sampling strategy from the dual-Doppler weather radar technique of Protat and Zawadzki (1999). The three "control variables", i.e., the quantities to be retrieved, are the zonal (eastward) horizontal wind component $V_X\ (nt, nz)$, the meridional (northward) horizontal wind component $V_Y\ (nt, nz)$ and $V_Z\ (nt, nz) = W\ (nt, nz) + V_T\ (nt, nz)$, where $W\ (nt, nz)$ is the vertical wind component and $V_T\ (nt, nz)$ is the terminal fall velocity of hydrometeors, *nt* is the number of time steps per retrieval day and *nz* is the number of vertical levels for the vertical profiles. The *nt* and *nz* parameters can be adjusted for different applications. When operating in profiler mode instead of the traditional weather radar PPI sampling, which mostly involves low elevation angles above the horizontal plane, the anelastic airmass continuity equation and the constraint that the vertical air velocity at ground is nil are not needed as part of the retrieval process. As a result, only the Doppler velocity constraint from the set of constraints used in Protat and Zawadzki (1999) is used, and includes all pointing angles to retrieve the vertical profiles of 3D wind. As a result, the cost function to be minimized can be simply written as:

$$J = \sum_{i=0}^{nt} \sum_{k=0}^{nz} \left(V_R\,(i,k) - V_R'\,(i,k) \right)^2 \qquad (1)$$

where

$$V_R'\,(i,k) = \left(V_X\,(i,k) - U_{ship}(i)\right) \cos\left(az(i)\right) \cos\left(el(i)\right) + \left(V_Y\,(i,k) - V_{ship}(i)\right) \sin\left(az(i)\right) \cos\left(el(i)\right) + \left(W\,(i,k) + V_T\,(i,k) - W_{ship}(i)\right) \sin\left(el(i)\right) \qquad (2)$$

with $V_R\,(i,k)$ the measured Doppler velocities, $V_R'\,(i,k)$ the theoretical Doppler velocities matched to the observed Doppler velocities $V_R\,(i,k)$ as part of the minimization process, $(U_{ship}(i), V_{ship}(i), W_{ship}(i))$ the three components of the ship speed producing apparent Doppler velocity in the cloud radar measurements that need to be subtracted to the theoretical Doppler velocities, and $(az(i), el(i))$ the azimuth angle of each radar beam with respect to the east (positive counter-clockwise) and the elevation angle of each radar beam with respect to the horizontal (positive upwards).

The different steps of the procedure to minimize the cost function J can be summarized as follows: 1) make an initial guess of the control variables (V_X, V_Y, V_Z) – we use zero by default ; 2) calculate the gradient of the cost function with respect to the control variables (as explained in Protat and Zawadzki 1999); 3) exit if the predefined convergence criterion is met; otherwise, 4) calculate a new guess of (V_X, V_Y, V_Z) using the conjugate–gradient method (Powell 1977); and 5) return to step 2 for a new iteration using this new guess until the convergence criterion is met. Once V_Z is obtained, previous studies have shown that its two components, W and V_T, can be separated using statistical approaches relating reflectivity to V_T (see description of different possible techniques and expected performance in Protat and Williams, 2011). However, because there

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is no reference observation to evaluate this in our dataset, this separation of W and V_T has not been included in the present analysis.

3 Results

The pilot study to test the new wind profiler mode was conducted during the YMCA field experiment (12 November 2019 to 17 December 2019). Large-scale conditions during the experiment were not favourable for the development of offshore propagating mesoscale convective systems and associated cloud anvils and tropical cirrus layers. Nevertheless, a variety of cloud cover types has been sampled over that period. In this section, we present results obtained for four very different cases to illustrate the capability to retrieve 3D winds from the cloud radar in profiler mode in different situations. The first case is a stratiform precipitation case that developed on 23-24/11/2019 within a horizontal flow characterized by multiple vertical wind shear layers. This case was over the ship for about seven hours. The second case is a shallow cumulus congestus case that developed in the evening of 24/11/2019 in a strong low-level vertical wind shear environment, as measured by the soundings. The third and fourth cases consist of an altostratus and a tropical cirrus outflow, respectively. In both cases, sampled clouds were detrained from surrounding deep convective activity on 04/12/2019. Then, we present a statistical analysis of comparisons with radiosonde winds using all retrieved horizontal wind profiles from 22/11/2019 to 04/12/2019.

Two types of measurements are used in this study to compare with retrieved horizontal winds, both bringing complementary insights. Note that we do not have independent measurements to assess the vertical wind component. However, this component is directly measured with the current sampling strategy, so it can be assumed accurate to within measurement and Doppler corrections uncertainties. The first measurements are ship-level horizontal winds measured at 24m height on the front mast by two automatic weather stations. Comparisons are made with the first valid radar range bin where winds can be retrieved (usually about 100m height). The limitations of such comparisons are the difference in heights of the measurements, and the fact that it does not allow for an assessment of the full vertical profiles, only those situations when low clouds are present. Since the final post-processed version of these weather station winds have not been produced yet, we only use these for qualitative illustration. The second type of measurements is soundings (Vaisala RS41-SGP radiosondes), which were launched every three hours from the ship during YMCA. This second source of validation has the major advantage of providing full vertical profiles of horizontal winds surrounding the cloud radar retrievals. However, balloons take about one hour to reach the tropopause in the Tropics and can drift by tens of kilometres from the initial launch location over that period. As a result, the main potential issue when comparing radiosonde and retrieved horizontal winds is that differences obtained include an unknown contribution from the true spatial and temporal variability of the wind components, including that produced by internal cloud dynamics, in addition to the retrieval errors.

These advantages and limitations have informed the way comparisons are made for case studies and on a more statistical basis in this section. Low-level time series of horizontal wind components have been averaged using the two wind measurements from the weather stations. These are displayed on the vertical cross-sections of retrieved winds at altitude zero with the same colour code. For radiosonde comparisons using case studies, we have selected individual four-hour periods of

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interest bounded by two radiosonde launches, and we assume that the two radiosonde wind profiles can be used as a proxy for the spatial and temporal variability of the horizontal wind components. The rationale for choosing four-hour periods is because this is the time difference between the time of launch of the first sounding and the arrival time of the second sounding at the tropopause. For each four-hour period, a joint horizontal wind – height distribution of the retrieved horizontal wind components is produced to compare the variability of these wind components with that derived from the two soundings. Subsequently, if the spread of wind retrievals (i.e., variability) within the four-hour period is bounded by the two radiosonde wind profiles, we qualitatively label the comparison as a "good agreement", because the retrievals are within the natural variability captured by the two soundings. Although these comparisons are more of a qualitative nature, they allow for a good visual assessment of the retrieved horizontal wind profiles.

Figures 1-3 show results obtained for the stratiform precipitation case. The sum of vertical air motion and terminal fall speed of hydrometeors (top panel of Fig. 1) is characterized by an expected sharp transition from downward vertical motions in the -2 to 0 ms^{-1} range in ice phase above the melting layer height (around 4.5 km), to values below -4 ms^{-1} in liquid phase, below the melting layer height. Stratiform regions are generally characterized by relatively small vertical air motions, rarely exceeding 0.5 ms^{-1} (e.g. Protat and Williams, 2011, in the same Darwin region). As a result, the sum is generally dominated by terminal fall speed. Layers of enhanced downward motions in ice phase closer to the melting layer result from the aggregation of ice crystals producing bigger particles as they fall within the stratiform region, as documented in numerous studies. Values of near zero vertical motions are also found near cloud top, which is also the expected signature of much smaller ice crystals falling at a much lower speed. The two retrieved horizontal wind components (middle and bottom panels of Fig. 1) are characterized by long-lasting structures of higher easterly and south-westerly winds just below (2 to 4 km height) and just above (6 to 8 km height) the melting layer, respectively. An upper-level south-westerly jet is also clearly visible on the retrieval (above 10 km height). Qualitative validation of the low-level winds is shown in Fig. 2. Except for a short period after 0000 UTC where some clear differences are observed, the agreement between ship horizontal winds and retrieved winds is good, with subtle changes in horizontal wind speed and direction picked up in the retrieval. Looking more closely at the ship time series, it appears that this short period is characterized by very large differences in excess of 10 ms^{-1} between the port and starboard weather station estimates, with our retrieved values being closer to one of the estimates.

A statistical comparison of the retrieved vertical profiles of the horizontal wind components with the radiosonde observations is shown in Fig. 3 (radiosondes are also superimposed to retrievals in Fig. 1) for the two 4-hours periods depicted in Fig.1. For each period we have two radiosonde profiles to compare with. Comparing profiles from the two radiosondes indicates that there is substantial variability of the zonal wind component above 6 km height for the first period (top panels of Fig. 3). The retrieved horizontal winds closely match the radiosonde profiles below 5 km height, and the agreement is also very good in the upper levels, with the two radiosonde observations generally bounding the retrieved horizontal wind distributions. This good qualtitative agreement for the stratiform precipitation case holds true for different types of cloud cover we analyzed, including a cumulus congestus case characterized by high vertical wind shear (Figs. 4 and 5), an altostratus case in a very light wind environment (Figs. 6 and 7), and a tropical cirrus case embedded in a north-westerly jet (Figs. 6 and 7).

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Deleted: Given the spatial and temporal mismatch between these two sources of data, we conclude that these comparisons clearly demonstrate that accurate vertical profiles of horizontal wind can be derived from the cloud radar using the proposed profiler mode, despite the small 8° off zenith angles used. The purpose of the remaining figures of this study is to demonstrate that t

Comparisons with ship-level weather stations and with the radiosondes bounding the congestus case (Figs. 4 and 5) indicate that the near-surface winds are well reproduced, and the strong vertical wind shear in the low levels (about 5 10^{-3} s^{-1} in the 0-3 km layer) is accurately captured by the retrieval. We note some large differences with the radiosonde on the V_y component at cloud top, which does not necessarily mean that the retrieval has failed, as tops of congestus clouds are notoriously turbulent. Therefore, these differences could be due to the internal convective-scale dynamics not captured by soundings obtained in clear-air. The altocumulus and cirrus cases are characterized by a much lower temporal variability of the wind components (see for instance the small difference between estimates from the two soundings for the cirrus case, Fig. 7b). Accordingly, the frequency distributions of retrieved horizontal winds over four hours is much narrower than within the other cases, and the peaks of the distributions align well with the radiosonde measurements for those two cases.

The case studies presented previously do not provide a quantitative evaluation of the retrieved horizontal winds. As explained earlier, the main challenge of these comparisons with soundings is that differences include two components: the errors from the retrieval, which is what we would like to characterize, and the spatial and temporal variability of the true horizontal wind components captured by the soundings as the balloons drift away from the ship location during the hour it takes from the balloon to go from ground to the tropopause. Despite these challenges, we can exploit the fact that the second term should vanish when the distance and the time difference between the retrieved and measured horizontal winds are small. In order to investigate these effects and quantify errors in our horizontal wind estimates as accurately as possible, all comparison points for the 22/11/2019-04/12/2019 period are binned as a function of distance (every 0.5 km from 0 to 10 km) and absolute time difference (every 2 minutes from 0 to 60 minutes) between sounding measurements and retrieval points. The statistical frequency distribution of errors (normalized to 100% in each bin), bias, and standard deviation of the differences are presented in Fig. 8 for distance and Fig. 9 for absolute time difference. Fig. 8 indicates that quantitative comparisons can be made between soundings and retrievals up to about 7 km distance (with fluctuations of the bias and standard deviation of about 1 and 1.5 ms^{-1}, respectively). However, it appears clearly that the frequency distribution of errors is more peaked for distances below 1 km, showing as expected some impact at relatively short distance (from 1 km and more) of the spatial variability on the accuracy of our error estimates. The statistical analysis of all comparison points at distances less than 0.5 km (6.4% of all points), which is our best estimate of the retrieval errors since they include the smallest possible contribution from the true spatial variability, indicate that virtually unbiased (less than 0.2 ms^{-1}) estimates of the two horizontal wind components are obtained, with a standard deviation of the error of 2.4 ms^{-1}.

Reorganizing the comparison points using bins of absolute time difference between soundings and retrieval points (Fig. 9) yield similar results to those obtained when binning using distance. From the samples used to produce Fig. 9, we obtain that the temporal evolution of the horizontal wind components has a large impact on our error estimates beyond time differences of 30 minutes, but a reasonably small effect on our error estimates for absolute time differences up to about 15-20 minutes (a variability of about 1 ms^{-1} for the bias and standard deviation of the error), with the distribution of errors getting broader for absolute time differences greater than about 15-20 minutes. As was observed for the analysis as a function of distance, the frequency distribution of errors is much more peaked for times less than about 6 minutes, which is therefore

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where we expect minimal contamination of our error estimates due to temporal variability. It is noteworthy that the frequency distribution for small distances is much more peaked than that for short time differences. This suggests that the temporal variability of the horizontal wind components has more impact on our error estimates than the spatial variability. The statistical analysis of all comparison points with less than 2 minutes of absolute time difference (8.5% of all points) confirms the small bias of the two horizontal wind components (less than 0.4 ms^{-1}) that was obtained using distances smaller than 0.5 km, and a similar but slightly higher standard deviation of the error (2.9 ms^{-1}) than when binning using distance. Using both distances less than 0.5 km and absolute time differences less than 2 minutes (3% of all comparison points) results in a bias less than 0.2 ms^{-1} and a standard deviation less than 2.5 ms^{-1} for both horizontal wind components, which we will consider as the final best estimates of the errors of our wind retrieval technique.

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4 Conclusions

In this study we have used dedicated shipborne Doppler cloud radar observations around Darwin, Australia, to evaluate the potential of retrieving vertical profiles of 3D winds using a stabilized platform pointing in successive off-zenith directions at regular intervals. A challenge with using such setup is that the maximum off-zenith angle is 8°, which does not correspond to a large projection of the horizontal wind components onto the radar beam directions. Using this 8° value currently implies that only ship motions up to 4° in any direction can be compensated for by the stabilized platform. Taking advantage of this "profiler mode" sampling, we have developed a variational 3D wind retrieval technique allowing for 1-minute 3D wind profiles to be estimated. Fully quantitative validation of the results was challenging, as there are no directly collocated observations in time or space available. However, statistical comparisons with radiosonde launches every 3 hours from the ship demonstrated that accurate 3D wind profiles could be derived from such cloud radar observations at small off-zenith angles for a large variety of cloud cover types encountered during the field experiment, with biases less than 0.2 ms^{-1} and a standard deviation of the errors less than 2.5 ms^{-1}. Given the positive results obtained with 8° angles, we will test even lower angles during our next shipborne field experiment. If satisfying results are obtained at even lower angles, this would improve our capability to retrieve 3D winds in much rougher seas than those encountered during the YMCA experiment.

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Acknowledgments

The Authors wish to thank the CSIRO Marine National Facility (MNF) for its support in the form of *RV Investigator* sea time allocation on Research Voyage IN2019_V06, support personnel, scientific equipment, and data management.

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Code availability

Codes developed for this study are protected intellectual property of the Bureau of Meteorology and are not publicly available.

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Data availability

All Doppler cloud radar, radiosonde, and ship underway data are available on the CSIRO Data Access Portal (https://data.csiro.au/dap/).

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available by September 2020 in accordance with the Australian Marine National Facility policy from the CSIRO Data Access Portal (https://data.csiro.au/dap/).¶

Sample availability

No samples were used in this study.

Author contribution

AP and IM collected the datasets used in this study. IM designed the stabilized platform operating modes. AP analysed the cloud radar and radiosonde observations and wrote and reviewed the manuscript. IM provided edits of the manuscript.

Competing interests:

The authors declare that they have no conflict of interest.

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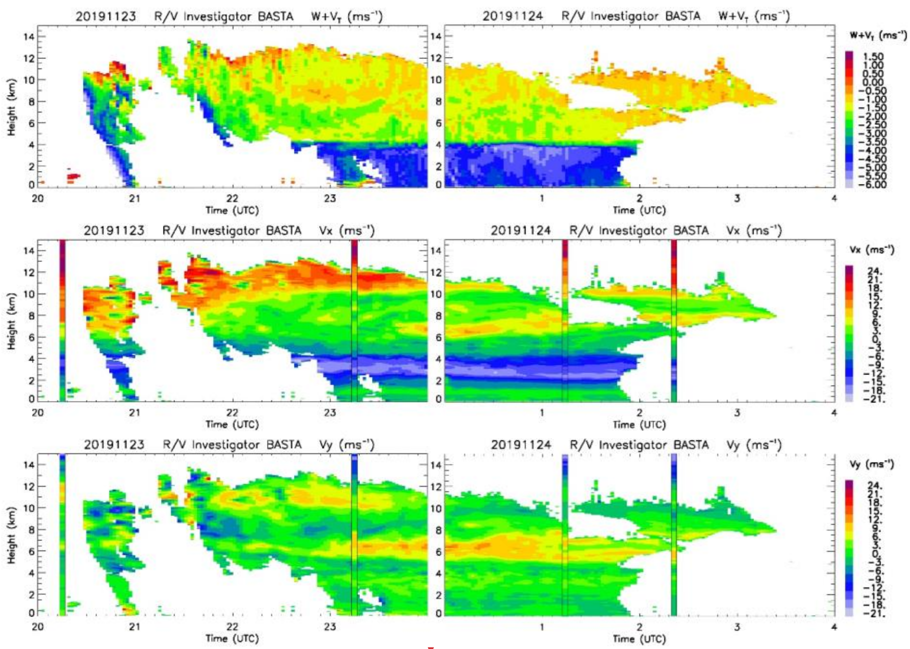
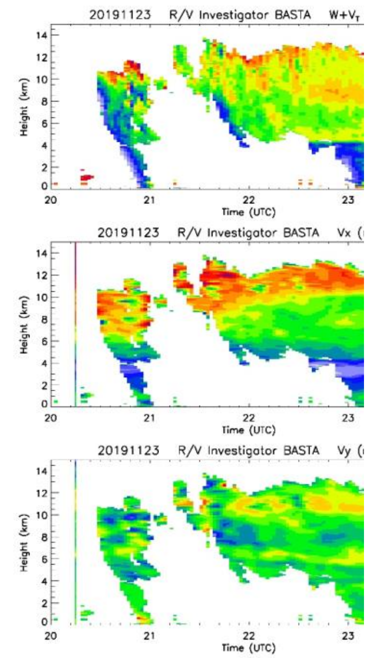


Figure 1: Time – height cross section of retrieved $W+V_T$ (up), V_X (middle), and V_Y (bottom) in a stratiform precipitation case sampled on 23-24/11/2019 by the BASTA cloud radar on *RV Investigator*. Vertical lines on the middle and bottom panels are the horizontal wind components measured by the soundings. The reference time for the soundings is the launch time at ground.



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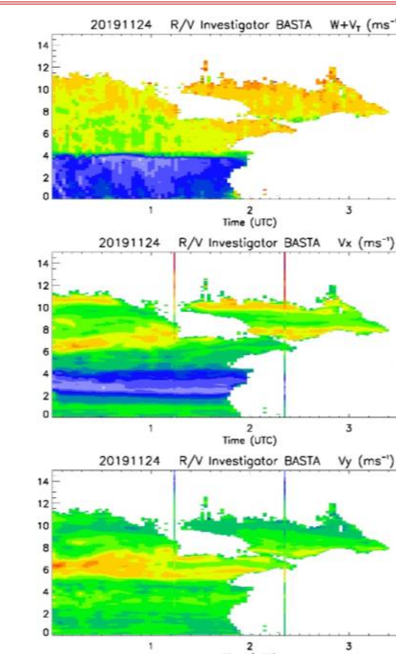

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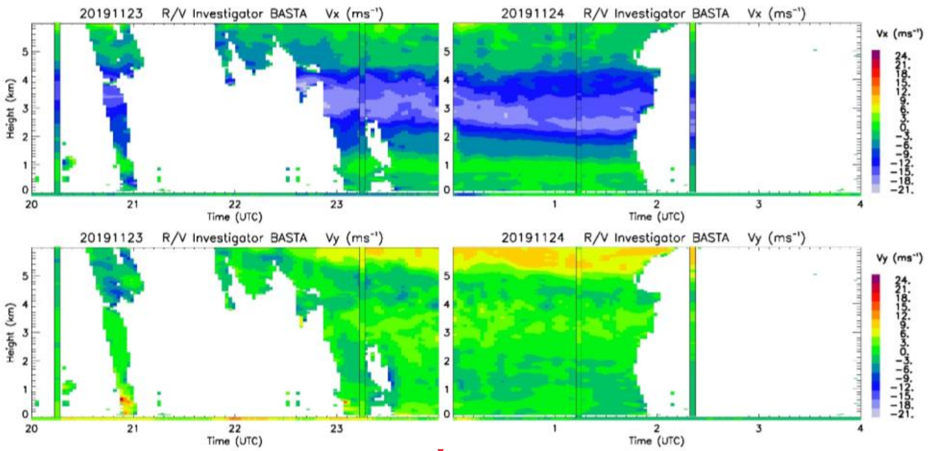

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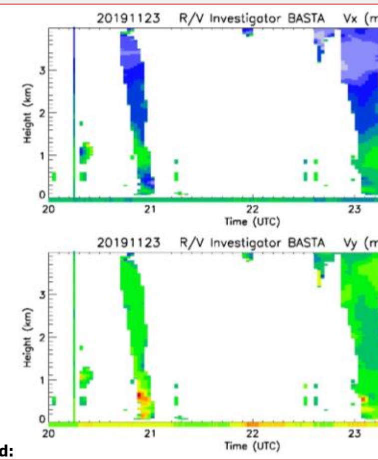

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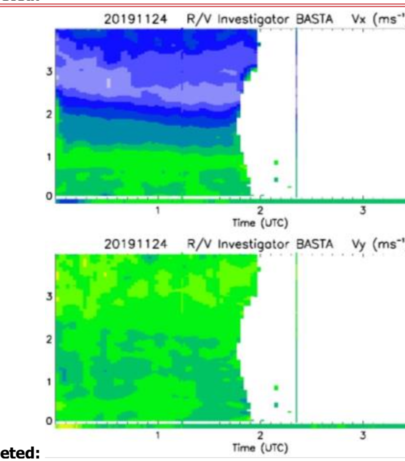


Figure 2: Time – height cross section of retrieved V_X (top) and V_Y (bottom) in the same case as Fig. 1 but for a maximum altitude of 4 km. The horizontal winds measured on the front mast of *RV Investigator* are displayed at height = 0 with the same colour scale as the retrieved winds.

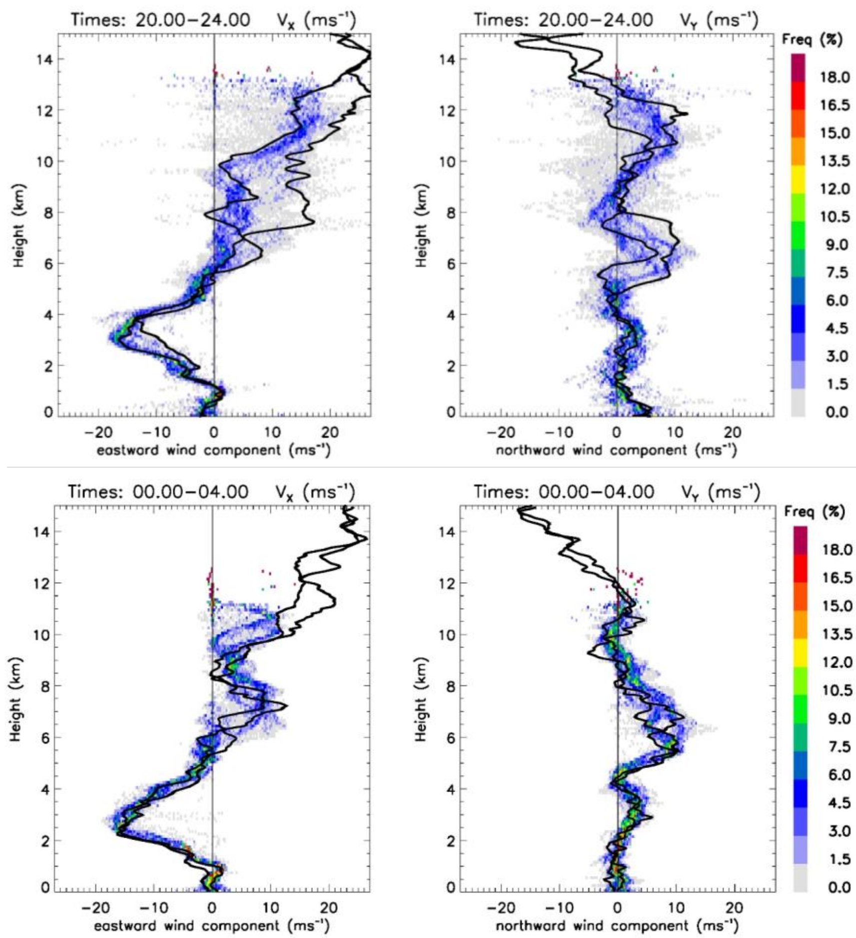


Figure 3: Comparison of V_X (left) and V_Y (right) joint wind – height frequency distributions (colours) and the same horizontal wind components measured by soundings for two time periods: 2000-2400 UTC on 23/11/2019 with sounding launches at 2015 and 2315 UTC (top panels) and 0000-0400 UTC on 24/11/2019 with sounding launches at 0115 and 0245 UTC (bottom panels).

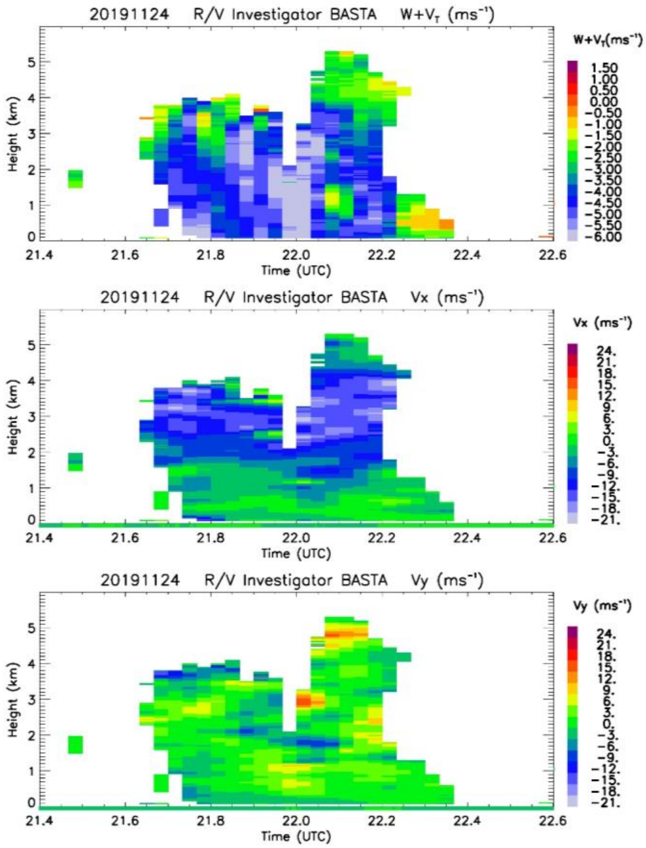
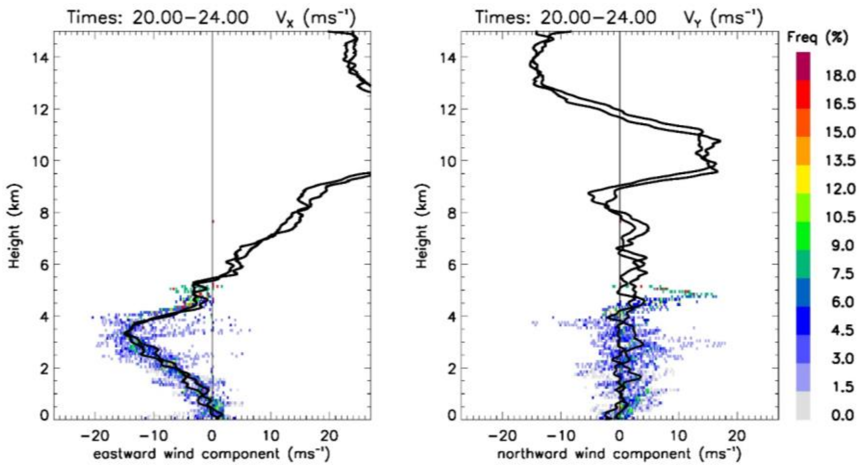


Figure 4: Same as Fig.2 but for the cumulus congestus case on 24/11/2019 and a maximum display height of 6 km.



775 **Figure 5: Same as Fig.3 but for the cumulus congestus case and the 2000-2400 LT period on 24/11/2019.**

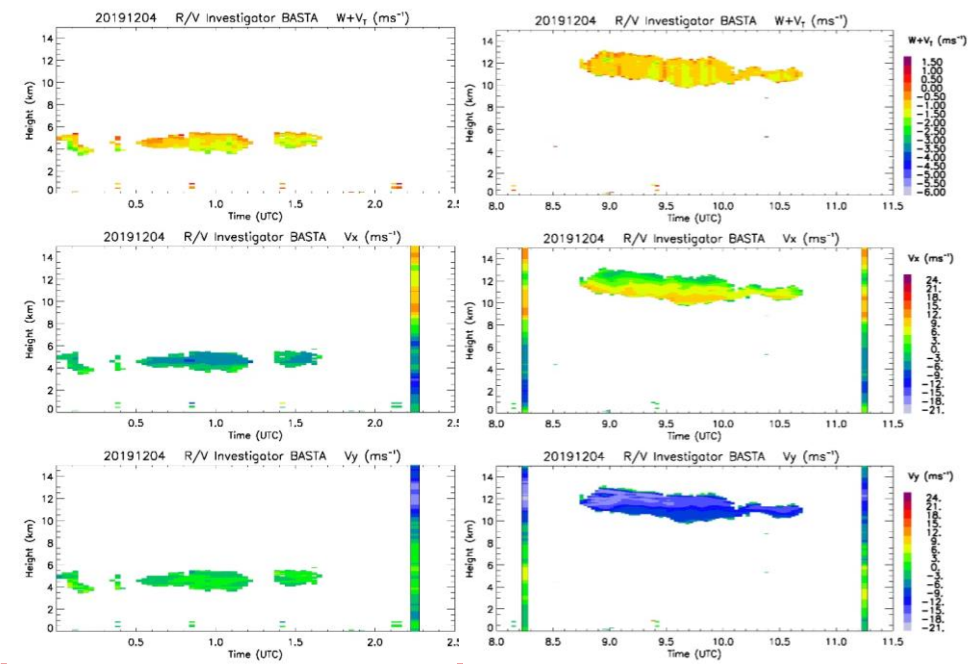
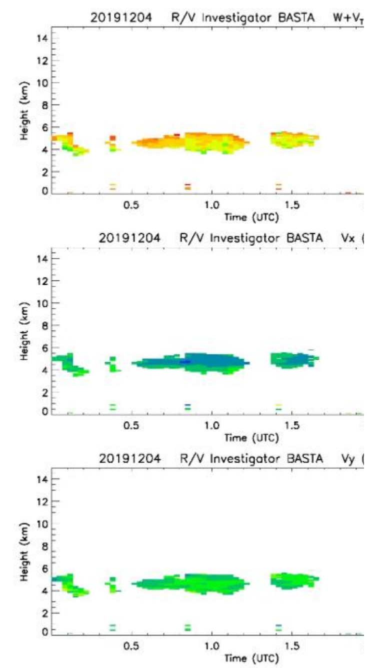


Figure 6: Same as Fig. 1 but for the altostratus (left) and tropical cirrus (right) cases sampled on 04/12/2019



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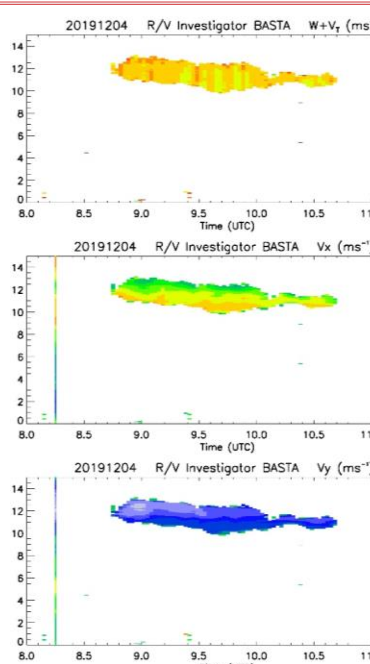

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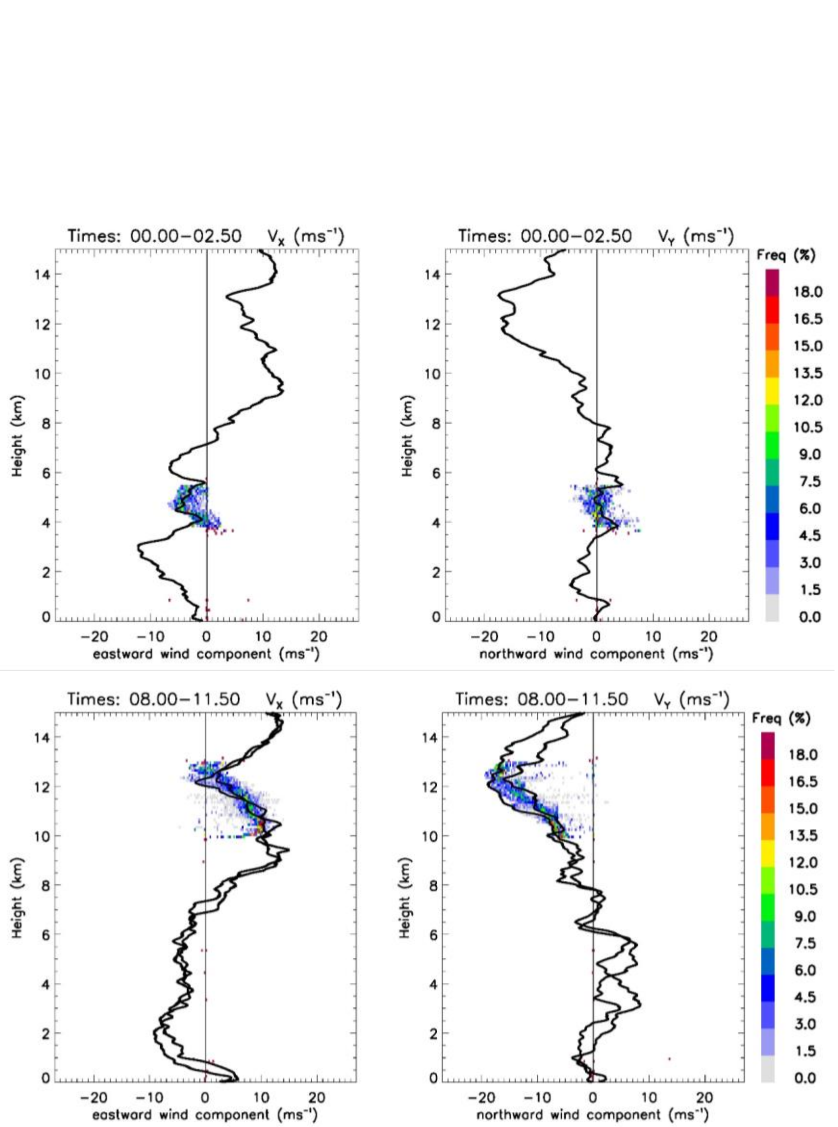

Figure 7: Same as Fig. 3 but for the altostratus (top panels) and tropical cirrus (bottom panels) cases sampled on 04/12/2019

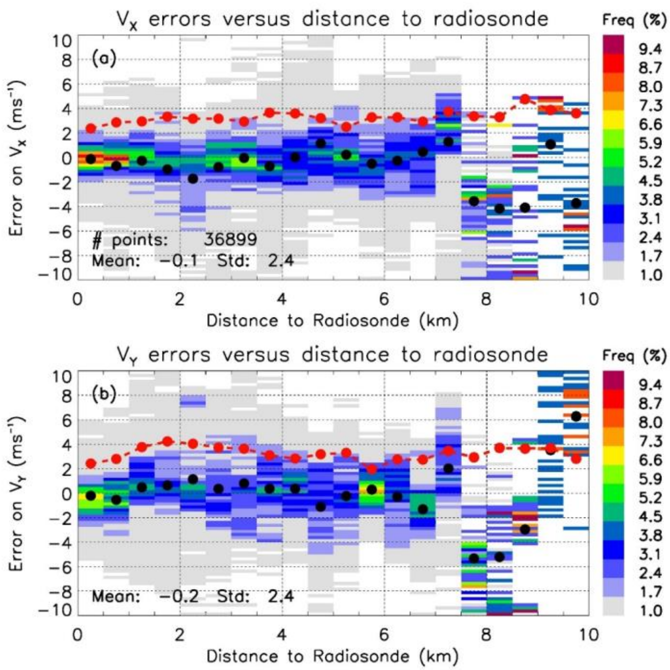

Figure 8: Frequency distribution of (a) eastward and (northward) wind component errors as a function of the horizontal distance between the ship and the balloon. The sign convention is (retrieved-radiosonde) wind. The frequency is normalized to 100% for each distance bin. Black dots and red dots are the estimates of the bias and standard deviation of the error for each bin, respectively. The mean bias and standard of the error for the first bin is given on each panel. The total number of points is given in panel (a).

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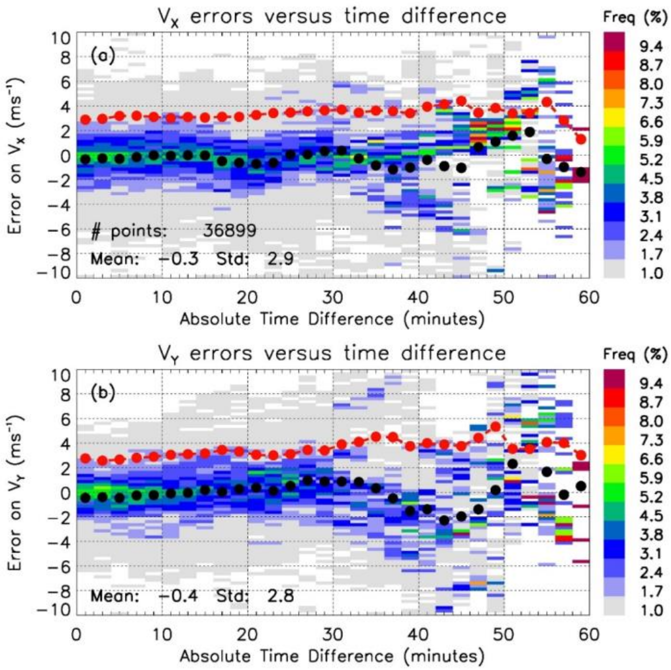

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Figure 9: Same as Figure 8 but using bins of absolute time difference between retrievals and radiosonde measurements.

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