Response to Editor's Comments

We would like to sincerely thank the Executive Editor, Editor (Dr.Gabriele Stiller) and all the three referees (2 anonymous and 1 interactive comments by Dr. Ulrich Schumann) for kind suggestions and comments, which helped in revising the manuscript. We have addressed all the reviewers' comments in order to make the manuscript publishable in your esteemed journal "Atmospheric Chemistry and Physics (ACP)". Point-by-point response on how we have addressed each recommendations/suggestions is given in the reply to the reviewer's comments and same is also implemented in the revised manuscript.

Please note that we have already responded to the open interactive comment by Dr. Ulrich Schumann and same is now implemented in the revised manuscript.

Now we are herewith submitting the revised manuscript and figures along with reply to the reviewer's comments for the consideration of publication.

All the authors listed on the manuscript concur with submission of the above mentioned manuscript.

We request Executive Editor and Editor to kindly process further and do the needful.

Response to anonymous Referee #1's Comments

Q1: *This study compares and assesses vertical wind data from five global atmospheric reanalysis data sets. As independent measurements, it uses VHF radar measurements from two tropical stations, one at Gadanki, India, and the other at Kototabang, Indonesia. This is a very important trial and should be published in the end.*

R1: We thank the reviewer-1 for his/her very positive comments and suggestions. We have addressed all the comments and implemented in the revised manuscript.

Q2: *The main issue of the manuscript is, I think, in the apparent large discrepancy between the radar measurement results and the reanalysis data. On the other hand, I think we can say that the five reanalysis data sets show qualitatively similar seasonal and vertical distribution of w; there are differences, but considering that omega depends heavily on forecast model of each reanalysis system, without direct observations assimilated, these differences (among the reanalyses) may be understandable.*

R2: Any reanalysis products assimilates as much as 10^7 observations per day, which is inclusive of both conventional (radiosonde, tower, aircrafts, wind profilers (wherever possible), etc.) as well as various satellite observations. It is to be noted that the vertical velocity provided by any reanalysis data centers is estimated indirectly from the horizontal wind components and temperature, which itself have mismatch among various reanalysis data (e.g., Das et al., 2016; Kawatani et al., 2016). Thus, this can possibly induce the discrepancy in the estimated vertical velocity among various reanalysis. Any wind profiler radar gives direct measurements of vertical velocity but over a single observational point. Whereas all the reanalysis data are averaged over the grid (e.g. ERA-Interim with 0.75 degree (latitude) x 0.75 degree (longitude)) which is possibly one of the main reasons for the mismatch between radar and reanalysis. We have now made a spatial sampling of w by considering different grid resolutions for a particular year and month to show the effect of spatial averaging on w, which is not included in the revised manuscript. In addition, it may also be due to the fact the different reanalysis uses different schemes and assimilation techniques.

Q3: *I am afraid that we even need to start from suspecting any errors in the data processing and analysis for reanalysis omega. Did the data really come from the correct (intended) grid point? Is the conversion from omega to w really correct? I do believe that the authors did the correct procedure, but we need some more cross-check information to confirm that they really did, simply because the difference from the radar measurements is too large. One note is that the authors should remove data at some lowest levels where the reanalysis systems simply extrapolate data below the surface (the altitude of Gadanki and Kototabang is 360 m and 865 m, respectively).*

R3: As mentioned in the manuscript, we have taken the data at the corresponding grid which is close to the radar location. We have used the equation (2) given in the revised manuscript to convert the omega (Pa s^{-1}) into vertical velocity (m s^{-1}). We have cross-checked every code and found no error. There are several literatures available, where vertical velocity is used from reanalysis (e.g. Uma et al., 2014; Das and Suneeth, 2020) as well as measured from MST/ST radar (e.g., Gage et al., 1991, 1992; Rao et al., 2003; Yamamoto et al., 2007; Rao et al., 2008; Uma and Rao 2009b, and both the magnitudes (re-analyses and radar) are comparable with the present study.

VHF radar at Gadanki provides observations from 3.6 km and Kototabang radar provides from 2 km, we have compared the re-analyses only from those altitudes.

As suggested by the reviewer, we have removed the data from the re-analyses below 2 km.

Q4: *Regarding the radar measurements, it would be very useful to discuss why w shows such seasonal and vertical distributions. What processes produce upper tropospheric ascending motion and lower tropospheric descending motion, the latter for Kototabang for all seasons and for Gadanki for April to October? Are there any publications that discuss this? There are several publications on the measurements of VHF wind profiler at Christmas Island (2N, 157W) (Gage et al., 1988, 1991, 1992). Their vertical wind profiles may look rather similar to what Kototabang measurements show. Thus, their discussion may be useful. Once we (rather theoretically) understand how the actual w distributions may look like, we can get more insight on why all these reanalyses show such distributions.*

R4: The vertical distribution of vertical velocity over Gadanki and Kototabang shows that the transport of air from the troposphere to the stratosphere is a two-step process. The downdraft below and updrafts above 10 km shows the convection transport of the air parcel up to 10 km and the slow ascending motion above 10 km slowly lifts the air parcel from 10 km to the stratosphere. This is prevalent in almost all the seasons over Gadanki and Kototabang. The detailed discussion on the seasonal and the vertical distribution of vertical velocity over Gadanki is explained by Rao et al., (2003), Rao et al., (2008) and Uma and Rao (2009). Rao et al., (2008) in addition to Gadanki data have also used Kototabang radar data to describe the seasonal and vertical characteristics of vertical velocity.

Following the reviewer-1's suggestion, we have discussed the VHF radar measured vertical velocity measurements over Christmas Island in the revised manuscript (Gage et al., 1991 and 1992). Gage et al. (1988) studied the comparison of only horizontal winds measured with VHF wind profiler with NMC and ECMF reanalysis thus, we are not including in our discussion.

Q5: *In summary, I think we need much more information (maybe direct or maybe indirect) that may be useful to understand why the radar measurements and reanalysis data show such different distributions.*

R5: Suggestion of the referee is well taken and we discussed these possibilities of differences between the reanalysis and radar observations in the revised manuscript. Additional analysis is also performed in one of the reanalysis data (ERAi) to evaluate the spatial averaging.

Q6: *Page 2, lines 43-49, and page 3, line 68, and other places: The use of the terms "direct" and "indirect" may need to be reconsidered. "Direct" may be used for in situ measurements (e.g., radiosonde horizontal wind measurements), while "indirect" may be used as "indirect estimation" e.g., of w from horizontal wind measurements/data to consider their divergence/convergence. For the case of radar measurements, we may use the term "remote sensing" measurements, because these may not be "direct" measurements (they are not in situ measurements) but at the same time these may not be "indirect" which implies indirect estimation from other variables in the context of this manuscript.*

R6: As suggested by reviewer we have modified the direct and indirect measurements.

Q7: *Pages 5-6, Section 2.1:*
The full location information on the two radar sites needs to be written in this section. The information on altitude, country/island, and the institutes that operate these radars is missing. Also, please explain the topography around each of these radar sites rather extensively. Gadanki is

*located within high land of a continent (with a horizontal distance of ** km from the oceans), while Kototabang is located within a narrow mountain range of an island (of a scale of ** km in northwest-southeast and ** km in northeast-southwest), etc. The topographic information may be very important to judge the representativeness of reanalysis data at a particular grid point (and at the same time, the representativeness of each of these radar measurements).*
The direct time information in UTC should be provided, because reanalysis data are in UTC. It would be useful to show the profiles of data number, i.e., of the original ones, of the quality controlled ones, of the finally used ones (after discarding data points >1 m/s and <-1 m/s), etc. The information on the quality control procedure is also needed. (The authors listed possible issues in the radar measurements, but they did not explain what they actually did to avoid such issues.)
R7: We have now given the topography information of both the sites, Gadanki and Kototabang. The figures are provided in UTC in the manuscript. The number of data points that have been discarded falls less than 1 % of the total data. As we know that the radar signal strength decreases with height following inverse square law. So we have adopted a procedure to neglect the data which does not lie within the specific threshold of SNR. This is described in the manuscript. The possible issues that can bias the vertical wind and how it is negligible in the mean *w* is already discussed by Rao et al., (2008).

Q8: *Page 7, line 157: Which MERRA-2 data product was used, ASM or ANA?*
R8: We have used ASM in MERRA-2. It is now mentioned in the revised manuscript.

Q9: *Pages 9-, Section 3: Please see my comments above. Also, investigation of a case or two (e.g., for a week or for a month) might be useful to understand what is going on for both radar measurements and reanalysis data.*
R9: Following the reviewer-1's suggestion, we have shown a case study for day-to-day comparison between the observations (Gadanki MST Radar and EAR) and reanalysis (ERAi). We thank referee for the valuable suggestion.

Q10: *Figure 8: Results from Gadanki and Kototabang should be shown in separate panels/ figures. ERA-Interim is used as a reference. But, considering that ERA-Interim the Reanalysis Ensemble Mean (REM) may be a better reference. Finally, a reference should be "subtracted", e.g., ERA5 minus REF, not REF minus ERA5.*
R10: Following the reviewer's suggestion, figures are now separated for Gadanki and Kototabang. Also, we have calculated the Reanalysis Ensemble Mean to show the inter-comparison between different re-analyses. The difference between the ensemble mean and the reanalysis is provided in the revised manuscript. We thank referee for this suggestion.

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Response to anonymous Referee #2's Comments

I like the premise of this paper very much: observational evaluation of reanalysis vertical velocities is much needed, perhaps especially within the broader Asian monsoon region. This is an important topic and I would like to see the paper published in the end. However, the presentation contains some significant gaps and unclear reasoning that should be addressed.

We thank the reviewer for his positive comments and suggestions. We have addressed all the comments and implemented in the revised manuscript.

Q1: *My main reservation is that the comparison as presented is almost entirely descriptive, with little analysis of the causes of biases or how they might inform further improvement of the reanalysis products (see also comment D below). It would be very helpful – if not essential – to include more interpretation of both the differences among the reanalyses and the biases relative to observations. For example, the introduction indicates that section 4 includes both a discussion and a summary of the results, but section 4 itself includes little discussion, only summary. Some questions to consider:*

R1: Any reanalysis products assimilate as much as 10^7 observations per day, which is inclusive of both conventional (radiosonde, tower, aircrafts, wind profilers (wherever possible), etc.) as well as various satellite observations. It is to be noted that the vertical velocity provided by any reanalysis data centres is estimated indirectly from the horizontal wind components and temperature, which itself have mismatch among various reanalysis data (e.g., Das et al., 2016; Kawatani et al., 2016). Thus, this can possible induce the discrepancy in the estimated vertical velocity among various reanalysis. Any wind profiler radar gives direct measurements of vertical velocity but over a single observational point. Whereas, all reanalysis data are averaged over a grid (e.g. ERA-Interim with 0.75 degree (latitude) x 0.75 degree (longitude)) which is probably one of the main reasons for the observed mismatch between radar and reanalysis.

Following the reviewer's suggestions we have revised the manuscript accordingly and estimated the following :

(1) Difference between the individual reanalysis with ensemble averaging of all reanalysis (Reviewer-1).
(2) We have now made a temporal and spatial sampling of *w* by considering different time and grid resolutions to show the effect of spatio temporal averaging on *w*.

Section-3 provides the results and discussion and section-4 only contains a summary. Now we have rephrased the sentence in the Introduction section.

Q2: *Can we understand anything about what the reanalyses are doing wrong (or right) from the observational validation or reanalysis-only intercomparison results?*

R2: We would like to point out to the reviewer that it is difficult to say whether reanalysis is doing wrong or right. In this aspect, we have contacted the reanalysis centre several times (through e-mail) but we could not find any definite answers from them. The inter-comparison of vertical velocity showed that there exist differences among the reanalysis itself (magnitude) as well with the radar observations. At this juncture, we would like to report the same which has never been reported earlier. However, we would like to point out that vertical velocity

in the reanalysis is an indirect estimation from the horizontal wind component and temperature, and earlier observations show that there is a mismatch among the horizontal wind of various reanalysis. In addition, it may also be due to the fact the different reanalysis uses different schemes and assimilation techniques, which is difficult to account for the bias in w. A table on schemes of different reanalyses data used in the present study is now included in the revised manuscript (Table 2).

Q3: *Do the differences indicate major problems or can they be largely understood in terms of spatiotemporal sampling? For example, the narrow column observed by the radar relative to the reanalysis grid scale – do comparisons of reanalyses with grid scales spanning a factor ten offer any context here? In a related question, does resolution of the nearby topography come into play in any obvious ways?*

R3: Following the reviewer's suggestion, we have done a small exercise with different spatial sampling with ERAi data set for a particular year and month and it is now included in the revised manuscript. The different grid spatial averaging does not significant impact on the *w*. The topography over the two locations can generate mountain waves if strong low-level winds are prevailing. Strong low-level winds are prevalent over Gadanki only from June to August and during these months, there is a critical level existing between 6 and 7 km due to the presence of strong wind shear, which will not support the propagation of mountain waves to higher altitudes. This wind shear exists throughout the year over Kototabang. Hence the effect of mountain waves will be minimal over both these locations on vertical velocity.

Q4: *Are there any clues as to how different types of data assimilation (3D-Var vs IAU vs 4D-Var) influence biases in vertical velocities? What about details of the model physics, such as convective or boundary layer scheme?*

R4: A table is attached in the revised manuscript about different schemes used by different reanalysis systems. It is very difficult to point out at this juncture that bias in the vertical velocity due to various assimilation schemes (Please see our R2).

Q5: *How robust are the results between the two sites? Does this have any implications for which conclusions, if any, can be generalized?*

R5: The results are robust from radars as it is only the technique for direct profiling the vertical velocity. There have been several global studies on vertical velocity during clear air as well as disturbed weather conditions using wind profiler radars. These results from the radar are consistent and hence the conclusions can be generalized.

Q6: *I appreciate the authors' attention to earlier editorial comments. I have included an annotated manuscript with some additional (optional) suggestions, which also references the specific comments below.*

R6: We sincerely thank the reviewer for his kind effort for providing an annotated manuscript. We have tried to address all the suggestions and comments raised by reviewer-2.

Q7: *A (Sect. 2) The descriptions of the reanalyses in section 2 should include indications of how vertical velocities are computed in each reanalysis, whether these estimates are impacted by data assimilation (i.e. forecast versus analysis versus IAU in the case of MERRA-2), and whether they represent time-average or instantaneous estimates. It would also be helpful to give some basic* *information about the model vertical coordinates, as I think vertical pressure velocities are usually estimated in these coordinates and then interpolated to the pressure grid. To the extent that these procedures are the same across multiple reanalyses the description could be consolidated, emphasizing differences in each subsection. Any other aspects of the model / data assimilation that might aid interpretation of the differences should also be included here.*

R7: We thank the reviewer-2 for the suggestion. Now we include a separate tabular column describing the schemes used in various reanalysis. However, based on the schemes used in reanalysis, it is difficult for the authors to conclude the bias in omega. Reanalysis computes vertical velocity using kinematic and adiabatic methods. The omega obtained from reanalysis is time-averaged and not instantaneous. A generalized model vertical coordinates which are interpolated to the pressure grid and other details are now described in the revised manuscript.

Q8. *(Method) Some of the specifics of the analysis are difficult to follow. For example, in l.287 it is indicated that directional tendencies are reported for a given height for every month when either the radar or reanalysis data exceeded ±1 cm s^{-1}. This screening is based on the monthly mean, correct? Then, a few lines later, it is indicated that the directional tendency is calculated only for absolute magnitudes greater than 0.1cms^{-1}. Is this now referring to the daily data? Are the results sensitive to these thresholds, especially in terms of the reanalysis evaluation?*

R8. We only estimated the directional tendency, if the data lies above ±0.1 cms^{-1} in either direction in both reanalysis and radars. Reviewer has rightly pointed out that the screening is based on the monthly mean. These sentences are modified accordingly in the revised manuscript.

Q9. *(Sect. 3, last two paragraphs) The directional tendency results for ERA5 are difficult to understand. The lack of strong updrafts or downdrafts at Gadanki seems to contradict the results shown in Fig. 3 (where ERA5 seems to have relatively strong vertical velocities and it is ERA-Interim more than ERA5 that looks like the outlier) and Fig. 6 (which shows a pretty robust seasonal cycle with many monthly averages well above the threshold). The results for Kototabang are likewise perplexing in the context of Fig. 3 and Fig. 7. How do you reconcile the directional tendency results in Fig. 9 with the profiles shown in these earlier figures?*

R9. We extremely thank reviewer-2 for point out this issue w.r.t ERA5. This is issue has come due to the two different periods of data used in the analysis. We used 1995 to 2015 data for ERAi, MERRA2, JRA55 and NCEP2, whereas for ERA5 the data used is from 2002 to 2015 for Gadanki. Similar things happened for Kototabang. Now we have corrected in the revised figure and sincerely apologize for the mistake.

Q9. *(Sect. 4, l.339-340) I like this thought, but more needs to be done to really provide a useful platform for improving the reanalyses. For one, it is not clear whether it is the 'methodology for calculating w' that lies behind the identified biases, as opposed to, e.g., different diurnal or day-to-day variations in convective occurrence (see comment 20), interactions between subgrid physical parameterizations and the large-scale flow, crude representation of local topography or land surface conditions, even just differences in spatial sampling area. This last is even suggested as the main reason for the differences in l.195-196, and it is not clear how reanalyses can address this beyond moving to finer and finer horizontal resolutions, which they are already doing. I recognize that it would be a monumental task to try to diagnose all of these and do not ask for a exhaustive investigation, but some investigation and discussion would be warranted. For example, operating on the hypothesis that the differences are mainly related to averaging, you could try imposing 'subgrid fluctuations' on the reanalysis products. What scale of fluctuation would need to be imposed to bring the reanalysis products in line with the observations? Is there any relationship between this value and the reanalysis grid size? Do the results make physical sense, or do they suggest that other factors must contribute?*

R9. Suggestion of the referee is well taken and we discussed these possibilities of biases and differences between the reanalysis and radar observation in the revised manuscript. Additional analysis is also performed in one of the reanalysis data (ERAi) to evaluate the spatial and temporal averaging (please refer R3).

Q10. *(Data availability) The data citations are incomplete. Both NASA (for MERRA-2) and the NCAR RDA (for all other reanalyses) have assigned doi numbers to the datasets used in this paper. These doi values should be used in data citations (input data doi at https://citation.crosscite.org/ for citation details) to help the data providers track the impact of their investment. Dates of access should also be included (since reanalyses occasionally undergo reprocessing to fix errors), along with the specific variables and resolutions used (to ensure reproducibility).*

R10.The data citations are now provided along with DOI in the revised manuscript. The data resolution is now provided in section-2.

Q11. *(Figure 3) Is it possible that the vertical profiles for MERRA-2 at Kototabang have been inverted somehow? The differences between these and ERA5/ERA-Interim are pretty striking, perhaps especially the downward shift of the maximum during May–June in MERRA-2 relative to the upward shift of the maximum in ERA5 and ERA-Interim (not to mention the radar profiles). I know that the orientation of the vertical coordinate may differ (top-to-bottom, bottom-to-top) in data files released by these different reanalysis producers. Please double-check this for MERRA-2, and perhaps also for NCEP-2.*

R11. We have rechecked the program/coding and found no error in the orientation of vertical coordinate (height).

Q12. *(Figure 8) Could Fig. 8 be made more effective building off of the presentation in Fig. 3, using difference plots relative to a particular reanalysis-based benchmark? I agree that the current presentation could help in terms of explicitly comparing quantitative biases across different reanalyses, but it is very difficult to pick out details of the individual profiles in the current figure. Another option might be to consolidate some months with similar profiles (it looks like the canonical seasons might work, but warm/cold/transition seasons could also work) and then split the Gadanki and Kototabang profiles (results for the two sites do not seem to share that much in common in the vertical distributions).*

R12. Fig. 8 (old manuscript) is now modified by doing ensemble averaging of all the reanalysis and each reanalysis is subtracted from the ensemble averaging. We have given separate figures for Gadanki and Kototabang in the revised manuscript.

Q13. *(Figure 9) The caption says this figure shows a comparison between the radars and various reanalysis products. Where are the directional tendencies based on the radar data? It is difficult to evaluate the reanalyses without this information. Please excuse me if I am missing something really basic about the presentation.*

R13. The directional tendency is calculated if both radar and reanalysis observe updrafts/downdraft simultaneously at the same height considered. So there will not be any tendency for radar and reanalysis separately.

Q14. *(l.33) Perhaps also mention the role of subsidence and adiabatic warming in the formation of stable inversion layers?*

R14. Sentence is included in the revised manuscript.

Q15. *(l.36,38) I think the use of 'control' here rather overstates the case, especially in l.36. It would be enough to delete 'controlling'; the second use in l.38 is ok on its own.*

R15. The word controlling is now omitted.

Q16. *(l.49) Please clarify what is meant by 'global estimates' and its relationship to 'direct measurements' versus 'indirect estimates'; there is also an extra comma here.*

R16. The word "globally" is now omitted and the sentence is revised accordingly.

Q17. *(l.57) Maybe mention here that this source of uncertainty is particularly important for reanalyses, where assimilation increments in horizontal winds may be comparable to this. It might also be helpful to rephrase the sentence to emphasize this assimilation adjustment rather than 'error'.*

R17. The above sentences are rephrased in the revised manuscript.

Q18. *(l.65) The connection of the above discussion to reanalysis estimates of vertical velocity should be made more explicit (i.e., why do these concerns apply to reanalysis products specifically)*

R18. These sentences are rephrased in the revised manuscript.

Q19. *(l.66) Suggest rewriting this sentence: 'reanalyses involve many approximations and assimilation-related adjustments, and are not error-free'*

R19. The above sentence is rephrased in the revised manuscript.

Q20. *(l.84) Technically a reanalysis vertical profile is also a column over a single location, just one with a broader footprint. Here it would be helpful to specify how the area of the column differs between the radar, the finest-grid reanalysis (0.25°, right?) and the coarsest-grid reanalysis (2.5°).*

R20. The area the radar looks at the height of 20 km is about 14 km (East-West) x 14 km (North-South), which is about 0.12 degree x 0.12 degree and it is much finer at a lower height (like an inverted cone). The finest grid is 0.28 (ERA5) and the coarsest grid is 2.5 (NCEP2/DOE) with respect to reanalysis and the grid resolution is uniform with height.

Q21. *(l.86) Phrasing needs care here: a number of studies have evaluated vertical motion across reanalyses (in the context of trajectories, wave activity, large-scale motion, etc.), so the primary novelty of this work is the evaluation against radar observations.*

R21. The above sentences are included in the revised manuscript.

Q22. *(l.88) This point is a little repetitive.*

R22. The point is deleted in the revised manuscript.

Q23. (*l.119) Rephrase: 'Quality control metadata for the EAR measurements are available online'*

R23. The above sentence is rephrased in the revised manuscript.

Q24. *(l.140) How long is 'long'?*

Q24. The vertical velocity is averaged over ten years. This is now included in the revised manuscript.

Q25. *(l.146) How is this 21 km upper limit identified in the reanalysis profiles, and approximately what pressure level does this correspond to? More generally, many of the results are presented in altitude coordinates. Are heights computed from the pressure levels assuming a constant temperature, from geopotential outputs from each reanalysis, another approach? Are data linearly interpolated to a common height grid? Could this have any influence on the comparisons in this paper (e.g., the reanalysis-derived updraft maxima being located lower than those observed by the radar)?*

R25. As we know that the radar signal strength decreases with height following inverse square law. Thus, the maximum height coverage by Gadanki MST radar as well as Kototabang Equatorial Atmospheric Radar is up to 21 km which is about 50 hPa, beyond which the signal is noisy. Thus, we took all reanalysis maximum

up to 21 km (if available). No reanalysis data were interpolated. The pressure co-ordinate is directly converted into height using Hypsometric equation. For inter-comparison, common height between radar and reanalysis is chosen.

Q25. *(l.152) Citation year for Hoffmann et al. should be 2019*
Reply: Corrected.

Q26.*(l.153) The ERA5 paper is now in early online release (https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803)*
R26. Citation corrected

Q27. *(l.165) NCEP-2 (as denoted here) was undertaken as a cooperation between NCEP and the Department of Energy (DOE); care should be taken in this text to acknowledge this and distinguish it from the NCEP-NCAR Reanalysis 1*
R27. Corrected in the revised manuscript.

Q28. *(l.171) The paragraph mentions only the original model resolution, but from this description the data are taken from the 2.5° data grid*
R28. Data is chosen from the nearest grid.

Q29. *(l.178) This information is not provided for the other reanalyses nor is it clear how it relates to the estimation of vertical velocity. I suggest that the authors try to provide a consistent and concise set of information for each reanalysis in this section, focusing on the points relevant to the data used in this paper.*
R28. Now description about each reanalysis and also a table about all the reanalyses is provided in the revised manuscript.

Q30. *(l.186) for dry air*
R30. Corrected.

Q31. *(l.188) daily mean is evaluated for 00–24UTC or shifted to match local solar time? I guess it shouldn't matter much as long as this is consistent between the radar and reanalysis*
R31. For Gadanki the instantaneous value at 12 GMT is taken whereas, for Kototabang, the entire 24 hrs of reanalysis data is averaged for the daily mean.

Q32. *(l.195) It looks like convective days in the reanalysis products are defined based on the screening from the radar data. How consistently do the reanalyses identify convective versus non-convective days based on measurements at the radar site? Wouldn't this screening also be sensitive to the differences in grid size? Some sensitivity testing would be helpful here, perhaps using precipitation thresholds as well as w.*
R32. Convective days may influence the long-term averaging of vertical velocity (for details see Uma and Rao., 2009), thus it has to be removed from the analysis. The radar vertical velocity threshold is a good proxy to identify the presence of convection (Uma and Rao., 2009) and thus the convective days are identified from the radar vertical velocity, if it is above ±1 m s^{-1}. These convective days are removed from both radar data as well as reanalysis data sets.

Precipitation thresholds cannot be used for removing the convective days as there may be dry convection where vertical velocity may exceed ±1 m s^{-1} but no precipitation is observed at surface level (e.g. Uma and Rao., 2009).

Short scale convection both in spatial as well as temporal scale is difficult to be captured by any reanalyses.

Different grid averaging of reanalysis (ERAi) is now included and discussed in the revised manuscript.

Q33. *(l.198) The meaning of 'global' here is not clear — should this be 'qualitative' to set it against 'quantitative' differences that might result from differences in sampling area (but see also comment 20)?*

R33. The word "Global" is omitted.

Q34. *(l.206) ERA5 should be written without the hyphen (as it is now in much of the manuscript; thank you)*

R34. Corrected.

Q35. *(l.216) It is not clear from the text whether these 'significant variations' are in the seasonal cycle, in the diurnal cycle, or both (since the previous sentence discusses seasonal variations in the diurnal cycle). Some additional clarification would be helpful.*

R35. It is seasonal variations in the diurnal cycle. The sentence is revised accordingly.

Q36. *(l.220) The temporal treatment is another source of potential differences in vertical velocities between the observational data (time averages over at least one hour) and reanalyses (usually instantaneous outputs, I think – please check – and usually only four times per day). Naively, it seems like this might offset some of the smoothing effect of the spatial sampling difference, but it should be mentioned and discussed either way.*

R36. The reanalysis outputs are averaged products. The issue of spatial sampling of reanalysis is addressed in figure 9 in the revised manuscript. Please refer R3.

Q37. *(l.231) Could this comparison be sensitive to the definition of 'convective' days? This may be especially relevant for Gadanki where the reanalyses may even have different diurnal cycles of convection. For example, Bechtold et al. (2014) reported that changes to the forecast model between ERA-Interim and ERA5 resulted in substantially improved representation of the diurnal cycle of convection over land.*

R37. It is to be noted that radar been a single point observation, even the small scale convection can be captured over both the radar location. During such event (even in a small scale convections), we observed high vertical velocity beyond ±1 ms^{-1}. Hence, data used in the present study after the screening is convection free which will not affect the results.

Q38. *(l.249) Does this result generalize to the observational validation — i.e. do the EAR results for Kototabang also support this conclusion? This information could be added to Fig. 7 and related discussion.*

R38. Yes, Gadanki results will be valid for Kototabang and it is already shown in Fig.9 (revised manuscript).

Q39. *(l.272) Some additional care might be needed in the presentation here, to distinguish when the values being quoted are absolute magnitudes of w (as here) versus when they are biases relative to a particular benchmark (as earlier in the paragraph).*

R39. We have now revised as ensemble averaging and discussion is modified in the revised manuscript.

Q40. *(l.278) This presentation ('underestimates'/'overestimates') is a little strange, since it seems to imply an evaluation of ERA-Interim against multiple benchmarks as opposed to an intercomparison among (presumably) equally uncertain reanalysis-based products. A more specific and less judgmental phrasing might help, something like: 'XX shows smaller positive values* *than YY and larger positive values than ZZ', or 'XX and YY both show downdrafts, but with larger amplitudes in XX', or maybe using stronger/weaker updrafts/downdrafts if you prefer.*

R40. Following reviewer-2's suggestion, the phrases are revised accordingly.

Q41. *(l.292) Should delete the space between 10 and % (also elsewhere in this and following paragraphs).*

R41. Deleted.

Q42. *(l.293) Is this ratio indicating that 10% of all 12UTC values exceed 0.1 cms^{-1} or that 10% of all positive values have magnitudes greater than 0.1 cms^{-1}? If the first, it is enough to remove 'of updrafts'; if the second, some additional text to clarify is necessary.*

R42. The figure represents that 10% of the time both radar and reanalysis observed updrafts simultaneously over a particular location. Now this sentence is rephrased in the revised manuscript.

Q43. *(l.301) Suggest to be more explicit: 'The fraction of downdrafts decreases above ...'*

R43. Corrected.

Q44.*Is this 'reaches a maximum' specifically referring to the increase above 17 km or to both the increase below 6km and above 17 km? If the latter, 'a maximum' should be changed to 'maxima'.*

R44. Corrected.

Q45. *(l.330) Here, do you mean 'the location of the peak w differs between radar and reanalysis data, as it also does over Gadanki' or just that 'the vertical location of the w maximum over Kototabang is different from that over Gadanki'?*

R45. The location of the peak w differs between radar and reanalysis.

Q46. *(l.331) Again, suggest revising this presentation style to be clearer and more objective (see also comment 28).*

R46. Corrected.

Q47. (l.338) These examples are a little strange. It is true that the behavior of physical parameterizations in the reanalyses (used to generate diabatic heating and convective mass fluxes) may be impacted by large-scale convergence / divergence (and hence by the same factors used to compute w), though the feedbacks between w and model physics are two-way, complex, and pretty different from how they are implied to be here. Or perhaps the authors refer to diagnosed diabatic heating (e.g., Yanai et al., 1973) and vertical motion along Lagrangian trajectory pathways? Note that the latter should be distinguished from 'convection', which is included in some transport models but I think usually based on vertical stability rather than w.

R47. Following reviewer-2's suggestion, we have modified these sentences accordingly.

Q48. (Fig. 5 caption) Should this reference be to Fig. 4?

R48. Corrected

References :

Das, S. S., Uma, K. N., Bineesha, V. N., Suneeth, K. V., and Ramkumar, G.: Four-decadal climatological intercomparison of rocketsonde and radiosonde with different reanalysis data: results from Thumba equatorial station, Q. J. Roy. Meteor. Soc., 142, 91–101, doi: 10.1002/qj.2632, 2016.

Kawatani, Y., Hamilton, K., Miyazaki, K., Fujiwara, M., and Anstey, J. A.: Representation of the tropical stratospheric zonal wind in global atmospheric reanalyses, Atmos. Chem. Phys., 16, 6681-6699, doi: 10.5194/acp-16-6681-2016, 2016.

Response to Interactive comments (by Dr. Ulrich Schumann)

Q1. *I fully agree that vertical air motion is crucial for atmospheric dynamics and under resolved in most of present numerical weather prediction products. This is true not only for the tropics but at all latitudes. I appreciate this study as a relevant contribution using interesting radar data (with which I have only little experiences).Please let me point out that vertical wind can be measured – at least in principle – also by other instruments including research aircraft. I recently published a study (Schumann, 2019) on relationships between horizontal kinetic energy spectra of vertical wind and horizontal divergence of the divergent horizontal wind components, which can be separated from the rotational wind components by known Helmholtz decomposition methods. I compared with airborne wind measurements in the upper troposphere and lower stratosphere at mid-latitudes and compared to some available model data. In particular, I found a total of 80 % of w variance near the tropopause occurring at scales between about 0.5 and 80 km. Perhaps these findings, and some of the related literature cited in my paper are worth mentioning in your paper.*

R1. We are very much thankful to the Dr. Schumann for going through our manuscript and providing positive suggestions. We have gone through this interesting paper and included all the necessary points in the revised manuscript.

Assessment of vertical air motion among reanalyses and qualitative comparison with VHF radar measurements over the two tropical stations

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Abstract

Vertical wind (*w*) is one of the most important meteorological parameters for understanding a range of different atmospheric phenomena. Very few direct measurements of *w* are available so that most of the time one must depend on reanalysis products. In the present study, assessment of *w* among selected reanalyses, (ERAi, ERA5, MERRA-2, NCEP/DOE-2 and JRA-55) and qualitative comparison of those datasets with VHF radar measurements over the convectively active regions Gadanki (13.5°N and 79.2°E) and Kototabang (0°S and 100.2°E) are presented for the first time. The magnitude of *w* derived from reanalyses is 10-50% less than that from the radar observations. Radar measurements of *w* show downdrafts below 8 to 10 km and updrafts above 8-10 km over both locations. Inter-comparison between the ensemble of reanalyses with respect to individual reanalysis shows that ERAi, MERRA-2 and JRA-55 compares well with the ensemble compared to ERA5 and NCEP/DOE-2. There is no significant improvement in the *w* due to the effect of different spatial sampling. Directional tendency shows that the percentage of updrafts captured is reasonably good, but downdrafts are not well captured by all reanalyses. Thus, caution is advised when using vertical velocities from reanalyses.

Key Words: Vertical velocity, MST Radar, Equatorial Atmosphere Radar, Reanalysis

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1 Introduction

Vertical air motion (*w*) in any region of the Earth's atmosphere reflects the structure and dynamical features of that region. Importantly, in the lower part of the atmosphere, sudden widespread changes in the weather are usually associated with variations in vertical air motion. The magnitude of *w* is a factor of ten or more smaller than the horizontal wind; nevertheless, it is crucial in the evolution of severe weather (*Peterson and Balsley*, 1979). Adiabatic cooling associated with upward motion leads to the formation of clouds and precipitation and adiabatic warming associated with downward motion leads to the dissipation of clouds. In addition, subsidence leads to adiabatic warming, which results in the formation of stable inversion layers. Extensive studies have been done on the relationships between *w* and precipitation/convection over the tropics (*Back and Bretherton*, 2009; *Uma and Rao*, 2009a; *Rao et al*., 2009; *Uma et al*., 2011 and references therein). Thus, *w* plays a vital role in day-to-day changes in the weather. Different scales of variability exist in *w* ranging from microscale to meso synoptic, and planetary - scales (*Uma and Rao*, 2009b). It also controls energy and mass transport between the upper troposphere and lower stratosphere (*Yamamoto et al*., 2007, *Rao et al*., 2008). In a nutshell, knowledge of *w* is helpful for evaluating virtually all physical processes in the atmosphere. Hence precise measurements of *w* could serve a guiding factor for studying many processes in the atmosphere.

The small magnitudes of *w* make it very difficult to measure, as the errors involved in measurements often exceed the actual values. Direct and indirect methods exist to measure *w* (e.g. Doppler measurements using radars for profiling, sonic anemometers in the boundary layer and also aircrafts) as well as indirect computational methods (e.g., adiabatic, kinematic and quasi-geostrophic vorticity/omega methods). Remote sensing measurements of *w* are thus restricted to locations where radars are situated. Using aircrafts *Schumann*, (2019) studied the

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Formatted: Font: (Default) Times New Roman, 12 pt, Not Italic, Complex Script Font: Times New Roman, 12 pt, Not Italic relationships between horizontal kinetic energy spectra of vertical wind and horizontal divergence of the divergent horizontal wind components, by separating it from the rotational wind components by known Helmholtz decomposition methods. In general, *w* is derived diagnostically from horizontal winds and temperatures, which is an indirect estimation. This estimation gives a general view on the distribution of ascending and descending motion on the synoptic-scale within the quasi-geostrophic framework (*Tanaka and Yatagai*, 2000; *Rao et al*., 2003).

Reanalyses evaluate the vertical pressure velocity (omega) using indirect estimation (e.g., *Dee et al*., 2011). Any reanalyses products assimilate as much as 10^7 observations per day, which is inclusive of both conventional (radiosonde, tower, aircrafts, wind profilers (wherever possible), etc.) as well as various satellite observations. However, reanalyses combine both observations and model outputs to produce systematic variation in the atmospheric state (e.g., *Fujiwara et al*., 2017). It is to be noted that the vertical velocity provided by any reanalysis data center is estimated indirectly from the horizontal wind components and temperature, which itself has mismatch among various reanalyses data (e.g., *Das et al*., 2016; *Kawatani et al*., 2016). Thus, this can possibly induce the discrepancy in the estimated vertical velocity among various reanalyses. For example, in the kinematic method, omega is estimated by integrating the mass continuity equation assuming inviscid adiabatic flow. However, this kinematic estimate suffers from uncertainties in the observations as omega is estimated from horizontal divergence (*Tanaka and Yatagai*, 2000). This source of uncertainty is particularly important for reanalyses, where assimilation increments in horizontal winds may be comparable to the uncertainty. A 10% error in the wind may lead to a 100% error in the estimated divergence (*Holton*, 2004). Omega from the thermodynamic energy equation is less sensitive to horizontal winds as it mainly depends on the temperature gradient. However, in this method the local rate of change in temperature must be measured

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accurately, meaning that observations must be taken at frequent intervals in time to estimate ∂T /∂t accurately (*Holton*, 2004). This methodology fails in areas of strong diabatic heating, especially where condensation and evaporation are involved. The quasi-geostrophic method for estimating omega neglects ageostrophic effects, friction and diabatic heating (*Stepanyuk et al.*, 2017). It is to be noted from the above discussions that calculating *w* from indirect estimation has more uncertainties. Hence reanalyses that use indirect estimation, involve underlying approximations and assimilations and are not error-free (*Kennedy et al*., 2012).

Other indirect methods can be used to derive *w* from radar measurements in the middle and upper atmosphere, where direct measurements of vertical wind are not possible due to technical constraints. These methods include Doppler weather radar, Medium Frequency (MF) radar and meteor radar. Doppler weather radar uses an indirect method to calculate vertical winds (*Liou and Chang*, 2009; *Matejka*, 2002). Meteor radar also cannot determine vertical velocity directly as the winds are determined from meteor showers using a wide beamwidth. As a consequence, *Laskar et al.* (2017) calculated vertical wind from meteor wind radar data based on a "Kinematic" method using the continuity equation and hydrostatic balance. *Dowdy et al.* (2001) have calculated vertical wind using the horizontal momentum and mass continuity equations from the MF radar data. However, indirect methods are only adopted when direct methods cannot be used.

Very-high frequency (VHF) and ultra-high frequency (UHF) vertical pointing radars are the most powerful tools for determining vertical air motion (velocity) with high temporal and vertical resolution. However, the magnitude may still not be directly comparable between reanalysis products and observations as the reanalyses provide the intensity of vertical air motion over wide areas (> 25 km^2), whereas the radar measurements provide information for a narrower column over a single location. Thus, the best way to assess reanalysis estimates of *w* against radar measurements is to compare its directional tendencies. A number of studies

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have evaluated vertical motion across reanalyses (in the context of trajectories, wave activity, large-scale motion, etc.), so the primary novelty of this work is the evaluation against radar observations. The present study focuses on the assessment of *w* among various reanalyses using VHF radar measurements from two tropical stations where the convective activity is frequent: Gadanki and Kototabang. Evaluations of this type are critically important as reanalyses estimates of *w* are widely used by the scientific community to understand and simulate a variety of atmospheric processes. In section 2, the data and methodology are described. Section 3 provides results and discussion followed by summary and concluding remarks in section 4.

2 Data and Methodology

2.1 Radar measurements

Remote sensing measurements of *w* are obtained from the Indian Mesosphere-Stratosphere-Troposphere Radar (IMSTR) located at Gadanki (13.5^{o}N and 79.2^{o}E) and the Equatorial Atmosphere Radar (EAR) located at Kototabang (0.2^{o}S and 100.2^{o}E). Figure 1a and 1b show the topography map of the location of both the radars, i.e. Gadanki and Kototabang respectively, generated by using the Shuttle Radar Topography Mission (SRTM) data (*Farr et al*., 2007). Gadanki is located in the southern peninsula of tropical India, about 90 km off the east coast and it is surrounded by hills. Kototabang is located in the western part of Sumatra Island and EAR is situated in the mountainous region with the highest peak of about 2 km. Both the IMSTR and EAR are pulsed coherent radars operating at 53 MHz and 47 MHz, respectively. These instruments are used to estimate *w* by measuring the Doppler shift in the vertical beam. The technical details and operational parameters of the IMSTR have been given by *Rao et al*. (1995) while those for the EAR have been given by *Fukao et al*. (2003). Both the radars specifications and parameters used for the present measurements are listed in Table 1.

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In the present study measurements of *w* from VHF radars are used to assess vertical motion between the surface and the lower stratosphere. Data collected from the IMSTR between 17:30 and 18:30 LT (LT=GMT+5:30 hr) from 1995 to 2015 are analyzed using the adaptive method (*Anandan et al*., 2001). This is the common operational mode of the IMSTR for deriving the winds and represents the only data available for such a long period of time. In general, 4-8 vertical profiles are averaged to create daily mean profiles. Averaging is conducted using the arithmetic mean as it represents the central tendency, which is generally used for wind averaging. In a vertically pointing beam, signal-to-noise ratio (SNR) decreases with height except in stable layers (like the tropopause) and in the presence of strong turbulence. Above 25 km, the SNR becomes constant in the absence of atmospheric signals. Data in this region can be therefore treated as noise and used to estimate the threshold SNR (*Uma and Rao*, 2009b). Noise levels estimated in this way lie between -17 dB and -19 dB with a 2σ value of 3 dB (where σ is the standard deviation). Thus data having SNR less than -15 dB are discarded from the present analysis. Data from intense convective days (checked for individual profiles), defined as *w* being less/greater than ± 1 ms^{-1} are also discarded as these data severely bias the climatological mean vertical velocity (e.g. *Uma and Rao*, 2009b). The data discarded is less than 1 % of the total data. Quality control metadata for the EAR measurements are available online (http://www.rish.kyoto-u.ac.jp/ear/data/index.html). The EAR operates continuously and this study uses hourly data (diurnal data of single day) from 2001 to 2015. The EAR data during convective periods are eliminated following the same criteria as for the IMSTR, a second screening step. Each full diurnal cycle (after removing convective profiles) is averaged and considered as a single daily profile for the EAR. For both radars, vertical velocity (cm s^{-1}) is directly estimated using equation (1)

$$w = -\frac{\lambda}{2} f_d, \qquad (1)$$

where λ is the radar wavelength (in cm) and f_d is the Doppler velocity (Hz).

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It is known that estimates of *w* derived from VHF radar measurements are vulnerable to biases due to tilting layers, strong horizontal winds (e.g., jet-stream), complex topography, Kelvin-Helmholtz instabilities and gravity waves (*Rao et al.*, 2008 and references therein). *Rao et al.* (2008) has discussed in detail the biases that can cause spurious diagnosis of downward wind as proposed by *Nastrom and VanZandt* (1994). In addition, they have also discussed the potential biases caused by beam pointing errors as mentioned by *Hauman and Balsley* (1996) and have conducted critical analysis to rule out beam pointing biases from VHF radar data. It is also to be noted that the topography over the two locations can generate mountain waves if strong low-level winds are prevailing. Strong low-level winds are prevalent over Gadanki only from June to August and during these months, there is a critical level existing between 6 and 7 km due to the presence of strong wind shear, which will not support the propagation of mountain waves to higher altitudes. This wind shear exists throughout the year over Kototabang. Hence the effect of mountain waves will be minimal over both these locations on vertical velocity. As proposed by *Nastrom and VanZandt* (1994) on the bias caused by gravity waves, *Rao et al.* (2008) have investigated biases caused by gravity waves by calculating the variances and found that downward wind measurements below 10 km are essentially unaffected by gravity waves. Their analysis clearly showed that the mean downward motion below 10 km and upward motion above 10 km are real and not caused by measurement biases, and also that the known biases do not change the direction of the background *w* when measurements are averaged over longer periods of 10 years.

2.2 *ERA-Interim* (ERAi)

ERAi is global reanalyses data which is developed by European Centre for Medium-Range Weather Forecasts (ECMWF). The data assimilation scheme used is 4D-Var of the upper-air atmospheric state and have effectively anchored both satellite and in-situ observations. This scheme updates parameters that define bias corrections required for

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satellite observations. The model has improved in the representation of moist physical processes. Advances have also been made with respect to soil hydrology and snow in land surface models. The detail of the model is given in (*Dee et al.*, 2011). We use 6-hourly vertical velocities from the ECMWF Interim reanalysis (ERAi) from 1995 to 2015. The grid resolution of ERAi is 0.75^{o} (latitude) x 0.75^{o} (longitude). The nearest grid points are taken for Gadanki (13.68^{o}N, 79.45^{o}E) and Kototabang (0.35^{o}S, 100.54^{o}E). Although 37 pressure levels up to 1 hPa resolution are available, we have restricted the dataset to 21 km, which is about 50 hPa, as that is the maximum radar range.

2.3 *ERA5*

ERA fifth-generation (ERA5) is the atmospheric reanalysis produced by ECMWF. It is an improved version of ERAi. The data assimilation scheme used is 4D-Var and it assimilates the NCEP stage IV quantitative precipitation estimates produced over the USA by combining precipitation estimates from the Next-Generation Radar (NEXRAD) network with gauge measurements. The moist physics scheme is improved by including freezing rain. The long wave radiation scheme is modified in ERA5. The evolution of the top soil layer, snow and sea ice temperatures are included. It uses observations from various satellites which include upper air temperature, humidity and ozone. It also used bending angles from GNSS. It provides much higher spatial (30 km) and temporal resolution (hourly) from the surface up to 80 km (137 levels). ERA5 also features much improved representation especially over the tropical regions of the troposphere and better global balance of precipitation and evaporation. Many new data types not assimilated in ERAi are ingested in ERA5 (*Hoffmann et al.*, 2019). The grid resolution of ERA5 is 0.28^{o} (latitude) x 0.28^{o} (longitude). The details are available in (Hersbach et al., 2020). We have taken hourly data from ERA5. The nearest grid points are again taken for Gadanki (13.63^{o}N, 79.31^{o}E) and Kototabang (0.14^{o}S, 100.40^{o}E), and the data period is 2002-2015.

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2.4 *MERRA-2*

The Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) is the latest reanalysis of the modern satellite era produced by the National Aeronautics and Space Administration's (NASA) Global Modelling and Assimilation Office (GMAO). The scheme used in MERRA-2 is an improved version of MERRA. It uses a three-dimensional variational (3D-Var) algorithm based on the grid point statistical interpolation and also uses an incremental analysis update. It assimilates bending angle observations, satellite radiances from both polar as well as geostationary infra-red and microwave sounders. In addition it also assimilates water vapor and ozone. MERRA-2 includes aerosol analysis and provide data for 42 pressure levels from the surface to 0.01 hPa with a temporal resolution of 3 h and horizontal resolution of 0.5^{o} (latitude) x 0.625^{o} (longitude). We used MERRA-2 Assimilation (ASM) data. Details have been provided by *Gelaro et al.* (2017). The nearest grid points are used for Gadanki (13.5^{o}N, 79.37^{o}E) and Kototabang (0.14^{o}S, 100.00^{o}E), with data spanning from 1995 to 2015.

2.5 *NCEP/DOE-2*

The National Center for Atmospheric Research and Department of Energy (NCEP/DOE-2) reanalysis is an updated version of NCEP-1 by fixing the known processing errors in NCEP-1. The variational scheme used is 3D-Var and it provides more accurate pictures of soil wetness and near-surface temperature over land, the land surface hydrology budget, snow cover, and radiation fluxes over the ocean. It is based on the NCEP operational model with a horizontal resolution of 209 km and 28 vertical levels. The temporal coverage is four times per day. NCEP/DOE-2 products are improved relative to NCEP-1, having fixed errors and updated parameterizations of physical processes, as evaluated by *Kanamitsu et al.* (2002). The grid resolution of NCEP/DOE-2 is 2.5^{o} (latitude) x 2.5^{o} (longitude). The data for

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the present study covers from 1995 to 2015 and is extracted at the nearest grid points to Gadanki (12.5°N, 77.5°E) and Kototabang (0, 100.00°E).

2.6 *JRA-55*

The Japanese 55-year reanalysis (JRA-55) is an updated version of the earlier JRA-25 with new data assimilation and prediction systems (*Kobayashi et al*., 2015). New radiation schemes, higher spatial resolution and 4D-var data assimilation with variational bias correction for satellite radiances have been used to generate the JRA-55 products. This reanalysis includes variation in greenhouse gas concentrations with time, as well as the new representations of land surface parameters, aerosols, ozone and sea surface temperature. The grid resolution of JRA-55 is 1.25° (latitude) x 1.25° (longitude). The nearest grid points are taken for Gadanki (13.75°N, 78.75°E) and Kototabang (0, 100°E) and the data period is 1995-2015.

For all the reanalyses data, w (in cm s^{-1}) is estimated using the formula :

$$w = -\frac{1}{g}\omega\frac{RT}{p} \qquad (2)$$

where ω is the vertical velocity in pressure coordinates (in Pa s^{-1}), T is the absolute temperature (K), p is the atmospheric pressure (hPa) and R (=287 J kg^{-1} K^{-1}) is the gas constant for dry air. To compare measured vertical wind with the reanalysis products, we take the reanalysis data corresponding to 12 GMT for Gadanki and the daily mean for Kototabang. The details of the schemes used in reanalysis are provided in Table 2.

3 Results and Discussion

Figure 2 shows the inter-comparision of layer averaged daily *w* measured from IMSTR with different reanalyses (ERAi, ERA5, MERRA-2, NCEP/DOE-2, and JRA-55) over Gadanki for (a) January 2007, and (b) August 2007. Both radar and all the reanalyses data sets are taken at 12 UTC, and the month and year are chosen in such a way to have maximum days of radar observations in two different seasons (winter and summer).

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Similarly, EAR observation is also compared with different reanalysis data but for January 2008 and August 2008 as shown in Fig.3. However, both EAR and reanalysis data are diurnal averaged (24 hrs). It is observed that the magnitude of *w* measured from radar observations is an order higher than the reanalysis data over both the locations (Gadanki and Kototabang). Most of the time, reanalysis data are comparable in direction with radar observations, whenever updrafts are observed. It is also observed that there is mismatch between the *w* estimated in the different reanalyses. *Gage et al.* (1992) described that by averaging radar data for a long-period of time can give a better measurement of *w* in clear-air condition and thus in this context, we have taken long-term averaging.

Figure 4 shows the climatological monthly mean altitude profile of *w* obtained from the IMSTR (observations) and the ERAi, ERA5, MERRA-2, NCEP/DOE-2 and JRA-55 reanalysis data over Gadanki. Although the magnitudes are of the same order between the observations and reanalyses, significant differences are identified in the figures. Convective days are discarded from the radar data (observations) as mentioned in the previous section and those days are also eliminated from all reanalysis data sets. The quantitative differences may be attributed to the spatial averaging implicit in the reanalyses products, whereas the radar measurements are for a single point. Thus we only discuss the tendency of *w* as it is used to represent the variation of *w*, rather than its magnitude. The IMSTR observations show updrafts between 8 and 20 km from December to April with the largest values in the tropical tropopause layer (TTL, 12-16 km). These features are not reproduced by any of the reanalyses, which all show downdrafts from December to April between 1 km and the tropopause level (mean tropopause is ~ 16.5 km). By comparison, downdrafts are observed in the IMSTR below 6 km in April, which may be attributed to pre-monsoon (March-May) precipitation and evaporation (*Uma and Rao*, 2009a). Vertical velocity in ERAi differs in both magnitude and direction from other reanalyses, especially in the lower troposphere from

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March to June. Meanwhile, the magnitude of vertical velocity in ERA5 is a little larger than that in the other reanalyses from May to June. Updrafts are observed in the TTL by the IMSTR during June, when all reanalyses show similar features but only located below the TTL. During July and August both the radar observations and the reanalyses show updrafts in the vicinity of the TTL. Updrafts are observed in the TTL from September to November but the peak in the updrafts is shifted lower than that observed by the IMSTR. Below 8 km, the IMSTR shows downdrafts from April to October. The reanalyses data are unable to reproduce downdrafts above 2 km.

We have also analyzed *w* from the EAR (Kototabang) where the observations are available for the full diurnal cycle (measurements of hourly averages for 24 hrs of observations). All reanalyses data over Kototabang are averaged for the full diurnal cycle. Figure 5 shows the monthly mean climatology of daily mean *w* from the EAR observations and the five reanalyses over Kototabang. All the reanalyses agree well with each other over Kototabang. The updrafts in the TTL are well reproduced by all five reanalyses although the magnitude and vertical location of the maximum in *w* remain lower than observed. However none of the reanalyses reproduces the downdrafts. A distinct bimodal distribution in *w* from May to September (two peaks between 8-10 km and 14-17 km) with a local minimum between 12 and 13 km is observed in the EAR measurements which is not observed in the reanalysis. The magnitudes of both updrafts and downdrafts are larger than those observed over Gadanki. JRA-55 produces the largest *w* among the reanalyses. The monthly means show significant differences in the direction of *w* between the observations and the reanalyses below 6 km.

Gage et al. (1992) studied the long-term diurnal variability of *w* at Christmas Island (2^{o}N) and found the *w* varies between ±4 cm s^{-1}. The observations showed updrafts below 4 km, downdrafts between 4-14 km and updrafts above 12 km. *Gage et al.* (1991) have

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To establish the robustness of the results we have used different averaging procedures to assess the consistency of the variability in *w* at monthly scales. Monthly mean climatological profiles of *w* from radar observations and various reanalyses over Gadanki and Kototabang are shown in Figure S1 (supplementary). Downdrafts in the troposphere are not captured by any of the reanalyses over either location. By contrast, updrafts in the TTL are generally reproduced in the monthly mean, though their magnitudes are often underestimated by the reanalyses. ERAi underestimates the magnitude of both updrafts and downdrafts over Gadanki, while NCEP/DOE-2 underestimates the magnitude of updrafts over Kototabang.

Monthly means calculated over five-year periods from both the radar data and ERAi are shown in Figure 6 for Gadanki and Figure 7 for Kototabang. The reanalysis shows similar

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Radar measurements of *w* at this location consistently show updrafts in the TTL region and downdrafts below 6 km (e.g. *Rao et al.*, 2008, Gage et al., 1991; 1992). ¶

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behavior to the overall climatology in each five-year average. The overall patterns of updrafts and downdrafts in the radar measurements of vertical velocity are also similar, indicating a consistent performance of the radar over the full 20 year analysis period.

To further elucidate potential biases in the results due to averaging, we have taken ERA5 at 12 UTC and compared it to the daily mean (obtained by averaging *w* at different times of the day) to show that the sampling restrictions at Gadanki do not bias the results obtained. Figures 8 and 9 show the mean *w* obtained at 12 UTC and also the mean obtained by averaging hourly analyses for each day for Gadanki and Kototabang, respectively. ERA5 is chosen for this evaluation as the data are available at one-hour intervals. The analysis shows some differences in the magnitude of *w*, with 12 UTC generally showing larger magnitudes compared to the daily means over Gadanki (although no such systematic differences are observed in Kototabang). The directional tendencies are also similar in both the profiles at both locations. This analysis shows that the results are not biased by taking data only at 12 UTC over Gadanki.

Our analysis to this point shows the level of consistency between the features observed by the radar and those in the reanalysis. To further understand the relative differences among the reanalyses we perform a monthly mean comparative analysis among the reanalyses, as shown in Figures 10 and 11 for Gadanki and Kototabang, respectively. We take an ensemble mean of all the five reanalyses and then subtracted the ensemble mean from each reanalysis. The differences are less than ±0.5 cm s^{-1} during December-January-February (DJF, winter). During MAM, the difference between the ensemble and reanalysis show ±2 cm s^{-1} below 5 km. Below 5 km NCEP/DOE-2 and ERAi is less, whereas ERA5, Merra-2 and JRA-55 are more than the ensemble. The difference above 6 km is less than ±0.5 cm s^{-1} above 6 km. JRA-55 shows a good comparison with the ensemble and above 10 km all the reanalyses the differences are minimal with the ensemble. During the monsoon (JJA), the

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difference is comparatively high in June compared to July and August. NCEP/DOE-2 and ERA5 are more and other reanalyses are less than the ensemble, however during July and August NCEP/DOE-2 it is less in the upper troposphere (10-18 km). Merra-2 and ERAi shows a good comparison with respect to the ensemble during July and August, JRA-55 also shows a good comparison in addition to Merra-2 and ERAi. During SON, the differences are comparatively less than MAM and JJA. The difference is less than ±0.5 cm s^{-1} during October and November except in September between 10 and 15 km where ERA5 and Merra-2 are more and ERAi and NCEP/DOE-2 are less than the ensemble. In general, ERA5 and NCEP/DOE-2 shows considerably more difference with the ensemble and other reanalyses (ERAi, Merra-2 and JRA-55) compare well with the ensemble.

Over Kototabang (Figure 11), it is interesting to note the difference between the ensemble and different reanalyses show a consistent pattern during all the months. JRA-55 and ERAi show good comparison with the ensemble, as the differences are less than ±0.2 cm s^{-1} in all the seasons, except in November where it exceeds ±0.5 cm s^{-1} in the lower and middle troposphere. Merra-2 is more and NCEP/DOE-2 is less than the ensemble at all the height regions. ERA5 is less below 10 km and more above with respect to the ensemble.

There may be some probable reasons for the differences in the vertical velocity measured by observations and those retrieved from reanalysis. The main bias in *w* might occur in the reanalysis due to the following (1) Indirect estimation of omega, (2) local topography influence in the reanalysis, (3) use of different schemes in the boundary layer, (4) interactions between subgrid physical parameterizations and the large-scale flow and (5) spatial and temporal sampling. However, it is difficult to address the above issues other than the spatial and temporal sampling. To elucidate the spatial-temporal averaging on the vertical velocity we have chosen different grid resolutions with Gadanki as a centroid and the map is shown in Fig. 12a. G1 to G5 represent different grid resolutions, varying from 0.7^{o} to 5^{o}. The

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data chosen is for January and July 2007 from ERAi. The height profile of *w* at different grid resolution and time is shown in Fig. 12b for January and in Fig.12c for July. It is observed that the grid resolution does not have any influence on the *w*. However, a significant change is observed between 00 and 12 UTC in the month of January which affected the diurnal mean in *w* (shown in the last panel). The same is not reflected in the month of July. The result shows that the narrowing down the reanalysis data spatially (reducing the horizontal sampling) will not improve the retrieval of *w* in any reanalyses.

The direction of *w* is an essential metric for comparing the reanalysis with the observations. We therefore show the directional tendencies from the IMSTR and the EAR measurements relative to those from the reanalysis data. Figure 13a shows the directional tendencies based on the IMSTR and the reanalyses over Gadanki, while Figure 13b shows the directional tendencies based on the EAR and the reanalyses over Kototabang. The directional tendency is calculated at each height for every month when the radar or reanalysis data exceed 0.1 cm s^{-1} in either direction. The directional tendency for each month is estimated and then aggregated into seasons. These directional tendencies are given in terms of percentage of occurrence with respect to height. The tendency is calculated separately for updrafts and downdrafts.

Over Gadanki during DJF all reanalyses produce updrafts (simultaneously by both radar and reanalysis) less than 10% of the time throughout the profile. During MAM these ratios increase to around 15%, with NCEP/DOE-2 producing updrafts about 25% of the time. During JJA and SON, the percentage occurrence increases with the height from 25% to a maximum of 50% between 12 and 14 km. The percentage occurrence of updraft then decreases from 14 to 20 km. This tendency trend is similar for all reanalyses. The maximum ratio of updrafts over Gadanki is located between 12 and 15 km altitude. The percentage occurrence of downdrafts over Gadanki is also less than 50% at all levels. During DJF and

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MAM the reanalyses produce downdrafts 40 to 50% of the time, a much higher frequency than that for updrafts (<10%). This fraction decreases above 10 km. By contrast, the percentage of downdrafts produced during JJA and SON is less than that of updrafts, with frequencies less than 25% at all levels during these seasons.

Over Kototabang the percentage occurrence of updrafts increases with height in all seasons reaching a maximum of 75- 90% between 10 and 14 km. Above 14 km the percentage decreases to a minimum of 5% at 19 km. Updrafts are rarely produced by the reanalyses altitudes less than 4 km. It is important to note that none of the reanalyses produce daily mean downdrafts exceeding 1 cm s^{-1} except ERAi and ERA5 which produced downdrafts below 6 km. The percentage of downdrafts increases above 17 km where it reaches a maximum and show occurrence frequencies around 65 to 75% above 18 km.

4 Summary

The present study assesses the vertical motion (*w*) in reanalyses against radar observations from the convectively active regions Gadanki and Kototabang. The assessment is carried out for five different reanalyses: ERAi, ERA5, MERRA-2, NCEP/DOE-2 and JRA-55. Measurements were collected using VHF radar at both locations. We have used 20 years of data from Gadanki and 17 years of data from Kototabang. The following points summarize the results of this unique study

1. The magnitude of *w* obtained from reanalyses is underestimated by 10-50% relative to the radar observations.
2. Observations over Gadanki showed updrafts from 8 to 20 km year around. All the reanalyses only reproduced this feature during JJA and SON when magnitudes were larger than 0.5 cm s^{-1} in the reanalyses data. However, the vertical location of the updrafts differs between the observations and the reanalyses. Downdrafts below 8 km are not captured well by reanalyses data.

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3. Over Kototabang, all five reanalyses did not consistently reproduce downdrafts below 8 km in all months. Updrafts in the UTLS are captured well; however, the peak in the vertical distribution of *w* is different as over Gadanki.
4. Inter-comparison between the ensemble and each reanalysis data shows the ERAi, MERRA-2 and JRA-55 compares well with the ensemble compared to ERA5 and NCEP/DOE-2. Analysis also showed that the reduction in spatial sampling in any reanalysis does not have significant improvement in the magnitude *w*.
5. Assessment of directional tendencies show that updrafts are reproduced reasonably well in all five reanalyses data but downdrafts are not reproduced at all.

Our analysis reveals that downdrafts are not well captured in all the five reanalyses data. The location of the largest updrafts is also shifted lower in reanalyses than in the observations. Hence, reanalysis data should be used with care for representing various atmospheric motion calculations (*viz*. diabatic heating, convection, etc.) that mainly depend on the direction of *w*. This study provides the reanalysis community an initial basis to improve the methodology for calculating *w* in reanalysis, as this is a much sought-parameter for atmospheric circulation calculations and analysis.

Acknowledgements

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Data availability: Analysed data (both radars and reanalyses) used in this study can be obtained on request. Raw time series data are available through open access in the following websites:

For Indian MST Radar : www.narl.gov.in

For EAR radar : www.rish-kyoto-u.ac.jp/ear/index-e.html

ERAi, ERA5, JRA-55 and NCEP/DOE-2 were downloaded from https://rda.ucar.edu and MERRA-2 from https://disc.gsfc.nasa.gov.in

Author's Contributions

KNU conceived the idea for validation of vertical velocity among the reanalyses. SSD, MVR, and KVS collected and analysed the MST radar spectrum data. All the authors contribute for generation of figures, interpretation and manuscript preparation. The data used in the present study can be obtained on request.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Figure captions

Figure 1. Topographical maps of the (a) Gadanki MST radar, and (b) Kototabang EAR sites in MSL, generated by using the Shuttle Radar Topography Mission (SRTM) data (*Farr et al.*, 2007). Dots in the map indicate the radar locations.

Figure 2. Intercomparision of layer averaged daily *w* (12 UTC) measured from MST Radar with different reanalyses (ERAi, ERA5, MERRA-2, NCEP/DOE-2, and JRA-55) (12 UTC) over Gadanki for (a) January 2007, and (b) August 2007.

Figure 3. Same as Fig.2, but for Kototabang. Please note that for Kototabang, *w* is diurnal mean (24 hrs mean) for both EAR and reanalyses for (a) January 2008, and (b)August 2008.

Figure 4. Climatological monthly mean altitude profile of *w* obtained from MST Radar and 5-reanalysis over Gadanki. Horizontal lines indicate the standard error.

Figure 5. Same as Fig.4, but over Kototabang.

Figure 6. Monthly mean *w* obtained from (a) MST Radar and (b) ERAi for 5 years interval (from top to bottom) over Gadanki (12 GMT).

Figure 7. Same as Fig.6 but for diurnal mean over Kototabang.

Figure 8. Height profile of *w* at 12 GMT and diurnal mean (with 1 hour resolution) over Gadanki extracted from ERA5 (highest available time resolution).

Figure 9. Same as Fig.8 but for Kototabang.

Figure10. Comparison of relative differences in *w* between the reanalysis for Gadanki. Individual month differences are estimated and then averaged for each month.

Figure 11. Same as Fig.10, but for Kototabang.

Figure 12. (a) Map for spatial averaging (grid resolution), and height profiles of *w* for different spatial averaging at 00, 06, 12, and 18 UTC respectively.

Figure 13. Comparison of directional tendency of *w* between the radars and various reanalysis data sets for (a) Gadanki and (b) Kototabang. Updrafts are shown in top and third panels and downdrafts are shown in middle and bottom panels (for details see text).

Figure S1 : Monthly mean climatology of *w* obtained from (a) radars, (b) ERAi, (c) ERA5, (d) MERRA-2, (e) NCEP/DOE-2, and JRA-55 over Gadanki (left) and Kototabang (right). Gadanki data are at 12 UTC and Kototabang data are diurnal mean.

Table captions

Table 1. The radar specifications and parameters used for the present measurements.

Table 2. Schemes of different reanalyses data used in the present study.

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Figure Captions¶
Figure 1. Climatological monthly mean altitude profile of vertical velocity obtained from MST Radar and 5-reanalysis at 12 GMT over Gadanki. Horizontal lines indicate the standard error. ¶
Figure 2. Same as Fig.1, but for diurnal mean over Kototabang. ¶
Figure 3 : Monthly mean climatology of vertical velocity obtained from (a) radars, (b) ERAi, (c) ERA-5, (d) MERRA-2, (e) NCEP-2, and JRA-55 over Gadanki (left) and Kototabang (right). Gadanki data are at 12 GMT and Kototabang data are diurnal mean.¶
Figure 4. Monthly mean vertical velocity obtained from (a) MST Radar and (b) ERAi for 5 years interval (from top to bottom) over Gadanki (12 GMT).¶
Figure 5. Same as Fig.4 but for diurnal mean over Kototabang.¶
Figure 6. Height profile of vertical velocity at 12 GMT and diurnal mean (with 1 hour resolution) over Gadanki extracted from ERA-5 (highest available time resolution). ¶
Figure 7. Same as Figure 6 but over Kototabang.¶
Figure 8. Comparison of relative differences in vertical velocity (*w*) between the reanalysis for Gadanki (solid line) and Kototabang (dash line). Individual month differences are estimated and then averaged for each month. Over Gadanki, data is taken for 12 GMT and for Kototabang it is diurnal.¶
Figure 9. Comparison of directional tendency simultaneously observed in radar and various reanalysis data sets for (a) Gadanki and (b) Kototabang. Updrafts are shown in top and third panels and downdrafts are shown in middle and bottom panels (for details see text).¶
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Figure 1. Topographical maps of the (a) Gadanki MST radar, and (b) Kototabang EA radar sites in MSL, generated by using the Shuttle Radar Topography Mission (SRTM) data (*Farr et al.*, 2007). Dots in the map indicate the radar locations.

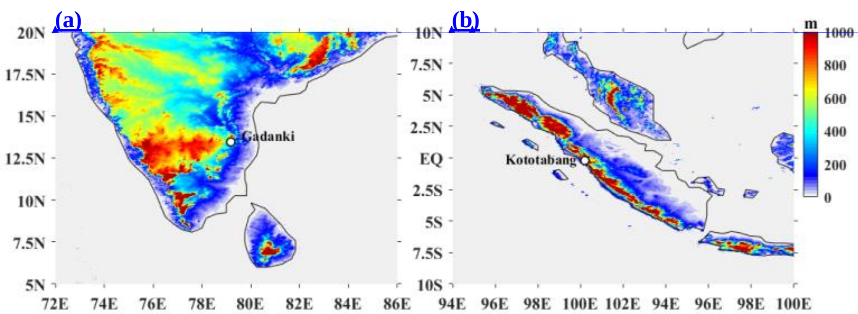

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Figure 2. Intercomparision of layer averaged daily *w* (12 UTC) measured from MST Radar with different reanalyses (ERAi, ERA5, MERRA-2, NCEP/DOE-2, and JRA-55) (12 UTC) over Gadanki for (a) January 2007, and (b) August 2007.

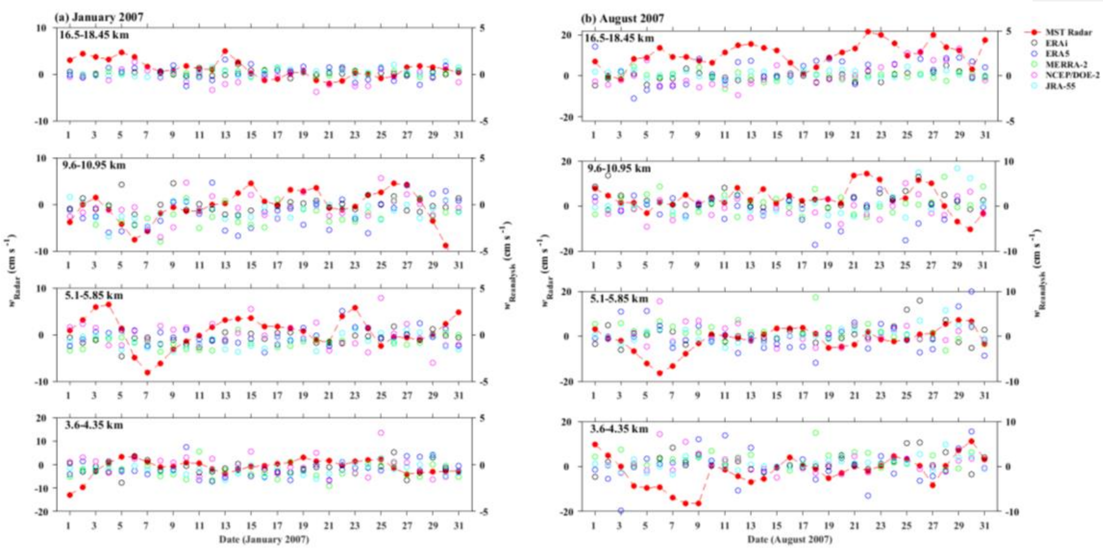

Figure 3. Same as Fig.2, but for Kototabang. Please note that for Kototabang, *w* is diurnal mean (24 hrs mean) for both EA radar and reanalyses for (a) January 2008, and (b)August 2008.

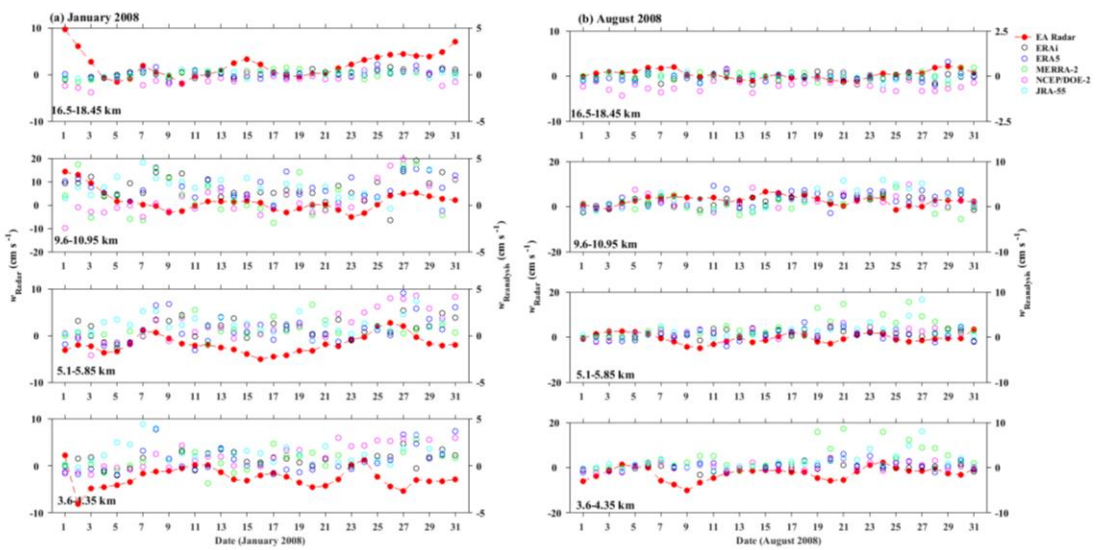

Figure 4. Climatological monthly mean altitude profile of *w* obtained from MST Radar and 5-reanalysis over Gadanki. Horizontal lines indicate the standard error.

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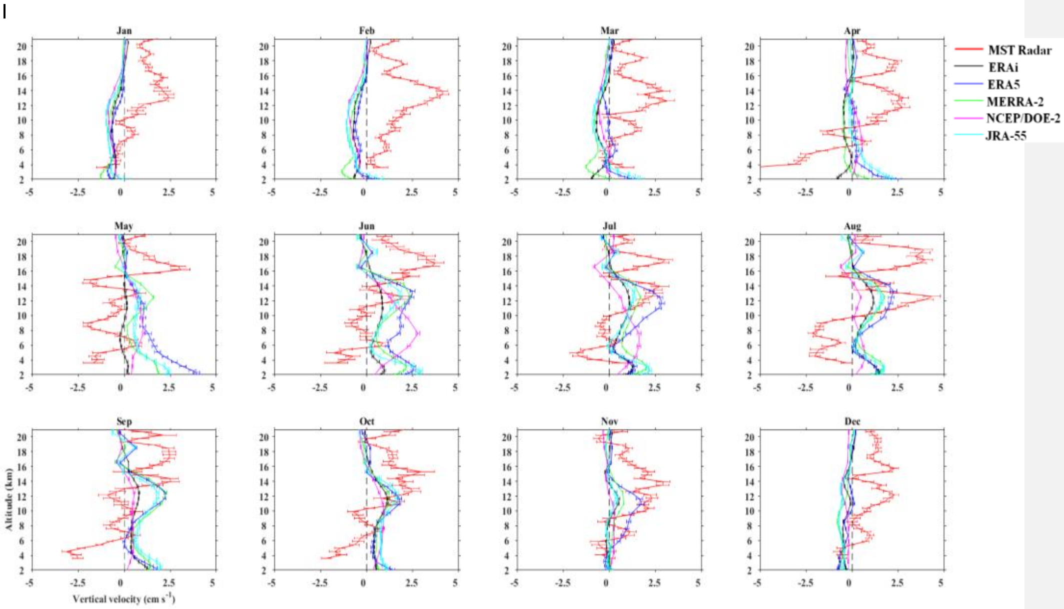

Figure 5. Same as Fig. 4, but over Kototabang.

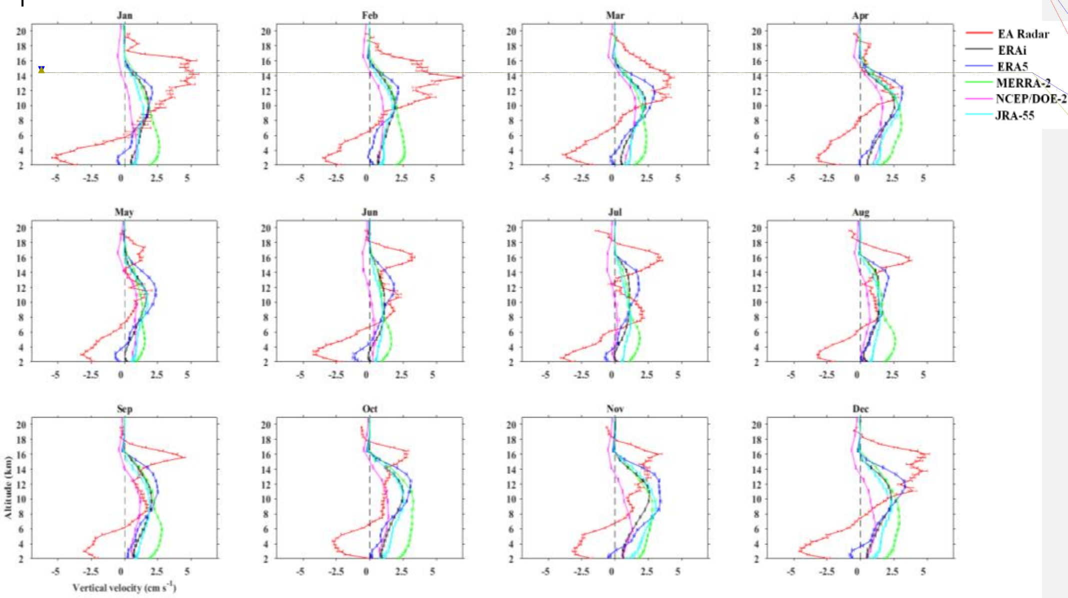

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Figure 6. Monthly mean *w* obtained from (a) MST Radar and (b) ERAi for 5 years interval (from top to bottom) over Gadanki (12 GMT).

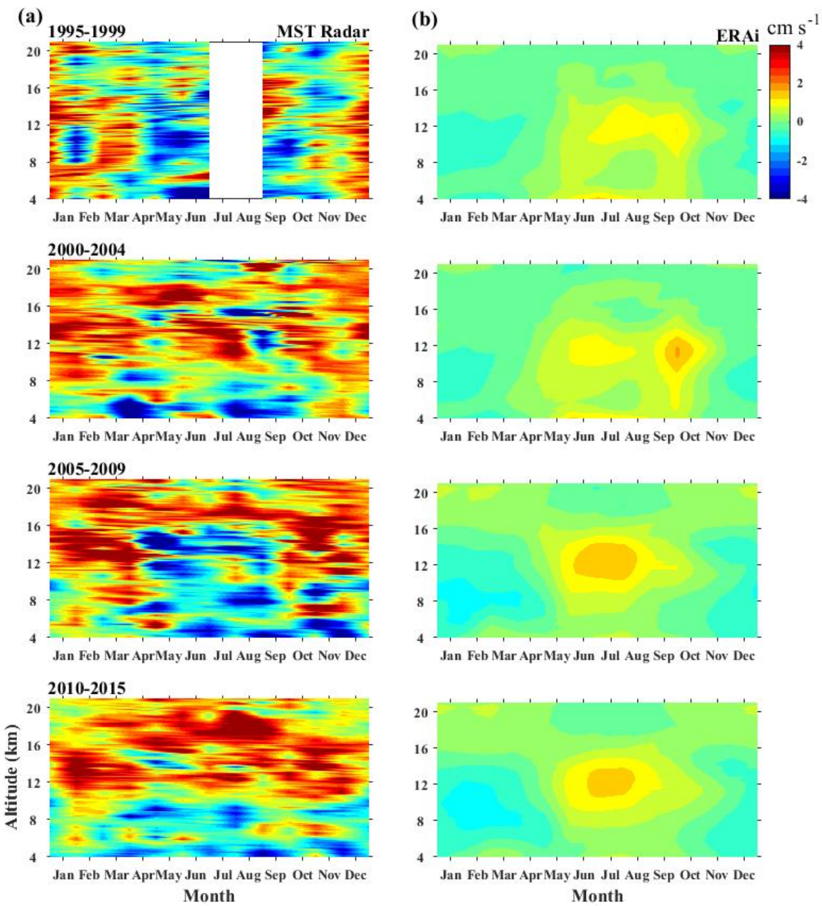

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Figure 7. Same as Fig. 6 but for diurnal mean over Kototabang.

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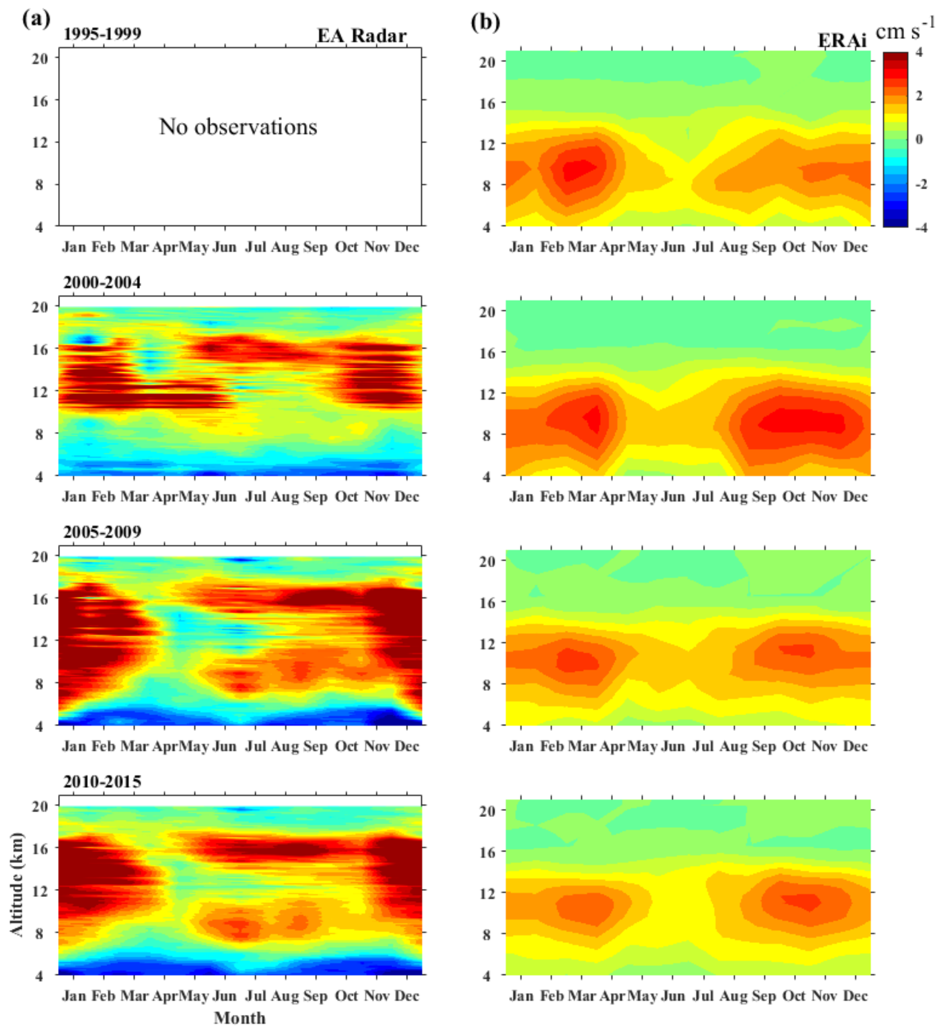

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Figure 8. Height profile of *w* at 12 GMT and diurnal mean (with 1 hour resolution) over Gadanki extracted from ERA5 (highest available time resolution).

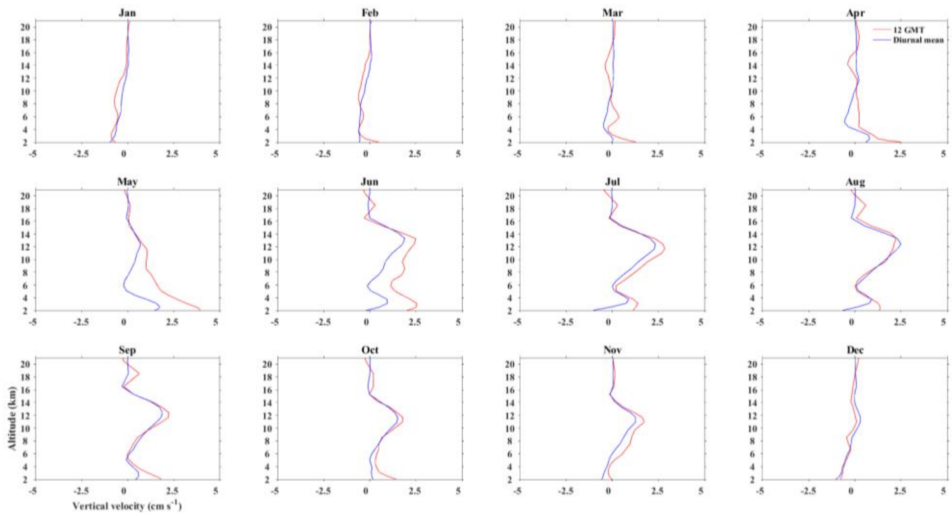

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Figure 9. Same as Fig. 8 but for Kototabang.

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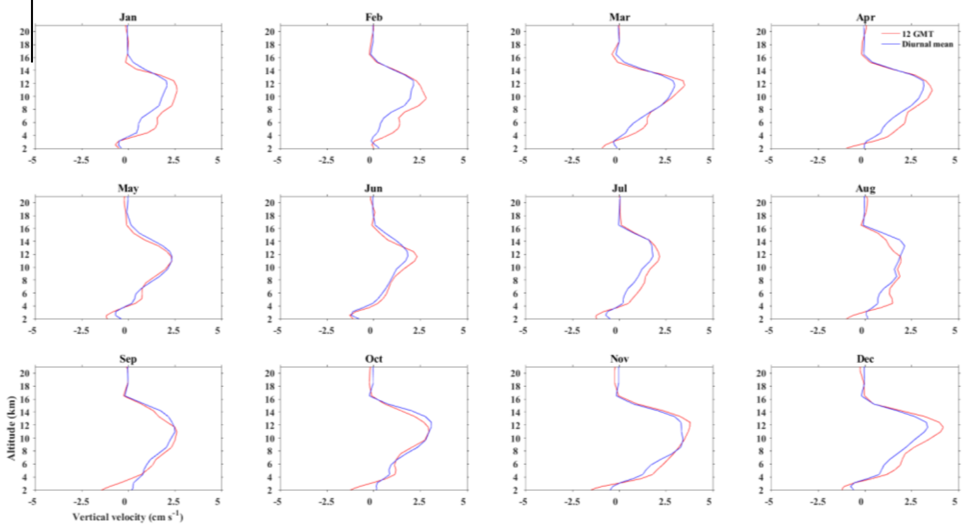

Figure 10. Comparison of relative differences in *w* between the reanalysis for Gadanki. Individual month differences are estimated and then averaged for each month.

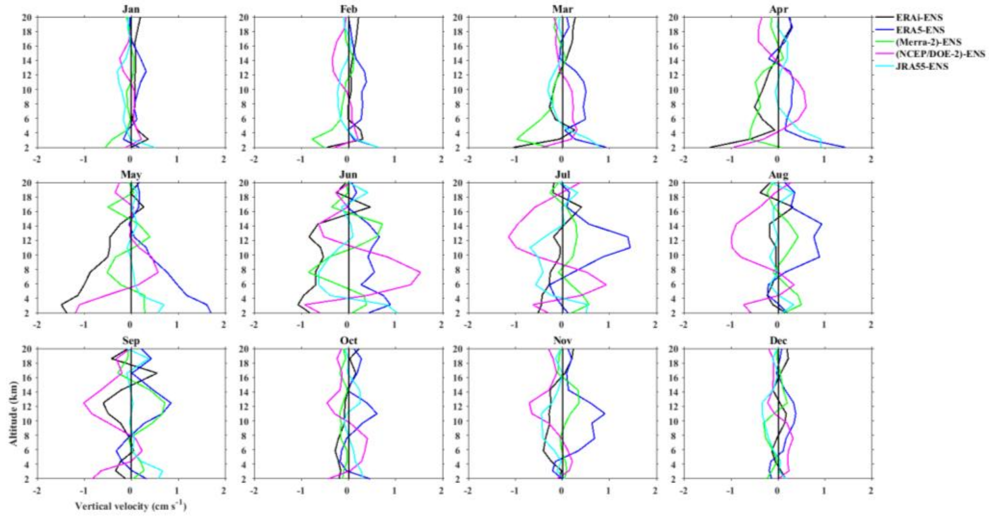

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Figure 11. Same as Fig.10, but for Kototabang.

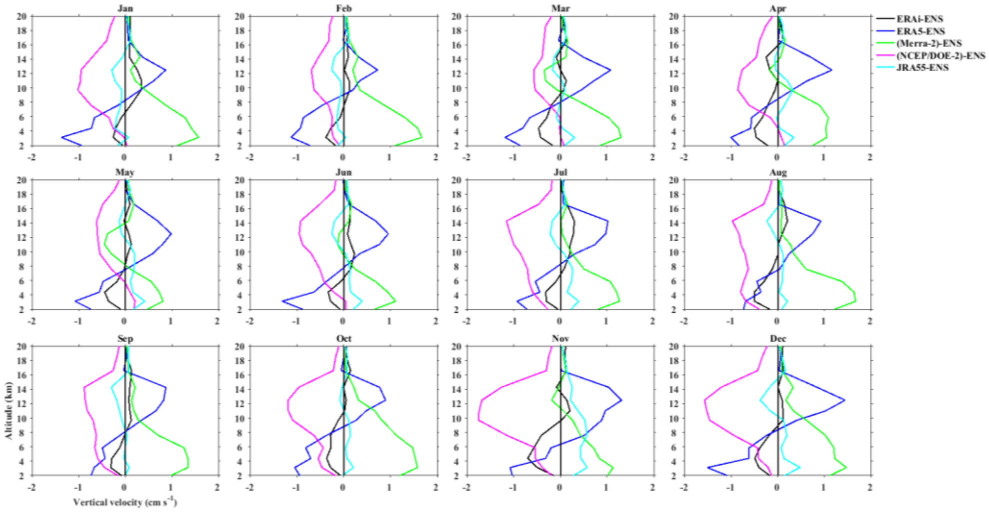

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Figure 12. (a) Map for spatial averaging (grid resolution), and height profiles of *w* for different spatial averaging at 00, 06, 12, and 18 UTC respectively.

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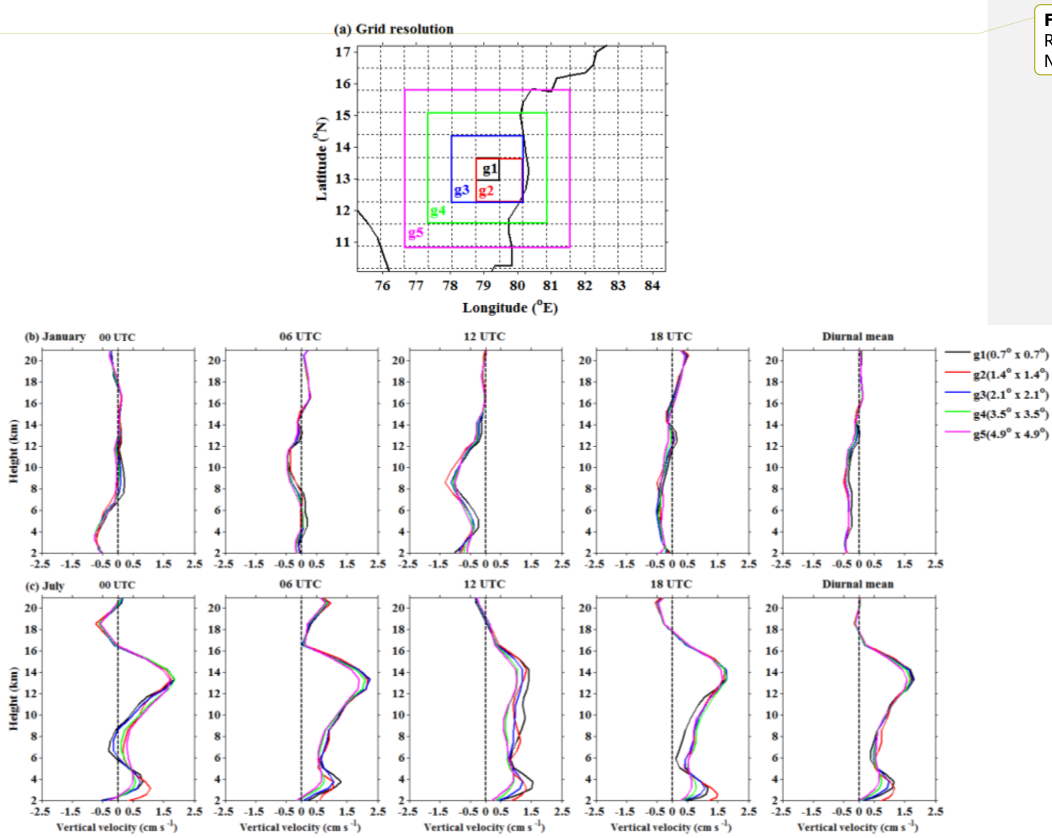

Figure 13. Comparison of directional tendency of *w* between the radars and various reanalysis data sets for (a) Gadanki and (b) Kototabang. Updrafts are shown in top and third panels and downdrafts are shown in middle and bottom panels (for details see text).

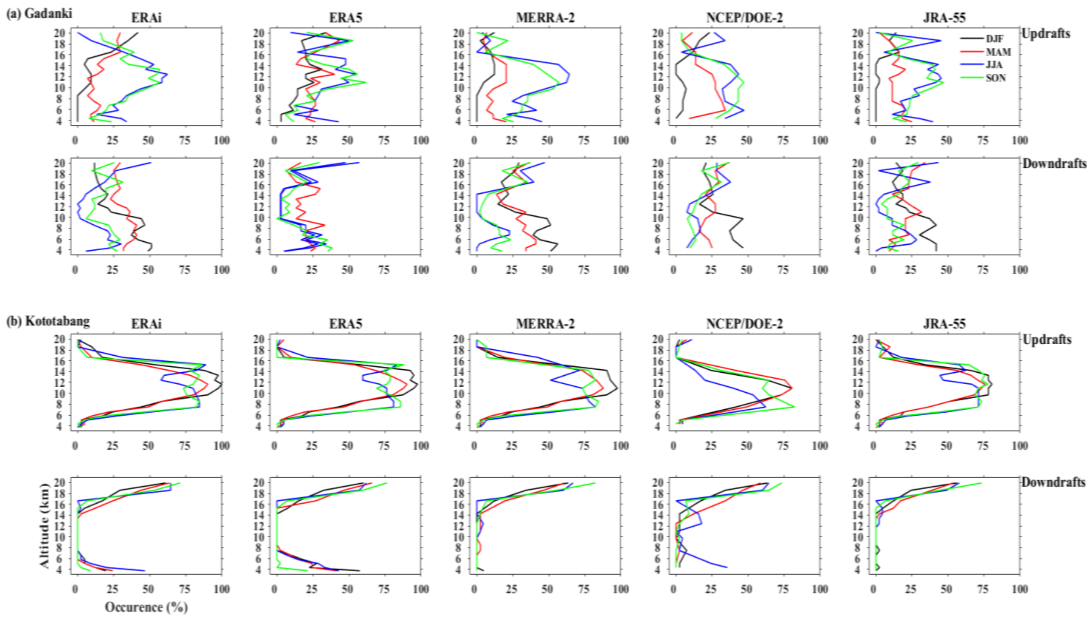

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Figure 132. Intercomparision of daily mean (12 UTC) *w* measured from MST Radar with ERAi over Gadanki for (a) January 2007, and (b) July 2007. *w* derived from ERAi is multiply with 10 to match with radar measured *w*. ¶
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Figure S1 : Monthly mean climatology of *w* obtained from (a) radars, (b) ERAi, (c) ERA5, (d) MERRA-2, (e) NCEP/DOE-2, and JRA-55 over Gadanki (left) and Kototabang (right). Gadanki data are at 12 GMT and Kototabang data are diurnal mean.

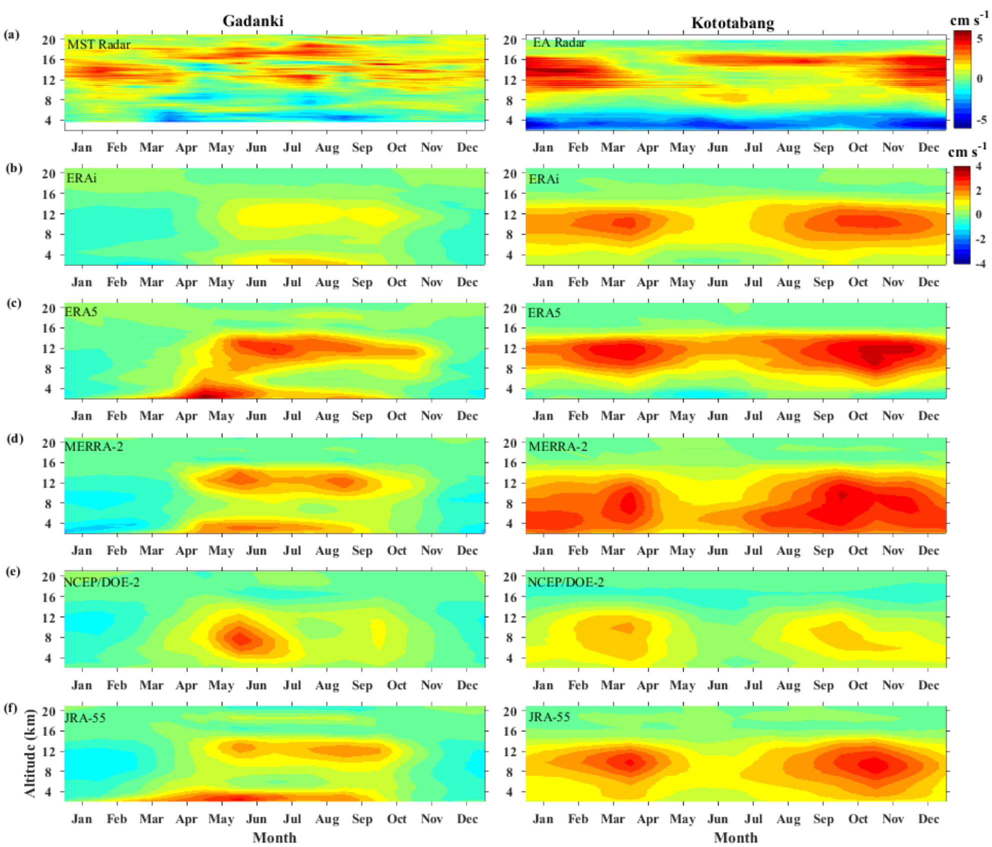

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Table 1. The radars specifications and parameters used for the present measurements.

Parameter	**IMSTR**	**EAR**
Frequency	53 MHz	47 MHz
Peak power	2.5 MW	100 kW
Maximum duty cycle	2.5 %	5 %
Antenna	1024, three-element Yagi antennas	560, three-element Yagi antennas
Beam width	3 degree	3.4 degree
Mode of operation		
Pulse width	16 μs with complimentary with 1 µs baud	0.5 to 256 μs
Inter pulse period	1000 μs	200 and 400 μs
Range Resolution	150 m	150 m
No. of FFT point	256	256, 512
No of coherent integration	64, 128, 256, and 512	16 and 32
No. of Incoherent integration	1	5 and 7
No. of beam	6	5
	10-degree off-zenith in East, West, North and South along with two orthogonal in zenith beams	10-degree off-zenith in East, West, North and South along with one zenith beams
Data format	Spectrum	Spectrum

Table 2. Schemes of different reanalyses data used in the present study.

Description	**ERA-Interim**	**ERA5**	**MERRA2**	**JRA55**	**NCEP2**
Spatial Resolution	0.75^{o} x 0.75^{o}	0.28^{o} x 0.28^{o}	0.5^{o} x 0.65^{o}	1.25^{o} x 1.25^{o}	2.5^{o} x 2.5^{o}
Longwave	*Mlawer et al.*, (1997)	*Morchrette*, (1991)	*Chou et al.*, (2001)	*Chou et al*., (2001)	*Mlawer et al.*, (1997)
Shortwave	*Fouquart and Bonnel*, (1990)	*Iacono et al.*, (2008)	*Chou and Suarez*, (1999)	*Briegleb*,(1992)	*Chou.*, (1992); *Chou and Lee*, (1996)
Convective Parametrization	*Tiedtke*, (1989)	Convective mass flux scheme *Tidkete*, (1989)	Relaxed Arakawa-Schubert (RAS, *Moorthi and Suarez*, 1992)	Prognostic Arakawa-Schubert with DCAPE	Simplified *Arakawa Schubert scheme*, (1974)
Cloud Scheme	*Bechtold et al.*, (2004)	*Bechtold et al.*, (2008)	*Molod et al.*, (2015).	*Kawai and Inoue*, (2006)	*Campana et al.*, 1994
Data Assimilation	4D var	4D var	3D var with IAU	4-D var	3D VAR
References	*Dee et al*., (2011)	*Hersbach et al*., (2020)	*Gelaro et al*., (2017)	*Kobayachi et al.*, (2015)	*Kanamitsu et al.*, (2002)
Vertical levels	L60	L137	L72	L40	L28