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

Kizhathur Narasimhan Uma[1], *Siddarth Shankar Das*[1], *Madineni Venkat Ratnam*[2], *and Kuniyil Viswanathan Suneeth*[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, ISRO, Trivandrum-695022, India
[2]National Atmospheric Research Laboratory, Dept. of Space, Gadanki-517112, India

*e-mail : urmi_nmrf@yahoo.co.in

Abstract

Vertical wind (*w*) is one of the most important meteorological parameters for understanding a range of? different atmospheric phenomena. ~~Only~~ Very few direct measurements of *w* are available, so that? and most of the time one must depend on reanalysis products. In the present study, assessment of *w* among selected reanalyses, (ERA-Interim, ERA-5, MERRA-2, NCEP-2 and JRA-55) and qualitative comparison of those datasets with direct 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 direct 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 reanalyses shows that ERAi is biased high relative to? overestimating NCEP-2 and low relative to other? underestimating all the reanalyses. Directional tendency shows that the percentage of updrafts captured is reasonably good, but downdrafts are poorly? 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 weather are usually associated with variations in ~~the~~ vertical air motion. The magnitude of *w* is a factor of ten or more smaller than the horizontal wind; nevertheless, it is ~~the~~ crucial in ~~component for~~ 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. 1 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 controlling day-to-day changes in weather. Different scales of variability exist in *w* ranging from.? ~~like~~ microscale to meso, synoptic, and planetary (space) scales (*Uma and Rao*, 2009b). It also conveys? modulates? controls ~~the~~ energy and ~~the~~ mass transport between the upper troposphere and lower stratosphere (*Yamamoto et al.*, 2007, *Rao et al.*, 2008). 2 In a nutshell, knowledge of *w* is helpful? crucial 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? are often larger than the actual values. Direct and indirect methods exist to measure *w* (e.g. Doppler measurements using radars for profiling and sonic anemometers in the boundary layer) as well as indirect computational methods (e.g., adiabatic, kinematic and quasi-geostrophic vorticity/omega methods). Direct measurements of *w* are thus restricted to locations where radars are situated. Global estimates are derived diagnostically from horizontal winds and temperatures. Indirect estimation, gives a general view on the distribution of ascending and

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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). However, reanalyses combine both observations and model outputs to produce systematic variation in the atmospheric state (e.g., Fujiwara et al., 2017). 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 errors in the observations as omega is estimated from horizontal divergence (*Tanaka and Yatagai*, 2000). 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 accurately, meaning that observations must be taken at frequent intervals in time to estimate $\partial T / \partial t$ 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 reanalyses are not error-free owing to the many underlying approximations and assimilations involved (*Kennedy et al*., 2012).

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~~There are few~~ Other indirect methods by which we can 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

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velocity directly as the winds are determined from meteor showers using a wide beam width. 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 ~~the~~ vertical air motion (velocity) directly with high temporal and vertical resolution. However, the magnitude may still not be directly comparable between reanalyses products and observations as the reanalyses provide the intensity of vertical air motion over wide areas (> 25 km^2), whereas the direct radar measurements provide information for the a narrower ? column over a single location. 7 Thus, the best way to assess reanalysis estimates of w against radar measurements is to compare ~~its~~ directional tendencies ~~with those of radar~~. To the author's knowledge, no studies yet exist concerning ~~with~~ the assessment of w products derived from 8 different reanalyses and evaluation of these products against radar measurements. The present study, which is therefore the 9 first of its kind, focuses on assessment of w among various reanalyses using VHF radar measurements from two tropical stations where convective activity is frequent: Gadanki (13.5°N and 79.2°E) and Kototabang (0.2°S and 100.2°E). 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 contains the main results followed by a discussion and summary of the results in section 4.

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2 Data and Methodology

2.1 Radar measurements

Direct measurements of *w* are obtained from the Indian Mesosphere-Stratosphere-Troposphere Radar (IMSTR) located at Gadanki and the Equatorial Atmosphere Radar (EAR) located at Kototabang. Both the IMSTR and EAR are pulsed coherent radars operating at 53 MHz (IMSTR) and 47 MHz (EAR) 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).

In the present study direct 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 daily 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 ~~areas of~~ 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). ~~It is found that~~ 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

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climatological mean vertical velocity (e.g. *Uma and Rao*, 2009b). The EAR provides quality check data online (http://www.rish.kyoto-u.ac.jp/ear/data/index.html). The EAR operates continuously and this study uses every hour 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, in 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 (in cm s^{-1}) is directly estimated using equation (1)

$$w = -\frac{\lambda}{2} f_d, \tag{1}$$

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

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 & 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. As proposed by Nastrom & 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 not affected 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 existing Known? biases do not change the direction of the background *w* when measurements are averaged over long~~er~~ periods.

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A

introduce how vertical velocities are computed (i.e. continuity on m levels) and whether they are impacted by data assimilation

2.2 *ERA-Interim*

We use 6-hourly vertical velocities from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (ERAi) from 1995 to 2015 (Dee *et al.*, 2011). The nearest grid points are taken for Gadanki (13.68°N, 79.45°E) and Kototabang (0.35°S, 100.54°E). Although 37 pressure levels up to 1 hPa resolution are available, we have restricted the dataset to 21 km, as that is the maximum radar range.

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2.3 *ERA5*

When compared to ERAi, the fifth ECMWF reanalysis (ERA5) 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.*, 2018). 13 The details are available in Copernicus climate change service report (Hersbach and Dee 2016 and https://cds.climate.copernicus.eu/cdsapp#!/home). 14 The nearest grid points are again taken for Gadanki (13.63°N, 79.31°E) and Kototabang (0.14°S, 100.40°E), and the data period is 2002-2015.

2.4 *MERRA-2* A

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). MERRA-2 data are provided on 42 pressure levels from the surface to 0.01 hPa with a temporal resolution of 3 h and horizontal resolution of 0.5° in latitude by 0.625° in longitude◦. Details have been provided by *Gelaro et al.* (2017). The nearest grid points are used for Gadanki (13.5°N, 79.37°E) and Kototabang (0.14°S, 100.00°E), with coverage from 1995 to 2015.

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2.5 *NCEP-2* 15

The National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalysis is based on the NCEP operational model with a horizontal resolution of 209 km and 28 vertical levels. Its temporal coverage is four times per day. NCEP-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 data for the present study covers 1995 to 2015 and is extracted at the nearest grid points to Gadanki (12.5^{o}N, 77.5^{o}E) and Kototabang (0, 100.00^{o}E) 16

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 SSTs. The horizontal resolution of the forecast model is ~60 km for JRA-55. The nearest grid points are taken for Gadanki (13.75^{o}N, 78.75^{o}E) and Kototabang (0, 100^{o}E) and the data period is 1995-2015. 17

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. To compare

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measured vertical wind with the reanalysis products, we take ~~the~~ reanalysis data corresponding to 12 GMT for Gadanki and the daily mean for Kototabang. 19

3 Results and Discussion

Figure 1 shows the climatological monthly mean altitude profile of *w* obtained from the IMSTR (observations) and the ERAi, ERA5, MERRA-2, NCEP-2 and JRA-55 reanalysis reanalyses data sets over Gadanki. Although the magnitudes are of the same order between the observations and reanalyses, (space) significant differences are identified in the figures. ~~It is to be noted that~~ C convective days are discarded w from ~~in~~ the radar data? analysis (observations) as mentioned in the previous section; ~~and~~ those days are also eliminated from all ~~the~~ reanalysis data sets. The quantitative? These 20 differences may be attributed to the spatial averaging implicit in the reanalyses products, whereas the radar measurements are for a single point. Thus ~~in the present study~~, we only discuss the tendency of *w* as it is used to represent the qualitative? 21 global variation of *w*, rather than its magnitude. The IMSTR observations show updrafts between 8 and 20 km, with the largest values in the tropical tropopause layer (TTL, 12-16 km), from December to April. 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? Comparatively, 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 March to June. Meanwhile, the magnitude of vertical velocity in ERA-5 22 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.

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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. ~~It is notable that~~ The reanalyses only produce downdrafts below 2 km and are unable to reproduce ~~the~~ downdrafts above 2 km. Earlier studies using the IMSTR showed similar seasonal characteristics for *w* (*Rao et al.*, 2008).

Uma and Rao (2009b) have reported the diurnal variation of *w* in different seasons; although their observations had ~~have~~ only 1-2 diurnal cycles per month over Gadanki. They found significant variations as large as 6 cm/s over Gadanki using the IMSTR. The present observations are limited to 16:30 to 17:30 IST, with all reanalysis data over Gadanki taken at 12 GMT (17:30 IST). Thus, time-averaged climatological mean biases can be neglected. 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 reanalysis data over Kototabang are averaged for the full diurnal cycle. Figure 2 shows the monthly mean climatology of daily mean ~~of~~ *w* ~~observed by~~ from the EAR observations and the five reanalyses over Kototabang. All the reanalyses agree well with each other over Kototabang. 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). The updrafts in the TTL are well reproduced by all ~~the~~ five reanalyses, although the ~~peak~~ magnitude ~~of *w*~~ and ~~its~~ 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. 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.

23 diurnal? seasonal?

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To establish the robustness of the results ~~obtained from both the observations and reanalyses~~ 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 ~~respectively~~ are shown in Figure 3. 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 they are often overestimated by the reanalyses. ERAi underestimates the magnitudes of both updrafts and downdrafts over Gadanki, ~~and~~ while NCEP-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 4 for Gadanki and Figure 5 for Kototabang. The reanalysis shows a similar 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 ERA-5 ERA5 at 12 GMT 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. 26 Figures 6 and 7 show the mean *w* obtained at 12 GMT and also the mean obtained by averaging hourly analysis 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 GMT generally showing larger magnitudes compared to the daily means over Gadanki (although no such systematic differences is observed in Kototabang). The directional

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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 reanalyses. To further understand the relative differences among the reanalyses we perform a monthly mean comparative analysis among the reanalyses, as shown in Figure 8. In this case, we ~~took~~ take ERAi as a reference and compare it with *w* products from other reanalyses. We ~~chose~~ choose ERAi, because the zonal and meridional winds from this reanalysis have been shown to compare well with radiosonde and rocket sounding observations over the Indian equatorial region (*Das et al.*, 2015). The solid lines in Figure 8 show ~~the~~ differences over Gadanki, while the dashed lines show differences over Kototabang. Over Gadanki, the difference between ~~the~~ ERAi and the other reanalyses is less than ±0.5 cm/s during December-January-February (DJF, winter). ERAi underestimates ERA5 compared to other reanalyses, while values based on MERRA-2 are ~~relatively~~ larger ~~than~~ relative to those in other reanalyses. During MAM, strong downdrafts are found below 5 km with comparable magnitudes in all five reanalyses. ERAi underestimates ERA5 and NCEP-2 during March, and all other reanalyses from April to September. Values of *w* in ERAi are larger than those in NCEP-2 above 8 km. All five reanalyses compare well at all atltiudes altitudes above 18 km. As expected, magnitudes are larger during JJA than during other months. From October to November, the magnitude reduces to ±1 cm/s 27 with values from ERAi smaller than those from all other reanalyses except NCEP-2.

~~Over Kototabang~~, The magnitude of *w* is ~~relatively~~ larger Over Kototabang than over Gadanki. ~~It is interesting to note that,~~ ERAi underestimates MERRA-2 in all months over this location ~~also~~ as well (MERRA-2 shows larger magnitudes compared to other reanalyses). Similarly values based on EARi ERAi are larger than those based on NCEP-2. From December to February ERAi underestimates

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MERRA-2 below 10 km and ERA5 between 10 and 15 km while overestimates NCEP-2 and JRA-55. The overall bias pattern remains the same during MAM, except for differences relative to JRA-55. From June-November, ERAi underestimates NCEP-2 and overestimates ~~all~~ the other three reanalyses.

reanalyses with?

The direction of *w* is an essential metric for comparing the observations ~~and reanalyses~~. We therefore show the directional tendencies from the IMSTR and the EAR measurements ~~with~~ relative to those from the reanalysis data. Figure 9a shows the directional tendencies based on the IMSTR and the reanalyses over Gadanki, while Figure 9b 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 1 cm/s 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 directional tendency is calculated for *w* only if the magnitudes lie above ± 0.1 cm/s for both radar retrievals and reanalyses. The tendency is calculated separately for updrafts and downdrafts.

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Over Gadanki during DJF all reanalyses produce updrafts at rates of less than 10 % of updrafts throughout the profile. During MAM these ratios increase to around 15 %, with NCEP-2 producing updrafts about 25 % of the time. During JJA and SON, the percentage occurrence increases with height from 25 % to a maximum of 50 % between 12 and 14 km. The percentage frequency? of updraft~~s~~ occurrence then decreases from 14 to 20 km. This tendency trend is similar for all ~~the~~ reanalyses except ERA5, for which the percentage occurrence is less than 25 % during in all seasons. 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 ~~the~~ levels. During DJF and MAM the reanalyses produce downdrafts 40 to 50 % of the time, a much

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higher frequency than that for compared to the updrafts (<10 %). 31 ~~However~~, these ratios decrease above 10 km. By contrast, the percentage of downdrafts produced during JJA and SON is less than that of ~~the~~ updrafts, with frequencies less than 25 % at in all ~~the~~ levels during these seasons. The performance of ERA5 over Gadanki appears to be is very poor, as the occurrence frequencies are very small for both updrafts and downdrafts. C

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 at altitudes less than 4 km. It is important to note that none of the reanalyses produce daily mean downdrafts exceeding 1 cm/s between 6 and 16 km. The percentage of downdrafts increases both below 6 km and above 17 km, where it reaches 32 a maximum of about 25 to 50 %. MERRA-2, NCEP-2 and JRA-55 show occurrence frequencies of downdrafts around 65 to 75 % above 18 km. The performance of ERA5 appears to be poor compared to the other reanalyses over this location as well. C

4 Summary

The present study assesses the vertical motion (*w*) in reanalyses against direct radar observations from the convectively active regions Gadanki and Kototabang. The assessment is carried out for five different reanalyses: ERA-Interim, ERA-5, MERRA-2, NCEP-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

a. The magnitude of *w* obtained from reanalyses is underestimated by 10-50% relative to the radar observations.

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b. Observations over Gadanki showed updrafts from 8 to 20 km year-round year around. The reanalyses only reproduced this feature during JJA and SON when magnitudes were larger than 0.5 cm/s in the reanalyses. However, the vertical location of the updrafts differs between the observations and the reanalyses. Downdrafts below 8 km are not captured well by reanalyses.

c. Over Kototabang, the reanalyses did not consistently reproduce? produce 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. 33

d. Inter-comparison among the reanalyses shows that ERAi overestimates NCEP-2 and underestimates the other three reanalyses with respect to the magnitude of w over both Gadanki and Kototabang. 34

e. Assessment of directional tendencies shows that updrafts are reproduced reasonably well in all ~~the~~ five reanalyses but downdrafts are not reproduced at all.

Our analysis reveals that downdrafts are not well captured produced in reanalyses. ~~and also~~ The location of the largest updrafts is also shifted lower in reanalyses than in the observations. Hence, ~~the~~ reanalyses 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 reanalyses, as this is a much sought-parameter for atmospheric circulation calculations and analyses. D 35

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data centre for providing the data through the portal of Research data archival (RDA) of NCEP/UCAR. One of the author KVS thank Indian Research Organisation for providing research associateship during this study.

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

For ERAi, ERA-5, JRA-55 and NCEP-2.: https://rda.ucar.edu E

For MERRA-2 : 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. 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. Climatological monthly mean altitude profile of vertical velocity obtained from the MST Radar and five reanalyses over Gadanki at 12 UTC. Horizontal lines indicate the standard error in each data set.

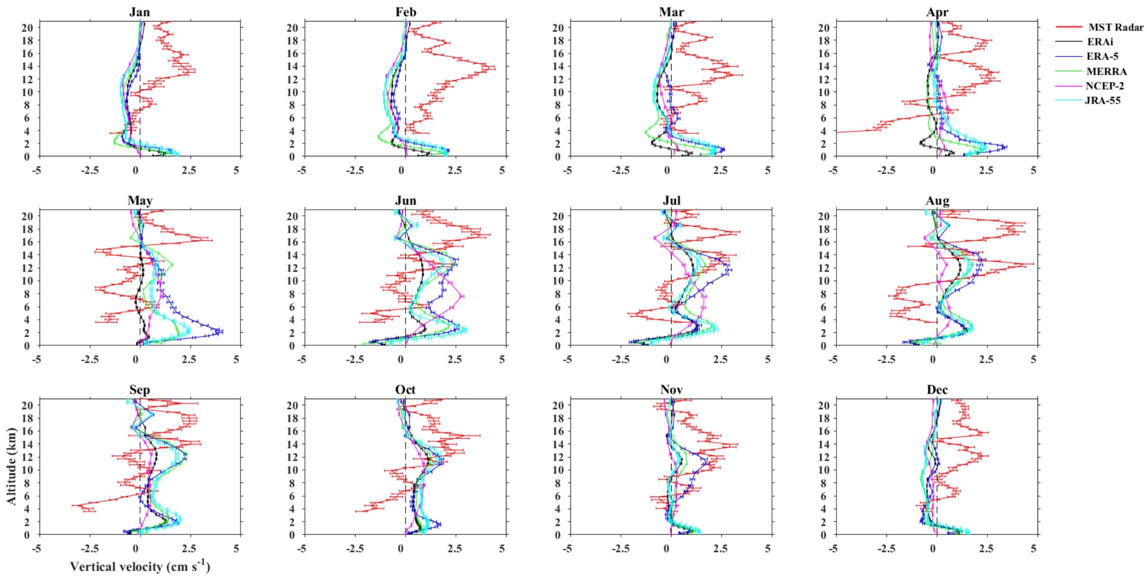

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Figure 2. Same as Fig.1, but for daily mean profiles over Kototabang.

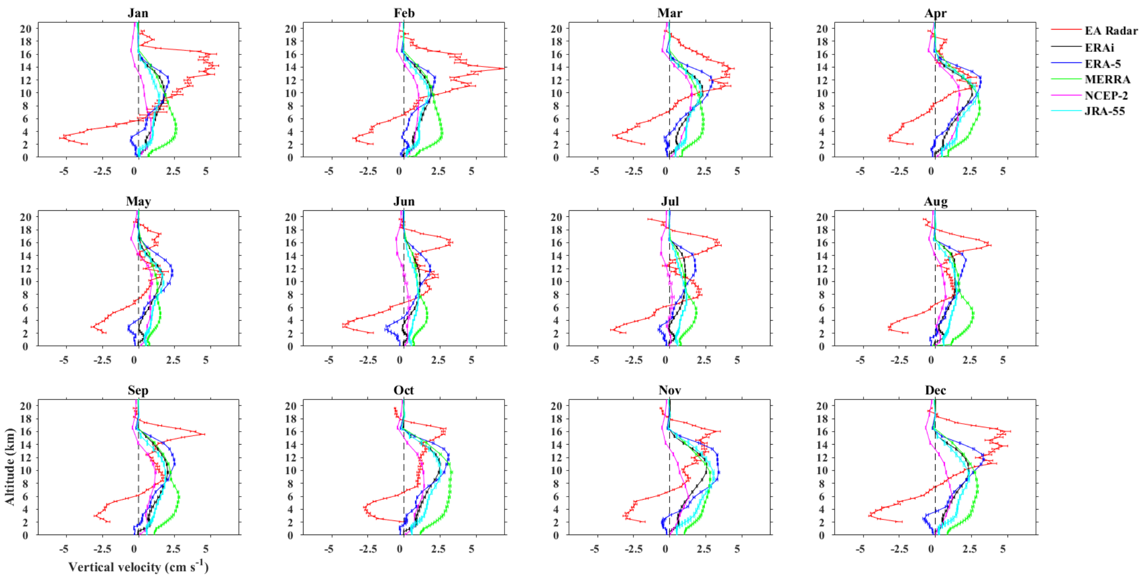

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Figure 3 : Monthly mean climatologies of vertical velocity obtained from (a) radars, (b) ERAi, (c) ERA5, (d) MERRA-2, (e) NCEP-2, and JRA-55 over Gadanki (left) and Kototabang (right). Gadanki data are at 12 GMT and Kototabang data are daily means.

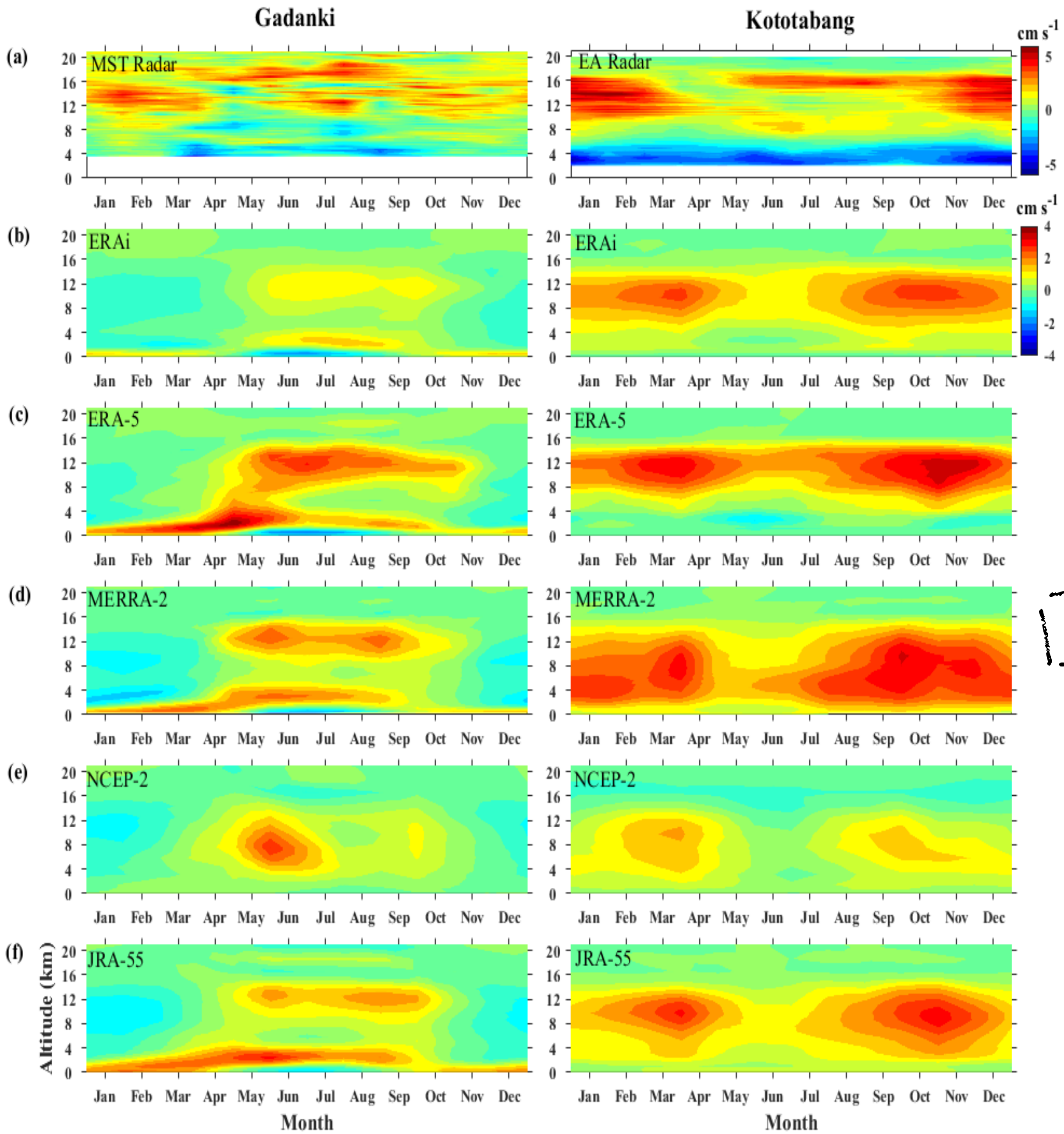

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Figure 4. Monthly mean vertical velocity obtained from (a) MST Radar and (b) ERAi for 5-years intervals (from top to bottom) over Gadanki (12 GMT).

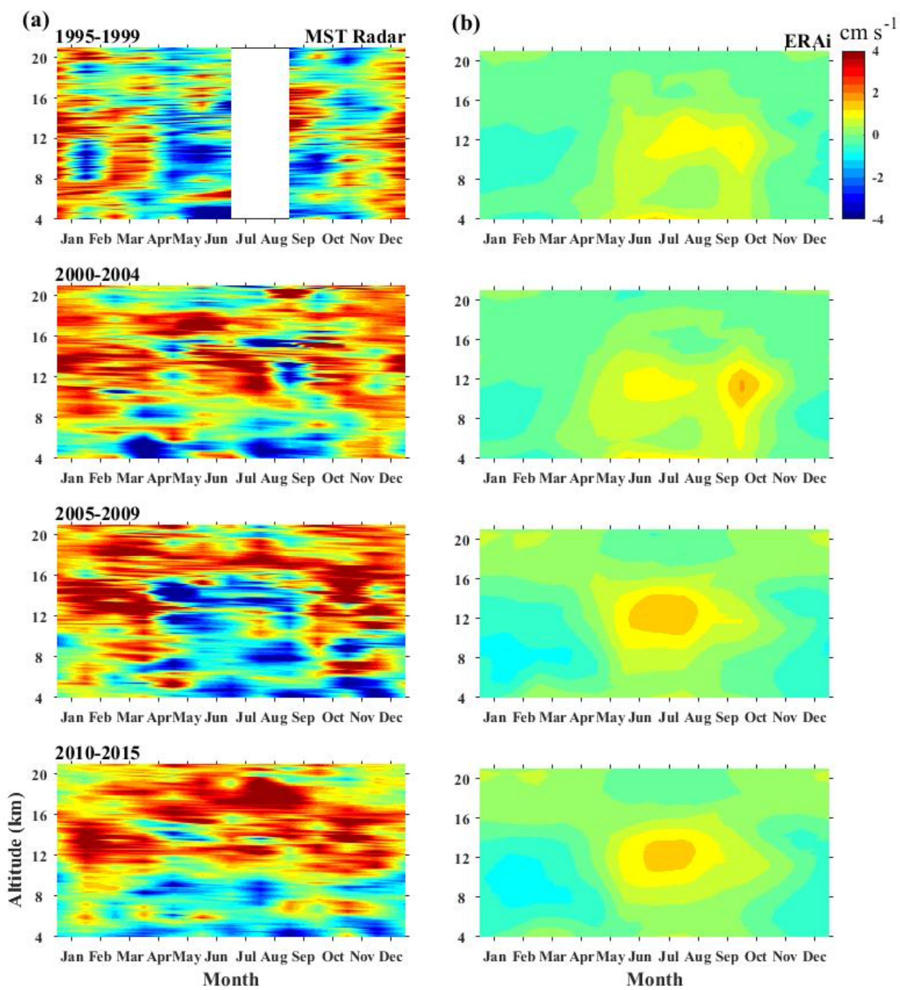

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Fig. 4?

Figure 5. Same as Fig.S2 but for daily means over Kototabang.

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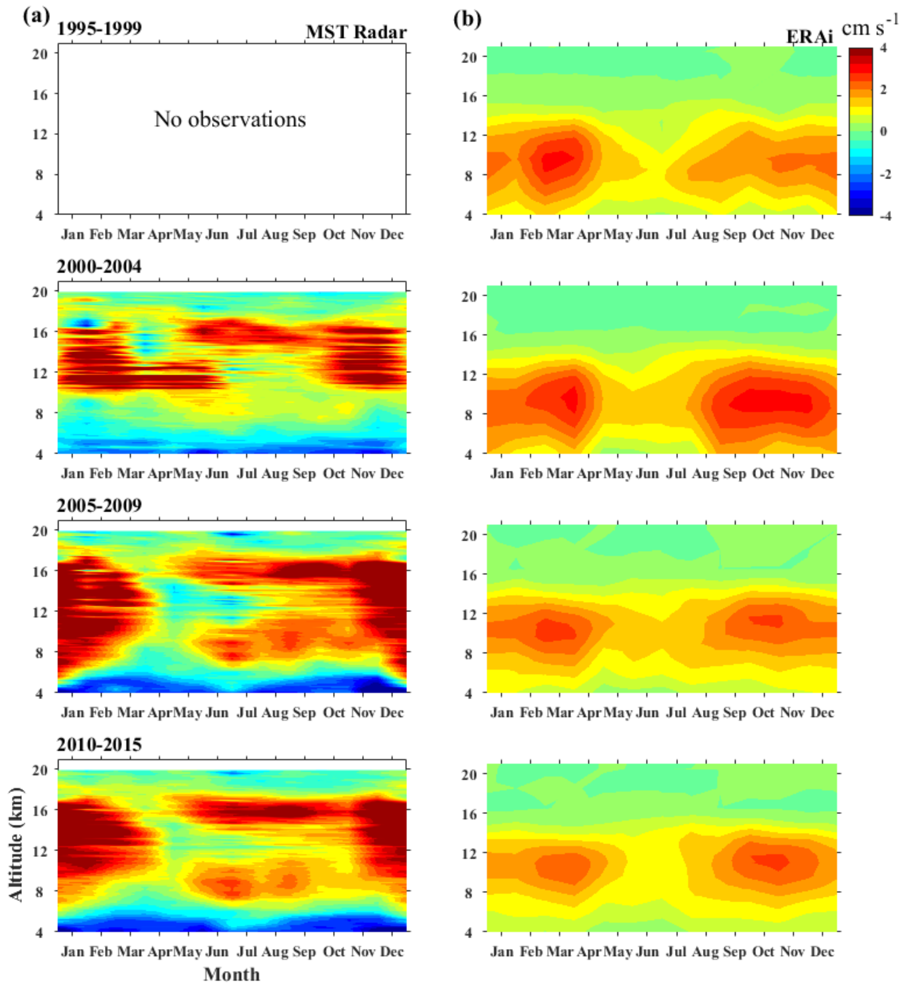

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Figure 6. Height profiles of vertical velocity for 12 GMT and from daily mean (with 1 hour resolution) over Gadanki extracted from ERA5 (highest available time resolution).

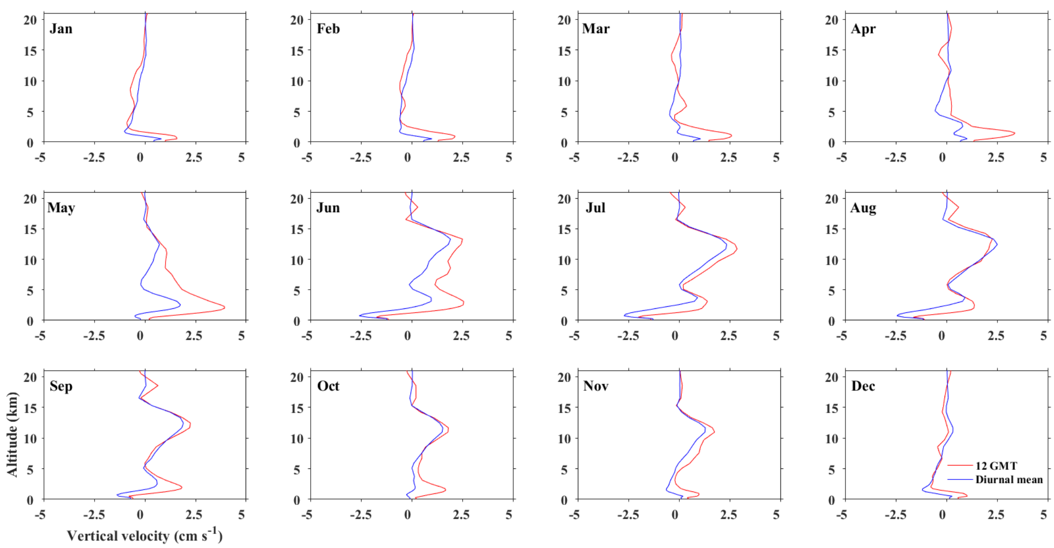

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Figure 7. Same as Fig.6, but for Kototabang.

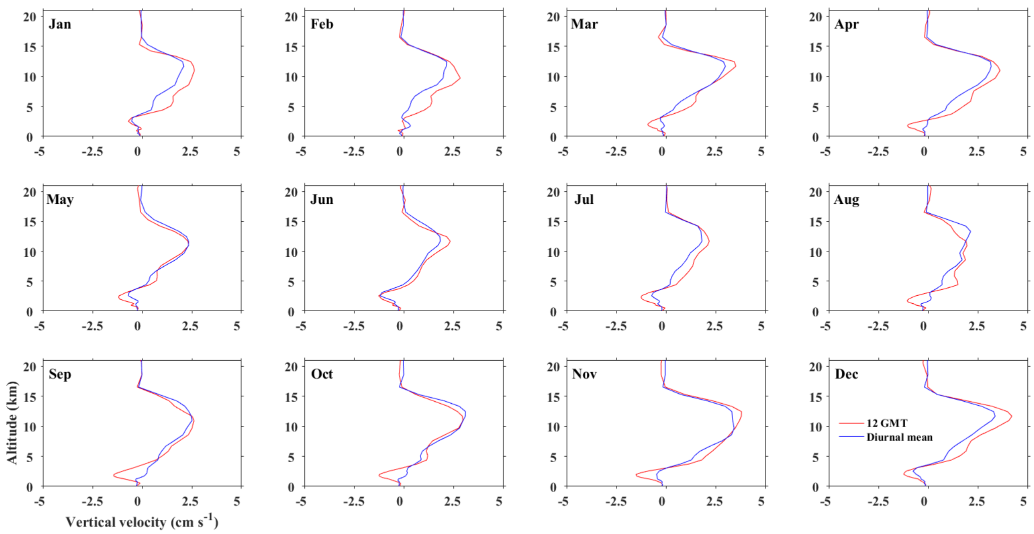

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Figure 8. Comparison of relative differences in vertical velocity (*w*) between the reanalysis for Gadanki (solid line) and Kototabang (dash line). Individual month differences are estimated relative to ERAi and then averaged for each month.

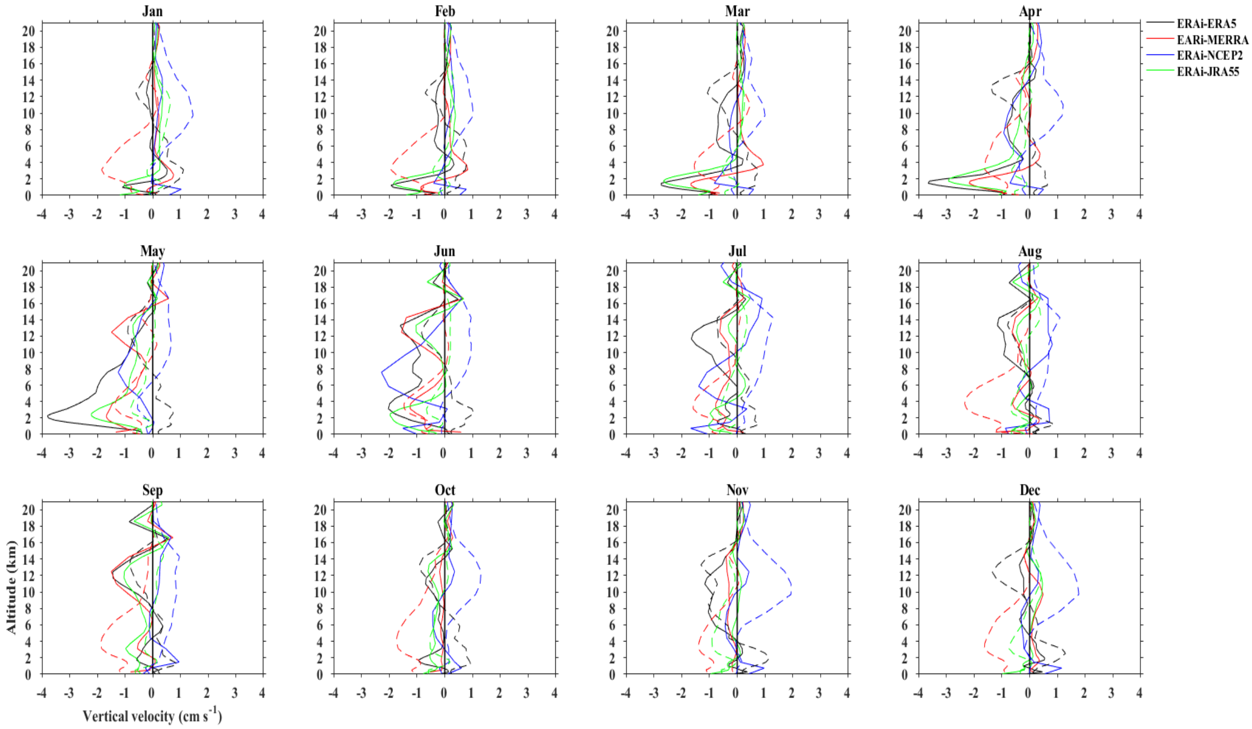

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Figure 9. Comparison of directional tendencies between the radars and various reanalysis data sets for (a) Gadanki and (b) Kototabang. Updrafts are shown in the upper panels and downdrafts are shown in the lower panels for each site (for details see text).

does this make sense in the context of Fig. 6?