Height correction of atmospheric motion vectors using satellite lidar observations from CALIPSO

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Abstract

Atmospheric Motion Vectors (AMVs) provide valuable wind information for the initial conditions of numerical weather prediction models. However, height assignment issues and horizontal error correlations require a rigid thinning of the available AMVs in current data assimilation systems. The aim of this study is to investigate the feasibility of correcting the pressure heights of operational AMVs from the geostationary satellites Meteosat-9 and Meteosat-10 with cloud top heights derived from lidar observations by the polar orbiting satellite CALIPSO. The study shows that the wind error of AMVs above 700 hPa is reduced by 12-17% when AMV winds are assigned to 120 hPa deep layers below the lidar cloud tops. This demonstrates the potential of lidar cloud observations for the improvement of the AMV height assignment. In addition, the lidar correction reduces the slow bias of current upper level AMVs and is expected to reduce the horizontal correlation of AMV errors.

1. Introduction

Observations from various geostationary and polar orbiting satellites are used to derive Atmospheric Motion Vectors (AMVs) by tracking clouds or water vapor structures in consecutive satellite images. AMVs provide outstanding global wind field coverage, especially over oceans, where in-situ wind observations are rare. Wind observations are particularly important for the initialization of numerical weather prediction (NWP) models (Baker et al. 2013) and therefore, AMVs are an essential ingredient for NWP. The positive impact of AMV assimilation in NWP models has been shown in several studies (e.g. Bormann and Thépaut 2004; Velden et al. 2005). However, the vertical height assignment remains a challenging task and introduces significant errors. These contribute up to 70% to the total AMV error (Velden and Bedka 2009) and can be horizontally correlated over several hundred kilometers (Bormann et al. 2003). Hence, AMVs are drastically thinned for the assimilation in NWP models and only a small fraction of the available observations is used.

Preceding studies (Velden and Bedka 2009; Weissmann et al. 2013) demonstrated that AMVs rather represent the wind in a vertically extended layer whereas they are traditionally assimilated at discrete levels. In addition, Weissmann et al. (2013) showed that the height of AMVs can be corrected using airborne lidar cloud top observations. The present paper further investigates these two approaches that can potentially reduce the errors of AMVs. Firstly, we treat AMVs as vertically extended layer observations instead of single level observations. Secondly, satellite lidar cloud top observations are used to correct AMV pressure heights. The paper is a follow-up study to Weissmann et al. (2013) where a small, regional sample of airborne lidar observations was used as testbed for the AMV height correction with lidar cloud top observations. As suggested in Weissmann et al. (2013), the present study conducts the transition to larger scales using a sample of satellite lidar observations with significantly larger size and longer temporal extent. Lidar cloud top height observations from the polar orbiting satellite CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) are used to correct the heights of Meteosat-9 and Meteosat-10 AMVs. A number of suitable vertical layers relative to the lidar cloud tops and relative to the original AMV heights are investigated. Furthermore, different depths of the vertical layers are tested to find an appropriate layer that should be assigned to AMVs in data assimilation systems. Operational collocated radiosondes are used to validate AMV winds before and after the height correction.

2. Data and method

a. Data

The present study comprises eight months (1 April - 6 October 2012 and 16 April - 13 June 2013) of operational AMVs that were derived hourly from the geostationary satellites Meteosat-9 (2012 period) and Meteosat-10 (2013 period) by EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites). Both satellites are positioned at 0° longitude and most of the height corrected AMVs are located over Europe and Africa, where radiosondes are available for wind verification.

Meteosat AMVs from four different satellite channels are used: infra-red observations (IR) at 10.8 µm, visible observations (VIS) at 0.8 µm and observations from the water-vapor channels (WV) at 6.2 µm and 7.3 µm. VIS-AMVs can only be tracked during daylight and are derived for clouds in the lower troposphere, whereas IR-AMVs occur throughout the troposphere and lower stratosphere. WV-AMVs from the two water vapour channels are mainly positioned in the upper troposphere. The AMVs considered in this study are derived by tracking cloud structures, whereas WV-AMVs tracking water-vapor structures in cloud-free areas are excluded. The final AMV pressure height for Meteosat AMVs is determined by different height assignment methods: IR-Window, IR/WV ratioing, H2O intercept and the CO2-slicing technique (details in DiMichele et al. 2012). On 5 September 2012, the EUMETSAT height assignment algorithm changed to the Cross-Correlation Contribution (CCC) method (Borde and Oyama 2008). This method provides a more consistent height assignment as the pixels that contribute most to the tracking process are used to set the AMV height. However, the information about the specific height assignment method is no longer available in the final data product.

Corresponding lidar cloud observations were obtained by the polar orbiting satellite CALIPSO that was launched in 2006 and flies at an inclination of 98.2 degrees in a sun-synchronous orbit at 705 km altitude. CALIPSO is part of the “A-Train”, which is a constellation of several international science satellites that fly in formation and therefore facilitate a wide variety of different observations of the same scenery from space. The lidar CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) aboard CALIPSO measures vertical profiles of the atmospheric backscatter at two wavelengths (532 nm and 1064 nm), which enables to determine the cloud top height with high horizontal and vertical resolution. Additional measurements of the depolarization at 532 nm allow determining the cloud phase. In this study, the official CALIPSO Level-2 cloud layer product is used. It provides inter alia the 1-km horizontally averaged cloud top height from the CALIOP lidar, the number of superimposed cloud layers, a quality index for clouds and the cloud phase. The vertical resolution of the CALIOP lidar is 30 m at altitudes of -0.5 km to 8.2 km and 60 m from 8.2 km to 20.1 km (for more information on CALIPSO see Winker et al. 2009; Winker et al. 2010; Hunt et al. 2009). Missing CALIPSO observations on 27 days of the 8-month study period lead to 220 days of available data.

b. Collocation requirements

AMVs are corrected with nearby CALIPSO lidar observations that are within 50 km horizontal distance and 30 min time difference from the location and time of each AMV. The median value of all available (at least 20) individual CALIPSO cloud top observations within this range is taken as representative cloud top. In addition, the root mean square differences between single lidar cloud observations and their median value must not exceed 70 hPa. All multi-layer cloud scenes are discarded. The EUMETSAT AMV quality index (QI) must be greater than 50, with 100 indicating the best possible value and 0 the worst. The quality index for CALIPSO clouds also ranges from 0 (worst) to 100 (best) and has to exceed a value of 90. In addition, the AMVs must be less than 100 hPa above and 200 hPa below the corresponding CALIPSO cloud top height. This interval is chosen to account for the fact that lidar observation and AMV may see different clouds due to the temporal and/or horizontal displacement and based on the assumption that AMVs represent the wind below the actual cloud top (Weissmann et al. 2013).

Figure 1 shows the position of Meteosat-9 AMVs and CALIPSO lidar observations on 1 April 2012 matching the described collocation requirements. For this day, we found 1247 collocated observations within the Meteosat-9 domain (approximately +/- 63° in each direction from 0° longitude and 0° latitude). Typically, there are around 1000 -1300 Meteosat AMVs per day that could be corrected with CALIPSO observations. Altogether, 243097 matches of Meteosat-AMVs and CALIPSO lidar observations are found in the complete period of 220 days.

The AMV wind is evaluated using nearby operational radiosondes. As the wind field is usually horizontally more uniform than cloud top heights, the collocation criterion for nearby radiosondes is extended to 150 km and 90 min from the corresponding AMV. Thereby, both the original AMV pressure height and the lidar cloud top height must be located at least 50 hPa below the highest level of the corresponding radiosonde. Given the comparably low number of operational radiosondes, the sample size reduces to 4478 matches of Meteosat-AMVs, CALIPSO lidar observations and operational radiosondes for the complete period.

The sample is divided into high-level AMVs with pressure heights < 300 hPa, mid-level AMVs with pressure heights between 300 hPa and 700 hPa and low-level AMVs with pressure heights ≥ 700 hPa. In total, 1259 high-level AMVs derived from the IR- and WV-channels (337 and 922 matches, respectively) are available. The respective CALIPSO observations are all classified as ice clouds. The mid-level data set consists of 1576 AMVs (611 IR AMVs and 965 WV

AMVs) and the corresponding CALIPSO cloud products comprise 67% ice clouds and 33% water clouds. The 1643 low-level AMVs from the IR- and VIS channels (219 and 1424 matches, respectively) are expected to correspond to water clouds only. Figure 2 shows the vertical distribution of all AMVs that are used in this study.

c. Height correction method

The applied AMV height correction with satellite lidar observations from CALIPSO follows Weissmann et al. (2013). AMV winds are compared to radiosonde winds vertically averaged over layers of varying depth (0-200 hPa): firstly for layers relative to the originally assigned AMV height and secondly for layers relative to the CALIPSO lidar cloud top height. If a layer reaches the lowest or highest radiosonde level, the layer depth is reduced accordingly. Three different layer positions are considered: (i) layers centered at the corresponding AMV height or lidar cloud top height, (ii) layers with 25% above and 75% below the corresponding height and (iii) layers from the corresponding height downward.

3. Results

a. VRMS differences and wind speed bias

Figure 3 shows the mean Vector Root Mean Square (VRMS) differences of AMVs and radiosonde winds. These differences are calculated as the mean of the square-root of the sum of the squared differences between AMV and layer-averaged radiosonde wind components u and v. VRMS values are calculated for assigning AMVs to vertical layers of increasing depth, which are computed by averaging radiosonde winds over the respective layer. The first set of layers uses the original AMV height as reference (grey lines); the second set uses lidar cloud top observations as reference (black lines). The corresponding wind speed bias is shown in Figure 4.

VRMS differences for high- and mid-level AMVs above 700 hPa (Fig. 3a – 3d) from WV- and IR-channels exhibit a distinct error reduction when AMVs are treated as vertically extended layers instead of as single level observations (which are the values for 0 hPa on the x-axis). Lowest VRMS differences are achieved either by layers below the lidar cloud tops or by layers with 25% above and 75% below the lidar cloud tops. The optimal depth of these layers varies from 120 to 200 hPa. Layers below the lidar cloud tops exhibit lowest VRMS differences for a depth of 100-150 hPa and layers with 25/75% above/below the lidar cloud tops yield best results for a depth of 150-200 hPa. Overall, the shape of the curves for these two lidar layers is fairly similar for the different subsets presented in Fig. 3a - 3d and small differences in the position of the minimum may also be a result of the limited sample size of individual subsets instead of systematic differences in between them. For all these four subsets, the minimum of VRMS differences for layers relative to the lidar cloud top is in the range of 0.5 – 1.5 m s^{-1} lower than the lowest values reached with layers relative to the original AMV height.

Figs. 4a and 4b exhibit a significant slow bias of high-level AMVs assigned to their original discrete height (values for 0 hPa on the x-axis). Such a slow bias has also been found in other recent studies (e.g. Bresky et al., 2012). Generally, the bias is reduced when AMVs are assigned to deeper layers and results indicate that assigning them for example to layers of 100-150 hPa below the lidar cloud tops can also largely remove the slow bias of current upper level AMVs. Overall, the results presented in Fig. 4 show that layers leading to low VRMS differences tend to be similar to layers leading to a low wind speed bias.

In contrast to high- and mid-level AMVs, low-level AMVs (Figs. 3e and 3f) show a less distinct benefit of incorporating lidar information. 200 hPa layers with 25/75% above/below lidar cloud tops and 200 hPa layers below lidar cloud tops (for IR and VIS, respectively) lead to the lowest VRMS differences, but results for layers of the same depth centered at the original AMV heights are only 0.1-0.2 m s^{-1} higher. As low-level AMVs are located at pressure heights greater than 700 hPa, the 200 hPa layers below the lidar cloud top are mostly layers from the lidar cloud tops to the lowest radiosonde level.

High- and mid-level AMVs overall exhibit a similar behavior and therefore all AMVs above 700 hPa are combined in Fig. 5. The combination of high- and mid-level AMVs will be referred to as “upper-level AMVs” in the following. Results indicate that lowest VRMS differences in combination with lowest wind speed bias values are achieved for either 120-130 hPa layers below the lidar cloud tops or 200 hPa layers with 25/75% above/below the lidar cloud tops.

b. Relative VRMS reduction for lidar layers and lidar levels

Figure 6 shows the relative reduction of VRMS differences when results for layers below the lidar cloud tops are compared to results of layers of the same depth centered at the original AMV heights (Fig. 6a) and results using the discrete original AMV heights (Fig. 6b). The shape of the curves in Fig. 6a and 6b is similar. For upper level AMVs (black lines), best results are yielded for layer depths of 100-120 hPa. Highest error reduction values are ~12% for lidar layers compared to layers centered at the original AMV heights (Fig. 6a) and ~17% compared to the discrete original AMV heights (Fig. 6b). The improvement is apparent in both upper level channels IR and WV (black dotted and dashed lines). Dividing between upper level ice clouds and water clouds leads to a similar error reduction and is therefore not shown. Correcting the height of low-level AMVs (grey lines) with lidar information only leads to a small error reduction, but the averaging over deep layers shows advantages over using discrete heights.

After demonstrating the benefit of assigning AMVs to vertical layers below lidar cloud tops, we now investigate how much of that error reduction could be achieved by assigning them to one representative discrete level relative to the lidar cloud top instead. The black solid line in Figure 7 represents the treatment of AMVs as a layer-average below the lidar cloud top (equivalent to the black solid line in Figure 6b), whereas the dash-dotted line represents the assignment of AMVs to the discrete mean pressure height of that lidar layer, i.e. a discrete level located half of the layer depth below the lidar cloud top. Results indicate that assigning AMVs to the mean pressure of the lidar layers achieves most of the reduction of assigning AMVs to vertically extended lidar layers. However, interpreting AMVs as layer-averaged winds leads to a relative reduction that is ~3% higher. The maximum of the curves is for both approaches at ~120 hPa, which corresponds to using discrete levels 60 hPa below the lidar cloud tops. The corresponding wind speed bias values at this maximum are for both approaches close to zero (not shown).

Figure 8 illustrates the distribution of differences between the original AMV pressure and the mean pressure level of 120 hPa deep layers below the lidar cloud top for upper level AMVs. About 75% of the AMVs are located above the mean pressure of the lidar layers and are thus shifted to lower altitudes (negative values) with the lidar height correction. As AMVs are derived by tracking the motion of the cloud, the lidar cloud top (dashed line) marks the natural upper edge where AMVs should be located. However, approximately 30% of the AMVs are located above the cloud, which may be related to an erroneous height assignment as well as to the temporal and horizontal displacement of AMV and CALIPSO lidar observation. On average, upper level AMVs are located 31 hPa above the lidar layer center (and correspondingly, 29 hPa below the lidar cloud top), with only small differences between the single channels WV and IR. In summary, this indicates that the operational processing of upper-level AMVs should consider that AMVs rather represent wind in a layer below the actual cloud tops, but the systematic height differences are likely dependent on the applied AMV processing systems and its settings.

c. Effects of using different subsamples

To investigate the effect of changes in the height assignment algorithm of EUMETSAT, the analyzed 220 days are divided into three different time periods in Table 1. The first one comprises 142 days before 5 September 2012, the day when the height assignment algorithm was changed to the CCC-method. The second period consists of 32 days starting on 5 September 2012 and the last period consists of 46 days from 16 April until 12 June 2013. According to the preceding results (see Fig. 6), the lidar layer depth is set to 120 hPa for upper level AMVs and 200 hPa for low-level AMVs. For upper level AMVs, the error reduction for assigning layers below the lidar cloud tops instead of the discrete original AMV heights is apparent in all three periods ranging from 11.4% to 18.9%. As stated before, low-level AMVs do not show a clear error reduction through the lidar height correction. However, one noticeable feature is the high error reduction for low-level AMVs in the second period from 5 September to 6 October 2012. This is likely related to a temporary degradation of the quality of low-level AMVs in the time period after the height assignment algorithm changed to the CCC-method (Salonen and Bormann 2012).

In order to utilize a reasonable large sample size, the collocation criterion for AMVs and radiosondes in this study is set to 150 km and 90 minutes (see Section 2.2.). However, the temporal and spatial displacement of AMVs and verification radiosondes introduces an additional error component that is expected to be independent of the AMV error itself and the height correction. Therefore, a weak collocation criterion leads to an underestimation of the actual relative error reduction. Figure 9 shows how the relative error reduction for upper level AMVs increases as the horizontal collocation criterion is tightened. Naturally, the number of matches decreases for smaller distances. The error reduction for 120 hPa layers below the lidar cloud tops relative to layers centered at the originally assigned AMV heights shows a strong increase from ~12% at 150 km to ~21% at 40 km (black solid line). When compared to the discrete original AMV height, the relative error reduction increases from ~17% to ~25% (grey dashed line). Reducing the time difference does not lead to clearly larger improvements and is therefore not shown.

This study uses a threshold for the AMV quality index QI of 50 (see section 2.2). Restricting it to higher values (up to ≥ 80) reduces the sample size to up to ~60%. Table 2 lists the relative error reduction for assigning 120 hPa layers (upper level AMVs) and 200 hPa layers (low-level AMVs) below the lidar cloud tops instead of the discrete original AMV heights for different quality thresholds. Restricting the sample to upper level AMVs with QI ≥ 80 shows slightly less improvement than including lower quality AMVs, but the differences are less than 2.5%. For low-level AMVs, the error reduction slightly increases when only AMVs with higher quality are regarded.

4. Conclusion

In this study, we use satellite lidar observations to correct the height of AMVs from Meteosat-9 and Meteosat-10 with lidar cloud top observations from CALIPSO. 220 days of data with altogether about 4500 collocated AMVs, CALIPSO observations and radiosondes are analyzed. We investigate appropriate layer depths and layer positions relative to the lidar cloud tops and relative to the original AMV heights by comparing AMV winds to radiosonde winds averaged over layers of the respective depth and position.

For upper level AMVs, we found that assigning 120 hPa layers below the lidar cloud tops leads to an improvement of ~12% compared to assigning layers of the same depth centered at the original AMV heights and of ~17% compared to using the discrete original AMV heights.

Similar results are yielded for 200 hPa layers with 25% of the layer above and 75% below the lidar cloud top. For AMVs above 700 hPa, the improvement is apparent in both channels and both for ice and water clouds.

AMVs below 700 hPa only show a small error reduction when layers relative to the lidar cloud tops are used instead of layers relative to the originally assigned AMV heights. Although there is no clear error reduction for these AMVs using lidar information, there is indication that lidar observations can reduce AMV errors in periods with lower AMV quality due to changes in the AMV processing. The reasons why the lidar height correction is showing much better results for upper level AMVs may be related to the fact that their wind errors are generally larger.

A tighter threshold for the horizontal distance between AMVs and radiosondes used for verification even leads to a clearly larger effect of the lidar height correction. The results imply that the lidar height correction can actually reduce the AMV wind error by over 20% compared to assigning AMVs to layers relative to the original heights and over 25% compared to using the discrete original AMV heights, but the sample size gets comparably small for a tight threshold.

Our results confirm the findings of preceding studies that AMVs are more representative of a vertically extended layer wind instead of the wind at a discrete level (Velden and Bedka 2009; Weissmann et al. 2013). Hernandez-Carrascal and Bormann (2013) showed in a simulated framework that AMVs rather represent the wind within the cloud instead of the wind at the cloud top or cloud base level. This is consistent with our finding that layers below the lidar cloud tops yield best results. Alternatively, assigning AMVs to a level centered at the mean pressure of the lidar cloud layer achieves most of the benefit of assigning AMVs to layers below lidar cloud tops. This is also similar to the results of Hernandez-Carrascal and Bormann (2013), where a discrete level at an adjusted pressure height can have similar effects as a layer-averaged wind.

In summary, the results of this study demonstrate that the errors of Meteosat AMVs above 700 hPa can be significantly reduced when information from lidar cloud top observations is incorporated. As already stated by other studies (Weissmann et al. 2013; Hernandez-Carrascal and Bormann 2013), the best layer depth and layer position relative to the original AMV height likely depends on the AMV processing and therefore varies from one data set to another. Lidars in contrast, provide high-resolution cloud top observations that are expected to be independent of the height assignment method used in the AMV processing. This implies that the horizontal correlation of AMV errors can also be reduced.

The study uses a sample size of ~4500 collocated AMVs, CALIPSO observations and radiosondes. The strongest restriction however, is the availability of radiosondes for verification that are not required for the lidar height correction itself. Per day, there are about 1000-1300 Meteosat AMVs with nearby CALIPSO observations that could be directly corrected with lidar information and it is assumed that the correction can also reduce the errors of AMVs from other satellites.

Our study demonstrates the potential of using lidar cloud observations from CALIPSO or other future space-based lidars for the height correction of AMVs. This suggests that NWP may benefit from assimilating lidar-corrected AMVs and treating them as layer-averaged AMVs in the future. However, even larger benefits for NWP may be achievable by using the lidar information to develop situation-dependent quality control functions. In addition, lidar-derived heights for AMVs could be used to validate different AMV processing algorithms.

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TABLES

		upper level AMVs		low level AMVs	
	time period	error reduction	counts	error reduction	counts
	All (220 days)	16.9	2835	7.1	1645
(1)	1 Apr. – 3 Sep. 2012 (142 days)	18.9	1725	5.1	999
(2)	5 Sep. – 6 Oct. 2012 (32 days)	11.4	406	18.5	249
(3)	16 Apr. – 12 June 2013 (46 days)	14.1	704	5.6	397

TABLE 1. Relative VRMS reduction in percent and number of matches for different time periods for assigning AMVs to layers below the lidar cloud tops instead of the discrete original AMV heights. The depth of the assigned layers is 120 hPa (200 hPa) for upper (low) level AMVs with pressure heights above (below) 700 hPa.

	upper level AMVs		low level AMVs	
QI	error reduction	matches	error reduction	matches
>= 50	16.9	2835	7.1	1643
>= 60	16.8	2573	8.0	1439
>= 70	16.6	2265	8.3	1254
>=80	14.5	1792	9.4	1003

TABLE 2. Relative VRMS reduction in percent and number of matches for different quality indices QI for assigning AMVs to layers below the lidar cloud tops instead of the discrete original AMV heights. The layer depth is 120 hPa (200 hPa) for upper (low) level AMVs with pressure heights above (below) 700 hPa.

FIGURE CAPTIONS

FIG. 1. Geographic position of 1247 collocated AMVs and CALIPSO lidar observations on 1 April 2012.

FIG. 2. Height distribution of all collocated AMVs and CALIPSO observations used in this study.

FIG 3. Mean VRMS differences between AMV winds and layer-averaged radiosonde winds for (a) high level IR-AMVs, (b) high level WV-AMVs, (c) mid level IR-AMVs, (d) mid level WV-AMVs, (e) low level IR-AMVs and (f) low level VIS-AMVs. Numbers in brackets are AMV counts for the respective graph. Grey lines represent layers relative to the original AMV pressure height, black lines relative to the lidar cloud top height. The three different layer positions are indicated by different line styles (cf. legend).

FIG. 4. As in Fig. 3 but for wind speed bias. Grey lines represent layers relative to the original AMV pressure height, black lines relative to the lidar cloud top height.

FIG. 5. Mean VRMS and wind speed bias of differences between AMV winds and layer-averaged radiosonde winds for upper level AMVs above 700 hPa (IR and WV combined). Altogether, 2835 AMVs are used (948 IR and 1887 WV). Grey lines represent layers relative to the original AMV pressure height, black lines relative to the lidar cloud top height. Note that the scales for bias and mean VRMS values are different.

FIG. 6. Relative reduction of VRMS differences between AMV and radiosonde winds for assigning AMVs to layers below the lidar cloud tops instead of (a) layers of the same depth

centered at the original AMV heights and (b) the discrete original AMV heights. Upper level AMVs above 700 hPa (black solid line) are additionally divided into upper level WV-AMVs (black dotted) and upper level IR-AMVs (black dashed). The grey solid line represents results for lower level AMVs (≥ 700 hPa).

FIG. 7. Relative reduction of VRMS differences between AMV and radiosonde winds for assigning AMVs to layers below the lidar cloud tops (solid line) and to the respective mean pressure levels of that layer below lidar cloud tops (dashed-dotted line) instead of the discrete original AMV heights.

FIG. 8. Histogram of height differences (hPa) between the original AMV pressure height and the mean pressure of the corresponding 120 hPa layers below the lidar cloud top for upper level AMVs above 700 hPa (1887 WV-AMVs and 948 IR-AMVs). The dashed vertical line corresponds to the pressure height of the lidar cloud top.

FIG. 9. Relative VRMS reduction of differences between AMV and radiosonde winds as a function of their horizontal distance for assigning AMVs to 120 hPa layers below the lidar cloud tops instead of layers centered at the original AMV heights (solid line) and the original discrete AMV heights (dashed line). The dotted line corresponds to the y-axis-label on the right and shows the sample size.

FIGURES

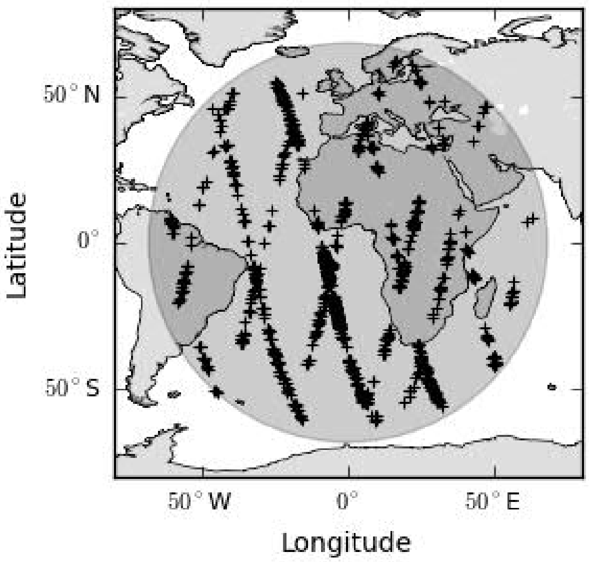

FIG. 1. Geographic position of 1247 collocated AMVs and CALIPSO lidar observations on 1 April 2012.

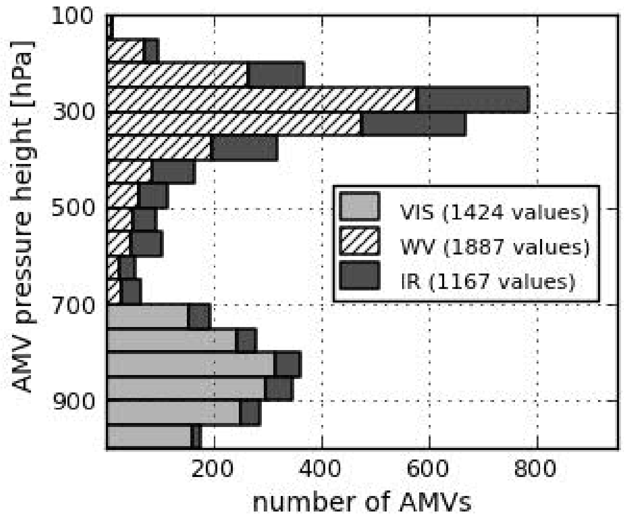

FIG. 2. Height distribution of all collocated AMVs and CALIPSO observations used in this study.

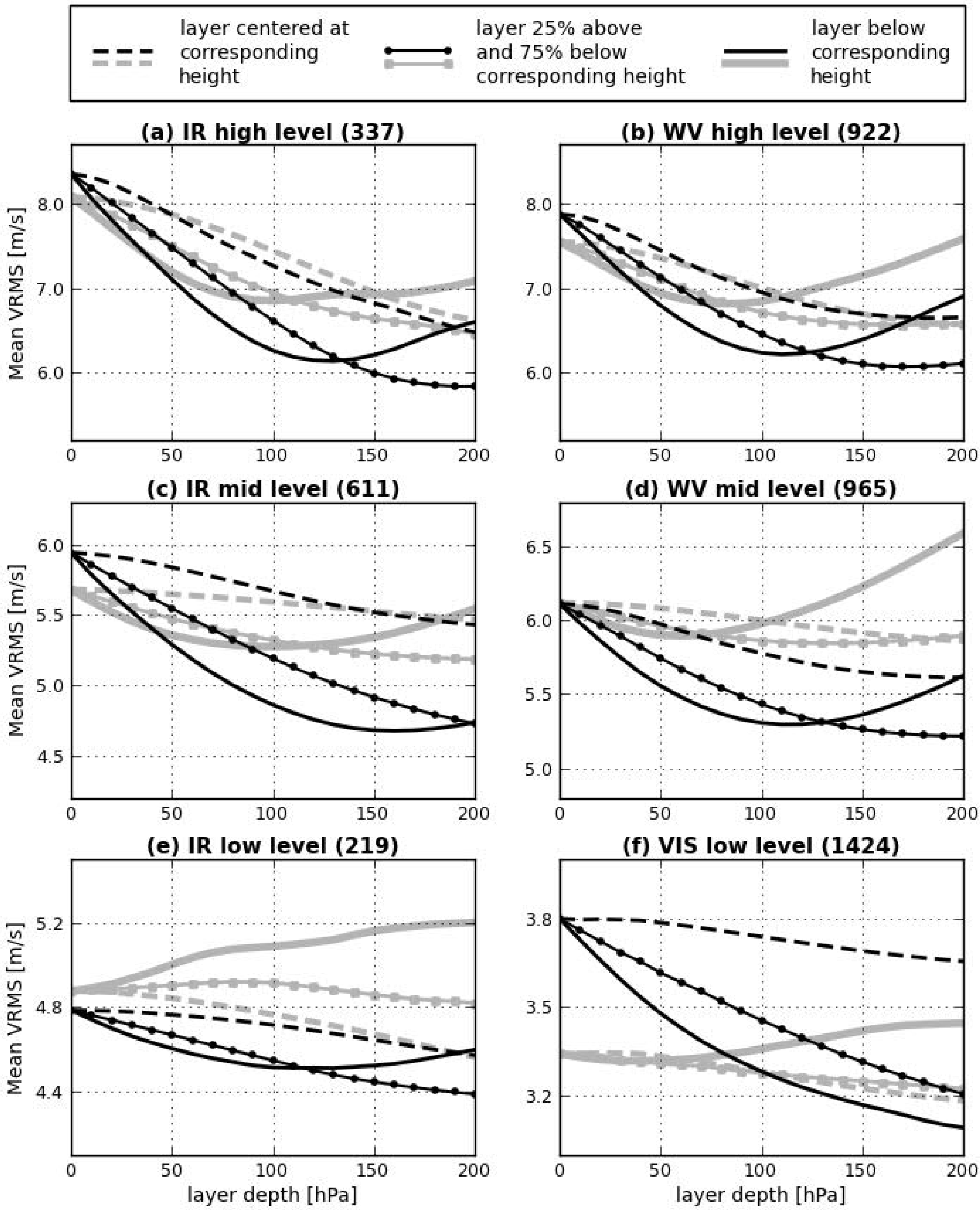

FIG 3. Mean VRMS differences between AMV winds and layer-averaged radiosonde winds for (a) high level IR-AMVs, (b) high level WV-AMVs, (c) mid level IR-AMVs, (d) mid level WV-AMVs, (e) low level IR-AMVs and (f) low level VIS-AMVs. Numbers in brackets are AMV counts for the respective graph. Grey lines represent layers relative to the original AMV pressure height, black lines relative to the lidar cloud top height. The three different layer positions are indicated by different line styles (cf. legend).

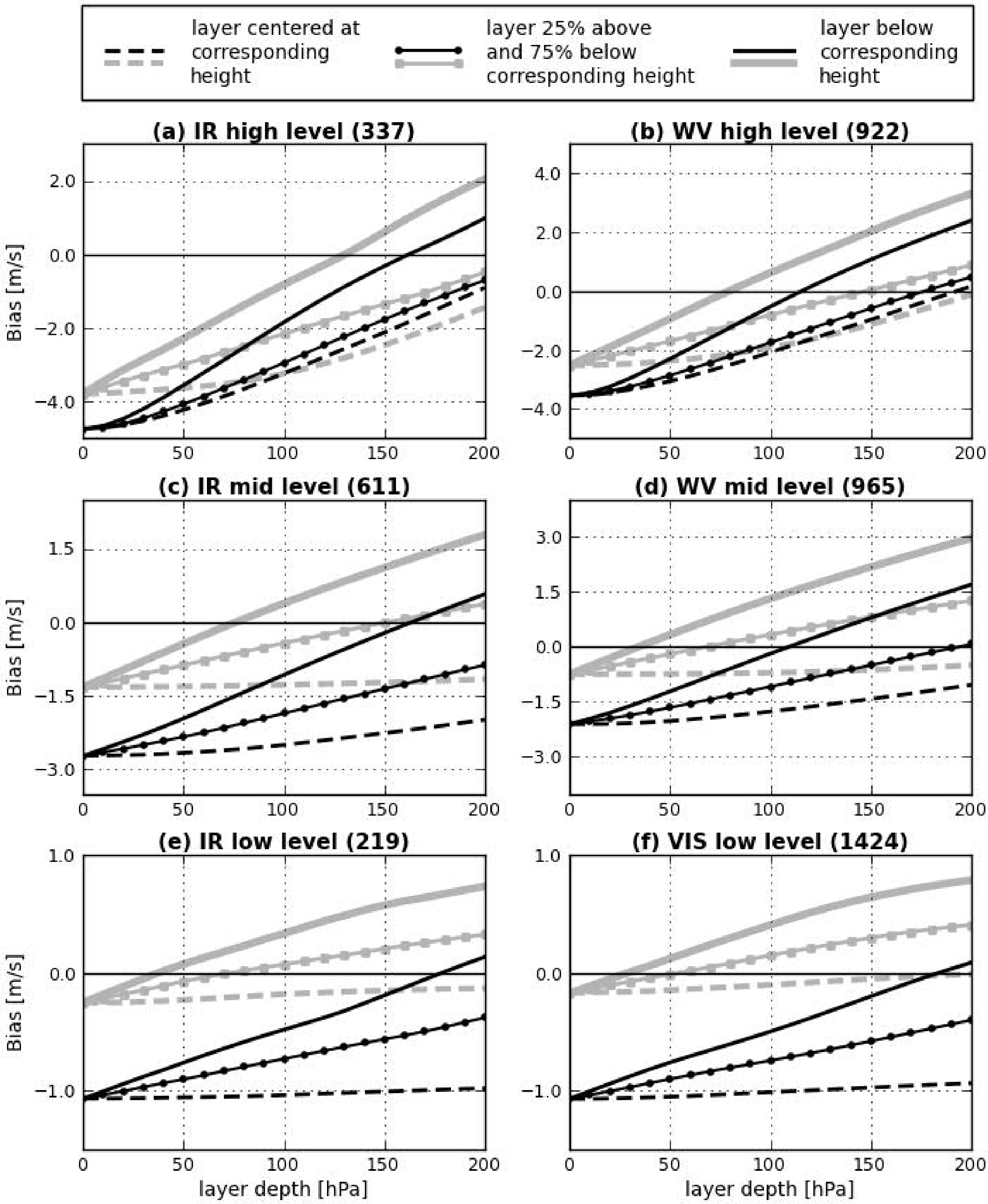

FIG. 4. As in Fig. 3 but for wind speed bias. Grey lines represent layers relative to the original AMV pressure height, black lines relative to the lidar cloud top height.

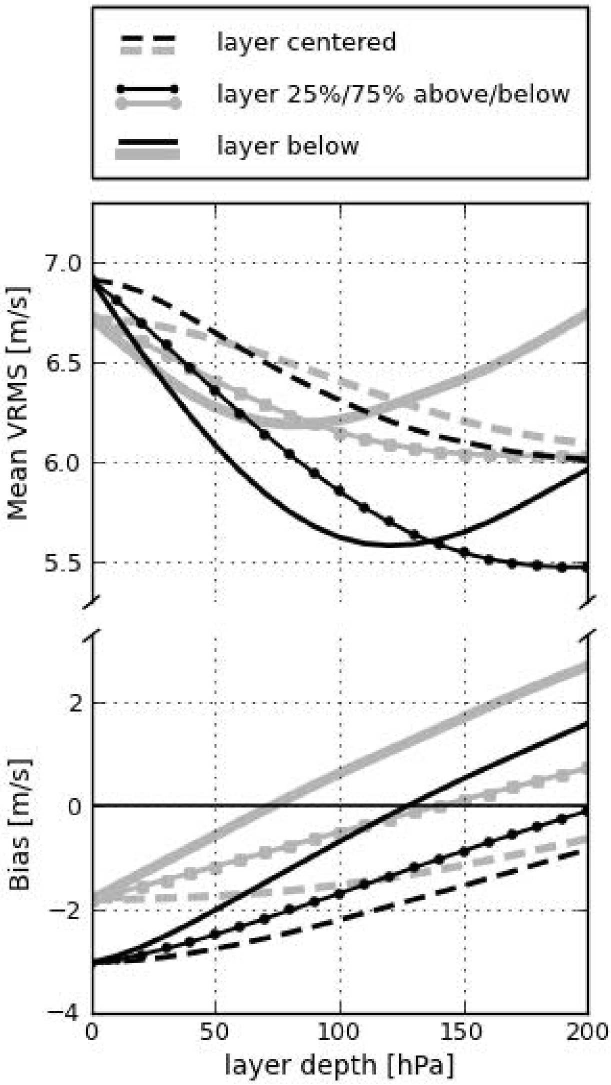

FIG. 5. Mean VRMS and wind speed bias of differences between AMV winds and layer-averaged radiosonde winds for upper level AMVs above 700 hPa (IR and WV combined). Altogether, 2835 AMVs are used (948 IR and 1887 WV). Grey lines represent layers relative to the original AMV pressure height, black lines relative to the lidar cloud top height. Note that the scales for bias and mean VRMS values are different.

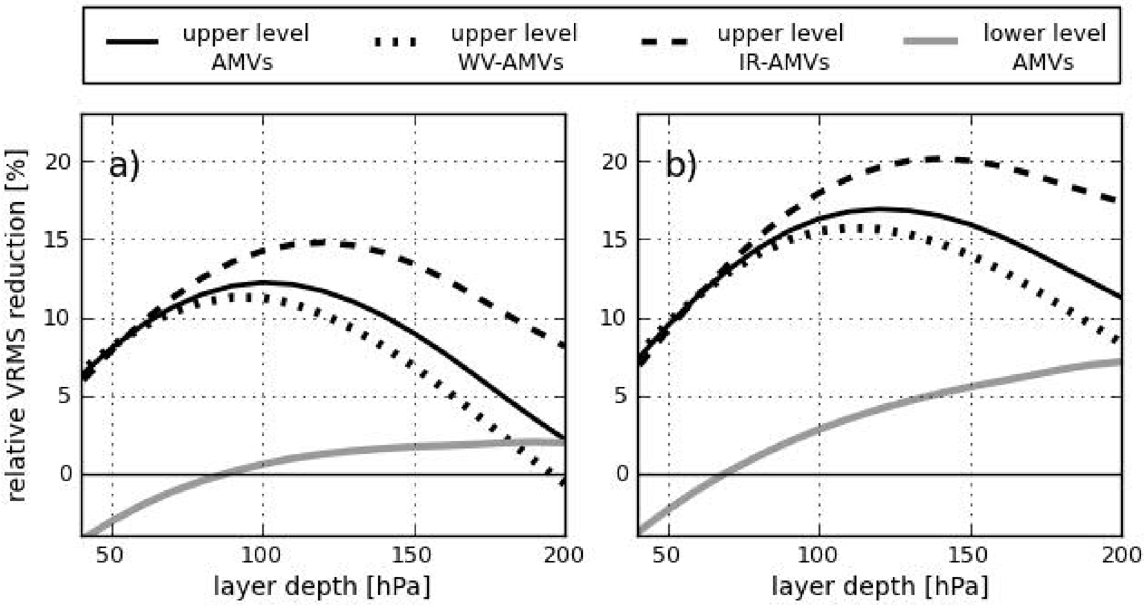

FIG. 6. Relative reduction of VRMS differences between AMV and radiosonde winds for assigning AMVs to layers below the lidar cloud tops instead of (a) layers of the same depth centered at the original AMV heights and (b) the discrete original AMV heights. Upper level AMVs above 700 hPa (black solid line) are additionally divided into upper level WV-AMVs (black dotted) and upper level IR-AMVs (black dashed). The grey solid line represents results for lower level AMVs (≥ 700 hPa).

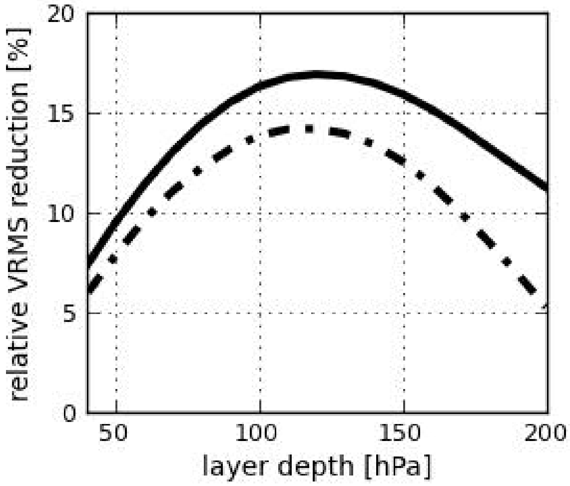

FIG. 7. Relative reduction of VRMS differences between AMV and radiosonde winds for assigning AMVs to layers below the lidar cloud tops (solid line) and to the respective mean pressure levels of that layer below lidar cloud tops (dashed-dotted line) instead of the discrete original AMV heights.

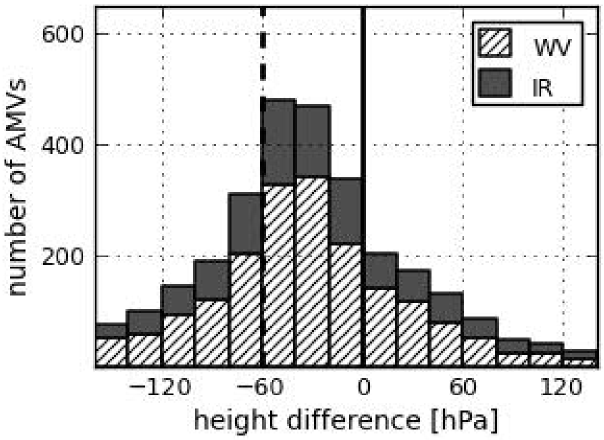

FIG. 8. Histogram of height differences (hPa) between the original AMV pressure height and the mean pressure of the corresponding 120 hPa layers below the lidar cloud top for upper level AMVs above 700 hPa (1887 WV-AMVs and 948 IR-AMVs). The dashed vertical line corresponds to the pressure height of the lidar cloud top.

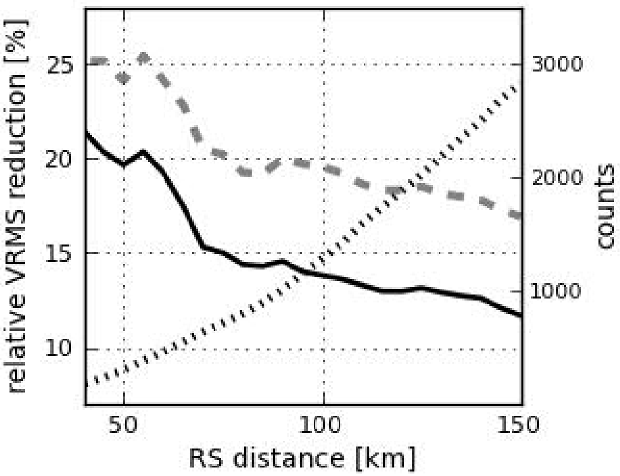

FIG. 9. Relative VRMS reduction of differences between AMV and radiosonde winds as a function of their horizontal distance for assigning AMVs to 120 hPa layers below the lidar cloud tops instead of layers centered at the original AMV heights (solid line) and the original discrete AMV heights (dashed line). The dotted line corresponds to the y-axis-label on the right and shows the sample size.