Comparison of MISR and Meteosat-9 Cloud Motion Winds

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Abstract

A detailed evaluation of cloud motion winds from the Multi-angle Imaging SpectroRadiometer (MISR) against a similar product from a geostationary satellite was sorely lacking. Previously, MISR winds were only compared to radiosonde and wind profiler observations, or forecast models. Although such comparisons showed relatively good agreements, they were limited in scope and suffered from representativeness and sample size issues. This study offers the most detailed evaluation of cloud motion winds from MISR to date. MISR's purely geometric stereo technique retrieves cloud motion and height simultaneously, and is potentially more accurate than traditional satellite winds relying on ancillary information for height assignment. Here, we analyzed one year of MISR and state-of-the-art Meteosat-9 wind retrievals, producing robust statistics based on 225,155 coincident wind pairs.

1 Introduction

Assimilating high-quality cloud motion winds (CMWs) from geostationary satellites e.g. Meteosat-9 and polar orbiters e.g. MODIS Aqua has a positive effect on model prediction skill. As Delsol et al. [1] describe, the numerical weather prediction (NWP) model of the European Centre for Medium-Range Weather Forecasts (ECMWF) uses winds from Meteosat-7, Meteosat-9, GOES-11, GOES-12, MTSAT-IR, MODIS Terra, and MODIS Aqua, which are obtained by tracking features in the infrared, visible and water vapor channels. This database is extensive but still not complete, most notably high latitudes are only sparsely sampled by MODIS. Better coverage and retrieval quality would result in a more complete dataset, which might lead to further improvements in weather forecasts.

The main source of errors in satellite winds lies in their retrieved cloud top heights (CTHs) [1]. They are usually obtained using ancillary information, such as, model temperature profiles, which themselves might be in some way biased. A method not relying on ancillary data could eliminate this source of error and therefore improve the quality of the reported winds. The Multi-angle Imaging SpectroRadiometer (MISR) uses such a stereo technique, which can retrieve cloud movements and heights simultaneously without any ancillary information [2]. In order to conclusively prove that MISR measurements are reliable, they have to be evaluated first with data from independent satellites measurements; as done in this work. Here, two different existing CMW datasets, specifically, from MISR and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board Meteosat-9 were compared. We investigated the dependence of the bias, root-mean-square-difference (RMSD) and correlation on various factors, such as, geographic location and MISR' cross-track position, separately for EW wind, NS wind and cloud top height.

2 Methodology

In this analysis, we used MISR and Meteosat-9 cloud motion winds, from the entire year of 2008. Because Meteosat-9 CMWs cover a latitude range from approximately $60\,^{\circ}$S to $60\,^{\circ}$N, we only considered MISR paths 150 to 230. MISR winds were extracted from the Level 2 Top of Atmosphere/Cloud Stereo Product, version F08-0017, which includes CMWs corresponding to target areas of 70.4 x 70.4 km^2.

Meteosat-9 with SEVIRI on board retrieves CMWs corresponding to comparable target areas of 72 x 72 km^2.

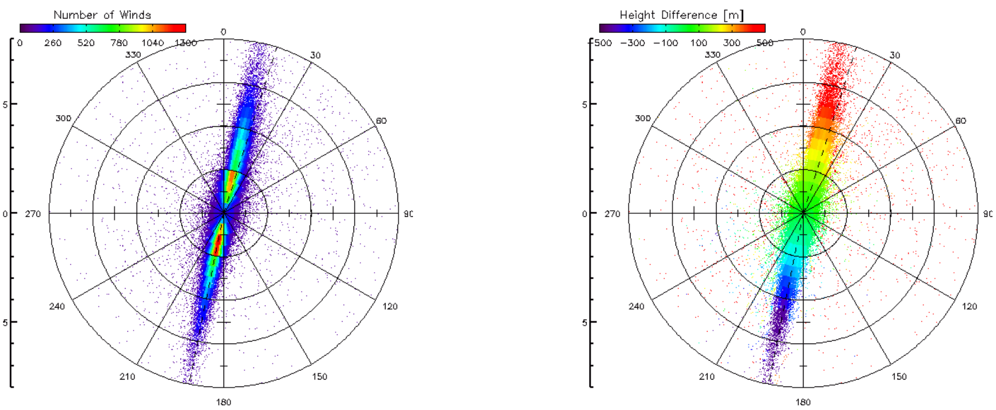
For the comparison only the Meteosat-9 standard visible and infrared channels were used. In addition, only high quality CMWs were considered, that is, MISR winds with a quality flag "good" or "very good" and Meteosat-9 winds with a quality index without first guess $\geq$ 0.8. Furthermore, MISR CMWs with an Orbit_QA or Orbit_qa_winds flag of -1 were excluded; these two flags indicate if a MISR orbit was registered poorly (= -1) or not (= 0), due to geo-location or co-registration errors (for further details see [3]). Also note that MISR reports CMWs with a so-called cloud motion source (CMS) flag, ranging from zero to five. Only winds with CMS of three and above were used, which ensured that only good quality low-level winds (CMS = 3), high-level winds (CMS = 4) or both low-level and high-level winds (CMS = 5) were included in the analysis.

In order to find collocated MISR and Meteosat-9 winds, we set a maximum allowed time difference of $\leq \pm$ 15 min and geographic distance of $\leq \pm 0.5\,^\circ$ in latitude and longitude. Within these time-space limits, the Meteosat-9 CMW closest in height to a MISR CMW was then selected. Each MISR path consists of 180 blocks, which are divided into 16 domains of 70.4 x 70.4 km^2, with each domain containing one cloud motion vector with an associated cloud top height. All those MISR and Meteosat-9 CMWs which met the above matching criteria were selected.

An important caveat to note is that MISR retrieves so called "clear sky winds" (see section 3 for explanation) next to "real" cloud motion winds. To filter these "false" winds out, all CMWs over land having a wind speed $\leq$ 2 m/s with a wind direction $330\,^\circ$ to $30\,^\circ$ or $150\,^\circ$ to $240\,^\circ$ or a wind speed $\leq$ 4 m/s with a wind direction $0\,^\circ$ to $30\,^\circ$ and $180\,^\circ$ to $210\,^\circ$, whose domain average cloud fraction was also $\leq$ 5% and the difference between retrieved CTH and scene elevation was $\leq$ 600 m, were excluded from this analysis. Due to the above limitations, the number of matches between MISR and Meteosat-9 dropped from a total of 849,216 to 225,155 for the year 2008. Finally, it was necessary to convert Meteosat-9 cloud top pressure (CTP) to geometric cloud top height, for which we used the ERA Interim Analysis Geopotential Data from ECMWF.

3 Clear Sky Winds

The MISR stereo product contains so called "clear sky winds" which represent cloud-free surface retrievals usually having small wind speeds and associated heights close to the true scene elevation. This occurs because there is no cloudy target selection in the MISR algorithm; therefore any suitable pattern, including clear-sky surface features, are tracked. Such retrievals arise almost exclusively over cloud-free land, because the cloud-free ocean surface is usually too dark and featureless for successful tracking.



(a) Wind rose of clear sky winds colored by sample number.

(b) Wind rose of clear sky winds colored by difference between retrieved height and scene elevation.

Figure 1: **Wind rose plots for clear sky scenes.**

Although these clear sky winds should not be assimilated in NWP models, they are very useful for putting lower bounds on the accuracy of MISR retrievals.

Unfortunately, clear sky winds are not explicitly labeled in the current MISR stereo product and, thus, have to be identified in post processing. We flagged a MISR retrieval over land as clear sky wind if its quality was ≥ 3 and the domain-mean cloud fraction was exactly 0%. With these settings a total of 150,389 clear sky winds were found in our data set, however, some of these were "real" cloud-motion winds due to errors in the MISR cloud mask. In order to exclude such real cloudy outliers, CMWs that had a zonal and meridional wind $\leq 4\sigma$ (σ(EW wind)= 2.42 m/s, σ(NS wind) = 3.60 m/s) and a difference in retrieved height and scene elevation $\leq 4\sigma$ (σ = 1259.33 m), were filtered out with σ being the standard deviation. This way 1.85% of the originally identified clear sky winds were removed to yield a final total of 147,602 cloud-free retrievals.

As shown in Fig.1a, most clear sky winds have either a northerly or southerly direction, and a small velocity. The standard deviation of the NS component is 1.95 m/s, about three times higher than that of the EW component (= 0.69 m/s). This was not unexpected, as the MISR stereo method is known to be more uncertain in the along-track (mostly meridional) direction than in the cross-track (mostly zonal) direction, because of the difficulty in untangling cloud motion and CTH from the measured along-track parallax (see [2]). This also means that along-track wind errors and CTH errors are strongly correlated. Fig.1b shows that the height error is always positive for northerly wind errors but negative for southerly wind errors, and decreases with along-track wind speed from $\pm$500 m for winds of 6 m/s to $\pm$ 160 m for winds $\leq$ 2 m/s, yielding a CTH sensitivity $\sim$ 83 m/ m/s.

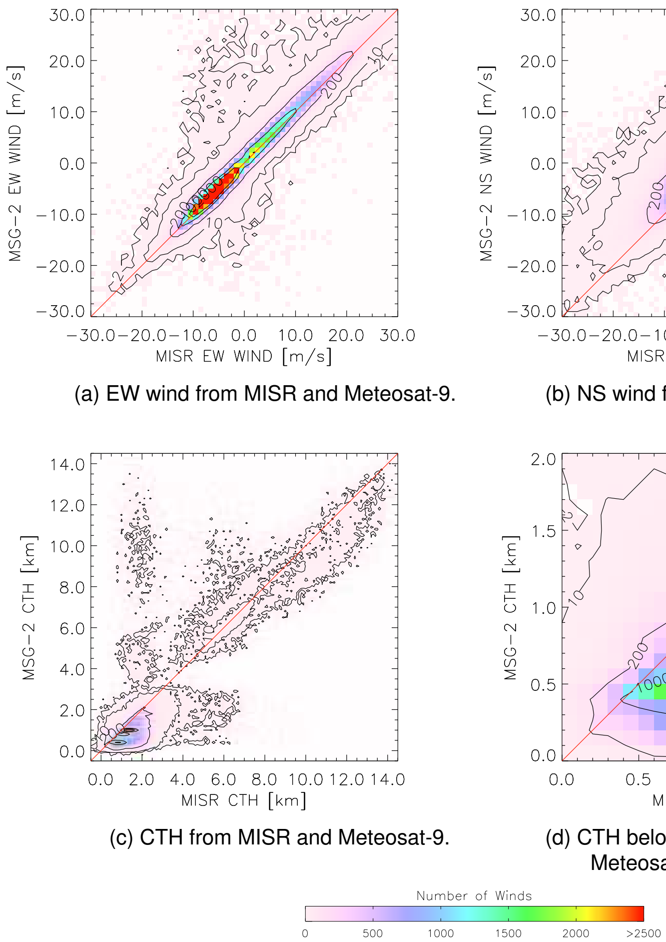
4 Analyses and Results

Overall 225,155 matched wind pairs were found, with 200,554 samples (89%) over water and 24,501 samples (11%) over land. Table 1 lists the bias, RMSD and correlation for the wind components and CTH separately over water, land, and water and land. Note, that all statistical parameters are smaller over water than over land, except for the CTH bias. For the latter, the bias is almost 100 m smaller, but the RMSD is about 650 m higher over land than over ocean. This indicates that the variability of CTH differences between MISR and Meteosat-9 is remarkably higher over land than over ocean.

VARIABLE	REGIME	STATISTICS			MEAN	
		Bias	RMSD	Corr	MISR	MSG-2
EW Wind	Water & Land	-0.42 m/s	2.52 m/s	0.97	0.43 m/s	0.86 m/s
	Water	-0.39 m/s	2.42 m/s	0.97	0.28 m/s	0.67 m/s
	Land	-0.72 m/s	3.19 m/s	0.95	1.68 m/s	2.40 m/s
NS Wind	Water & Land	-1.13 m/s	4.13 m/s	0.84	0.02 m/s	1.15 m/s
	Water	-1.06 m/s	3.96 m/s	0.85	0.11 m/s	1.17 m/s
	Land	-1.72 m/s	5.25 m/s	0.73	-0.76 m/s	0.96 m/s
Wind Speed	Water & Land	0.21 m/s	3.32 m/s	0.87	10.28 m/s	10.07 m/s
	Water	0.22 m/s	3.14 m/s	0.88	10.34 m/s	10.12 m/s
	Land	0.10 m/s	4.52 m/s	0.83	9.76 m/s	9.65 m/s
CTH	Water & Land	450 m	1078 m	0.89	2130 m	1680 m
	Water	462 m	987 m	0.88	1883 m	1421 m
	Land	355 m	1637 m	0.87	4142 m	3787 m

Table 1: **Overall bias, RMSD and correlation for EW wind, NS wind, wind speed and CTH between MISR and Meteosat-9. For reference, the means of MISR and Meteosat-9 variables are also listed.**

The bias in the wind components is always negative, that is, the MISR wind components are more easterly and northerly than the Meteosat-9 ones. Overall, Meteosat-9 underestimates CTHs compared to MISR, in addition to retrieving stronger zonal and meridional winds. The zonal (EW) wind shows better agreement between MISR and Meteosat-9 than the meridional (NS) wind. This could be partly explained by MISR retrieval sensitivities, where pixel quantization in the along-track (mostly meridional) direction yields a bigger error than in the cross-track (mostly zonal) direction. Fig.2 shows the distributions of EW wind, NS wind, and CTH for the collocations over water and land as density plots. As shown, most



(a) EW wind from MISR and Meteosat-9.

(b) NS wind from MISR and Meteosat-9.

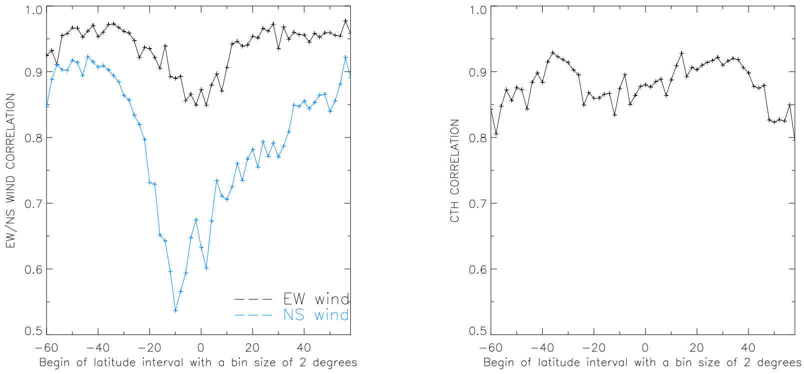
(c) CTH from MISR and Meteosat-9.

(d) CTH below 2 km from MISR and Meteosat-9.

Figure 2: **Density plot of MISR vs. Meteosat-9: a) EW wind, b) NS wind, and c) and d) CTH. Color refers to the number of wind pairs in a given bin.**

wind vectors have a zonal wind component ranging from 0 to $\pm$10 m/s and a meridional wind component ranging from 0 to $\pm$ 8 m/s with CTH between 1.0 and 1.1 km.

The horizontal lines in Fig.2d are due to the Meteosat-9 retrieval technique, where the height assignment methods use forecast temperature profiles and favor specific height (pressure) levels. The wider spread in Fig.2b highlights a worse relationship between MISR and Meteosat-9 in the meridional wind direction compared to the zonal wind direction (Fig.2a). Fig.2c shows that most collocations were found at lower height levels which employ the Meteosat-9 window channel IR EBBT (equivalent blackbody brightness temperature) height assignment method. It is also shown that for MISR CTHs of one to three kilometers, Meteosat-9 often retrieves CTHs between three to five and eight to twelve kilometers. This behavior originates from collocations using the CO_2 slicing method of Meteosat-9, which mostly represented collocations over ocean, too. Almost all of the collocations found using this method with a MISR CTH of one to three kilometers and a Meteosat-9 CTH of three to five kilometers, were found in the South Atlantic Ocean between $40\,°$S and $60\,°$S. Visual analysis confirmed, that multilayer or broken cloud fields were often present in this area. As referenced in Naud et al. [4], MISR is more sensitive to low-level clouds of high contrast, and even if high cirrus clouds are present,it tends to track the more optically thick low-level clouds. Therefore, these collocations most likely corresponded to cases where Meteosat-9 tracked high-level clouds while MISR tracked low-level clouds. The CMWs with MISR CTHs of one to three kilometers and Meteosat-9 CTHs of eight to twelve kilometers could not be assigned to one specific area. The reasons for these diverse retrieved CTHs of MISR and Meteosat-9 cloud also lie in the different sensitivities in retrieving clouds, where variable cloud height levels are present, but this was not investigated.



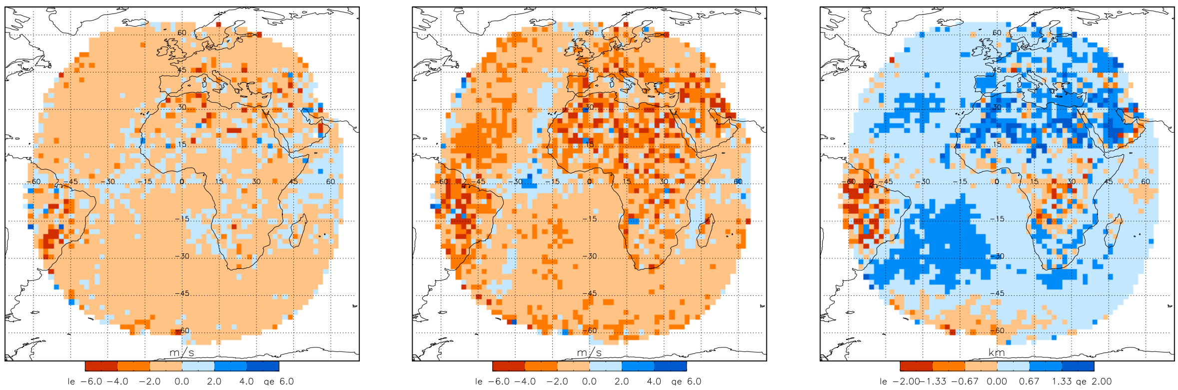
(a) Correlation for EW wind and NS wind.

(b) Correlation for CTH.

Figure 3: **Zonal distribution of MISR - Meteosat-9 comparison for EW wind, NS wind and CTH. The black line indicates EW wind and the blue line refers to NS wind.**

The zonal dependence of MISR - Meteosat-9 differences is analyzed in Fig.3. In panel (a) the zonal and meridional wind have their correlation minima in the Tropics. The correlation in NS wind is particularly small (< 0.6) between $12°$S - $4°$S. In addition, EW winds show less pronounced zonal dependence than NS winds. For both wind components the correlation is larger in the Southern Extra-Tropics (SH) than in the Northern Extra-Tropics (NH). Further investigations showed that MISR and Meteosat-9 had very good agreement in EW wind climatology, with prevailing westerlies in the NH and SH, and Tropical trade winds coming from the east. In all three zonal regions, the mean NS winds agree in sign, but differ in magnitude, meaning Meteosat-9 has stronger southerlies in SH and the Tropics, while MISR indicates stronger northerlies in NH. The statistical parameters of the collocated CTHs display slightly different behavior, where e.g. the correlation does not show any zonal dependency. Here, MISR CTHs are consistently higher by 400 to 500 m, which could be a result of Meteosat-9, erroneously assigning a large number of winds to low levels, as seen in the case study in section 5.

In order to gain a better understanding where the largest differences between the collocated CMWs occur, an investigation of the spatial distribution of biases was done. Fig.4 plots the annual-mean bias in the wind components and CTH, calculated for collocations within grid cells of $2°$ latitude x $2°$ longitude.



(a) EW wind [m/s].

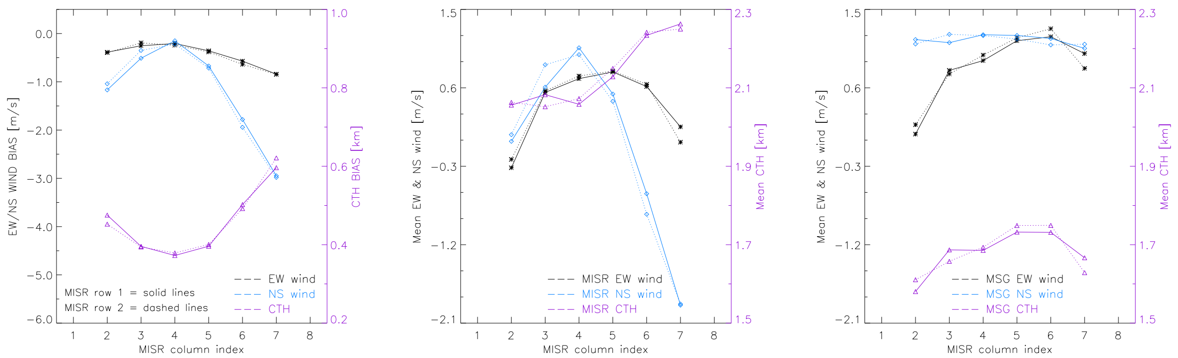
(b) NS wind [m/s].

(c) CTH [km].

Figure 4: **Geographic distribution of MISR - Meteosat-9 bias.**

As already shown the zonal wind component shows better agreement, especially over ocean, with the bias mostly within $\pm$ 2 m/s, see Fig.4a. Over parts of Brazil, North Africa and the mountainous regions of Europe, however, bigger biases up to -6 m/s were observed. A possible explanation could be the occurrence of strong vertical winds, which are often associated with convective clouds in the tropical regions and over mountainous terrain. Because the MISR algorithm assumes no vertical cloud motion, strong updrafts can introduce errors in the retrieved horizontal wind. The bias in the meridional wind components is significantly larger than those in the EW wind, especially over land where biases greater than 2 m/s are very common. Similarly to the EW wind, the bias in NS wind is also mostly negative, that is, MISR is more northerly than Meteosat-9. The statistics for CTH also shows better results over water than over land (see also Table 1). Regions with biases below 0.67 km are spread mostly throughout the oceans and some continental regions. High negative biases (Fig.4c) are detected in Brazil and for some spots in Central Africa. It is difficult to speculate on the explicit reasons for these wind and CTH differences without further analysis. As mentioned before, neglecting the vertical wind causes errors in MISR horizontal wind components. In addition, CMW retrievals are generally more difficult over land, as indicated by the frequent exclusion of such Meteosat-9 winds by the ECMWF forecast model, and which is also shown here by the poor agreement between MISR and Meteosat-9 collocations over continents. Furthermore, MISR is more sensitive to low-level clouds than Meteosat-9, therefore, differences in multilayer clouds might simply due to different retrieval sensitivities.

Another interesting feature is the dependence of the comparison statistics on MISR cross-swath domain position. The upper (first) row of a MISR block is the one lying more northerly, whereas the bottom (second) row lies southerly. The eight cross-swath domains are arranged in a way that the first one on the left side (labeled "1") is the westernmost one and the last one on the right edge (labeled "8") is the easternmost one. Because the matching routine looks for a Meteosat-9 CMW that is nearest to a MISR CMW (one per domain), each collocation can be referenced to a specific MISR domain, row and block. Fig.5a shows the dependence of the bias in EW wind (black line), NS wind (blue line), and CTH (purple line) on the MISR cross-swath position. In our dataset, no collocations were found within MISR domains 1 and 8, because in these edge domains hardly any MISR CMWs were retrieved.



(a) Dependence of bias in EW wind, NS wind and CTH on MISR domain index.

(b) Dependence of MISR EW wind, NS wind and CTH on MISR domain index.

(c) Dependence of Meteosat-9 EW wind, NS wind and CTH on MISR domain index.

Figure 5: **Dependence of statistical parameters of EW wind, NS wind, and CTH on MISR cross-track position. Here, black refers to EW wind, blue to NS wind and purple to CTH. Collocations found in the top (first) row of a MISR block are displayed by a solid line and ones found in the bottom (second) row are displayed by a dashed line.**

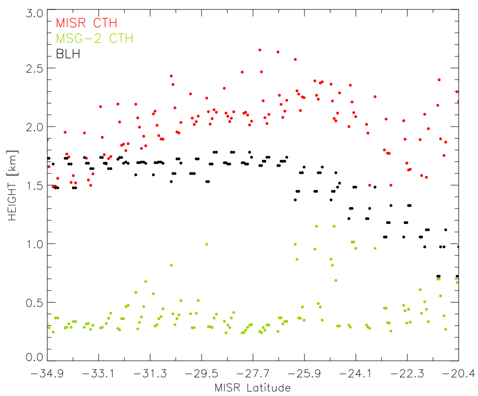
A significant variation in the bias of all three displayed wind variables with MISR domain number is visible. The smallest biases of around -0.2 m/s for the wind components and around 370 m for the CTH can be found in the middle of a MISR block, in domain four. The absolute bias then increases towards the edge domains two and seven. However, there is a clear east-west asymmetry with the largest biases occurring in the easternmost domain number seven: around -0.8 m/s for the EW wind, -3.0 m/s for the NS wind, and around 600 m for the CTH. In general, the EW wind bias does not vary so significantly with cross-swath position as the bias in NS wind and CTH, the latter two of which are highly correlated. This is probably due to the better geo-rectification of MISR in the cross-track (EW) direction and the different cross-track and along-track sensitivities. The larger biases detected in the MISR edge domains are probably a result of as yet unknown errors in the MISR look-vectors or residual registration issues. Fig.5b confirms that it is the mean MISR NS wind that shows a strong cross-swath dependence, whereas the mean Meteosat-9 NS wind plotted in Fig.5c does not show this behavior and is quite constant. From this it is obvious that the observed cross-track variation of the NS wind bias is a result of MISR retrieval issues, which should be addressed in the future.

In a similar vein, we also analyzed the dependence of differences on Meteosat-9 viewing zenith angle (VZA), but we could not detect a general worsening of the comparison parameters with increasing VZA.

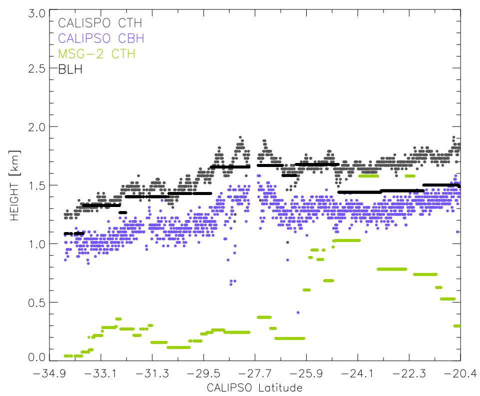
5 Case study

Fig.4c shows an extensive area in the South Atlantic from $35\,°$S to $15\,°$S with a large positive difference in cloud top heights between MISR and Meteosat-9. Visual analysis confirmed that in this region MISR CTHs were systematically higher than Meteosat-9 CTHs by one kilometer, despite wind speed and direction retrievals being very consistent. For further investigation, MISR orbit 46,033 was selected, because it included the largest number of scenes with this particular behavior.

MISR orbit 46,033 was collected on 13 August 2008 from 09:39:22 UTC to 11:18:16 UTC, from which we selected an area between $34.9\,°$S to $20.4\,°$S for a detailed analysis. A large marine stratocumulus field dominated this region persistently during the whole day, where the MISR path sampled the open cell part of the cloud field. For this MISR track, Meteosat-9 winds had very low CTHs compared to MISR CTHs. In order to investigate these discrepancies, cloud top heights and cloud base heights (CBHs) from the nearest CALIPSO orbit were used, which sampled the closed cell part of the cloud field, laying west of the MISR path. The plotted MISR track was collected between 10:13 UTC and 10:41 UTC, while the CALIPSO track corresponded to a time period between 14:57 UTC and 15:01 UTC on 13 August 2008. As an additional, independent data set, boundary layer heights (BLHs) from the ECMWF ERA Interim reanalysis were also used in the comparison; these BLHs are said to be equivalent with CTHs in a marine stratocumulus field [5].



(a) Comparison of CTHs from MISR (red) and Meteosat-9 (green) from part of the orbit 46033 and the corresponding boundary layer heights (black).



(b) Comparison of CALIPSO CTHs (gray) and CBHs (purple), the corresponding boundary layer heights (black), and Meteosat-9 CTHs (green).

Figure 6: **Comparison of CTHs from MISR, Meteosat-9, CALIPSO and the corresponding ERA Interim boundary layer heights.**

In Fig.6a MISR CTHs are plotted in red and Meteosat-9 CTHs in green. The average MISR CTH for this track was 2.0 km, while the collocated mean Meteosat-9 CTH was about 0.5 km. BLHs from the ERA Interim reanalysis data are displayed in black, corresponding to the location and time of MISR CTHs. As shown, the boundary layer heights laid more in the range of MISR CTHs, with a mean of 1.5 km. Note that the BLHs are a reanalysis product with a "coarse" $1.5\,°$ resolution; therefore, some discrepancies are expected when compared to high resolution MISR and Meteosat-9 measurements. The retrieved CALIPSO CTHs and CBHs, colored in black and purple, respectively, are also compared to the corresponding BLHs in Fig.6b. Currently, CALIPSO cloud top heights are considered the most accurate CTHs measurements from space and are often used as reference in comparisons [6].

In our particular case, the mean CALIPSO CTH was 1.6 km and the mean CBH was 1.2 km. The corresponding ERA Interim BLHs followed the CALIPSO CTHs very nicely, which was also evident in a mean BLH of 1.5 km, very close to the CALIPSO mean. It is safe to say that the ERA Interim reanalysis BLHs were representative of CTHs in this case. Also note that the BLHs for the MISR and CALIPSO times and locations were very similar, which was consistent with the persistent nature of the cloud field. By comparing the CALIPSO CTHs and the ERA Interim reanalysis BLHs separately with MISR and Meteosat-9, we concluded that MISR CTHs were more representative of the actual CTHs than the collocated Meteosat-9 CTHs. One possible reason for the very low Meteosat-9 CTHs in our Stratocumulus field might have been the influence of warm sea surface temperatures on the Meteosat-9 height assignment method. In total, 129 collocated cloud motion winds of MISR and Meteosat-9 were used here, of which 128 were retrieved using the window channel IR EBBT height assignment method of Meteosat-9. This method finds CTHs by comparing the retrieved EBBT with a forecast temperature profile. Along the MISR track a broken marine stratocumulus field is visible. Due to the relatively coarse Meteosat-9 spatial resolution of 3 km, the retrieved EBBT was likely contaminated by the warmer sea surface. By using such positively biased cloud-top temperatures to find the corresponding pressure levels, one obtains positively biased pressures and negatively biased CTHs.

It is well known, that geostationary satellites have difficulties retrieving the correct CTH for low-level clouds, especially in subsidence areas in the Atlantic or when very scattered low clouds occur. In areas where NWP profiles show a temperature inversion, Meteosat-9 CMWs rely on an inversion height assignment instead of the standard height assignment methods[7], forcing cloud heights to the level of the temperature inversion. Normally, clouds cannot be located above this inversion layer (personal communication with Régis Borde, EUMETSAT) and winds below the inversion are expected to be consistent with the cloud movements. In cases without temperature inversion a different technique is used to correct CTHs of low level cumuli type clouds, which is based on the work of Le Marshall et al. [8]. In this approach, the height of the CMW is set to the cloud base (CBH assignment method), because it has been observed that these clouds tend to travel with the wind at cloud base [9]. Both of these techniques were tested for Meteosat-9 and were found to generally assign more accurate CTHs for low-level cumuli type clouds. However, it was not possible to attain improved heights for all low-level cloud clusters. Especially in cases of very scattered low clouds where warm sea surface temperatures and cold cloud tops were merged together, the CBH assignment method assigned clusters too low, even below 1000 hPa. Therefore, an additional filter was implemented to reduce this problem, affecting 10 - 15% of CMWs.

In sum, the Meteosat-9 CTHs in this case study were assigned to very low levels and did not agree with more realistic CALIPSO and MISR heights. This indicates that there are still some unresolved difficulties in Meteosat-9 height assignment in low-level cumuli type clouds, notwithstanding the above correction techniques particularly designed for these clouds.

6 Summary and Conclusions

In this work the relationship between high quality CMWs from MISR and Meteosat-9 was investigated in a large, statistically significant data set. For the year 2008, a total of 225,155 matched wind pairs were found with 89% of the collocations over water and 11% over land. One of our general findings is that MISR and Meteosat-9 EW wind components compare better than NS wind components. Analysis of seasonal and zonal dependencies also support this conclusion. Another basic finding is that the techniques agree better over water than over land. In particular, MISR - Meteosat-9 differences in EW wind, NS wind and CTH are increased over land, as shown by larger RMSDs. For example, the RMSD in CTH was about 67% higher over land than over water, as shown in Table 1.

The level of agreement also varied with geographic location, for example the linear correlation between the NS wind components was significantly lower in the tropical regions than in the extra tropics. Furthermore, in some regions, such as Brazil and North Africa, high negative biases and large RMSDs were noticed in the CTHs, which, we hypothesized, could be due to comparing low-level clouds detected by MISR (apples) with high-level clouds detected by Meteosat-9 (oranges). However, further studies have to be conducted to unequivocally clarify this aspect. We also investigated the dependence of the comparison on MISR cross-swath location. To our surprise, the biases in both wind components and CTH showed a clear dependence on cross-swath position, as demonstrated in Fig.5a. In particular, the biases in the NS wind and CTH were highly correlated, and showed high absolute values in MISR edge domains and low absolute values in the innermost MISR domains, without a large variation in the

RMSD. The exact reason for this cross-swath bias is unclear at this stage and requires more detailed analysis; nevertheless, potential errors in MISR look-vectors are a good candidate. A similar analysis concerning the effect of Meteosat-9 viewing zenith angles (VZAs) on the comparison revealed small overall dependence on VZA for the wind components, but relatively large variations for the bias in CTH.

A case study of a marine stratocumulus field in the Southeast Atlantic Ocean showed large differences between MISR and Meteosat-9 CTHs, although wind speed and direction agreed very well. Here, CTHs captured by MISR were approximately one kilometer higher than CTHs from Meteosat-9. A further comparison with CALIPSO lidar heights and model boundary layer height estimates revealed that MISR CTHs were more realistic than Meteosat-9 ones. This was probably due to a low bias in the Meteosat-9 brightness temperature height assignment method, which puts winds unreasonably close to the surface, especially in case of broken cloud fields.

Quality-controlled CMWs from operational geostationary and polar-orbiter platforms have long reached a maturity where they have a positive impact on numerical weather forecasts; nevertheless their height assignment can still be significantly improved. The MISR instrument presents a new source of CMWs derived by a unique stereo method, which simultaneously retrieves cloud heights without the need for any ancillary information. The potential of this novel data set, however, can only by realized if its errors are well characterized. Our comparison study represents a step in that direction. Here, we found that MISR CMWs were in good overall agreement with Meteosat-9 winds and regarding CTHs were even more accurate under certain conditions, as demonstrated by a marine stratocumulus case. In addition, MISR has the advantage of retrieving CMWs at high latitudes, which are not covered by geostationary platforms and at present only sparsely sampled by MODIS. Therefore, height-resolved measurements of cloud motion by a future MISR-like instrument with a wider swath and day/ night capability could fill current observational gaps and, further improve numerical weather forecasts.

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