Inter-comparison of MERIS, MODIS and MISR cloud top heights

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ABSTRACT

The objective of this study was to assess the accuracy of MERIS cloud top pressures through an inter-comparison with CO_2-slicing MODIS cloud top pressures and stereo MISR cloud top heights, both instruments of which are onboard the NASA-TERRA platform. For ground-based "truth" measurements, millimetre wavelength cloud radars data were used at the ARM SGP and UK Chilbolton sites. Cloud top pressures were transformed into heights using ECMWF Operational analysis profiles. An excellent agreement was found between MERIS, MISR and the radar cloud top heights when single opaque clouds were present. When clouds were optically thin, MERIS cloud top pressure retrievals were not available and when more than one cloud layer was present, MERIS CTH often referred to the lowest cloud top or some altitude between cloud layers. MISR cloud top heights referred to low clouds in multiple layers conditions, due to their higher contrast, and MODIS CTHs were found too low for low clouds, slightly too high for mid-level clouds and within the cloud extent or near the top of high clouds.

1 INTRODUCTION

A new series of polar orbiters has recently been launched with a new generation of instruments onboard that use different ways of observing the Earth and different methods of observing clouds in particular. The ENVISAT satellite was launched on March 1st 2002 with the Medium Resolution Imaging Spectrometer (MERIS) onboard. MERIS observes the Earth with 15 very narrow spectral channels in the visible and near-infrared. Cloud top pressures (CTPs) are estimated using a channel in the Oxygen absorption A-band centred at 0.76μm [1]. In order to assess the accuracy of this product, we compared MERIS CTPs with other ground-based and satellite instruments over two locations: the Atmospheric Radiation Measurement (ARM) program Southern Great Plain (SGP) site near Lamont, OK (36.62°N-97.5°W) and the Chilbolton Facility for Atmospheric and Radio Research (CFARR) site in Southern England (51.15°N, 1.43°W). At both sites, vertically pointing MilliMeter wavelength Cloud Radars (MMCR) are continuously and automatically operated to monitor clouds. The CFARR 94GHz and the SGP 35GHz MMCR data are both processed using a code developed by [2] and a continuous cloud mask indicates the presence of hydrometeors every 10s at a 75m vertical resolution, giving a ground "truth" value of cloud top height (CTH) at the time of the ENVISAT overpass. This assessment of MERIS cloud top pressure accuracy was also conducted by comparing them with retrievals from the Multi-angle Imaging SpectroRadiometer (MISR) and the MODerate resolution Imaging Spectrometer (MODIS). Both instruments are onboard TERRA, which was launched in December 1999. The instruments and techniques used to retrieve and compare cloud top heights are presented in the next section. Section 3 presents the results for both sites, and section 4 summarises our conclusions.

2 INSTRUMENTS AND PRODUCTS

The MMCR instruments give vertical profiles of cloud presence every 10s and cloud boundaries (masks) can be obtained with a 75m accuracy. The cloud mask can identify hydrometeors and can partly distinguish them from clutter such as vegetation debris or insects. Because MMCRs are detecting precipitation as well as cloud, cloud bases are detected with a vertically pointing lidar as these instruments are not as sensitive to rain droplets below cloud base. The radar cloud top height time series were sampled over 5, 10, 20 and 40 minutes centred on MERIS and MODIS start times, in order to get a full picture of the CTH variability over time in situations of broken clouds. The median CTH was then calculated over these time periods, as well as the frequency of cloud occurrence.

MERIS is a pushbroom imaging spectrometer onboard ENVISAT that measures the solar radiation reflected by the Earth, in 15 spectral bands, programmable in width and position, in the visible and near infra-red. The algorithm used to estimate the cloud top pressure uses reflected solar radiation within the Oxygen A-band absorption band centred at 0.76µm. The algorithm is based on the assumption that the mean photon path length of the reflected solar radiation is related to the amount of absorption measured in the O_2 A-band. In a cloudy atmosphere the mean photon path length is primarily determined by the air mass above the cloud, i.e. the cloud top pressure. However multiple scattering of photons within the clouds, between cloud layers and between clouds and the surface significantly increases the photon path and must therefore be considered. This is done by the inversion of radiative transfer calculations using artificial neural networks. The radiative transfer calculations are pre-computed and the algorithm was developed for clouds with optical thickness greater than 5. The algorithm is described in more detail in the ATBD [1]. As only one MERIS channel was selected within the O_2 absorption band, the algorithm cannot determine the penetration depth of the photons into the cloud. Only an estimate using the total optical depth is possible. For multi-layer clouds with an optically thin uppermost level cloud, the penetration depth will be underestimated, leading to an overestimation of the upper cloud top pressure. The overestimation is larger for thinner top-level clouds. In general, the retrieved cloud top pressures are found between the lower and the upper cloud tops.

MISR is composed of 9 pushbroom cameras observing the Earth in 3 visible and one near infrared channels, from 9 different view angles. Cloud top heights (CTHs) are retrieved using a (purely geometrical) stereo-matching technique partly developed at UCL [3]. The stereo heights are corrected for wind advection when the operational wind retrieval is flagged as satisfactory. When this was not the case, coincident radiosonde profiles were used from nearby stations providing profiles of N-S winds that give a height correction to be applied onto the uncorrected operational stereo cloud-top heights.

MODIS is a whiskbroom imager with 36 channels from the visible to the CO_2 absorption band at 15μm and retrieves cloud top pressures using the CO_2-slicing technique [4]. Because of signal to noise issues at low altitudes for the channels near the 15μm wavelength, this technique cannot be used for low level cloud top pressures. Instead, the 11μm brightness temperatures is used to derive the cloud top pressures using Global Data Assimilation System (GDAS) temperature profile data from NCEP (National Centers for Environmental Prediction).

MERIS and MODIS operational products are cloud top pressures but to directly compare with the radar CTHs and MISR stereo heights, they were transformed into heights using ECMWF operational analysis profiles collected at 1200UT for CFARR and 1800UT for SGP. MERIS, MODIS and MISR CTHs were sampled over areas centred on the radar sites and covering ±0.2°, ±0.1°, ±0.05° and ±0.02° in latitude and longitude. This allowed us to fully account for the most frequent CTH in broken cloud situations. Median CTHs were calculated within each latitude-longitude box and compared with the radar median CTHs. If the median CTHs varied substantially between each time period for the radar or each box for the satellite instruments the case was rejected. The frequency of CTH occurrence within each box was also estimated.

A pixel by pixel comparison between MERIS and the other two TERRA instruments was not performed because of the time delay between the two satellite overpasses; in general ENVISAT is followed by TERRA within about 30 minutes. Finally, MERIS full resolution products were not available, so the reduced 1.2km resolution cloud top pressures processed at the Freie Universitat Berlin were used instead. MISR CTH resolution is 1.1km, and MODIS resolution is 5km for cloud top pressures.

3 COMPARISON BETWEEN MERIS, MISR, MODIS AND RADAR CTH

In order to classify all the cases examined in this comparison, we distinguished between low-level, mid-level and high-level clouds; between continuous and broken clouds and between single and multi-layer clouds. The cases were selected from January 2003 until August 2003 for all the level 1 MERIS data that the Freie Universitat Berlin had received to date. The SGP MMCR did not function properly before mid-February 2003 so coincidences between ENVISAT and TERRA prior to this date were ignored. The CFARR MMCR ceased functioning in March 2002 and started operating again from April 2003, so dates prior to this were not taken into account. MISR swath width is narrow (≤360km) so only three orbits out of the 233 that cover the entire globe can be used for a single point on the ground at mid-latitude. Every orbit has a repeating cycle of 16 days, subsequently each site is observed by MISR only 5 to 6 times a month even if TERRA overpasses occur everyday. This limited the number of available cases when both satellites observed the sites within a reasonable time delay. In order to increase the number of comparisons, MERIS was compared with the radar for several dates when no MISR overpass was occurring over the CFARR site. The CTHs from all instruments including location and date are summarised in table 1.

Table 1: Summary of all comparisons performed at SGP and CFARR between MERIS, MISR, MODIS and radar, from February to July 2003, according to a cloudy situation. When more than one cloud layer is detected by the radar, the cloud top heights of the highest layer as well as one below are given and marked with (*). MISR CTH was different for the small latitude-longitude boxes and are indicated next to the CTH given by the ±0.2° box ($^{\#}$).

Cloud situation	Date and location	MERIS and Radar CTH (km)			MISR, MODIS and Radar CTH (km)				MODIS cloud optical depth (whole column)
		Time of overpass (UT)	MERIS	Radar	Time of overpass (UT)	MISR	MODIS	Radar	
Low continuous	2003-02-15, SGP	16:58	1.9	2.0	17:30	2.2	0.8	2.1	99
	2003-05-20, CFARR	10:57	1.8	2.3	No TERRA coincidence				
	2003-07-04, CFARR	10:43	1.8	1.6	No TERRA coincidence				
Low broken	2003-05-11, CFARR	10:42	CTHs too variable		11:10	1.0	0.6	1.1	18 (max)
	2003-06-05, CFARR	10:54	2.0	2.1	No TERRA coincidence				
	2003-06-12, CFARR	10:35	1.7	1.6	11:10	1.5	0.9	2.0	7
Low multi-layer	2003-05-27, CFARR	10:37	1.2	2.5/1.4*	11:10	1.2	2.3	2.5/1.4*	47
Mid-level continuous	2003-06-07, SGP	16:39	4.3	4.6	17:30	4.5	6.1	4.7	25
Mid-level broken	2003-06-09, SGP	17:15	4.9	6.2	17:15	5.4	7.1	6.2	2.3
	2003-06-18, CFARR	10:46	2.5	4.2/1.8*	No TERRA coincidence				
High multi-layer	2003-05-15, SGP	17:01	5.0	11.7	17:25	9.0	10.6	11.6	28
	2003-05-31, SGP	16:58	5.5	12.4	17:25	9.0/5.3[#]	10.6	11.8	15
	2003-07-01, CFARR	10:38	Too variable	8.5	No TERRA coincidence				

3.1 Comparison over ARM SGP site

We found 11 coincidences between TERRA and ENVISAT with the 35GHz radar fully functioning from January to August 2003. However, only 5 cases contained clouds thick enough to allow the MERIS retrieval to function properly.

One occasion showed a low single and continuous cloud, and we found a difference of 0.1km between radar CTH and MERIS CTH. Half an hour later, the radar CTH was at 2.1km (0.1km higher), whilst MODIS CTH was 0.8km for all boxes and MISR CTH was not available with wind correction in the operational product. However, the uncorrected MISR CTH is at 1.8km, only 0.3km lower than the radar and when we used the coincident radiosonde wind profile to correct MISR CTH, we found a CTH at 2.2km, only 0.1km higher than the radar.

Two occasions showed a mid-level cloud situation. The clouds were continuous on one occasion and scattered on the other. For the continuous mid-level cloud case, the delay between the ENVISAT and TERRA overpasses was nearly one hour, however the radar CTH only varied from 4.6km to 4.7km during that time period. MERIS CTH was in good agreement at 4.3km, as well as MISR at 4.5km. MODIS CTH was found at 6.1km, which could be caused by the presence of higher clouds in the vicinity of the site that could have signified a large signal in the 5km MODIS pixels even if not present over the SGP site. The broken mid-level cloud case gave a radar CTH at 6.2km for both overpasses. MODIS CTH above the site was at 7.4km for the ±0.02° box, but there were high clouds before and after the satellites overpasses detected by the radar so maybe again the large MODIS pixels may partially detect high clouds that are not detected by the radar at the time of the overpass. MERIS and MISR CTH are found below the radar cloud base height. In the case of MERIS this could be due to the low optical depth of these clouds as MODIS cloud optical depth is found to be 2.3 in the pixel directly above the site. In the case of MISR, there could be problems with the wind correction as the uncorrected MISR CTH is at 6.3km, very close to the radar retrieval. When MISR CTHs were corrected using the radiosonde wind profiles, we found an even lower MISR CTH. It could be possible that the wind speeds and directions were highly variable on this day, making the wind retrieval and correction a challenging and impractical task.

The last two cases were high cloud situations, and on both occasions more than one cloud layer was present. On the first occasion, two layers were present at the time of ENVISAT overpass that became a single layer at the time of TERRA overpass. The radar CTH was fairly continuous from one overpass to the next, from 11.7km to 11.6km 30 minutes later. The MERIS CTH was lower, at 5km, which was very close to the top of the lowest layer. On the contrary, MODIS

CTH was very close to radar CTH at 10.6km, whilst MISR CTH was lower at 8.6km when uncorrected and 9km when corrected with a coincident radiosonde wind profile. MISR estimated cloud fractions in all latitude-longitude boxes were very low and a map of MISR CTHs around the area showed that the detection rate was very small over an entire area North west of the site where MODIS detected high cloud. A true colour image of the area was produced using the red, green and blue channels of MISR Nadir camera and revealed the presence of high, thin and smooth clouds in the area in question. As these clouds were also visible on red-channel anaglyphs produced with the An-Af and Cf-Df cameras, we suspect that the problem came from the stereo retrieval itself. Finally, the second high cloud case gave a radar CTH at about 12km, which indicated the top of a high cloud beneath which could be seen scattered mid-level clouds on the radar reflectivity plot. MODIS optical depth for the scene indicated thin clouds, below the limit of MERIS sensitivity. Consequently, MERIS CTH was at a level closer to the mid-level clouds than the top of the high cloud. MODIS CTH was 10.6km, closer to the base than the top of the cloud. MISR CTH was found near the highest cloud base when considering the largest area, but close to the mid-level clouds when reducing the area around the site. The contrast displayed by the mid-level scattered clouds was probably higher than the one displayed by the thin cirrus cloud above them, which caused the stereo CTHs to be assigned at the top of the mid-level cloud [5].

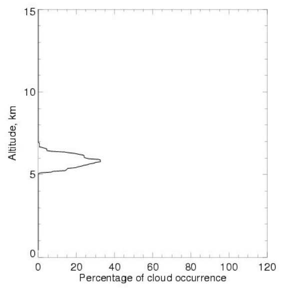

Fig. 1. Radar cloud occurrence as a function of height over a 40 minutes period centred on MERIS overpass time at SGP (17:17UT, 2003-06-09). The median radar CTH was found at 6.2km, MERIS median CTH was found at 4.9km.

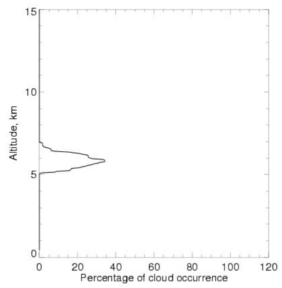

Fig. 2. Radar cloud occurrence as a function of height over a 40 minutes period centred on MODIS start time (17:15UT, 2003-06-09) at SGP. The median radar CTH was found at 6.2km, MISR median CTH at 5.4km, MODIS median CTH at 7.4km and optical depth at 2.3.

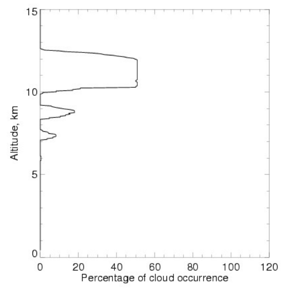

Fig. 3. Radar cloud occurrence as a function of height over a 40 minutes period centred on MERIS overpass time at SGP (17:00UT, 2003-05-31). The median radar CTH was found at 12.1km, MERIS median CTH was found at 5.5km.

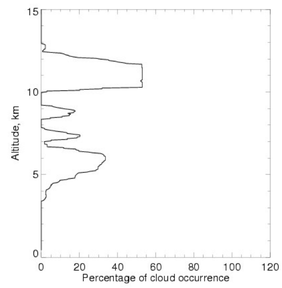

Fig. 4. Radar cloud occurrence as a function of height over a 40 minutes period centred on MODIS start time (17:25UT, 2003-05-31) at SGP. The median radar CTH was found at 11.8km, MISR median CTH at 9.9km for the ±0.2° box and 5.3km for the others, MODIS median CTH at 10.6km and optical depth at 14.5.

3.2 Comparison over CFARR site

From April 2003 until August 2003, 8 dates were found with clouds over the radar at the time of a MERIS overpass. Out of these 8 dates, 3 were found to also have a coincident TERRA overpass with the site within MISR's field of view. When the radar observed a single layer, low level cloud, we found that clouds were broken on 3 occasions, and this could be measured by estimating the number of pixels with a CTH retrieval out of the total number of pixels available in the satellite instrument sampled area or the radar time period. On one occasion, MERIS cloud cover was about 6% for the ±0.2° box and no cloud was detected in the 0.05° and 0.02° boxes. The MERIS median CTH was found at 1.5km for the ±0.2° box and 1.6km for the ±0.1° box. However, the radar displayed a significant difference between the median CTH for the 5 minutes sampling period (CTH=1.3km) and for the longer time periods (2.2km, 2.3km and 2.4km for 10, 20 and 40 minutes respectively). Because of these large variations, we discarded this case from our comparison. For the other two occasions where broken clouds were observed, there were few variations from one time period to the next for the radar or between the differently sized areas for MERIS. When we included these last two cases in the data pool that contained cases where a single level low cloud was present, we found that for these 4 occasions in total, the difference between the radar and MERIS CTH was 0.1±0.3km on average. The other three cases showed more than one cloud layer and on these occasions MERIS CTH did not refer to the highest cloud layer. One case showed two low cloud layers with cloud-top heights at 1.4 and 2.5km respectively. MERIS CTH referred to the lowest layer. Another occasion showed scattered mid-level clouds above a continuous low cloud layer. MERIS CTH was found between the top of the low-level cloud and the base of the scattered mid-level clouds. Finally, the last occasion showed a continuous high cloud with some mid-level and low broken clouds beneath. MERIS CTH was found

to be varying between 2.9km for the largest box to 4.7km for the smallest box, so it was not possible to identify which layer it was referring to.
On three occasions, MISR and MODIS CTH were available 30 minutes after ENVISAT overpass. One of these occasions was the case when broken clouds were found and a reliable comparison between MERIS and the radar could not be performed. MISR and MODIS median CTHs for the largest box were fairly consistent with values from the smaller ones, and the estimated cloud fraction greater than for MERIS. The radar cloud fraction on the contrary was low. However, it was possible to retrieve a median CTH for the 20minutes and 40minutes time period and they were found to equal 1.1. and 1.2km respectively. MISR CTH was 1.0km for the largest box and MODIS CTH was 0.6km. Both instruments were found in fairly good agreement with the radar. The next case was a two low-level clouds situation. MISR CTH was found to agree with MERIS and assigned at the top of the lowest layer whereas MODIS CTH was very close to the radar CTH for the highest layer. Finally, the third case was a low slightly broken single layer cloud situation. MODIS CTH was found to vary from 0.6km for the largest box to 0.9km for the smaller ones. The radar indicated a CTH at 2km, so MODIS CTH clearly underestimated the cloud top height. MISR CTH was found at 1.5km for all boxes, so 0.5km lower than the radar CTH which is within the estimated accuracy of the instrument. It should be noted that the CTH without wind correction is at 2.3km, so closer to the radar CTH. It may be possible that some errors in the wind speed retrieval caused the correction to be slightly too large.

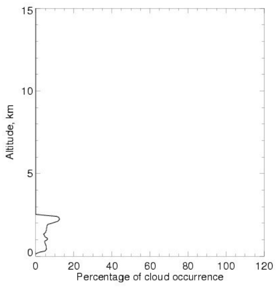

Fig. 5. Radar cloud occurrence as a function of height over a 40 minutes period centred on MERIS overpass time at CFARR (10:42UT, 2003-05-11). The median radar CTH and MERIS median CTH were varying too rapidly from one time period / one box to the next.

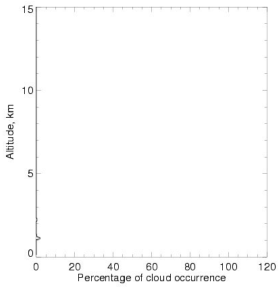

Fig. 6. Radar cloud occurrence as a function of height over a 40 minutes period centred on MODIS start time (11:10 UT, 2003-05-11) at CFARR. The median radar CTH was found at 1.2km for the 40 minutes time period, MISR median CTH at 1.0km, MODIS median CTH at 0.6km and optical depth at 4.3.

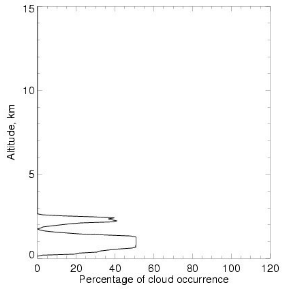

Fig. 7. Radar cloud occurrence as a function of height over a 40 minutes period centred on MERIS overpass time at CFARR (10:39UT, 2003-05-27). The median radar CTH was found at 2.5km for the highest layer and 1.4km for the lowest, MERIS median CTH was found at 1.2km.

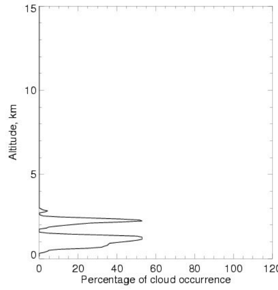

Fig. 8. Radar cloud occurrence as a function of height over a 40 minutes period centred on MODIS start time (11:10UT, 2003-05-27) at CFARR. The median radar CTH was found at 2.4km for the heist layer and 1.4km for the lowest, MISR median CTH at 1.2km, MODIS median CTH at 2.3km and optical depth at 47.

4 CONCLUSION

Two ground-based sites were used for a comparison of MERIS, MISR and MODIS CTHs with radar CTHs. Altogether, MERIS CTHs were compared with the radar CTHs on 13 occasions. 7 cases showed low clouds, 3 with a stable and fairly continuous cloud top from ENVISAT to TERRA overpasses, another 3 with scattered clouds and one with more than one cloud layer. 3 mid-level cloud cases and 3 high cloud cases were also found.
When the clouds were single and not highly broken (low and mid-level clouds for these cases):

- MERIS and MISR CTHs agreed well with the radar, with a mean difference between the radar and MERIS CTHs of 0.1±0.3km and for the three cases with radar and MISR CTHs, with a mean difference of 0.2±0.3km.
- MODIS CTHS were found lower than the other instruments, with differences as large as 1.5km for low clouds, whereas they were found slightly higher than the radar CTHs for mid-level clouds

When the clouds were in multi-layer situations with one or more layers broken:

- MERIS CTHs referred to either the top of the lowest layer or between layers
- MISR CTHs referred to the top of the second highest layer if they displayed a higher contrast than the highest layer
- MODIS CTHs agreed well with the radar and were always found if not at the top of the highest layer at least within the extent of the cloud

This comparison demonstrated the ability for MERIS CTH to perform in excellent agreement with radar retrievals for single cloud layers with an optical depth greater than 5. If a single cloud layer was present with an optical depth less than 5, the retrieval did not give any CTH, and if more than one layer was present, with the highest layer of optical depth less than 5, either MERIS CTH referred to the top of the lowest layer or was found at an intermediate altitude between cloud layers. In this latter case, the retrieval routine treats both cloud layers as a single one with an optical depth equivalent to the entire atmospheric column optical depth and a cloud top height equivalent to the mean photon path length of the multi-layer cloud system.

MISR CTHs were found to be sensitive to the contrast displayed by the cloud layers (in terms of brightness and features) and to some extent on how well the operational wind retrieval performed.

These comparisons showed that MERIS and MISR tend to have a similar problem when observing multi-layer cloud situation in that the retrieved CTH tends to be assigned to the lowest layers. The reasons behind this behaviour are somehow different, although it should be noted that both instruments observe clouds in the visible and near infrared at which wavelength thin clouds have a lower signal than in the thermal infrared. MISR CTH retrieval algorithm is sensitive to the contrast between the near-nadir (±26º) and nadir view given by a cloud. Low clouds tend to be brighter in the visible and display a larger contrast than higher clouds. This causes MISR CTHs to often refer to the next highest cloud layer in a multiple layer scene. The MERIS CTP retrieval algorithm is sensitive to cloud optical depth and is based on radiative transfer simulations for single level cloud situations. If the highest cloud has a very small optical depth but the total column optical depth is greater than 5, the retrieved MERIS CTH will be placed between the two cloud layers. If the highest cloud is much thinner than the lower one, this will cause MERIS CTH to be very close to the top of the lower layer.

MODIS CTHs were found to be too low for low clouds. For these cases, only the 11µm brightness temperatures were used and there is clearly an issue of the reliability of the temperature profiles at low altitude. Mid-level clouds were found at higher altitude than given by the radar, this could be due to broken high clouds signal being embedded in the 5km pixels but not overpassing the radar. High cloud cases gave a good agreement between MODIS and radar CTHs, with MODIS CTHs within the vertical extent of clouds if not at the top. MODIS CTHs were not found sensitive to the number of cloud layers in the atmosphere in accordance with [6].

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