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OPERATIONAL MULTI-SPECTRAL METHODS FOR THE HEIGHT ASSIGNMENT OF CLOUD-TRACKED WINDS

At EUMETSAT the current operational height assignment is based on the so-called water vapour intercept method. This scheme utilises the radiances measured in the water vapour absorption and the infrared window channel to derive the temperature at the top of semi-transparent clouds. Another possibility to estimate the cloud-top pressure is the carbon dioxide (CO_2) absorption method that has already been successfully used with the imager data from the previous GOES satellites. The current Meteosat imager does not incorporate a CO_2 channel, however such a channel is foreseen for Meteosat Second Generation (MSG). In preparation for the new generation, the current operational height assignment techniques, as well as techniques utilising the CO_2 -channel together with new improved concepts for the existing techniques have been developed.

The paper responds to Action CGMS 28.28.

OPERATIONAL MULTI-SPECTRAL METHODS FOR THE HEIGHT ASSIGNMENT OF CLOUD-TRACKED WINDS

(CGMS 29, Action 28.28)

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ABSTRACT

At EUMETSAT the current operational height assignment is based on the so-called water vapour intercept method. This scheme utilises the radiances measured in the water vapour absorption and the infrared window channel to derive the temperature at the top of semi-transparent clouds. Another possibility to estimate the cloud-top pressure is the carbon dioxide (CO_2) absorption method that has already been successfully used with the imager data from the previous GOES satellites. The current Meteosat imager does not incorporate a CO_2 channel, however such a channel is foreseen for Meteosat Second Generation (MSG). In preparation for the new generation, the current operational height assignment techniques, as well as techniques utilising the CO_2 -channel together with new improved concepts for the existing techniques have been developed.

The described height assignment methodologies have been implemented at EUMETSAT in the MSG Meteorological Products Extraction Facility (MPEF) prototyping environment and have been applied to both GOES imager and sounder data as well as Meteosat data. This has enabled an evaluation of the reliability of the different methods as well as validation against current operational height assignment schemes. This paper will describe the height assignment techniques for semi-transparent clouds that will be applied to MSG data and the current results from the validation activities.

1. INTRODUCTION

Currently the largest single source of error of the Atmospheric Motion Vectors (AMVs) is the height assignment of the derived displacement vectors. For opaque clouds the derived Equivalent Blackbody Temperature (EBBT) gives a good estimate of the cloud top, however for high level semi-transparent clouds, the EBBT method is not sufficient. The radiation emitted from lower level clouds and surface that penetrates the cloud increases the observed radiance, hence causing an over-estimation of the cloud top temperature. In order to correct the effect of semi-transparency several techniques have been developed and successfully employed.

The contribution from lower level scenes can be compensated with the water vapour/infrared (WV/IR) intercept method (Schmetz et. al., 1993, Nieman et. al., 1993) or the CO_2-slicing approach (Eyre and Menzel, 1989, Nieman et. al, 1997, Tokuno, 1996). In an early comparison study by Nieman et. al. (1993) the two methodologies were compared and proven to be of comparable quality. The Meteosat Second Generation (MSG) will on its SEVIRI instrument incorporate additionally to the infrared window channels also channels in the water vapour absorption region and a channel in the CO_2-absorption band. It will therefore be possible to apply height assignment schemes based on both the WV/IR intercept method as well as the CO_2-slicing simultaneously. This will enable the derivation of long term statistics comparing the performances of the two systems not only as relative height differences but also the definition of their contribution to the AMV errors.

A further improvement is expected from the enhanced performance of the MSG imager SEVIRI. The selection of the spectral bands for the SEVIRI is based on the past experience with remote sensing instruments, especially the instruments on-board the operational meteorological satellites Meteosat, GOES and NOAA. Table 1 describes the expected performance of the SEVIRI spectral channels.

The signal to noise specification figures provided in Table 1 are improved with respect to Meteosat and GOES-9 (NEdT is for the infrared channels of 0.5 and 0.3 K respectively). The sampling frequency of SEVIRI will be 3 km at the SSP (Sub-Satellite Point) and the imaging frequency is 15 min. The current corresponding values for Meteosat are 5 km and 30 min. respectively. With these improvements combined with the multitude of channels it can be expected that not only the height assignment per se will be improved but also the cloud detection. Also errors originating from multi-layered cloud and cloud contamination will be improved.

Table 1. The MSG SEVIRI channels.

Channel	Bands	Centre Frequency	Spectral Band (99% energy limits)	Dynamic Range	Noise Specification
		µm	µm		Image Noise [NEdR & NEdT]
HRV	Visible & Near IR	(0.75)	Broadband (peak within 0.6 - 0.9)	0 – 459 W/m^2 sr µm	1.07 W/m^2 sr µm
VIS 0.6		0.635	0.56 – 0.71 (98% energy limits)	0 – 533 W/m^2 sr µm	0.53 W/m^2 sr µm
VIS 0.8		0.81	0.74 – 0.88	0 – 357 W/m^2 sr µm	0.49 W/m^2 sr µm
IR 1.6		1.64	1.50 – 1.78	0 – 75 W/m^2 sr µm	0.25 W/m^2 sr µm
IR 3.9	Window	3.92	3.48 – 4.36	0 – 335 K	0.35 K @ 300 K
IR 8.7		8.70	8.30 – 9.10 (98% energy limits)	0 – 300 K	0.28 K @ 300 K
IR 10.8		10.80	9.80- 11.80 (98% energy limits)	0 – 335 K	0.25 K @ 300 K
IR 12.0		12.00	11.00 – 13.00 (98% energy limits)	0 – 335 K	0.37 K @ 300 K
IR 6.2	Water Vapour	6.25	5.35 – 7.15	0 – 300 K	0.75 K @ 250 K
IR 7.3		7.35	6.85 – 7.85 (98% energy limits)	0 – 300 K	0.75 K @ 250 K
IR 9.7	Ozone	9.66	9.38 – 9.94	0 – 310 K	1.50 K @ 255 K
IR 13.4	Carbon-dioxide	13.40	12.40 – 14.40 (96% energy limits	0 – 300 K	1.80 K @ 270 K

The major advantage of the MSG SEVIRI instrument is the possibility to apply different schemes for the correction of the observed radiances of semi-transparent clouds simultaneously. Furthermore different channels and combinations of channels can be utilised. Several channels can also be utilised as a backup for the primary channels, e.g. the primary infrared window channel is the 10.8 micron channel, however it will also be possible to utilise the 12.0 micron channel. The impact of low level moisture can in such a situation be compensated, hence providing a possible backup solution in case of problems with the 10.8 channel.

2. HEIGHT ASSIGNMENT OF SEMI-TRANSPARENT CLOUDS

2.1 The WV/IR intercept method

The WV/IR intercept correction method (Sjewach, 1982) is based on the fact that the radiances in the water vapour absorption channel and the infrared window channel vary linearly for a single cloud when looking at different parts with different amount of semi-transparency of that cloud. The relationship between the observed radiance L_{ir} and L_{wv} can be determined by (Schmetz et. al., 1993):

This formulation shows that all radiance pairs L_{ir}, L_{wv} from one cloud layer with variable transparency

$$L_{wv} = xL_{ir}\frac{L_{wv}^{clr} - L_{wv}^{op}}{L_{ir}^{clr} - B_{ir}^{cld}} + \frac{xL_{ir}^{clr}L_{wv}^{op} + (1-x)L_{ir}^{clr}L_{wv}^{clr} - L_{wv}^{clr}B_{ir}^{cld}}{L_{ir}^{clr} - B_{ir}^{cld}}$$

where

$$L_{wv}^{op} = B_{wv}^{cld}t_{wv}^{A} + L_{wv}^{A}$$

$$x = \frac{1-t_{ir}^{cld}}{1-t_{wv}^{cld}}$$

located at a specific altitude lie on a straight line between the clear sky-radiances L_{ir}, L_{wv} and the theoretical radiances B_{ir}^{cld}, L_{wv}^{op} for the opaque cloud.

The theoretical relationship between the satellite observed radiances for opaque clouds at different levels in the two channels can be determined by

$$B_{wv}^{cld}t_{wv}^{A} + L_{wv}^{A} = f(B_{ir}^{cld})$$

It should be noted that in order to perform the height assignment it is assumed that the cloud emissivity in the two channels in question is the same. This is generally true for ice clouds, but not for extremely thin clouds that are first detected in the WV-channel and later in the IR channel (Schmetz et. al., 1993). The linear relationship is determined by the cloud mean radiance and either with model predicted clear sky radiances (Nieman et. al., 1993) or by utilising clear sky radiances in the vicinity of the cloud in question (Schmetz et. al., 1993). In order to derive the cloud top temperature radiances for an opaque cloud at different pressure levels are calculated with a radiative transfer model (RTM). The RTM calculations require atmospheric humidity and temperature profiles that are generally given by a numerical weather prediction model. The corrected cloud top temperature is defined by the intersect of the line determining the linear relationship and the opaque cloud curve. Figure 1 presents an example of the intercept correction scheme. The red line is the theoretical opaque cloud curve and the blue line is a regression line defined by observed clear sky and cloud cluster mean radiances. Due to this non-linearity in the thin part special care has to be taken in the determination of points used to derive the regression line. This nonlinearity can also be detected in Figure 1.

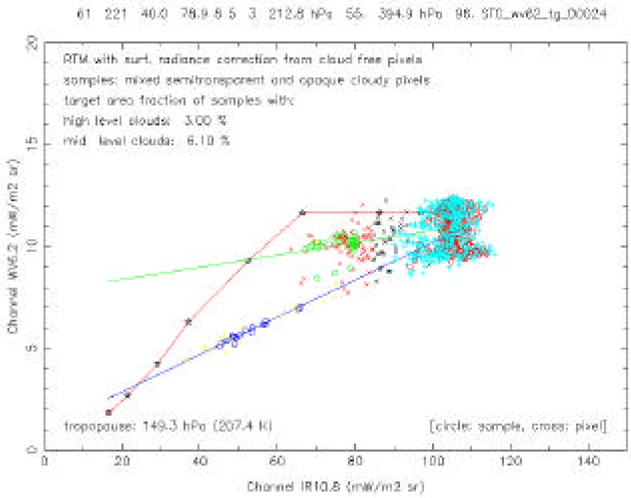

Figure 1. The current operational WV/IR intercept method applied to Meteosat data at EUMETSAT.

2.2 The CO_2 rationing method

The determination of the cloud top pressure using a CO_2 and a infrared window channel is based on equation 3 (e.g. Nieman et. al., 1993):

$$\frac{R_{CO_2} - R^{clr}_{CO_2}}{R_{ir} - R^{clr}_{ir}} = x^{CO_2}_{ir} \frac{R^{op}_{CO_2}(p) - R^{clr}_{CO_2}}{R^{op}_{ir}(p) - R^{clr}_{ir}} \qquad (3)$$

It can be seen that for clouds that have the same emissivity in the two channels the dependency on emissivity in the radiative transfer formulation is removed. A further approximation, which generally stands well for infrared window and CO_2-channel, is that the observed cloud fraction should also be the same. With these simplifications the cloud top pressure can be determined by computing the left-hand ratio with observed satellite data. The background radiance can either be determined with observed cloud free radiances or with radiative transfer calculations using NWP data. The right hand side is computed with radiative transfer calculations for opaque clouds at different levels using again NWP profiles. The cloud top pressure is found at the level where the observed ratio matches the calculated ratios.

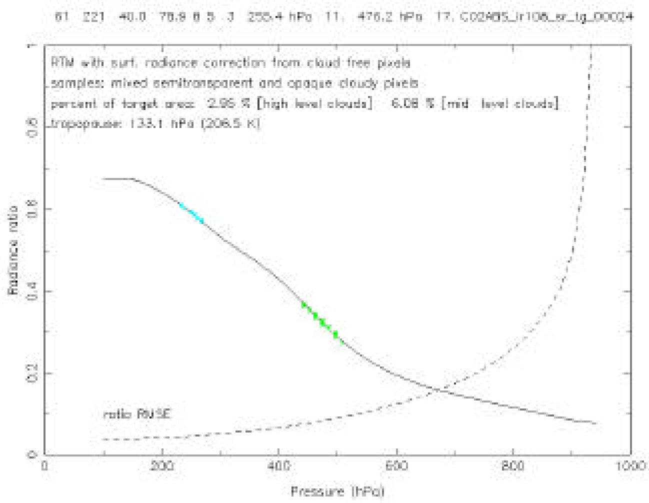

Figure 2. The CO_2 ratioing method applied to a target on 20 June 1997 1200 GMT.

The CO_2 method fails when the difference between the observed radiance differences in either channel becomes smaller than the instrument noise. For the example in Fig. 2 this happens around 680 hPa. In the presented example the corrected pressure is 255.4 hPa whereas the intercept method estimates the cloud height to 212.8 hPa. Another complication occurs in multi-layered cloud situations where the CO_2 method will produce a height somewhere between the two cloud-layers. For optically thick clouds the ratio for the observations are close to one again limiting the application of the method. In these cases however, the equivalent blackbody temperature (EBBT) of the cloud is sufficient for the cloud top estimate.

2.3 Selection of cloud pixels

The determination of which pixels belong to the cloud under investigation is in the current operational environment based on the multi-dimensional histogram analysis. The histogram analysis provides mean cloud radiances that are used for the intercept method. In preparation for MSG a new scheme has been developed. The analysis is based on a multi-spectral pixel based classification scheme (Lutz, 1999) that provides for each pixel cloud type and cloud phase. Within the AMV height assignment the results from the CLA are further evaluated. This evaluation attempts to extract only stable representative pixels from each cloud class and is based on local mean, standard deviation and the cloud type of the neighbouring pixels. It further utilises predicted errors of the observed radiances in order to extract only the most homogenous pixels for the height assignment.

3. VALIDATION

The WV/IR intercept method and the EBBT-height are already implemented in the operational MTP MPEF. However, there are some differences especially in the selection of pixels for the intercept method. Furthermore the current Meteosat does not contain a CO_2-channel and therefore the developed methodology has to be validated with GOES-sounder data.

3.1 Preliminary results using the GOES-8 sounder data

The CO_2-method was exclusively applied to GOES-8 sounder data, covering most of continental US and some parts of the western Atlantic. The possible targets were extracted by the MSG Atmospheric Motion Vector (AMV) scheme maximising the contrast for every possible target. 41 targets of the size of 24*24 pixels were extracted. The minimum size of the identified cloud free area was defined to be 5% of the target area. Also only clouds covering at least 5% of the target area were analysed. In cases where the cloud free area was not large enough or no cloud free area was identified the background radiance was determined by the RTM derived surface radiances. Table 2 presents the comparison results again EBBT height assignment and between the WV/IR intercept method and the CO_2–scheme using GOES-8 data. The current validation provides results similar to the ones given by Nieman et. al. (1993) for VAS, which gives confidence in the current implementation.

Table 2. Comparison of height assignment methodologies for semi-transparent clouds.

	GOES-8 19 Jul 96	VAS 29 Jan 92	VAS 30 Jan 92	VAS 31 Jan 92
No. of cases	41	87	61	199
CO_2-IRW	-54	-76	-56	-78
H2O-IRW	-120	-86	-110	-129
CO_2-H2O	-65	-10	-54	-41

3.2 Comparisons against stereo height estimates

As a new tool for comparison, the stereo height determination (e.g. Campbell 1998), was implemented and applied to simultaneous observations by Meteosat-7 and Meteosat-5. Figure 3 shows a sub area over the ITCZ where the stereo-height has been compared to the EBBT scheme. Heights with a pressure within 200 hPa are coloured in green, targets for which the EBBT approach provides a pressure 200 hPa or higher than the stereo-scheme is in blue and the cases where the stereo heights are significantly lower is in red. It is clear from Fig.3 that in general the agreement is reasonable, but the larger amount of semi-transparency the larger the difference.

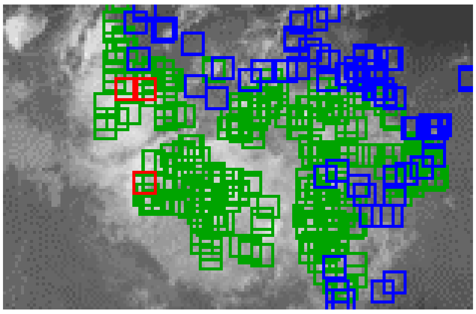

Figure 3. EBBT vs. stereo heights for 20 June 1997.

Figure 4 shows the comparison between the WV/IR intercept method and stereo-heights. The colour coding is the same as for Figure 3. A distinct area with failed semi-transparency correction (blue targets) can be identified over the South Atlantic. These targets are related to an extremely thin cloud that is not well depicted with Meteosat-7. A large amount of the ‘red’ targets are related to problems matching the cloud targets from the different viewing angle, hence causing an error in the stereo-height approach. For the ‘green’ targets the agreement is reasonable, providing a RMS difference of 82 hPa, which is comparable to the results achieved in Table 2.

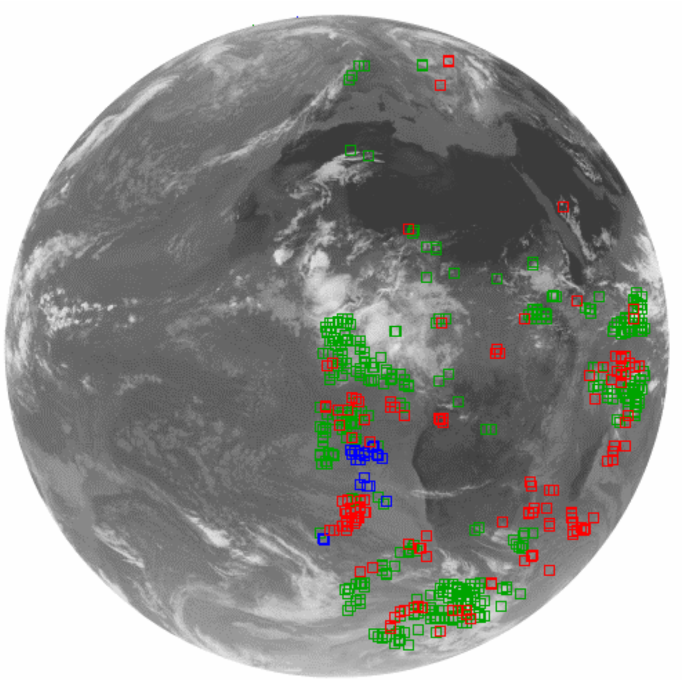

Figure 4. WV/IR intercept method vs. stereo-heights for 20 June 1997 1200 GMT.

4. PIXEL-BASED HEIGHT ASSIGNMENT WITHIN CLOUD ANALYSIS

The cloud top height assignment is part of the pixel–based intermediate cloud analysis (CLA) within the MSG MPEF. The CLA processing is an important pre-processing step to derive operational products from meteorological satellites like atmospheric motion vectors (AMV).

The cloud top height (pressure) within the intermediate CLA is derived using a composite of the height assignment methods described in Chapters 2 and 3.

The cloud top height will be derived for each cloudy pixel. In a first step the level of best agreement between the measured radiances in channel 10.8 µm (or channel 12.0 µm) and the calculated radiances from the RTM tables is determined. The pressure of that level is considered to be the cloud top pressure of an opaque cloud. In case the measured radiance of a cloudy pixel is higher than the calculated clear sky radiance, the cloud top height is set to the lowest level above surface.

However since some of the clouds are semi-transparent, the cloud top height needs to be corrected. This is done with the methods described in Chapter 2

All methods will run in parallel and the final result will be selected out of these. It is obvious that these methods will not run on each cloudy pixel, even on the same pixels, which is due to the fact that the channels get their signal from different parts of the atmosphere. It is therefore very important to pre-select which method can be applied to which cloudy pixel.

The criteria for applying a method are:

- the measured radiance of the cloud in channel IR10.8 has to be smaller than the calculated clear sky radiance by a threshold
- the measured radiance of the cloud in channel WV6.2, or WV7.3, or IR13.4 has to be smaller than the calculated clear sky radiance in the respective channel by a (channel dependent) threshold
- either the standard deviation (over 3x3 pixels) in channel WV6.2, or WV7.3, or IR13.4 has to be larger than a (channel dependent) threshold, or the difference of the brightness temperatures between channels IR10.8 and IR12.0 has to be larger than a threshold.
- the cloud phase is set to ice phase (this criterion will be re-evaluated after the launch of the MSG satellite)

The final CTH for each pixel will be selected as follows:

- the result of CTH1 will be used, if the WV6.2/IR10.8 rationing method can be applied,
- otherwise the result of CTH2 will be used, if the WV7.3/IR10.8 rationing method can be applied,
- otherwise the result of CTH3 will be used, if the IR13.4/IR10.8 rationing method can be applied,
- otherwise the result of the opaque cloud height assignment will be used

The pixel-based height assignment serves in the beginning mainly as an analysis tool for the CLA. It is foreseen that in the future the pixel-based height assignments may complement the cluster based approach in the AMV.

5. VALIDATION OF THE PIXEL BASED HEIGHT ASSIGNMENT

The height assignment algorithm was tested with different sets of satellite data, i.e. Meteosat-6, GOES-8 sounder.

In the following an example of the results of the rationing methods applied to Meteosat-6 data (taken on June,20 1997 at 12:00 UTC) is given. Meteosat-6 has only three channels available (VIS, WV and IR), therefore only the WV6.2/IR10.8 rationing method can be applied in addition to the opaque cloud height assignment.

With the criteria listed above, the WV6.2/IR10.8 rationing method was applied to 27 % of the cloudy pixels. For 20% of these pixels the height was not corrected (i.e. opaque high-level clouds). The mean height correction for the other 80% of the pixels was 200 hPa.

Figure 5 shows the results for the successful application of the WV6.2/IR10.8 rationing. In this figure blue indicates clear ocean, green indicates clear land, black indicates all clouds where the rationing method was not applied, and grey/white indicates the cloud top height values as derived from the rationing method with the scale from dark grey (~400 hPa) to white (~ 150 hPa).

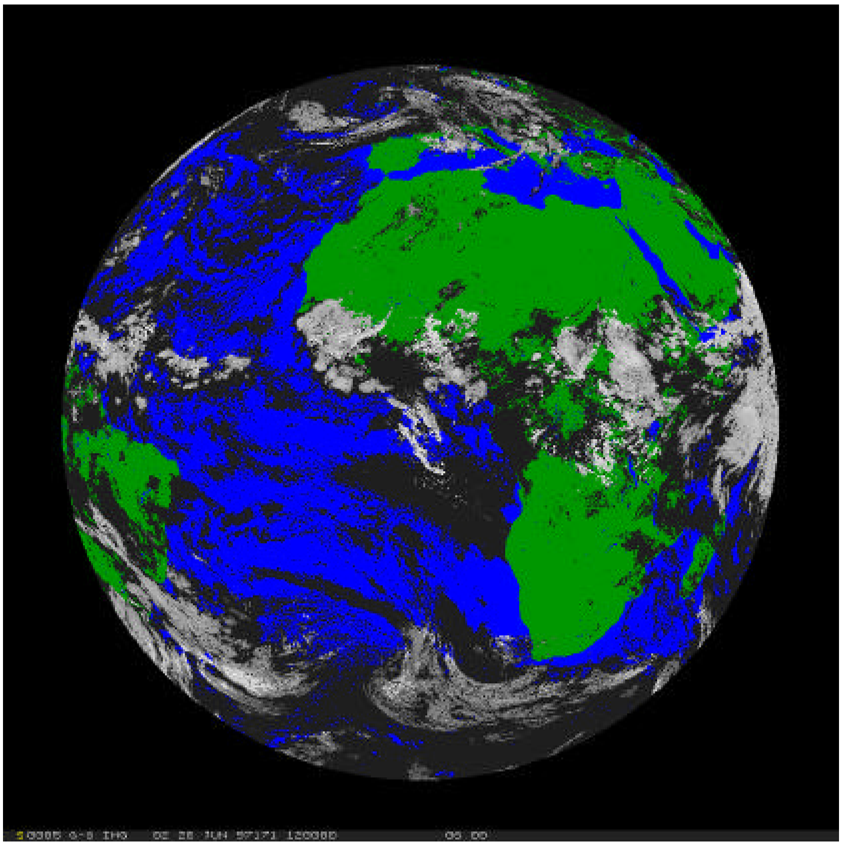

Figure 5. Cloud top heights as derived with the WV6.2/IR10.8 rationing method, with:

blue - - clear ocean,
green - clear land,
black - all clouds where the rationing method was not applied,
grey/white - cloud top height values as derived from the rationing method with a scale from dark grey (~400 hPa) to white (~ 150 hPa).

6. CONCLUSIONS

The height assignment of semi-transparent clouds is at EUMETSAT based on existing methodologies that have already been proven in operations. The Meteosat satellites do not contain a CO_2-channel, hence only the WV/IR intercept method is currently used operationally at EUMETSAT.

The advent of the Second Generation Meteosat enables the derivation of heights for semi-transparent clouds simultaneously with several methods. Two principal methods have been implemented with several new extensions. The developed methodologies have been validated with both GOES-8 sounder data and with current Meteosat data. For the latter data verification against the operational cloud height assignment has been performed. The MSG height assignment methodologies provide a robust baseline for the estimation of cloud tops necessary for the Atmospheric Motion Vectors, with RMS differences between the methods and against the current operational method of 80 hPa or less. The current implementation provides a solid starting point for further development and tuning that can only be performed with real MSG data. This work will be performed during the commissioning of MSG-1, ensuring a mature cloud height assignment scheme at the start of the operational extraction of meteorological products at EUMETSAT.

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