Interpretation of Structure Displacements within Cloud-free Water Vapour Scenes of METEOSAT

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ABSTRACT

Water vapour (WV) scenes are operationally searched for structure displacements for many years. Displacements of intermediate and high level clouds are interpreted in kind of wind vectors by inclusion of information from the infrared channel of METEOSAT. But displacement vectors from pure WV-structures cannot be related to structures within images of the other channels and are expected to extend the experience into hitherto unknown fields. In contrast to a tendency of simply matching these structure displacements to a model wind field, we still try to interpret them as independent wind vectors. A series of height assignment methods is tested regarding altitude sensitive parameters like wind shear and brightness contrast of pixels within a segment used for structure tracking. The results are verified comparing them to wind data from various sources. From a statistical point of view and for cases of high wind shear it is concluded that methods using the effective brightness temperature lead to better height assignment than others which are based on the contribution function explicitely. From the individual point of view a cloud-free structure contains information from a rather thick layer of the atmosphere, the displacement vectors being a vectors sum of motions in several heights. Consequently it depends on the individual situation whether a displacement reflects the motion at a welldefined height (= is a wind vector) or should be taken as a collective motion of an essential part of the higher troposphere. Neither characteristics of the radiances spectrum nor the group of pixels dominating the tracking process are found to deliver a unique relation for a better matching to the wind profile in this complex task.

1. Introduction

It is the unique feature of the water vapour channel and its images taken by METEOSAT to supply information from the state and dynamics of the intermediate and upper troposphere which cannot be obtained from the other channels as well. This paper reports on results obtained from continuing earlier work published in a series of papers that are reproduced in the proceedings to foregoing workshops (Büche et al. 1996; 1994; and references given therein). It aims in a systematic study of the height assignment task of cloud-free WV structures being convinced that WV structure information is an independent one. I. e., displacement vectors of water vapour structures should be related to the motions of air packages and not conditionally accepted if they match a wind field experienced from other sources.

Up to now it is unknown which altitude is appropriate for the description of the motion of WV structures that are free from intermediate and high level clouds. Nor is it clear, whether displacement vectors should be attributed to a single level or rather be interpreted as the motion of a fairly thick atmospheric layer. The latter way corresponds to the fact that the radiance signal is the integrated information from an essential part of the higher troposphere. At the beginning of WV studies Fischer et al. (1981) calculated the height where the contribution function peaks and attributed it to the tracked structures. Later on the model of the European Space Operations Centre (ESOC; Holmlund,

1993) used the effective brightness temperature to define a height which is calculated from a small number of the coldest pixels in a segment. For the time being EUMETSAT avoids to give one single height for the water vapour structure which contains the information from the atmosphere in integrated form only. Instead of this at least three characteristic numbers of the contribution function are offered and the decision on their further use together with the displacement vector is left to the user (Holmlund, 1998). The height assignment of cloud-free WV structures in segments of GOES 8/9 images is done using the effective brightness temperature taken at the site of highest radiance gradients (Velden et al., 1997).

For the evaluation of wind vectors to be described in the following chapters three different data sets are available: (1) atmospheric profiles from the model analysis of the European Centre for Medium Range Weather Forecast (ECMWF); (2) from radiosonde (RS) ascents; and (3) from the European Model of the Deutscher Wetterdienst (DWD-E). The radiative transfer calculations are done using the programme LOWTRAN7 (Kneizys et al., 1988) and since 1996 the code MODTRAN3.5 (Anderson et al., 1995).

2. Methodology

The main details of getting displacement vectors of WV structures from an evaluation procedure applied to a series of three consecutive METEOSAT images are reported within earlier contributions to this series of Workshops (Büche et al., 1996, and references given therein). Segments from a regular grid of 32 x 32 pixels are taken out of the intermediate image to track the WV structures in the preceeding as well as in the following image. The pair of displacement vectors resulting from an application of the cross correlation method is accepted as a good one, if the relative vectors difference: $\left|\overrightarrow{d_1} - \overrightarrow{d_2}\right|$ divided by their average length, $(\left|\overrightarrow{d_1}\right| + \left|\overrightarrow{d_2}\right|)/2$, does not exceed 0.6 (0.8). To be sure that the tracked structures are not related to intermediate or high level clouds, all pixels within the corresponding infrared (IR) scene should have an effective IR brightness temperature greater than minus 10 ºC.

The height assignment to the tracked water vapour structures can be done in several ways: The first group of definitions makes use of the contribution function thereby relating to atmospheric profiles of temperature T *and* humidity H in the course of the calculation. A second group of height definitions uses the so-called effective brightness temperature which is calculated from the calibrated radiances of the pixels involved. By inversion of Planck's function the resulting effective temperature is used to interpolate the height in the atmospheric temperature profile. The following height definitions are different and have their individual characteristics. The first expression (Eq. 2.1) gives the maximum of the contribution function CNTRBF(z):

$$z_1 = z(\text{CNTRBF} = \text{Max!}) \qquad (2.1)$$

which is in the region of the atmosphere where the main part of the radiation entering the detector is emitted. The second definition

$$z_2 = \text{Norm}^{-1} \int z \, \text{CNTRBF}(z) \, dz \qquad (2.2)$$

leads to an averaged level which usually is higher up in the atmosphere than z_1. It relates contributions from various heights to a single level. In an analogous way an average lateral velocity of the tracked structures is given by:

$$(u,v)_{eff}(\text{CNTRBF}) = \text{Norm}^{-1} \int (u(z), v(z))\text{CNTRBF}(z) \, dz \qquad (2.3)$$

which takes into account that motions in various altitudes contribute to the displacements of structures. The second group of height definitions is based on the effective brightness temperature T_{eff} which is calculated from the radiance of the tracked structure. The equation

$$z_3 = T_{prof}^{-1} (T_{eff}) \qquad (2.4)$$

uses the atmospheric temperature profile $T_{prof}(z)$ only. T_{eff} is extracted from the calibrated pixels of the WV image ($=T_{eff}$ (WV)) or from a radiative transfer calculation ($=T_{eff}$ (rad(T,H))) taking into account the actual profiles of temperature and humidity. A radiance value does not reveal immediately information on depth within the atmosphere but is the sum of radiation being emitted along the axis of sight and entering the detector. Therefore this global information is simply tried whether it is able to deliver a suitable single level height or not. The definitions (Eqs. 2.1 through 2.4) given so far are not immediately related to the characteristics of the tracked structure. To overcome this kind of arbitrariness Büche et al. (1994) reported a method how the relevant site of the structure can be taken into account (e. g. where the appropriate atmospheric profile is found) as well as the representative radiance (group of important pixels) may be defined. In the present context two different ways are reported. The first is based on the coldest pixel within the segment:

$$z_3^{cold} = T_{prof}^{-1} \left(T_{eff}(\text{coldest pixel})\right) \qquad (2.5)$$

presuming the uppermost part of the structure to be most important for the tracking process. In contrast to this single level definition of height the details of a structure are taken into account by using an effective velocity

$$(u,v)_{eff}(\text{corr.coeff.}) = \text{Norm}^{-1}\, \Sigma\, (u(T_{ij}), v(T_{ij}))\, cc_{ij} \quad (2.6)$$

with cc_{ij} being the relative contribution of the pixel pair ij to the maximum of the segment's correlation coefficient and T_{ij} the effective brightness temperature of the tracking pixel. This definition gives most of weight to the height of those pixels being important within the correlation procedure.

The comparison of WV structure displacement vectors $\vec{d}$ and wind vectors $\vec{w}$ is done giving three numbers: (1) the relative difference between the velocities, 2(w-d)/(w+d); (2) the angle of $\vec{d}$ relative to $\vec{w}$; and (3) the relative difference of the vectors $\vec{d}$ and $\vec{w}$, $2\left|\vec{w}-\vec{d}\right|$/(w+d). It should be noticed that only two out of three numbers are statistically independent. To decide on the appropriate method of height assignment a remarkable lowering of difference or standard deviation for the correct method compared to the others is expected. In practice displacement vectors can get very small, e. g. one or two pixel units. Then the direction information is tremendously reduced to steps of 90 or 45 degrees. Therefore structure displacements shorter than 3 pixels are cut.

3. Verification of WV-winds

3.1 The case of June 21, 1989

The experience from earlier work [Büche et al., 1996] on the METEOSAT-4 scene of June 21, 1989 revealed that images and ancillary data are not free from contradictions. Calibrated radiances of pixels used during the tracking procedure were found to be greater than radiances calculated from profiles used in the height assignment. Differences of - (0.30 ... 0.40) ± (0.12 ... 0.25) were found in cases along a regular grid over the North Hemisphere and profiles from the ECMWF model as well as from radiosonde ascents distributed over the full scene. Nevertheless the separation of cloud-free scenes from cloudy ones is effective, the cloudy scenes showing reduced differences but a much higher scattering, a result which is expected for two almost independent situations. Furthermore the equivalence of radiances calculated from radiosonde profiles on one hand and from ECMWF profiles on the other has been approved on average.

The vector field of structure displacements showed 106 vectors under conditions where the sky was not covered by intermediate or high level clouds. They were compared to the wind vectors corresponding to Eqs. 2.1 through 2.5. All resulting differences were quite similar, especially no advantage for a specific height attribution over the other methods could be revealed from the standard deviations. The situation did not change if very small displacements and a few very bad cases were cut thereby reducing the number of cases to 69. A typical value for the relative vectors difference is 0.50 ± 0.27 after application of cuts. This situation was found to be unsatisfactory and initiated a change over to a more recent scene: for details the scene of June 6, 1996, 12 hrs UTC, is studied and in some respect the full month June, 1996, 12 hrs UTC.

3.2 The case of June 1996

Since 1989 an exchange of satellite (METEOSAT-4 to METEOSAT-5) was done and the operational WV calibration procedure has been improved (on February 4,1994). For June 6,1996, a clear day over most parts of west and central Europe, the field of displacement vectors from a segment of the North Hemisphere shows remarkably more good vectors than from the scene in Ch.3.1.

The full scheme of comparisons between WV radiances from images and from the available ancillary data is given in Table 1. There is only a marginal difference between WV and ECMWF or RS profiles, but a much greater one for profiles from the European model of the DWD. Standard deviations up to 14% show that there is quite a lot of scattering among radiances. This seems to be acceptable as long as segment averages of radiances are compared to local data from the model. But the same number 14% applies if RS data are compared to analysis data of the ECMWF model evaluated for the same geographical position. This time there is no offset on average. Part of this scattering is induced by the calibration procedure. Around June 6, 1996, the calibration constant is changed almost every 3 days. This long-term scattering leads to at least 1% radiance scattering. Since radiosonde profiles are the reference profiles of the models, a scattering of e.g. 14% between RS and ECMWF radiances is thought to contribute to the inherent uncertainty of a height attribution via the effective brightness temperature using ECMWF data.

Cloud-free scenes x	y	$2\frac{L_x - L_y}{L_x + L_y}$	Cases	Comment
ECMWF	WV	-12 ± 11 %	226	North Hemisphere*)
ECMWF	WV	-14 ± 12 %	2529	Full Disc
DWD-E	WV	-35 ± 13 %	112	North Hemisphere (red.*)
RS	WV	-12 ± 14 %	59	Full Disc
RS	ECMWF	0 ± 14 %	59	Full Disc
DWD-E	ECMWF	-22 ± 16 %	252	North Hemisphere (red.*)
RS	DWD-E	22 ± 10 %	9	North Hemisphere (red.*)

Table 1. Verification of WV radiances for various profiles and scenes which are free of intermediate and high-level clouds on June 6, 1996. (*) A 1024 x 1024 pixel segment from the North Hemisphere (reduced to the region of the model).

Height z \ Difference	$2\frac{V_{EC} - V_{WV}}{V_{EC} + V_{WV}}$	$Angle(\vec{V}_{EC}, \vec{V}_{WV})$	$2\frac{\overrightarrow{V_{EC}} - \overrightarrow{V_{WV}}}{V_{EC} + V_{WV}}$	z-z(CNTRBF=Max!)	Cases
$z(L_{WV} \rightarrow T_{eff})$	-6,1 ± 31,7%	3,4 ± 26,4°	0,457 ± 0,305	1,718 ± 1,043 km	106
$z(L_{EC} \rightarrow T_{eff})$	-1,0 ± 32,6%	4,2 ± 27,2°	0,459 ± 0,303	2,177 ± 0,883 km	107
z(CNTRBF=Max!)	-19,2 ± 34,2 %	0,6 ± 22,1°	0,449 ± 0,300	0	97
$\int z$ CNTRBF·dz	-16,7 ± 36,6%	1,3 ± 25,1°	0,486 ± 0,310	1,087 ± 0,700 km	104

Table 2. Comparison of WV displacement vectors to ECMWF-model wind vectors for cloud-free scenes in the North Hemisphere of June 6, 1996 after a cut of very short displacements and/or obviously very bad cases.

If profiles from the European model of the DWD are used, an offset of more than two standard deviations is found. This reflects that the DWD model contains more humidity in higher layers of the troposphere than the model of ECMWF and in several cases than the RS profiles, too. Nevertheless, temperature profiles are almost the same. It is because of the stated offset that DWD-E model data are not included into the following comparison of wind vectors. Concluding this section, the results from ECMWF and RS profiles give some hope that both methods of height assignment can be studied in an objective way.

The comparison of WV-displacement vectors to wind vectors from ECMWF-model is given in Table 2. Four different altitude assignments (Eqs. 2.1, 2.2, 2.4, 2.5) are tried leading to heights between 1 and 2.2 km above the maximum of the contribution function. None of these heights reveals an advantage over the others regarding e.g. the relative vectors difference (column 4). The verification

Wind shear / Height z	$2\left|\vec{V}_{RS} - \vec{V}_{WV}\right| / (V_{RS} + V_{WV})$							
	≤ 10 % km^{-1}	cases	10...60 % km^{-1}	cases	60...100 % km^{-1}	cases	≥ 100 % km^{-1}	cases
$(u,v)_{eff}$ (corr.coeff.)	33 ± 23 %	35	40 ± 34 %	246	76 ± 56 %	33	78 ± 55 %	22
z (L_{WV}(coldest) → T_{eff})	33 ± 23 %	35	40 ± 34 %	247	74 ± 57 %	33	64 ± 54 %	22
z (L_{WV} → T_{eff})	33 ± 23 %	35	41 ± 34 %	246	77 ± 55 %	33	86 ± 60 %	22
z (L_{RS} → T_{eff})	32 ± 23 %	35	43 ± 34 %	247	79 ± 56 %	33	78 ± 56 %	22
z(CNTRBF = max!)	33 ± 23 %	35	49 ± 38 %	246	110 ± 53 %	33	131 ± 60 %	22
∫z CNTRBF dz	34 ± 23 %	35	47 ± 36 %	247	93 ± 59 %	33	121 ± 58 %	22
$(u,v)_{eff}$ (CNTRBF)	43 ± 32 %	35	53 ± 37 %	246	93 ± 57 %	33	107 ± 45 %	22
$2\frac{L_{RS} - L_{WV}}{L_{RS} + L_{WV}}$	-13 ± 12%	35	-11 ± 17%	247	-3 ± 13 %	33	-4 ± 14 %	22

Table 3: Relative differences between wind vectors from radiosonde ascents and WV structure displacements over cloud-free regions from METEOSAT during the full month June, 1996, 12 hrs UTC. The total number of selected radiosonde ascents within METEOSAT's field-of-view is 337. The last row gives the relative differences for the corresponding radiances L.

of structure displacements using radiosonde wind vectors does not show a clear situation. None of the height assignment methods leads to a remarkably lower standard deviation that is a hint at the appropriate height attribution method. Even worse, no distinction between cloud-free (0.58±0.44) and cloudy (0.53±0.44; full disc results) cases is observed. In addition to that a cut of small displacement vectors reduces the number of cases without noticeable change of result. Therefore progress is expected from regarding more detailed information on atmospheric profiles and/or tracked structures. The next step is to separate cases of weak variation of wind vectors with height z from those with a strong variation, i.e. to take wind shear into account. According to Table 2 a relative difference of 0.30 of wind vectors over half a kilometre in height leads to wind shear of 60% km^{-1}. This number is taken to be a reasonable lower limit for cases which are sensitive to the given altitude assignment methods. Cases with wind shear smaller than 10% km^{-1} (both between the main pressure levels including $z_1 ... z_3$) are considered as the reference group.

Table 3 reproduces the results for the relative wind vectors difference as a function of the height assignment method and of wind shear. The last row shows that radiances calculated from the RS profiles are equivalent to radiances from the related pixels with a tendency to a small offset for cases with low wind shear. There is no sensitivity with respect to the height assignment method for weak wind shear. In contrast to this two groups of relative differences in wind vectors are noticed for strong wind shear. Height assignment methods that refer to the contribution function directly result in less agreement than others which make use of the effective brightness temperature. But with respect to one of the two groups it is not concluded, that a specific method is better than another one. It may be argued that heights which are taken from the effective brightness temperature have another quality than heights which are defined from the contribution function. In the first case only the temperature profile is used and the humidity profile not immediately but via the calibration procedure with a few selected cases. In the second case the individual humidity profiles are needed in addition to the temperature ones. It is surprising that heights estimated from calculated radiances where humidity

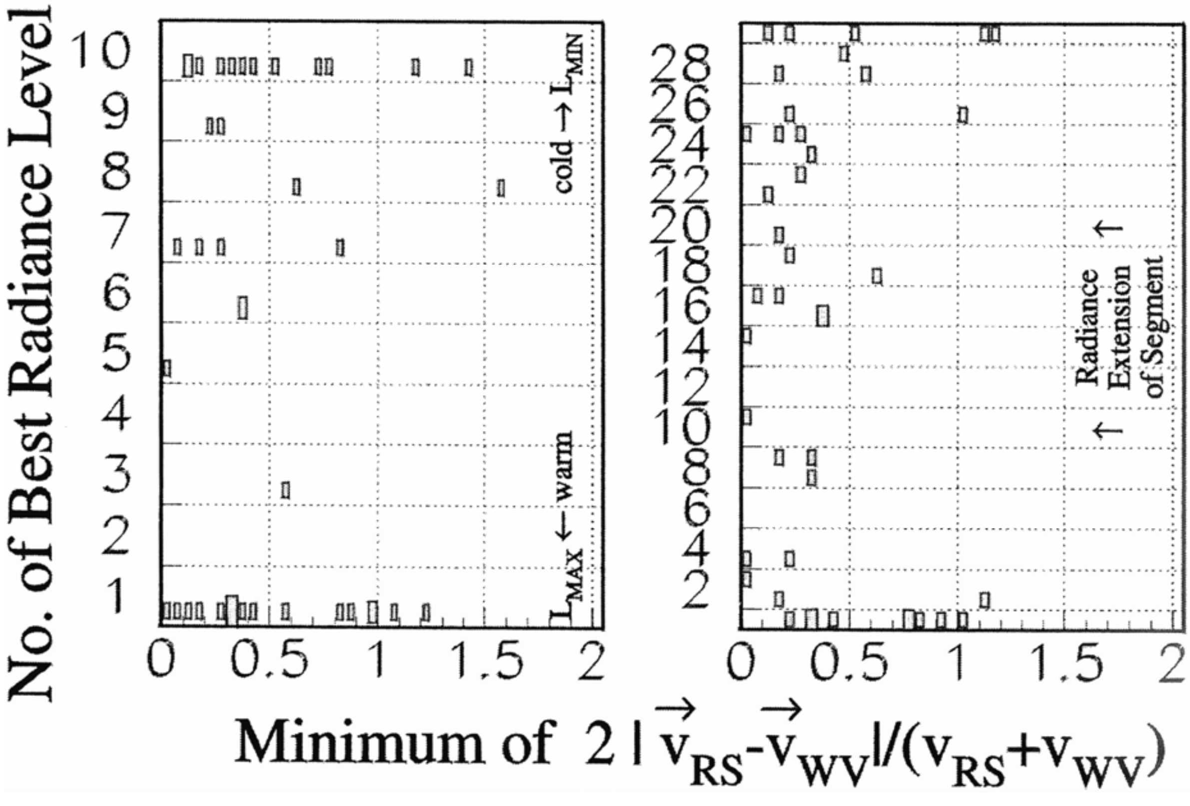

Fig. 1: Water vapour structure wind compared to radiosonde winds if the altitude (calculated from the effective brightness temperature) varies freely over once (left) or three times (right) the extension of the radiances spectrum of the segment. The cases are given in a two-dimensional histogram over the minimum relative vectors difference on the horizontal axis and over the related number of the best level (10/30 steps) on the vertical one. The amount of entries per 2-dimensional bin (on the third axis out of the paper) corresponds to the area of a rectangle. Scene from 6 June, 1996 12 hrs UTC.

profiles are essential, lead to better results than the other height definitions from the contribution function.

3.3 Further aspects

If a height assignment is correct, the difference between the reference wind and the displacement vector is supposed to be a minimum or at least a relative one. To test this hypothesis in connection with the effective brightness temperature, the radiances L of the pixels are subdivided into e. g. 10 steps between the maximum and the minimum values. Minimising the relative vectors difference as a function of the quasi-continuous step number it is realised, that only a few cases have their minimal difference within the segment's range of radiances (Fig. 1 left). The overwhelming part of the differences is beyond the lower or upper ends of the radiances spectrum (Fig. 1 right). I. e., the radiance information from the segment in general is not enough to find the height where reference wind and displacement are matching. This statement remains true if cases of strong wind shear are studied exclusively. The situation is even worse: Some of the segments whose displacements are dominated by warm pixels during the tracking process are found beyond their minimum, some beyond their maximum radiance, and vice versa. In other words, there is no unique relation between pixels which contribute most to the result of the tracking process on one hand, and the radiances needed for matching of the displacement vectors to the reference wind field on the other!

The following test is concerned with semitransparent WV-structures and superimposed motions in various altitudes. To test the reaction of the tracking procedure to such a situation a series of 3 consecutive scenes is constructed synthetically. One real scene is taken and shifted in height (e. g. ± 1 km) by adding a small amount ± $|\Delta T|$ of effective brightness temperature to the radiances of the pixels. The resulting scenes are successively shifted one in horizontal (almost longitudinal) direction, the other in vertical (almost meridional) direction. Then the radiances of the two scenes are superimposed (and divided by 2). The reaction of the tracking procedure to this composed situation is as follows. As long as $\Delta T = 0$, the motions occur at the same height, and displacements are found preferably under 45 degrees, i. e. the direction of the vectors sum of motions, but with a low yield of good vectors. If the constructed motions occur at two different heights, $\Delta T > 0$, the structure displacements are found with a high yield and to follow preferably the motion of the warm part of the synthetical scene. This is caused by the greater contrast in the warm component of the synthetical image which is introduced from the elevated effective brightness temperature. Depending on the actual situation in real scenes, the greater contrast may be connected also to the cold parts of the segments so that the displacements follow the cold structures.

Since METEOSAT WV-images are taken in one wavelength band only, cloud-free WV scenes cannot be sliced into high-level and intermediate level structures. There is no way to decide on the relative position of structures in altitude and to study single layer scenes exclusively. Therefore displacement vectors may be interpreted as the sum of motions that are related to air masses not necessarily moving at the same speed into the same direction. This must be taken into account especially in cases of strong wind shear, and may explain the much higher values of their relative vectors differences given in Table 3.

4. Conclusions

It could be shown that radiances from cloud-free scenes of recent METEOSAT WV images are statistically almost equal to radiances calculated from atmospheric profiles which are supplied from the model analysis of ECMWF as well as from radiosonde ascents. This fact warrants that the comparison of various height assignment methods for structure displacements is done in an objective way and is not influenced from contradictions inherent to data from various sources. As long as structure displacements are faced to wind vectors without regarding further characteristics of the atmosphere, no advantage for one method over the others is found which could be a hint at the appropriate height assignment method. The situation changes when wind shear is taken into account. Those methods which are based on the effective brightness temperature of the pixels result in smaller differences between displacements and profile wind than others that make use of the contribution function explicitly. The same is true if not a specific level is defined but an effective wind velocity is calculated from the individual brightness temperatures of the pixels on one hand or from weighing the altitude dependent velocities by the contribution function on the other.

From the statistical point of view a height definition via the effective brightness temperature results to be an appropriate way. The details of this kind of definition seem to be of marginal importance with a tendency in favour of using the coldest pixels of the segment. From an individual point of view the situation is confusing. If the effective brightness temperature is varied freely over three times the width given by the radiances spectrum in order to find the level where displacement vectors match the wind profile, the result is getting to be ambiguous. Only a few cases show a minimum of the relative vectors difference between structure displacement and profile wind vector within the width of the radiances spectrum. The overwhelming part has its minimum beyond the lowest or highest radiances of the related segment. And for each of these two groups the displacement vectors are generated by substantial contributions from warm or cold parts from the WV structure within the segments. I.e., there seems to be no way how to find a signature of the segment's structure that leads to the best wind at a definite height.

The satellites of METEOSAT second generation are expected to reduce integration of information stated above for the data taken by the existing series of satellites. The increased resolution in space and time will preserve more details of structures even in cloud-free WV scenes and approach displacement to wind vectors. The two WV channels split in wavelength will allow first steps of a multi-channel analysis of atmospheric WV motions. This is expected to help in disentangling the open questions in the height assignment task as well as in the assimilation of results into the atmospheric models.

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