A Bispectral Method for the Height Determination of Optically Thin Ice Clouds

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Abstract

This paper presents a bispectral method for the height determination of optically thin ice clouds from satellite measurements from two adjacent points of an ice cloud layer. Using two wavelengths in the spectral region of the water vapor band at 6.3 μm and the window region at 11 μm a transcendental equation is derived on the assumption that both points of the cloud do have the same temperature but different optical thicknesses. The solution of the transcendental equation yields the cloud temperature, and via the temperature profile, which must be known, it also yields the height. The effect of the water vapor above the cloud is corrected by calculating the radiances at cloud height from the measured radiances using a radiative transport model (RTM). For this purpose the humidity profile has to be known.

The method is at first verified by means of simulated data calculated with a RTM and then by a comparison of results from NOAA-6 data with lidar measurements performed from an aircraft. It becomes evident from the use of simulated data that the method gives highly accurate results for clouds at altitudes between 6 km and 12 km which are observed at various zenith angles. In some cases the differences between calculated and real heights are only a few metres, if the temperature and the humidity profile are known exactly. In addition, the influence of erroneous atmospheric profiles on the accuracy is investigated. It is shown that the effect of a deviating temperature profile on the accuracy of cloud height determination is approximately the same as that of the standard method for height determination of optically thick clouds. On the other hand, a deviating humidity profile can cause an additional error which depends on the cloud height, the zenith angle of observation and the water vapor content. The application to HIRS/2 data aboard NOAA-6 and the comparison with lidar measurements makes it evident that the bispectral method yields much better results than the use of only one IR-channel. The difference between the mean height determined with the bispectral method from satellite data and the averaged height measured with the lidar is only about 600 metres.

Zusammenfassung: Eine bispektrale Methode zur Höhenbestimmung optisch dünner Eiswolken

Es wird eine bispektrale Methode zur Höhenbestimmung von optisch dünnen Eiswolken mit Hilfe von Satellitenmessungen an zwei nebeneinander liegenden Stellen einer Eiswolkendecke vorgestellt. Durch die Verwendung von zwei Wellenlängen im Spektralbereich der Wasserdampfbande bei 6,3 μm und im Fensterbereich bei 11 μm wird unter der Annahme, daß beide Meßstellen der Wolke die gleiche Temperatur, aber unterschiedliche optische Dicken haben, eine transzendente Gleichung abgeleitet, deren Lösung die Wolkentemperatur und damit über das als bekannt vorausgesetzte Temperaturprofil die Höhe ergibt. Der Wasserdampfeinfluß oberhalb der Eiswolke wird korrigiert, indem die gemessenen Strahldichten mit Hilfe eines Strahlungsübertragungsmodells schrittweise auf das Niveau der Wolken zurückgerechnet werden. Dazu muß das Feuchteprofil bekannt sein.

Das Verfahren wird zunächst mit Hilfe simulierter Daten, die mit einem Strahlungstransportmodell berechnet werden, und danach durch einen Vergleich von Ergebnissen aus NOAA-6 Daten mit Lidarmessungen, die von einem Flugzeug aus durchgeführt wurden, verifiziert. Die Rechnungen mit simulierten Daten ergeben, daß das Verfahren in Höhenbereichen von 6 km bis 12 km und bei verschiedenen Zenitwinkeln Ergebnisse von hoher Genauigkeit liefert. Die Abweichungen der berechneten von den tatsächlichen Höhen betragen stellenweise nur wenige Meter. Weiterhin wird der Einfluß fehlerhafter Atmosphärenprofile untersucht. Diese Untersuchungen ergeben, daß der Einfluß des Temperaturprofils auf die Genauigkeit der Höhenbestimmung etwa so groß ist wie beim normalen Verfahren zur Höhenbestimmung optisch dicker Wolken, während ein abweichendes Feuchteprofil noch einen zusätzlichen Fehler verursachen kann, der von der Höhe der Wolke, dem Zenitwinkel und dem Wasserdampfgehalt abhängig ist. Die Anwendung des Verfahrens auf Daten des HIRS/2

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Instrumentes an Bord von NOAA-6 macht die Vorteile gegenüber monospektralen Verfahren deutlich. So beträgt die Differenz zwischen der aus den Satellitendaten abgeleiteten mittleren Höhe und der gemittelten Höhe aus den Lidarmessungen nur 600 Meter.

Résumé: Une méthode bispectrale pour la détermination de la hauteur de nuages glacés de faible épaisseur optique

On présente une méthode bispectrale pour déterminer la hauteur de cirrus de faible épaisseur optique à l'aide d'un satellite qui permet le calcul de la température du nuage en mesurant la radiation émergente d'une couche nuageuse en deux points très proches. Utilisant deux longueurs d'onde, l'une dans la bande de la vapeur d'eau à 6.3 μm el l'autre dans la fenêtre atmosphérique à 11 μm, on établit une équation transcendante, en supposant que les deux points proches du nuage ont la même température. La solution de cette équation donne la température du nuage et, en tenant compte de la distribution verticale de la température, on en déduit la hauteur. L'effet de la vapeur d'eau au-dessus de la couche nuageuse est corrigé à l'aide d'un modèle de transport radiatif (MTR) en calculant la radiation au niveau du nuage à partir du rayonnement mesuré. A cet effet, on doit connaître la distribution verticale de la vapeur d'eau.

Pour vérifier la méthode, des données simulées ont été utilisées avec le MTR pour calculer la hauteur des nuages. Ensuite, on a comparé les résultats provenant des données du satellite NOAA-6 à des mesures à l'aide d'un lidar monté à bord d'un avion. L'utilisation de données simulées montre de facon évidente que la méthode donne des résultats très precis pour des nuages situés entre 6 km et 12 km, observés à différents angles zénithaux. Dans certains cas, les différences entre les hauteurs calculées et observées s'élèvent seulement à quelques mètres, si les profils de température et d'humidité sont connus exactement. En outre, l'influence de profils atmosphériques erronés sur la précision est examinée. Il est prouvé que des déviations du profil de température produisent des effets sur la précision comparables à ceux des méthodes conventionelles pour déterminer la hauteur de nuages à grande épaisseur optique. Par ailleurs, des déviations du profil d'humidité donnent lieu à des erreurs additionnelles dépendant de la hauteur des nuages, de l'angle zénithal d'observation et de la teneur en vapeur d'eau. L'application à des mesures de HIRS/2 à bord de NOAA-6 et la comparaison avec des mesures à l'aide d'un lidar indiquent que la méthode bispectrale donne des résultats supérieurs à ceux obtenus à l'aide d'un seul canal spectral infrarouge. La différence entre la hauteur moyenne des nuages déterminée avec la méthode bispectrale et la hauteur mesurée à l'aide d'un lidar s'élève seulement à 600 mètres.

1 Introduction

The height determination of clouds from satellites with the aid of a thermal infrared channel has been a routine task for a long time. However, this only applies to optically thick clouds which have an emissivity close to one, i.e. generally for low lying water clouds. On the other hand, it is well known that the emissivity of ice clouds in the spectral region at 11 μm can be considerably below one (FRITZ and WINSTON, 1962). Therefore deriving the height of ice clouds from measurements in only one IR channel results in large errors. Consequently, when tracking cloud structures for wind determination due to uncertainties in cloud height there will be large differences between the average wind speed derived from satellite data and the real wind speed.

Initially to solve these problems, bispectral methods were developed which use two channels, one in the window region at about 11 μm and another in the visible region (SHENK and CURRAN, 1973; REYNOLDS and VONDERHAAR, 1977). These methods attempt to derive the emissivity of the ice cloud by means of the dependence of the reflected solar radiation on the optical thickness. If the relation between the optical thickness and the emissivity is known, a relatively accurate estimation of the cloud temperature can be made. The big disadvantage of these methods however, is that they cannot be used at night. This is avoided with methods that use two channels in the terrestrial spectral region. SZEJWACH (1982) uses one channel in the window region and another covering nearly the whole spectral region of the water vapor band. Assuming that the averaged emissivities for these spectral regions are the same for both channels, he calculates a regression line by comparing the radiances of both wavelengths. The regression line enables him to determine the cloud temperature graphically. According to our own calculations however, this assumption cannot be applied to smaller spectral intervals, which confines the applicability of this method mainly to METEOSAT-data. On the other hand, the use of METEOSAT-data poses problems, since the calibration, especially in the water vapor channel, is very difficult and inaccurate. Furthermore, the influence of the water vapor above the cloud is not taken into account with this method.

In the following a bispectral method will be presented wich uses measurements in narrow spectral intervals of the thermal window and the water vapor band to determine the cloud temperature. The selected spectral regions and bandwidths correspond to channels of the HIRS/2 instrument aboard NOAA-6. The method takes into account the influence of the water vapor above the ice cloud. Knowledge of the ground temperature and emissivity of the cloud is not necessary. The verification of the method by using simulated as well as NOAA-6 data shows that a considerable more accurate cloud temperature determination is possible than with the window channel alone.

2 Method

2.1 Fundamental Equations

The basic concept of the method which will be introduced in the following, goes back to CAYLA (1978). For the determination of ice cloud temperatures, satellite measurements in two spectral regions, i.e. in the window region at 11 μm and in the region of the water vapor band at 6.3 μm are used. The measurements should be made at two points of an ice cloud which are close to each other. At the measured points the ice cloud layer must vary in optical thickness. The measured points should have the same temperature and must be in thermodynamic equilibrium with the ambient temperature. As will also be shown, by measuring at two points and selecting suitable wavelenghts it is possible to eliminate unknown quantities like the transmissivity of the cloud and the background radiation below the cloud which is assumed to be equal at both points.

Since the emissivity of an ice cloud usually is less than one, only part of the radiation measured by the satellite comes from the cloud itself, the other part has its origin in atmosperic layers above and below the cloud or is emitted by the ground. Therefore, neglecting the reflectivity of the cloud, the radiation measured by the satellite is given by the following relationships (see also Figure 1):

$$
\begin{aligned}
L_{11}^{1} &= (L_{11}^{B}\ t_{11}^{1} + (1 - t_{11}^{1})\, B_{11})\, t_{11}^{A} + L_{11}^{A} \\
L_{11}^{2} &= (L_{11}^{B}\ t_{11}^{2} + (1 - t_{11}^{2})\, B_{11})\, t_{11}^{A} + L_{11}^{A} \\
L_{6}^{1} &= (L_{6}^{B}\ t_{6}^{1} + (1 - t_{6}^{1})\, B_{6})\, t_{6}^{A} + L_{6}^{A} \\
L_{6}^{2} &= (L_{6}^{B}\ t_{6}^{2} + (1 - t_{6}^{2})\, B_{6})\, t_{6}^{A} + L_{6}^{A}
\end{aligned}
\qquad (1)
$$

where:

$L_{11}^{1}, L_{11}^{2}, L_{6}^{1}, L_{6}^{2}$ = measured radiances at the satellite

L_{11}^{A}, L_{6}^{A} = emisson of the atmospheric layer above the ice cloud

L_{11}^{B}, L_{6}^{B} = emission of the atmospheric layer below the ice cloud and from the ground

t_{11}^{A}, t_{6}^{A} = transmissivity of the atmospheric layer above the ice cloud

B_{11}, B_{6} = blackbody radiation corresponding to cloud temperature

$t_{11}^{1}, t_{11}^{2}, t_{6}^{1}, t_{6}^{2}$ = transmissivity of the ice cloud

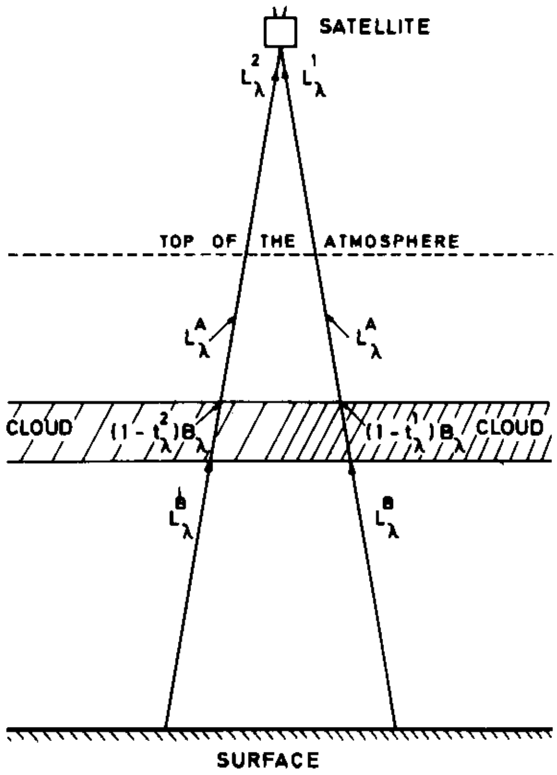


Figure 1
Radiances emitted by the various atmospheric layers according to equations (1).

The subscribts stand for the wavelength, the superscripts indicate the cloud point. However, there are only four equations for the nine quantities which are independent of each other (t_{11}^1, t_{11}^2, t_6^1, t_6^2, L_{11}^B, L_6^B, L_{11}^A, L_6^A, B_{11}). Therefore, the system of equations cannot be solved. But, as indicated by model calculations, some terms can be neglected. In the window region the emission of the atmospheric layer above the cloud is almost zero ($L_{11}^A \simeq 0$) and thus the transmissivity of this layer is nearly one. Temporarily the corresponding terms are also neglected in the water vapor channel, i.e. the transmissivity is set to one. However, one must then accept the error that arises from the fact that in this spectral region the order of magnitude of the emission of the upper atmospheric layer may possibly be as great as that of the total measured radiation depending on the cloud height and observation angle. Yet, with the technique explained below, this error can also be corrected. Now we get:

$$\begin{aligned} L_{11}^1 &= L_{11}^B\, t_{11}^1 + (1-t_{11}^1)B_{11} \qquad & L_6^1 &= L_6^B\, t_6^1 + (1-t_6^1)B_6 \\ L_{11}^2 &= L_{11}^B\, t_{11}^2 + (1-t_{11}^2)B_{11} \qquad & L_6^2 &= L_6^B\, t_6^2 + (1-t_6^2)B_6 \end{aligned} \tag{2}$$

After some simple rearrangements, the emissions L_{11}^B and L_6^B below the ice cloud are eliminated from (2) and we have:

$$\frac{B_{11}-L_{11}^1}{B_{11}-L_{11}^2} = \frac{t_{11}^1}{t_{11}^2} \qquad \frac{B_6-L_6^1}{B_6-L_6^2} = \frac{t_6^1}{t_6^2} \tag{3}$$

By now most unknown quantities have been either neglected or eliminated. The remaining unknown quantities are the required blackbody emission and the ratio of the cloud transmissivity at the two cloud points for both wavelenghts. Model computations with ice clouds of different optical thicknesses show that these ratios are almost the same for the spectral region at 11 μm and the 6.3 μm water vapor band. Table 1 gives some examples of these model computations. Transmissivity ratios were calculated for two zenith angles and two ice cloud layers with the same geometrical thickness but different ice content (corresponding to different optical thicknesses). One should note that the ratios have always

■ **Table 1** Ratio of the transmissivity of ice clouds with different ice crystal concentration (n1, n2: number of ice crystals per cm³ corresponding to different optical thicknesses) at the wavelengths 6.3 μm and 11 μm for two zenith angles. The geometrical thickness of the cloud layer is 1 km.

cosine of zenith angle = 0.95			
number of ice cryst.	n2 = 0.025	n2 = 0.075	n2 = 0.095
n1 = 0.035	t^1_{11}/t^2_{11} = 0.904	1.511	1.864
	t^1_6/t^2_6 = 0.904	1.495	1.825
n1 = 0.050	t^1_{11}/t^2_{11} = 0.775	1.294	1.596
	t^1_6/t^2_6 = 0.779	1.285	1.569
n1 = 0.100	t^1_{11}/t^2_{11} = 0.460	0.770	0.949
	t^1_6/t^2_6 = 0.472	0.781	0.954
cosine of zenith angle = 0.65			
number of ice cryst.	n2 = 0.025	n2 = 0.075	n2 = 0.095
n1 = 0.035	t^1_{11}/t^2_{11} = 0.861	1.830	2.481
	t^1_6/t^2_6 = 0.865	1.800	2.413
n1 = 0.050	t^1_{11}/t^2_{11} = 0.687	1.459	1.979
	t^1_6/t^2_6 = 0.694	1.443	1.934
n1 = 0.100	t^1_{11}/t^2_{11} = 0.322	0.685	0.929
	t^1_6/t^2_6 = 0.332	0.692	0.928

nearly the same value. Hence, it is permissible to equate the transmissivity ratios in most cases with the result:

$$B_{11} = \frac{L_6^1 L_{11}^2 - L_6^2 L_{11}^1}{L_6^1 - L_6^2 - f \cdot (L_{11}^1 - L_{11}^2)} \qquad (4)$$

where: f = B(6,3 μm, T)/B(11 μm, T)

B = Planck function

T = cloud temperature

The function f describes the ratio of blackbody emission for both wavelengths. This ratio, however, depends on the cloud temperature which is the desired quantity. Equation (4) is a transcendental equation having on the lefthand side the Planck function at 11 μm and on the right, in addition to measured quantities, the ratio of Planck functions at 11 μm and 6.3 μm.

The solution of (4), i.e. finding of the right temperature, can only be achieved iteratively. Since both sides of the equation are strong monotonous functions depending on the temperature the root of (4) can easily be found with a simple iteration method. Thus, assuming some reasonable temperature of ice clouds for the computation of the function f the blackbody radiance on the left side of equation (4) can be calculated. This result can be inserted into the right side again after a transformation of the Planck function into the corresponding temperature. The iteration procedure is terminated if the difference of the temperatures between two iteration steps is smaller than a prescribed value, for example 0.1 K. We tested some other methods too, for example Newton's method and found that all of them are working well. On an average only 5 to 10 steps are needed for the iteration. The problem of finding the root of (4) is not a mathematical but a physical one, because the existence of a root depends on the validity of the physical assumptions made for the derivation of equation (4). Assuming that a solution exists, it can be demonstrated that this solution is unique. The existence and uniqueness of a root will not be discussed here since these problems will be investigated and described in more detail in a further paper.

2.2 Accounting for Water Vapor Above the Cloud

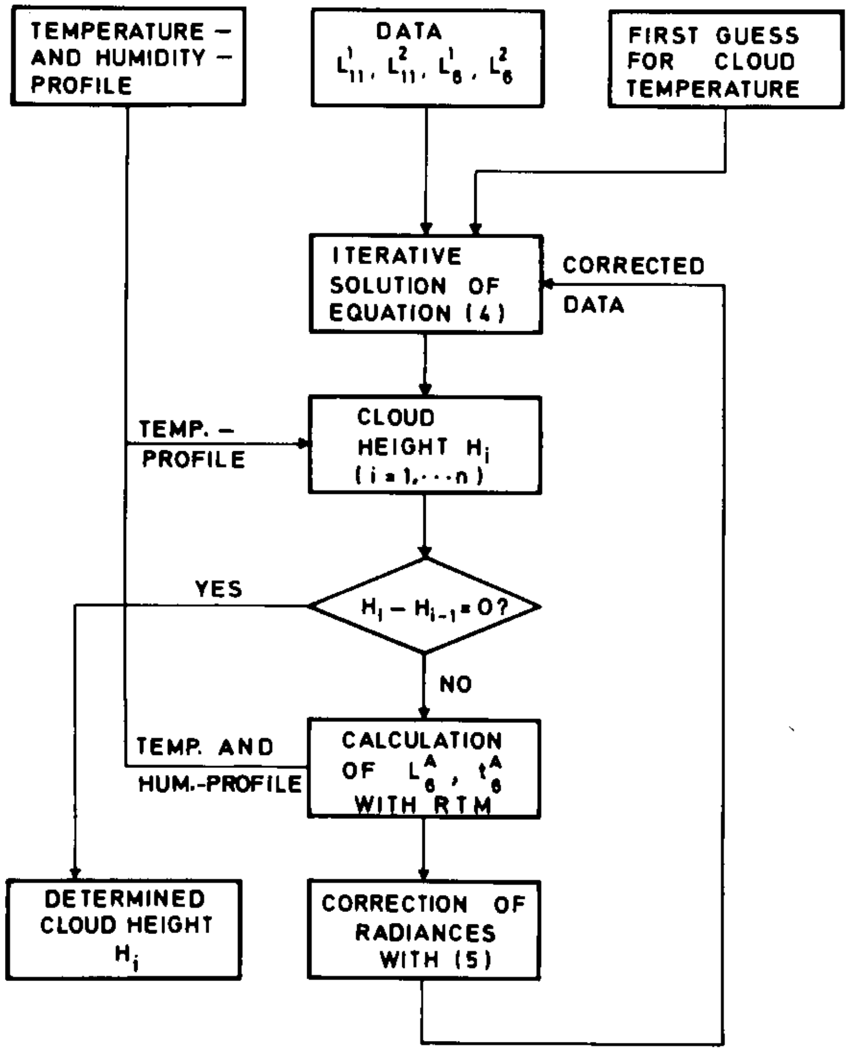
To derive Equation (4) it was necessary to neglect the emission of the atmospheric layer above the cloud. At 11 μm in the window region this is thoroughly justified because calculations show that the contribution of this atmospheric layer to the total emission amounts only to approximately 0.01 %. On the other hand, the contribution of this layer in the water vapor channel can be as great as the total radiation which arrives at the satellite. This depends on the length of the optical path through the upper atmospheric layer, i.e. on the height of the ice cloud and the zenith angle of the upward radiance. Therefore, the consideration of the water vapor above the cloud is essential for the accurate determination of the cloud temperature. This is done by correcting the measured quantities, i.e. the radiances are recalculated to remove the influence of the upper atmospheric layer. Assuming that the humidity profile is known a RTM can be used to calculate the corrected radiances $L_{6,c}$ according to the following equation:

$$L_{6,c}^{1} = \frac{L_6^1 - L_6^A}{t_6^A} \qquad\qquad L_{6,c}^{2} = \frac{L_6^2 - L_6^A}{t_6^A} \tag{5}$$

The RTM supplies the emission L_6^A of the upper atmospheric layer as well as its transmissivity t_6^A (see also Section 3.2). On the other hand, the exact calculation of these quantities is only possible with the knowledge of the height of the cloud and hence the thickness of the upper layer of the atmosphere. As yet, this is not the case. However, the previous iteration to determine the temperature using (4) provides the initial height which can be used for the calculation of temporary values for L_6^A and t_6^A.

If both measured quantities in the water vapor channel are now corrected according to (5) and a second iteration for the temperature determination is carried out by means of (4), an improved second height can be obtained. A second correction of the measured quantities according to (5) corresponding to the second height and a repeated temperature determination lead to a further improvement of the derived cloud height. The whole procedure can be carried out, until the cloud height no longer changes. The radiances $L_{6,c}^1$ and $L_{6,c}^2$ which have then been determined, correspond to the cloud height, i.e. these radiances would be measured at this altitude. This implies that the Equations (2) completely describe the radiative transfer up to the cloud top. The temperature determination with (4) will then lead to accurate results and the terms which are originally neglected no longer have any effect.

The total procedure for the determination of cloud heights fundamentally consists of two steps of computation which are carried out one after another (see Figure 2). The first step determines the temperature, the second corrects the measured radiances. For the correction of these quantities the knowledge of the temperature and humidity profiles is necessary.



• Figure 2
Scheme for height determination of optically thin ice clouds. Necessary are the temperature and humidity profile, the measured radiances L^1_{11}, L^2_{11}, L^1_6, L^2_6 and a first guess for the cloud temperature. The solution of (4) yields the height H_i (i = 1, ..., n) via the temperature profile. Corresponding to this height H_i a RTM calculates the emission L^A_6 and the transmissivity t^A_6 of the upper atmospheric layer using the temperature and humidity profile. The corrected data are then used in Equation (4) again. If the difference of two successively determined heights is approximately zero the procedure is terminated.

3 Calculations

3.1 Data Simulation

For the verification of the procedure, in a first step radiances at wavenumbers $\nu = 900\ cm^{-1}$ and $\nu = 1488\ cm^{-1}$ were simulated with a RTM (not identical with the RTM used to correct the radiances) corresponding to channels 8 and 12 of the HIRS/2 instrument aboard NOAA-6, the data of which will be used for cloud height determination. The RTM uses the matrix operator method (PLASS et al., 1967) and takes into consideration three atmospheric layers as well as a black emitting ground. The middle atmospheric layer represents the ice cloud. Ice particle concentrations from 0.02 to 0.05 cm^{-3} have been assumed according to an optical thickness of about 0.5 to 1.0 at 11 μm. Within the cloud layer scattering and absorption by ice particles are considered as well as absorption due to water vapor. In the layers above and below the cloud only water vapor absorption is taken into account. The profiles for temperature and humidity were taken from the standard atmospheres according to McCLATCHEY (1972). Within the ice cloud the temperature is kept constant and assumed to be the mean value between upper and lower cloud level temperatures. The water vapor pressure corresponds to the saturation value above an ice surface. To simulate the data, calculations are performed at the wavenumbers mentioned above for two different ice particle concentrations in a cloud layer at a particular height. The four required radiances are calculated at the top of the atmosphere for ten zenith angles, thus covering the range of observation angles available from satellite measurements.

3.2 Calculation Procedure

The computer program for the height determination of high clouds is rather simple and does not need much computer time (max. 10 seconds for ten zenith angles on an IBM-3081). As input data the program requires the radiances and the profiles for temperature and humidity as well as a first guess of temperature to start the iteration in (4) (see also Figure 2). For the temperature determination with Equation (4) usually 5 iterations are sufficient. The correction of the simulated radiances for the water vapor channel with Equation (5) usually has to be made three times. The RTM for the correction of radiances in the spectral region of the water vapor band uses a method proposed by BOLLE (1967). The necessary transmission functions for water vapor are available as polynomials valid for spectral band widths of 25 cm^{-1} according to MÜLLER (1976). The part of the program which corrects radiances needs more computations than the other parts, with result that the height determination of lower lying clouds takes somewhat more computer time than that of the higher ones.

3.3 Results

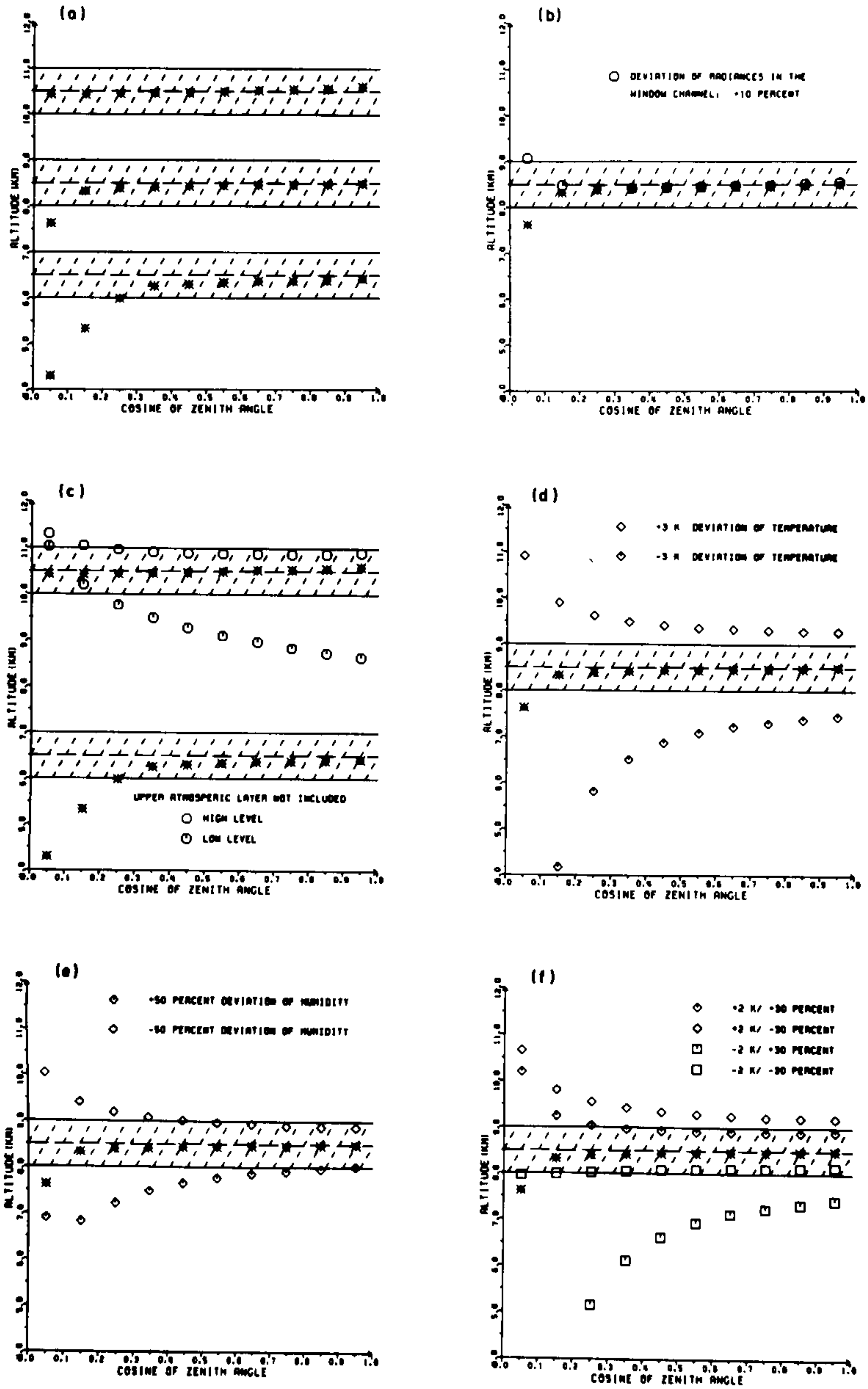
Figures 3a–3f show the results of height determination using simulated data. The results are depicted as function of the zenith angle of the radiances emerging at the top of the atmosphere. The broken line corresponds to the mean height of the clouds. The clouds considered have a geometrical thickness of one kilometer and are located at altitudes from 6 km to 12 km. The atmospheric profiles correspond to midlatitude conditions in summer. As can be seen in Figure 3a, the derived heights almost always correspond very well to the mean heights of the ice clouds. In some cases deviations are only a few metres.

Because the water vapor is taken into consideration, the accuracy of the method hardly depends on the height in the case of small zenith angles. In the case of very large zenith angles and low lying clouds larger errors occur. However, this range of zenith angle is not important for the following investigations because the HIRS/2 instrument has a largest observation angle of 49.5 degrees according to a cosine of zenith angle of about 0.5. The observation angle is defined as angle between the nadir direction and the line of sight of the satellite.

Figure 3c shows how much the result can be affected by the amount of water vapor present in the upper atmosphere. The cloud height is calculated both with and without considering the water vapor above the cloud for two cloud layers at different heights. It is evident that taking the water vapor into account leads to very good results even for low lying clouds while the calculations without the correction of the radiances have large errors. In case of high clouds the differences between corrected and non-corrected data are normally small, but this depends on the amount of water vapor. High absolute humidity can lead to noticeable errors in the determined heights of high level clouds.

• Figure 3a–3f Real and calculated heights for ice clouds as function of the cosine of zenith angle which is defined as the angle between the direction of the zenith and that of the radiance emerging at the top of the atmosphere. The horizontal broken line represents the mean height, the sloping dashed lines the vertical extent of the cloud. The stars denote in all cases the calculated heights from simulated data if the profiles of temperature and humidity are known exactly.

The computations have been performed for clouds at three different altitudes (a), for deviations of the radiances in the window channel (b), with and without correction of the water vapor in the upper atmospheric layer for clouds at two different altitudes (c), for deviations of the temperature profile (d), for deviations of the humidity profile (e) and finally for simultaneous deviations of the temperature and humidity profiles (f).


(a)
(b)
DEVIATION OF RADIANCES IN THE WINDOW CHANNEL: +10 PERCENT
(c)
UPPER ATMOSPHERIC LAYER NOT INCLUDED
HIGH LEVEL
LOW LEVEL
(d)
+3 K DEVIATION OF TEMPERATURE
-3 K DEVIATION OF TEMPERATURE
(e)
+50 PERCENT DEVIATION OF HUMIDITY
-50 PERCENT DEVIATION OF HUMIDITY
(f)
+2 K/ +30 PERCENT
+2 K/ -30 PERCENT
-2 K/ +30 PERCENT
-2 K/ -30 PERCENT
ALTITUDE (KM)
COSINE OF ZENITH ANGLE

Errors of the radiances in one or both channels do not affect significantly the accurracy of the method. This can be seen in Figure 3b which shows computations with an error of + 10 percent in the window channel. Results of computations with the same error in the water vapor channel or in both channels are looking very similar. The influence of the contrast between the two radiances measured at both cloud points was tested too, where the contrast is defined as the ratio of $| L_{11}^1 - L_{11}^2 | / (L_{11}^1 + L_{11}^2)$. The computations show that the contrast can be as small as 0.1 % without causing considerable deviations from the results achieved with large contrast calculations. Hence it can be stated that the influence of the absolute accurracy of the radiances and of the contrast between the two radiances can cause an additional error of less than 100 metres.

3.4 Effect of Deviating Atmospheric Profiles

So far, the simulation of data and the subsequent derivation of cloud heights have been made with the same temperature and humidity profiles. However, it must be assumed that in the case of satellite measurements the atmospheric conditions in a certain region are only approximately known. Of course, radiosondes provide some information about temperature and humidity, but this is not sufficient because of their low resolution in space and time. Furthermore, the humidity measurement at high altitudes is very inaccurate with the present radiosondes. In any case, for large areas of the globe which are not covered by radiosonde stations one has to assume the climatological mean values.

Figures 3d and 3e demonstrate the height difference due to deviations of the temperature and humidity profiles. The model consists of an ice cloud of 1 km thickness with the lower level at an altitude of 8 km. According to statistics by APPLEMAN (1955) such ice clouds can often be found in Central Europe. For the data simulation the atmospheric profiles again correspond to summer values of mid-latitudes. The profiles are now systematically varied at all altitudes. In the case of the temperature profile this change is assumed to be ± 3 K relative to the correct temperature. The result in Figure 3d clearly indicates that an exact knowledge of the temperature profile is decisive in the height determination. In the case of small zenith angles errors of height determination occur which are of the same order of magnitude as those of the conventional method which treats clouds as blackbodies. These errors are due to the fact that the heights are derived directly from the temperature profiles. However, the errors of our method can increase considerably with increasing zenith angle whereby assuming a temperature that is too low yields less accurate results than assuming one that is too high. The explanation for this is that the correction of the radiances becomes larger with increasing optical path through water vapor containing layers. Since an underestimation of the temperature results in a height that is too low after the first iteration, the radiances are overcorrected. This again results in an increased tendency toward lower heights in the following steps that determine the temperature by iteration and correct the radiances. Therefore large inaccuracies arise especially in the case of zenith angles near the horizon. However, this range of zenith angles is not covered by the HIRS/2 instrument.

On the other hand, deviating water vapor profiles generate smaller errors (Figure 3e). This is shown for variations in the absolute humidity of ± 50 % relative to the correct profile. The reason for this is that only the error in the water vapor content above the cloud is reflected in the results while the water vapor mass below the cloud has no effect. Once again longer optical paths generate larger errors corresponding to larger zenith angles. An overestimation of the water vapor content (+ 50 %) will result in a somewhat larger error than an underestimation (− 50 %).

Figures 3d and 3e show the effect of temperature and humidity when one of these parameters is kept constant, i.e. corresponds to the correct value. The results make it obvious that incorrect temperature profiles reduce the accuracy of the height determination more than incorrect humidity profiles. This is an important aspect in the overall error estimation since the humidity at high altitudes usually is not as well known as the temperature. However, it must be added that this only applies to ice clouds with heights above 8 km. The influence of water vapor becomes more important for lower clouds. In this case it may happen that the method yields no suitable results, but for the most part ice clouds are located above this level.

Figure 3f shows the results when both quantities are varied at the same time. A mean deviation which is smaller than the variations for just one parameter is assumed. This assumption is made because of the small probability of a large simultaneous deviation of humidity and temperature in the magnitude of ± 50 percent and ± 3 K. Thus the temperature variation is assumed to be ± 2 K for the whole profile while the humidity varies by ± 30 %. As can be seen a superposition of errors occurs at some cases, i.e. the total error is approximately the sum of the individual errors. This is valid for the combinations − 2 K/+ 30 % and + 2 K/− 30 %. On the other hand, the individual errors in the combination − 2 K/− 30 % and + 2 K/+ 30 % counteract in such a way that the total error will be smaller. For the total error, varying both parameters shows that assuming a temperature that is too low and too much water vapor gives rise to greater errors than assuming too high temperature and too little water vapor. The conclusion is that if the atmospheric profile is not known sufficiently the total error can be minimized by systematically tending towards higher temperatures and lower amounts of water vapor.

4 Application to Satellite Data

4.1 Satellite Data

For demonstration of the applicability to satellite measurements, data of the HIRS/2 instrument aboard NOAA-6 were used. The HIRS/2 instrument has 19 channels in the IR-spectrum. Channel 8 and channel 12 used in the further investigation have central wave numbers of 900 cm^{-1} and 1488 cm^{-1}. The half power widths are 35 cm^{-1} and 80 cm^{-1}. A single scan line of this instrument consists of 56 pixels and has a largest observation angle of 49.5 degrees. The resolution of both channels in one scan line is about 20 km at the subsatellite point and decreases with increasing angle of observation. The data are calibrated and the geographic coordinates are known for each pixel.

To apply our method the 56 pixels of a scan line are subdivided into 28 subsequent pairs of neighboring pixels. Since the half power width of channel 12 is 80 cm^{-1} the correction of the radiances according to Equation (5) in the water vapor band is performed by integrating the results obtained from calculations with the spectral transmission functions of MÜLLER (1976) which have a bandwidth of 25 cm^{-1}. The computer time needed for processing one scan line with 28 pairs of pixels is about 4 s (on an IBM 3081) which means that the method is well suitable for operational use.

4.2 Results and Comparison with Measurements

The results discussed in the following refer to a passage of NOAA-6 on the 10th of July 1981. At the time of the passage in situ measurements by means of a lidar aboard the german meteorological research aircraft ('Falcon') over the eastern part of France were performed. The lidar aboard the Falcon can measure the distance from the aircraft to clouds with a frequency of 10 Hz and with an accuracy of three metres. Since the Falcon can registrate temperature, humidity and pressure the profiles of temperature and humidity are available up to the flight level and this level can be calculated exactly. Above this level climatological data have to be used.

A meteorological analysis shows a weak cold front westward of the river Rhine in connection with thunderstorms moving slowly eastward. There was a thick stratus at heights of about 4 km to 5 km.

Above the stratus layer existed a thin but extended cirrus cloud. The flight path above the cirrus cloud had a length of about 100 km. In the neighborhood of the flight path six heights could be determined from HIRS/2 data for the comparison. The results are the following: the mean value of the determined cloud heights is 10.1 km where the maximum is 11.3 km and the minimum is 8.9 km. On the other hand, the lidar measurements show that the mean height of the ice cloud was 10.7 km. This seems to be a good agreement and the results are much better than those achieved from the window channel alone. Within the considered area the brightness temperatures have values from 250 K to 275 K in the spectral region of 11 μm according to heights from 8 km to 4 km. It is also evident that a stratus layer below the ice cloud does not affect the results of the height determination. This can also be confirmed by calculations with simulated data. However, it must be mentioned that a single comparison of derived and measured heights does not permit a final judgement on the accuracy of our method because the mean height determined from satellite data refers to an area while the mean height measured with the lidar refers to the line of the flight path.

The processing of all available data of the passage of the 10th of July shows that the height determination fails in about 60 percent of all considered pairs of pixels. By means of calculations with simulated data it can be shown that our method for height determination fails if some of the physical conditions for the validity of Equation (4) are not given. Thus, the reasons for a failure can be that there are no ice clouds in field of view at both pixels or the temperature of the ice cloud is different at both pixels.

5 Conclusion and Outlook

A bispectral method based on satellite measurements in the spectral regions of the thermal window and the 6.3 μm water vapor band has been developed for the purpose of determining the temperature of ice clouds with an emissivity of less than one. The influence of water vapor absorption above the ice cloud has been taken into account. The verification of the method with simulated data yields very good agreement between real and derived cloud heights. The accuracy of the method depends only slightly on the cloud height and on the zenith angle of observation. As shown, it is essential to consider the effect of water vapor especially when the height of clouds at lower levels is to be determined. If the effect of water vapor is not being accounted for accurate results can only be obtained for ice clouds at very high altitudes. The knowledge of the atmospheric profiles for temperature and humidity is of great importance. Particularly, a deviating temperature profile causes larger errors than does a deviating humidity profile. The combined assumption of too low temperature and too much water vapor leads to a larger total error than the assumption of too high temperatures and too little water vapor. In any case, for use of satellite measurements both parameters should be known as accurately as possible.

The application to HIRS/2 data makes it evident that the proposed method is well suitable for operational use and yields much better results than the conventional method using only one IR-channel. A stratus layer below the ice cloud does not affect the results. However, since our method is not yet completely verified more flights for comparing results of satellite data with lidar measurements have to be performed in the future.

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