MET O 19 BRANCH MEMORANDUM No. 102

THE VALIDITY OF A FLAT CLOUD MODEL FOR INFRA-RED SOUNDING

by

P.D.Watts

March 1990

Meterological Office Unit (MET O 19c)
Robert Hooke Institute for Co-operative Atmospheric Research
Clarendon Laboratory, Oxford, OX1 3PU

1. Introduction

This paper examines the suitability of a flat topped cloud model for use with infra-red soundings, with particular reference to TOVS (TIROS-N Operational Vertical Sounder) measurements. Until recently most retrieval methods have treated the effects of clouds as a source of noise which must be corrected before the inversion of radiances to atmospheric profiles of temperature and humidity. Such a process, normally referred to as cloud–clearing, has been achieved in a number of ways; see for example Smith 1968, Chedin 1984, Eyre and Watts 1987. Normally one of two approaches is taken depending the cloud conditions: either rejection of soundings or at least channels that appear contaminated by cloud, or correction of the observed radiances for the effects of cloud. Recently, methods have been developed where the cloud is treated explicitly as part of the inversion process which then becomes non–linear and demands iterative methods of solution (Susskind et al. 1984, Eyre 1989). Whether the cloud in a field of view (FOV) is treated implicitly or explicitly it is usually assumed to be a single layer of uniform temperature – what we may call a flat cloud model. This paper investigates the errors that result in radiances calculated from a cloudy FOV when this assumption is made. No attempt is made here to estimate how such errors propagate into a particular retrieval product, but their magnitude will be a guide to their importance.

Calculating radiances from the atmospheric state is called the forward calculation and the representation of the state and of the physics of radiative transfer is called the forward model. Thus *forward model errors* are caused by an inappropriate or inaccurate model. For clear sky calculations the forward model error is usually dominated by shortcomings in the physics (line shapes, strengths etc.) or in knowledge of the instrument characteristics (filter functions etc). Representation of the continuous atmospheric profile by a set of discrete levels is a model approximation which will also lead to errors, but these are likely to be small. Similarly, representation of cloud by a flat surface may introduce forward model errors: clouds rarely have flat tops.

2. Method

The importance of a flat cloud forward model error has been investigated in the following way. The temperature structure of common cloud classes has been established from AVHRR (Advanced Very High Resolution Radiometer) data. Sets of clouds of each class have been generated from these structures and the HIRS radiances calculated from each using the U.S. Standard Atmosphere to define the atmospheric profile. These are the *true* radiances. The mean temperature of each cloud is calculated and its height or cloud top pressure found from the Standard Atmosphere. This defines the cloud according to the flat cloud model and radiances calculated using it are the *flat cloud* radiances. Comparison of flat cloud and true radiances gives an estimate of the forward model error.

2.1 Cloud characterisation

Three classes of cloud were characterised: cirrus, cumulus, and mixed layer cumulus and cumulonimbus. The first we expect to be most homogeneous or flat–

topped, the last we expect to be the least so. Regions of the appropriate cloud type were identified on an AVHRR channel 4 ($11\mu m$) image and an area approximately the size of the HIRS footprint ($\approx 17\ Km^2$) was selected. Care was taken to ensure no clear or partly clouded pixels were included in the area. Both can be tested for quite stringently using threshold and coherence tests (see for example Saunders, 1988) but this was not done here.

Using an image display, clear pixels are easily identified by eye, partly cloudy less so. (The effect of including partly cloudy pixels will be to increase the temperature variability of the cloud and thus increase the estimated forward model error.)

The pixels in the selected area were histogrammed according to temperature; examples are shown in figure 1. Eleven areas or clouds were selected; 4 cumulus, 3 mixed layer and 4 cirrus. For radiance calculations the fine resolution histograms were degraded to frequencies at standard temperatures every 5 K. The limited scope of this study allows us to use AVHRR channel 4 temperatures as cloud–top temperatures even though there will be some atmospheric absorption above the cloud. A more serious problem is that of semi–transparent cloud, e.g. some cirrus, where it overlays another much lower cloud layer. The temperature range found here is likely to be greater than that found in mixed layered opaque cloud and as such will give rise to larger forward model errors. Unfortunately the AVHRR data can not be used to give temperatures for the tops of semi–transparent cloud and therefore this class of clouds is omitted from the study.

To obtain a statistical sample, the clouds in table 1 were perturbed in two ways.

(a) Each cloud was shifted up and down one standard temperature level so that the original cloud is specified at offsets of -5, 0, and +5 K.

(b) The frequencies or fractional cloud at each level were randomly and independently perturbed by up to 30%. 20 cases were generated in this manner which should retain the class identity of the cloud, i.e. a perturbed cumulus, for example, will have a distribution that is typical of cumulus and will remain distinct from cirrus.

(a) and (b) together give 60 clouds for each original characterisation. Figure 2 shows the mean frequency distributions on the standard levels of the individual clouds after perturbation. The cloud types were appended so that finally there were 240 cases of cumulus, 180 cases of mixed–layer and 240 cases of cirrus.

The flat cloud model for each case was defined as having a mean temperature

$$T_{flat} = \frac{\Sigma_i f(T_i).T_i}{\Sigma_i f(T_i)}$$

where $f(T_i)$ are the frequencies given in figure 2. Its corresponding pressure is found by linearly interpolating the standard atmosphere. This is a somewhat arbitrary definition: we could have defined a mean pressure and from this obtained the mean temperature. This matter is discussed further in section 4.

2.1 Radiance calculations

Radiances were calculated using a fast transmittance model (Weinreb et al. 1981, Eyre 1984) with the standard atmosphere defining the temperature and humidity. Clear column radiances, R_o, were obtained with the lower boundary conditions of the integration given by the suface temperature and pressure. Cloudy radiances, R_i were obtained with the boundary conditions given by the cloud top temperature and pressure. The radiance for a FOV with fractional cloud cover n is, for the flat cloud;

$$R_{model} = nR_{flat} + (1 - n)R_o$$

and for the real cloud;

$$R_{true} = n\frac{\Sigma_i f(T_i)R_i}{\Sigma_i f(T_i)} + (1 - n)R_o$$

Equivalent brightness temperatures were derived from the radiances using the Planck function.

3 Results

Graphs of the mean and standard deviation of the difference flat–true cloud brightness temperatures are given in figure 3. Values are shown for the three cloud classes and for the HIRS channels used in the current operational retrieval scheme. These results are for a fully cloudy FOV i.e. $n = 1$. All the mean differences are positive, i.e. flat cloud brightness temperatures are higher than the true cloud values. For all cloud classes and channels the standard deviations are less than the means and are also small (order 0.1 K) relative to the spread of temperatures present in the cloud (order 10 K). The two higher sounding water vapour channels HIRS 11 and 12 have the largest differences, the stratospheric (HIRS 1,2,3) and window (HIRS 8,13) channels have the smallest. The pattern of the differences with channel is similar for the different cloud classes but the magnitude varies: mixed layer cloud gives the largest means, cirrus gives the largest standard deviations.

4 Discussion

Before commenting on the importance of errors of this nature in the context of retrievals we will try to explain some of the features noted above.

There are two consequences of non-flat clouds that we will see give opposite contributions to the flat–true cloud difference. The first arises from the non-linearity of the Planck function with temperature; the second because channel weighting functions have significant values above the cloud top.

Figures 4a,b and c show the increasing non-linearity of the Planck radiance with temperature as the wavenumber increases from the HIRS longwave channels around $900cm^{-1}$ to the shortwave channel 14 at $2213cm^{-1}$. The effect the non-linearity at $2213cm^{-1}$ will have on flat and true cloud brightness temperatures is shown in figure 5. The hypothetical non-flat cloud shown has a uniform distribution of temperatures from 250 to 290 K and therefore a flat cloud temperature of 270 K. The corresponding flat cloud radiance is about 1.5 $mW.st^{-1}(cm^{-1})^{-1}m^{-2}$ as indicated. This is clearly less than the true radiance which is the mean of the emitted radiance at about 1.9 $mW.st^{-1}(cm^{-1})^{-1}m^{-2}$. Thus the effect of the Planck function is to give flat-cloud brightness temperatures that are lower than the true values. The difference is greatest for the shorter wavelength channels.

The weighting function effect is demonstrated in figures 6a and b. Figure 6a shows channel brightness temperatures against cloud top temperatures; for very high and cold cloud all channels see only the cloud top, as the cloud lowers and warms atmospheric absorption becomes important and a deficit appears between the cloud temperature and the brightness temperature. The deficit is smaller for the more transparent channels. Again we can create an uniformly distributed non-flat cloud (figure 6b) with temperatures ranging between 230 and 270 K and a flat cloud temperature of 250 K. This gives a flat cloud brightness temperature (HIRS 5 shown) that is greater than the true brightness temperature which is the mean of the channel brightness temperature range shown. (The true brightness temperature should of course be calculated from the mean radiance but we are interested here in the weighting function effect and assume a linear relation between radiance and temperature.) The strength of this effect depends on the degree to which the brightness temperature in Figure 6a deviates from a straight line and this will depend on the position and shape of the weighting function and to some extent on the temperature and humidity of the atmosphere. The greatest non-linearity would be found with a channel with an infinitely narrow weighting function which either measures the cloud temperature or the atmosphere but never a mixture. Figure 6a shows strong non-linearities in channel 12 around 240 K or 400 mb, in channel 11 around 600 mb and in channel 4 around 400 mb. Not suprisingly, these levels roughly correspond to the level of the peak of the respective weighting functions. Most channels show some non-linearity.

We may now interpret figure 3. All the mean differences are positive indicating that the Planck effect is generally less than the weighting function effect since the Planck effect gives negative values. Channels 1,2 and 3 are stratospheric and not significantly affected by cloud. Mid-tropospheric channels 4–7, 13,14 and 15 have moderate differences caused by the weighting function effect; in the shortwave chnnels, 13,14 and 15, this is reduced by the Planck effect. The window channel 8 and the near window channel 10 have very little weighting function or Planck effects. Finally, the water vapour channels 11 and 12 show strong weighting function effects presumably somewhat reduced by a moderate Planck effect.

It is worth returning to the question of the definition of the flat cloud by way of its mean temperature. In practice this mean value is not known and in a retrieval scheme the *flat cloud* is not so much a definition as an assumption, a restriction on the flexibility of the forward model. The flat cloud parameters that best fit a set of HIRS measurements are evidently not those of our mean temperature definition – it produces HIRS radiances that are consistently high. The best flat cloud available would be higher and colder (or with a lower FOV coverage) than the mean temperature version. Consequently, in any real retrieval scheme the results presented here for the mean brightness temperature differences would be shifted so that some channels would have negative values. Exactly how much will depend on the scheme and how the channels are weighted in the inversion but we may suppose mean differences would be generally smaller than the present results. The size standard deviations would probably not change significantly.

4.1 Implications for sounding

The flat cloud is a good model for non-flat clouds, even for cumulo-nimbus and mixed layer clouds where the range of temperatures present may be in excess of 20 K. Even with full cloud cover we may expect around only 0.2 K error in the flat-cloud brightness temperatures for the worst affected sounding channels. The water vapour channels are more affected and could be 0.5 K in error. With typical amounts of cloud of an average roughness we may expect maximum errors of around 0.1 K, twice that in the water vapour channels. As mentioned in section 2.1 semi–transparent cloud has not been studied here and is likely to give larger errors. However, for the majority of cloud types met in practice, the above conclusions stand.

What of other forward model errors? Spectroscopic error characteristics are not well known, mainly because of a lack of a good ground truth measurement. It is however, likely that such errors propagate into forward calculations principally as biases which can be monitored and corrected (Fleming et al. 1986). Variable concentrations of minor constituents (e.g. ozone) will give forward model errors; whether they give rise to bias or random errors depends on the monitoring and correcting system and how fast the concentrations vary. Modelling the profile as a set of discrete values is another unquantified error source but at least it could, in principle, be investigated.

Comparing measurements with calculations from radiosondes puts an upper limit on the total forward model error but such comparisons are strongly contaminated with colocation and radiosonde errors. Some empirical evidence on the total error is available from experiments with a retrieval scheme (McNally 1990). Non–linear retrievals (see Eyre 1989 for details) using cloud contaminated radiance measurements were performed using a range of different assumed forward model noise levels. It was found that a noise level of 0.4 K gave the most accurate retrievals as measured by colocated radiosondes. Similar experiments performed on a larger sample but with less coincident radiosondes give a value of 0.3 K (+/- 0.05 K). The scheme retrieved cloud parameters and had a flat-cloud model so that these figures include the flat-cloud forward model error discussed here.

From these rough indications of the forward model noise level we may tentatively conclude that the flat-cloud model does not impose serious restrictions on the use of HIRS measurements in cloudy conditions. There may be exceptions in extreme conditions for certain channels, notably HIRS 12, but generally we may expect flat-cloud errors to be lower than errors from other sources. However, the flat-cloud errors are not totally insignificant and we at least have a good idea of the form they take. The bias and standard deviation patterns are fairly constant for all types of cloud and modelling them in a retrieval scheme (through a radiance bias vector and error covariance) would be straightforward.

5 Summary

The errors in HIRS brightness temperatures arising from the use of a flat-cloud model have been estimated. The form of the errors have been qualitively explained in terms of two effects: non-linearity of radiance with temperature through the Planck function and atmospheric absorption above the cloud level. Errors are found to be small considering the large range of temperatures present in a FOV containing cloud. It is suggested that they are also smaller (with exceptions) than other less well quantified sources of forward model error and as such do not preclude the use of the flat-cloud model for TOVS sounding in cloudy areas. On the other hand they are large enough, and consistent enough, to warrant modelling in cloudy radiance retrieval schemes.

REFERENCES

CHEDIN A., SCOTT N.A. (1984). *Proc. of the 1st Int. TOVS study conference. Igls, Austria. August 1983. A report from CIMSS University of Wisconsin, Madison, USA, Ed P.Menzel, pp.14–79.* Improved Initialisation Inversion Procedure.

EYRE J.R.(1984). *Met O 19 Branch memorandum No. 75* User guide to TOVS-RAD: a program for calculating synthetic HIRS-2 and MSU equivalent brightness temperatures.

EYRE, J.R. AND WATTS, P.D. (1987). *Q.J.R.Meteorol.Soc.* **113**, *pp.1349–1376* A sequential approach to cloud–clearing for satellite temperature sounding.

EYRE J.R. (1989). *Q.J.R.Meteorol. Soc.,* **115**, *pp.1001–1037.* Inversion of cloudy satellite sounding radiances by non–linear optimal estimation. parts I and II.

FLEMING H.E., CROSBY D.S., AND NEUENDORFFER A.C. (1986). *J. Clim. Appl. Meteorol.,* **25**, *no.6* Correction of satellite temperature retrieval errors due to errors in atmospheric transmittances.

MCNALLY A.P., (1990). *Oxford University D.Phil. thesis in preparation.* Satellite sounding of atmospheric temperature and humidity.

SAUNDERS R.W. AND KRIEBEL K.T. (1988). *Int. J. Remote Sensing.* **9**, *no.1, pp.123-150* An improved method for detecting clear sky and cloudy radiances from AVHRR data.

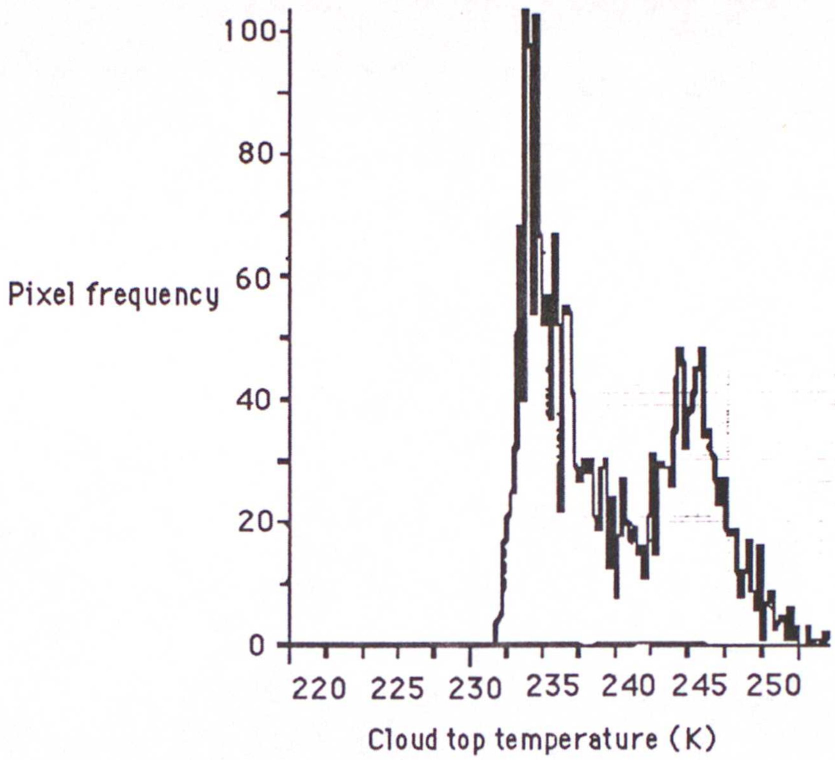
SMITH W.L. (1968). *Mon. Weath. Rev.,* **96**, *pp.387–396* An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements.

SUSSKIND J., ROSENFIELD J., REUTER D. AND CHAHINE M.T., (1984).*J.Geophys. Res.,* **89**, *pp.4677-4697* Remote sensing of weather and climate parameters from HIRS2/MSU on TIROS–N.

WEINREB M.P.,FLEMING H.E.,MCMILLIN L.M. AND NEUENDORFFER A.C. (1981) *NOAA Tech. Report NESS 85* Transmittances for the TIROS operational vertical sounder.

Figure 1: AVHRR cloud characterisation

(a) Mixed layer cumulus



(b) Frontal cirrus

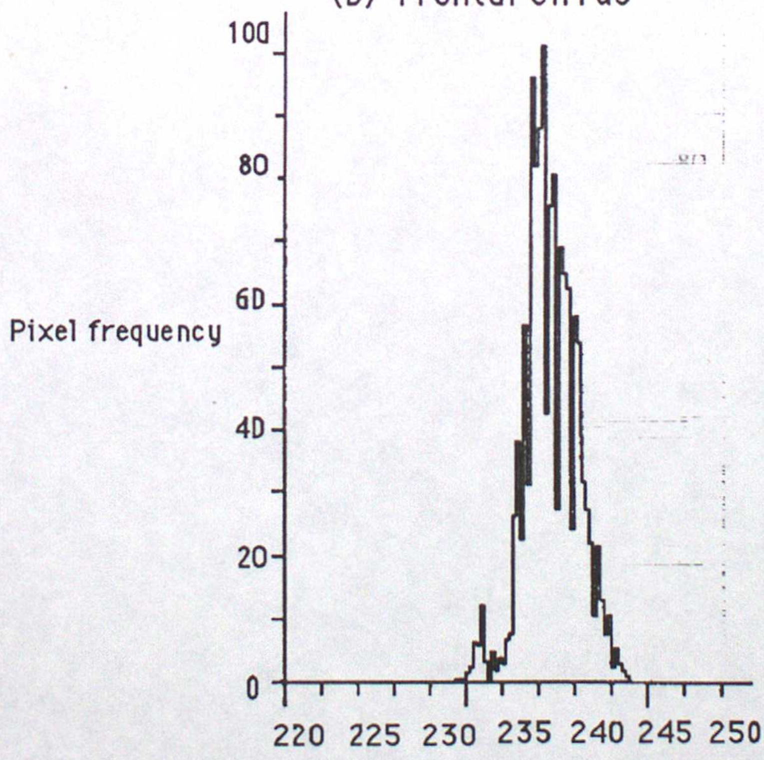


Figure 2: Cloud temperature distributions

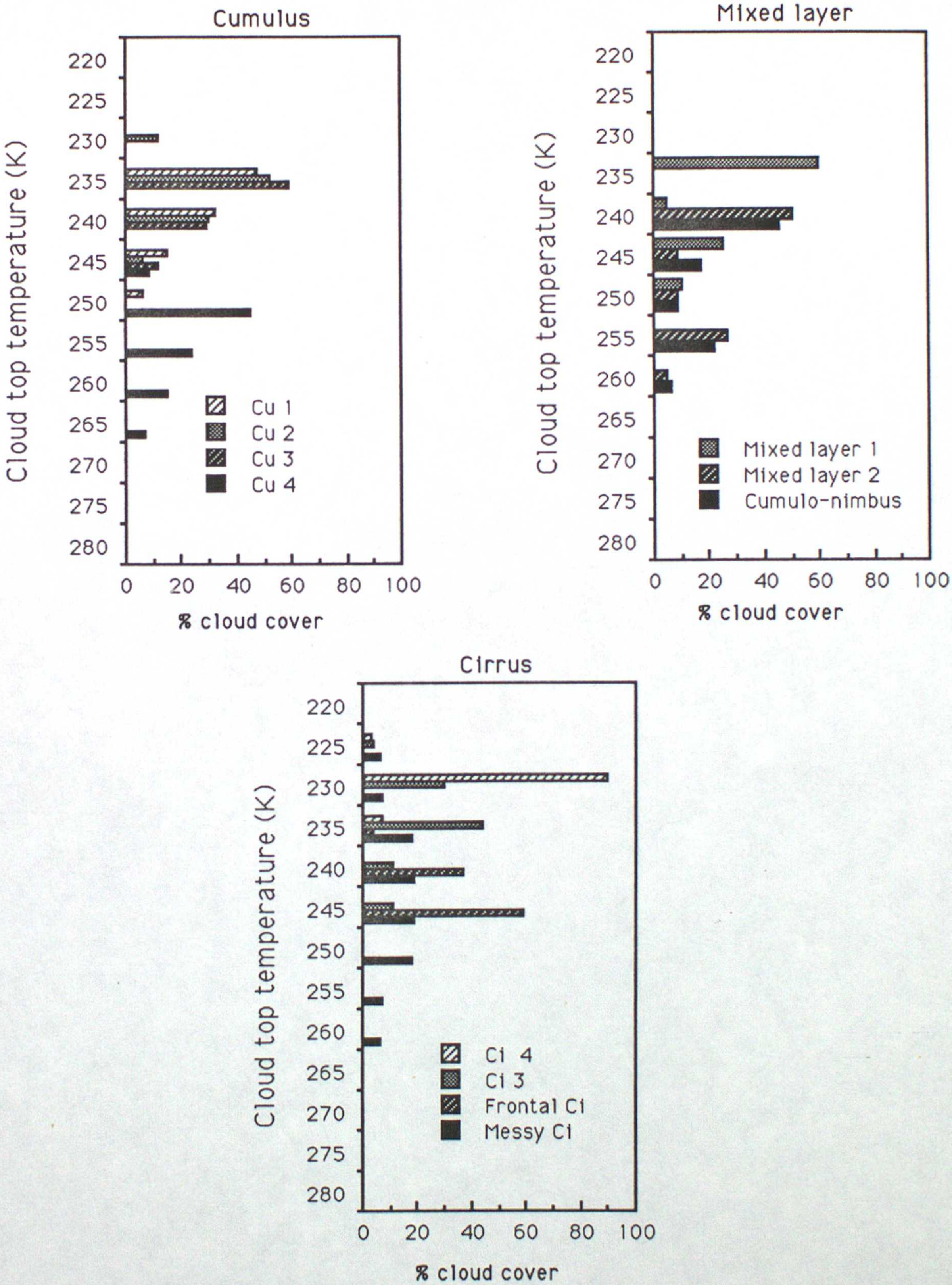


Figure 3a: Mean brightness temperature differences: Flat-true cloud

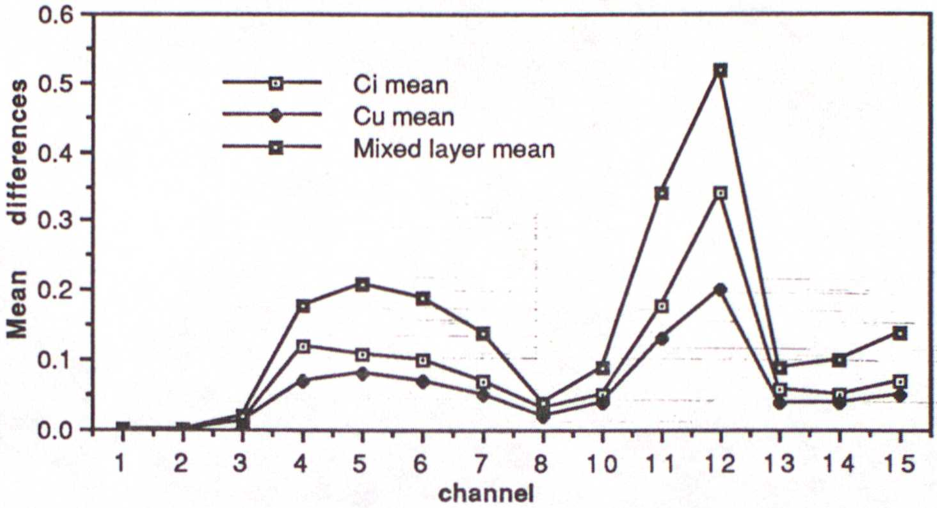


Figure 3b: Standard deviation of brightness temperature differences: Flat-true cloud

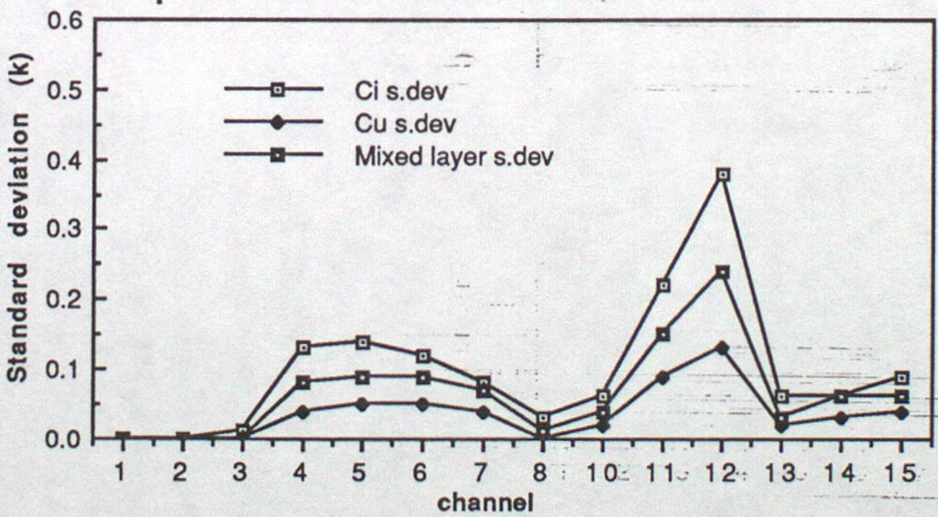
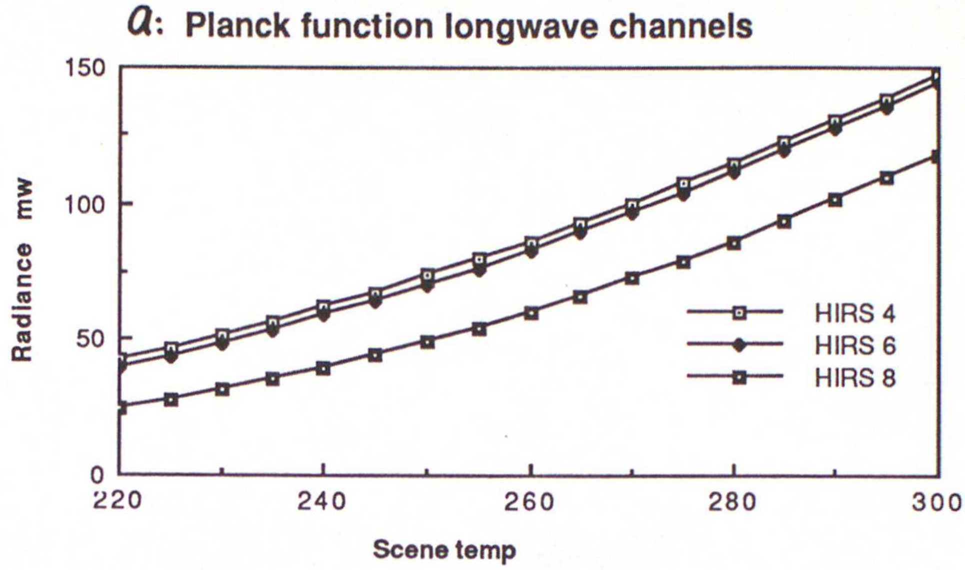
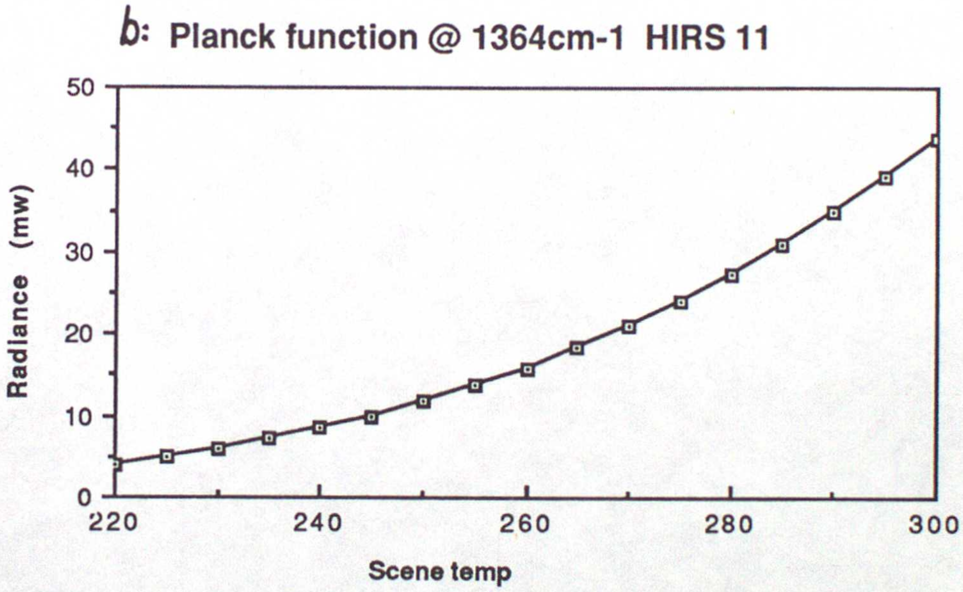


Figure 4


a: Planck function longwave channels
Radiance mw
Scene temp
HIRS 4
HIRS 6
HIRS 8
0
50
100
150
220
240
260
280
300


b: Planck function @ 1364cm-1 HIRS 11
Radiance (mw)
Scene temp
0
10
20
30
40
50
220
240
260
280
300

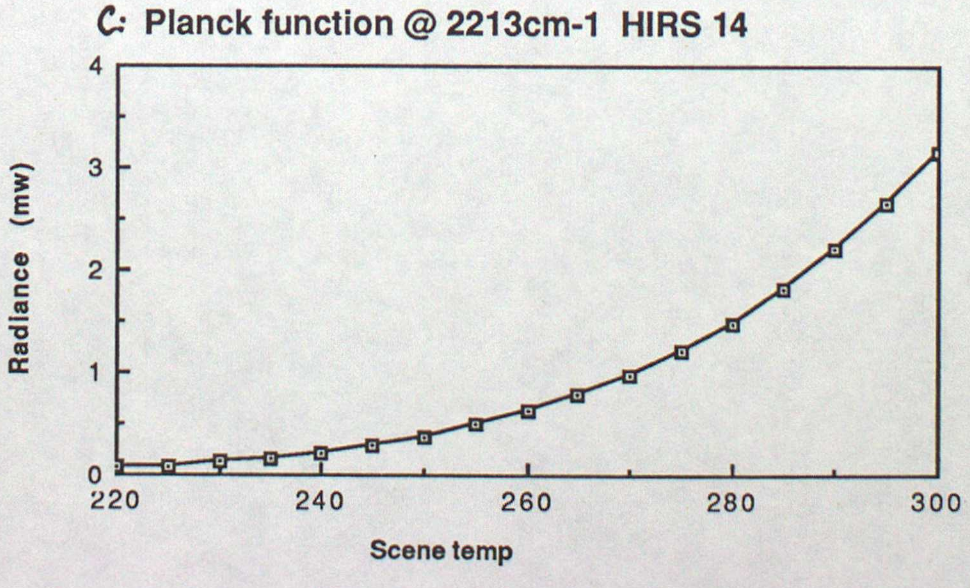

c: Planck function @ 2213cm-1 HIRS 14
Radiance (mw)
Scene temp
0
1
2
3
4
220
240
260
280
300

Figure 5: Flat and true cloud radiances with the Planck function effect (@2213cm-1) and an evenly distributed cloud

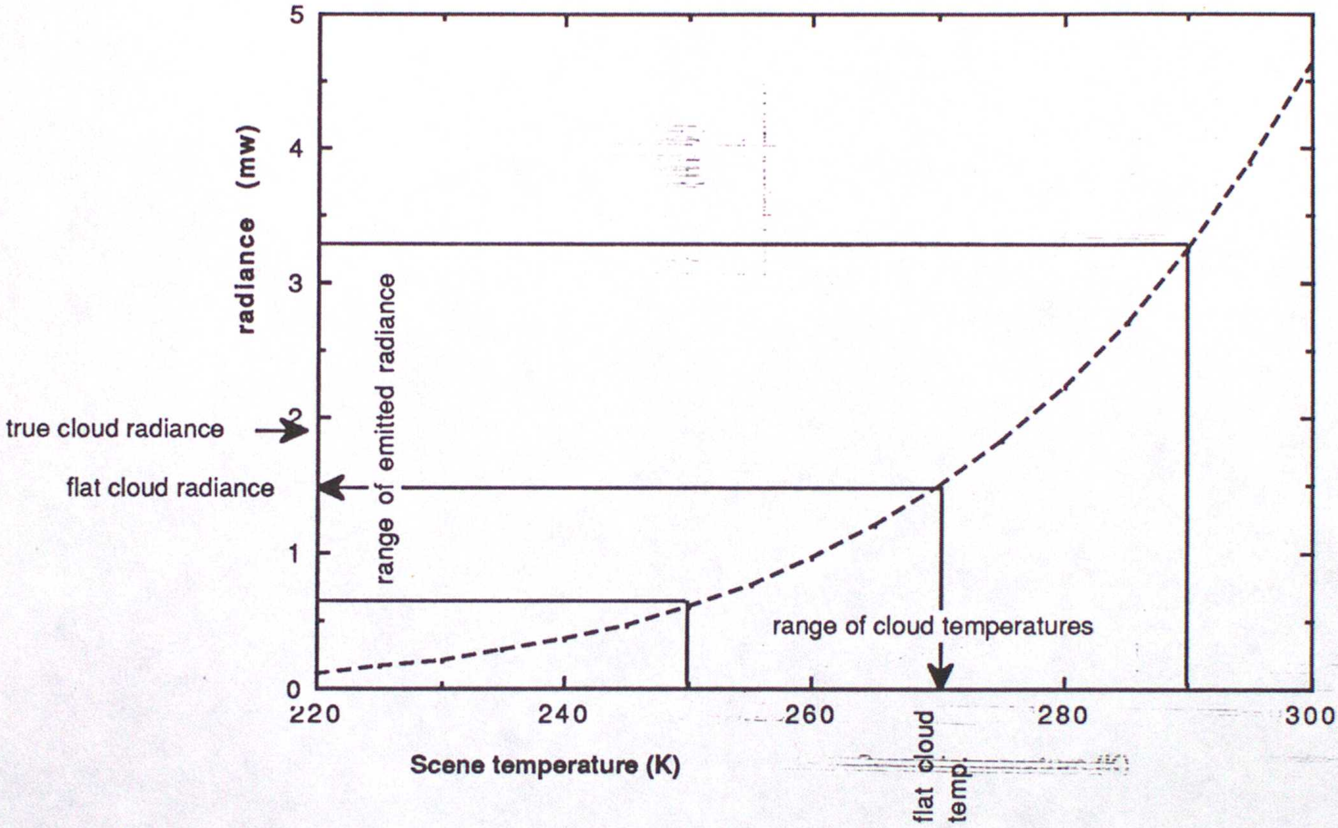


Figure 6a: HIRS brightness temperatures with cloud temperature

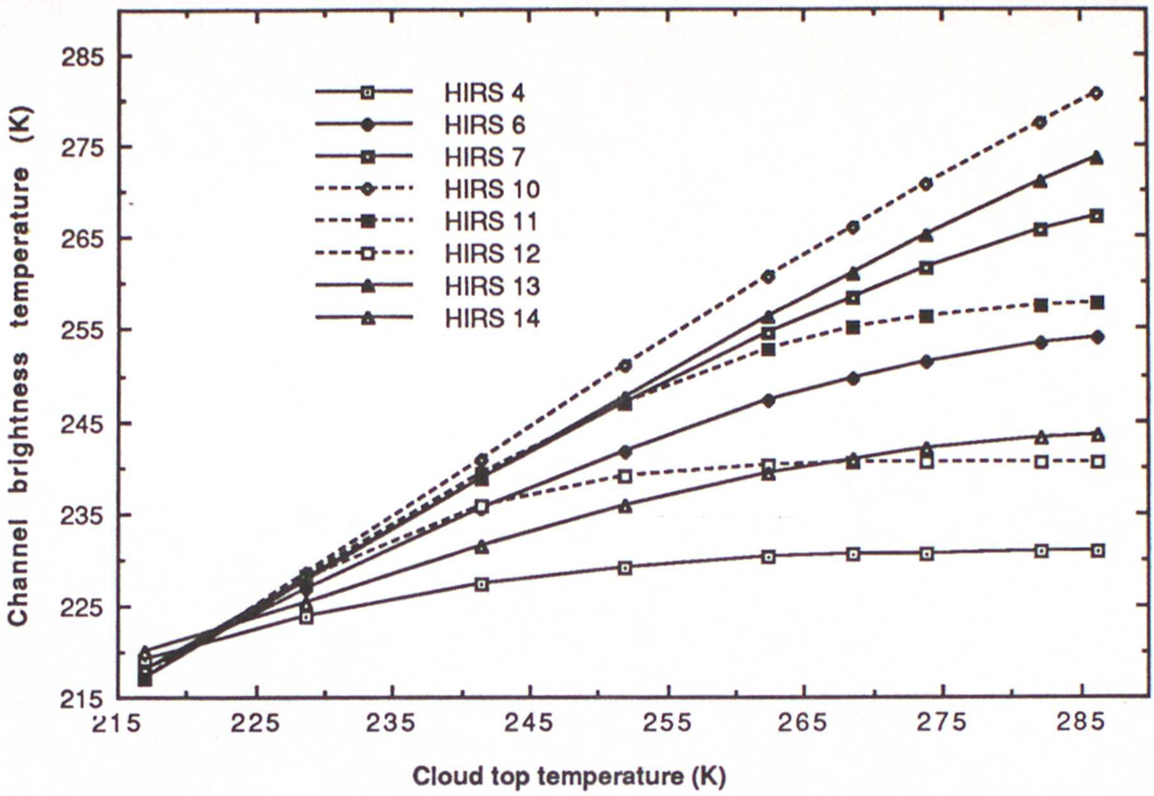


Figure 6b: Flat and true cloud brightness temperatures with the Weighting function effect. HIRS 5, evenly distributed cloud