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by

GRAEME PENNEY

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Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
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FR Division, Meteorological Office, London Road,
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ABSTRACT

A comparison of the results from a radiative transfer model with the results from a number of existing liquid water path algorithms is described. The model was then used to test the sensitivity of these algorithms to changes in sea surface temperature, wind speed, integrated water vapour, cloud temperature and to noise in the brightness temperatures. Results showed a wide variety in the performance of the algorithms. The algorithms which best compared with the model were those which used a polarization difference technique. The sensitivity studies showed that no one factor was significantly important to all the algorithms. A minimum error for current liquid water path algorithms is estimated at 0.05 kg/m^2.

Contents

1 Introduction

The amount of cloud liquid water in the atmosphere has a large effect on the earth's radiation balance. Radiation interacts strongly with liquid water and so it affects the amount of radiation reaching and leaving the earth's surface. Because of this, the accurate measurement of cloud liquid water is of great interest in a number of areas: in climate modelling, as a parameter for numerical weather prediction, in the removal of cloud effects so that surface features can be measured, and also in associated cloud studies, such as aircraft icing.

Microwave remote sensing techniques are well suited to measuring cloud liquid water. Microwaves are able to penetrate clouds, so can measure emissions from the whole depth of cloud, whereas visible and infra-red techniques can only measure the very tops of the clouds. They also have the advantage that, if no precipitation sized particles are present, very little scattering occurs, greatly simplifying the radiative transfer processes involved.

The latest microwave imager is the special sensor microwave/imager (SSM/I) which is currently on board the F10 and F11 Defense Meteorological Satellite Project (DMSP). A number of attempts have been made to obtain cloud liquid water paths (LWP) from SSM/I data. Unfortunately it is very hard to validate these algorithms, as it is difficult to obtain accurate values of LWP by and method. Radiative transfer models are often used to develop algorithms and then independent sources such as existing algorithms, ground based radiometers or airborne probes are used to validate them. In this investigation a radiative transfer model has been used as an independent source to test a number of existing algorithms. Investigations into how accurately they can calculate the model's LWP value and also how sensitive the algorithms are to changes in sea surface temperature (SST), wind speed (WW), integrated water vapour (IWV), cloud temperature and to brightness temperature noise have been carried out. The final results of this study will be to give a clear indication of the expected errors associated with SSM/I LWP retrievals.

2 Theory - SSM/I Liquid Water Path Algorithms

Liquid water droplets absorb strongly in the millimetre wavelength spectral region. Absorption decreases with increasing wavelength, so a thin cloud's optical depth at 85.5 GHz is an order of magnitude greater than at 19.35 GHz. Scattering is negligible at SSM/I frequencies provided the cloud is non-precipitating. Cloud above an emitting surface can modify the radiance field in two ways. Firstly, brightness temperatures (T_Bs) will change from the apparent surface temperature to the cloud temperature as cloud LWP increases. Secondly a reflecting surface polarizes electromagnetic radiation: the cloud will depolarizes this signal. So to measure LWP using SSM/I, we need either a strongly polarising surface or a surface which appears colder (or warmer) than the cloud. The ocean surface fulfils both criterion. Conversely most land surfaces are good emitters and the signal is neither strongly polarised or radiometrically distinct from the cloud. Consequently most SSM/I LWP algorithms are only valid over the oceans.

2.1 Surface and Atmospheric Effects

Many surface and atmospheric parameters can effect measured brightness temperatures. The absorption and emission characteristics of water depends upon it's temperature. An increase in temperature causes a decrease in the mass extinction coefficient of cloud water. This can lead to the seemingly paradoxical result that an optically thin cloud of fixed liquid water content radiates more brightly as it's thermodynamic temperature decreases (Petty and Katsaros 1992). Changes in sea surface temperature can also effect observed brightness temperatures.

Wind induced roughening of the ocean surface depolarizes the average scene brightness temperature and whitecapping (foam) increases the overall brightness temperature for all frequencies, polarization and view angles. It has also been proposed (Bliven et.al.) that precipitation can alter sea surface roughness and consequently the measured brightness temperature. Heavy precipitation has a damping effect upon large waves, but generates a large number of small scale waves; total roughness increases. This leads to an overall small increase in brightness temperature. More importantly, precipitation sized droplets (> 100 microns) have a much higher scattering efficiency than small drops and also absorb more radiation. At high frequencies (> 70 GHz) scattering by ice particles and precipitation sized droplets dominates the observed signal for heavy rain, and measured brightness temperatures become insensitive to cloud LWP. Even at low frequencies precipitation effects can dominate and LWP retrievals are difficult. It is therefore extremely difficult to retrieve LWP in precipitating systems, best results can be expected at the lowest frequencies.

For non-precipitating fields of view the most important effect on measured brightness temperature, other than LWP, is water vapour. At low frequencies this is less true and surface effects are very important. Water vapour absorption between spectral lines increases with frequency at a similar rate to liquid water absorption.

Different frequencies and polarizations respond to these surface and atmospheric parameters in different ways. So by using a number of channels, algorithms can attempt to estimate the effects of these parameters and the LWP can be corrected. A good example is estimating the water vapour burden. The SSM/I has a channel at a weak water vapour line (22.235GHz). To a first approximation this channel is only sensitive to the amount of atmospheric water vapour. So by measuring the 22.235GHz brightness temperature, the effects of water vapour can be estimated. Information on wind speed can be obtained by measuring the polarization at a particular frequency. Wind roughening of the ocean surface depolarizes the observed brightness temperature. By measuring the extent of this depolarization, wind speed can be estimated and can then be accounted for. So to correct for surface and atmospheric parameters an algorithm must be multichannel.

2.2 Different Types of Algorithm

A variety of algorithms are investigated in this paper; they are based on one of two main techniques. The spectral technique works on the principle that as cloud is introduced into an ocean atmosphere, observed brightness temperatures change from the apparent temperature of the sea to the cloud temperature. As more and more liquid water is introduced, cloud emissivity changes from zero to unity - the observed brightness temperature would then equal the cloud temperature. At this point, this technique has reached saturation, inclusion of any more liquid water would have no effect on measured brightness temperatures.

The polarization technique works on the principle that reflection from the sea surface polarizes brightness temperatures, while cloud liquid water depolarizes the signal. Therefore a strongly polarized signal would indicate a low LWP, while an unpolarized signal would indicate a high LWP. This technique saturates once the signal is completely unpolarized.

Algorithms can also be categorised by how they were developed - whether they are statistically based or physically based. Statistically based algorithms simply try to fit (by linear regression) brightness temperatures, or a function of brightness temperatures, to a 'ground truth' LWP value. Advantages of statistical algorithms are that they require little knowledge of the physics involved, require no information on sensor calibration and they usually end up to be simple linear equations and so are computationally undemanding. Disadvantages are that the algorithm relies totally on the 'ground truth' data set. These 'ground truth' values are found by various means: airborne probes, airborne microwave sensors and ground based microwave radiometers. Problems arise in the compatibility of point measurements of LWP from these sensors with an SSM/I LWP value averaged over an entire footprint. LWP values are very hard to measure and the amount of data available is usually over a small region and includes only a limited set of meteorological conditions. Because of this, statistical algorithms can end up being biased to a particular region or set of meteorological conditions and there is no guarantee that it will perform well if applied to a different region or set of conditions (Petty 1990).

A way around these problems is to use synthetic data. Using a forward radiative transfer model a large data set can be produced for a wide variety of atmospheres. Linear regression is then used in the usual way to produce an algorithm. Unfortunately, use of synthetic data means that you lose two important advantages of statistical algorithms - a detailed knowledge of the physics and of the sensor calibration, is required by the radiative transfer model (Petty 1990).

Physically based algorithms take theoretical models for the dependence of brightness temperatures on LWP and then attempt to invert the relationship. In their purest form, physical algorithms would literally be an inverted forward radiative transfer model. These have the advantage that they are not tailored to a particular region, and so should be able to be applied globally. The relationship between brightness temperatures and LWP is not linear, it is therefore more appropriate to represent this relationship with a physical algorithm, than with a linear equation; though some non-linear functions of brightness temperature can transform retrievals of LWP from a non-linear problem to a nearly linear one (Petty 1990).

Disadvantages of physical algorithms are that they are usually quite complicated and so are more demanding computationally. They also rely heavily on knowledge of the physics involved and information on the sensor calibration.

The physical algorithms reviewed in this paper are based on fairly simple models of the atmosphere. An equation is found from these which requires the input of factors such as integrated water vapour, wind speed, sea surface emissivity, oxygen transmittance, sea surface temperature etc. These factors are usually found by one of three methods. Firstly they may be simply set to an average value. Secondly they may be estimated using an algorithm designed to retrieve that particular factor. Thirdly, a few algorithms require you to input additional information such as sea surface temperature or cloud top temperature. The coefficients in these equations are then nearly always tuned using either synthetic or real data.

2.3 Effect of Precipitation

SSM/I LWP algorithms are much better at representing some types of radiative environment than others. In areas of precipitation the rainfall has a high horizontal inhomogeneity; this is on a scale smaller than the size of a footprint. Because the inhomogeneous brightness temperature is averaged over the footprint and the LWP is not proportional to brightness temperature there is an underestimation in retrieved LWP. This is known as the beam filling problem. Large particles (>100 microns) are present in areas of precipitation. The Rayleigh approximation is no longer valid for large particles and Mie theory is required to calculate the absorption (and hence emission) characteristics of the droplets. The drop size distribution also becomes important. Large particles cause scattering which can effect brightness temperatures and polarizations. These factors greatly complicate the radiative transfer processes involved and make retrievals of LWP extremely difficult in precipitating areas.

3 Method

This investigation used a radiative transfer model developed by S.J.English (English 1991). An input atmosphere was selected and then the model was run to produce a complete set of seven SSM/I brightness temperatures. The next step was to pass these brightness temperatures through the various liquid water path (LWP) algorithms and calculate values for the LWP. These LWP values could then be compared with the LWP from the initial atmosphere.

The atmospheres used were from a set of 1,200 radiosonde ascents which defined temperature and mixing ratio at forty pressure levels. These are divided into three sets of 400 ascents; arctic, mid-latitude and tropical. It was also possible to specify arbitrarily the sea surface temperature (SST), wind speed (WW), mean sea level pressure (MSLP), liquid water path (LWP) and cloud base and top levels.

3.1 A Comparison Between Model and Algorithm LWP values

The first investigation was into how well model LWP values compared with the algorithm calculated LWP values. Forty arctic atmospheres were picked at random from the data set. SST(280K), WW(5.0m/s) and cloud thickness(950-970mb) were held constant. LWP values were varied from 0 up to 0.6 kg/m^2 in steps of 0.1 kg/m^2. At each step the model produced forty sets of brightness temperatures and these in turn were used to calculate forty LWP values for each algorithm. The mean and standard deviation of these values were noted, and a graph plotted from the results. Standard deviations are represented as error bars on the graphs. This investigation was repeated using forty randomly selected mid-latitude and forty randomly picked tropical atmospheres. SST, WW and cloud thickness values used, were the same as those shown above for the arctic case.

3.2 Sensitivity to Changes in Sea Surface Temperature

The second investigation was into how sensitive the algorithms were to changes in sea surface temperature. WW(5.0m/s), LWP(0.3kg/m^2) and cloud thickness(950-970mb) were held constant while SST was varied from 0 - 30 ^{0}C. Atmospheres were picked in the following way - arctic (0-10 ^{0}C), mid-latitude (8-24 ^{0}C) and tropical (20-30 ^{0}C); where there was an overlap both sets of atmospheres were used. Again forty LWPs were calculated (eighty where there was an overlap) for each algorithm, from which a mean and standard deviation were calculated.

3.3 Sensitivity to Changes in Wind Speed

The third investigation was into how sensitive the algorithms were to changes in wind speed. Forty mid-latitude atmospheres were picked at random. SST(280K), LWP(0.3kg/m^2) and cloud thickness(950-970mb) were held constant, while wind speed was varied from 0 to 25m/s. Mean LWP values and standard deviations were obtained as before.

3.4 Sensitivity to Changes in Integrated Water Vapour

The fourth investigation was into how sensitive the algorithms were to changes in integrated water vapour (IWV). WW(5.0m/s), SST(280K), LWP(0.3kg/m^2) and cloud thickness (950-970mb) were held constant. Cloud temperature was kept roughly constant and IWV varied from 0 - 40 kg/m^2. This was achieved by searching through the 1,200 ascents for atmospheres with a 950mb temperature between 278 - 288K. These were then split up into a number of smaller groups of ascents, grouping together ascents which have a similar IWV. These groups were then entered into the model one at a time. LWPs were calculated as before, and from these means and standard deviations were obtained.

3.5 Sensitivity to Changes in Cloud Temperature

The fifth investigation was into how sensitive the algorithms were to changes in cloud temperature. WW(5.0m/s), SST(280K), LWP(0.3kg/m^2) and cloud thickness(950-970mb) were held constant. IWV was kept roughly constant and cloud temperature varied from 265 - 300K. This was managed in the same way as mentioned previously. A set of atmospheres were found all with IWV between 8 - 27 kg/m^2. These were then split up into a number of smaller groups of ascents, grouping together ascents which have a similar 950mb temperature. These sets were entered into the model, LWPs calculated and means and standard deviations found as explained above.

3.6 Sensitivity to Noise in the SSM/I Brightness Temperatures

The sixth and final investigation was into how well the algorithms coped with noise in the SSM/I brightness temperatures. The model was run on forty mid-latitude atmospheres; WW(5.0m/s), SST(280K), LWP(0.3kg/m^2) and cloud thickness(950-970mb) were held constant. Forty sets of brightness temperatures were produced. The 19GHz vertical brightness temperature values were then increased by 0.5K (to represent channel noise) and used to calculate forty LWP values for each algorithm. Mean and standard deviation values were calculated from these. This was then repeated, but this time 0.5K was subtracted from the original 19GHz vertical brightness temperatures. A measure of how sensitive an algorithm is to noise in the 19GHz vertical channel was taken to be the difference between the LWP calculated when the brightness temperature was increased by 0.5K and the LWP calculated when the brightness temperature was decreased by 0.5K. The 19GHz brightness temperatures were then set back to their original values.

This experiment was repeated seven times and a different channel/polarization was varied each time, so the sensitivities to each channel and polarization were calculated.

An overall sensitivity study was also carried out. A set of brightness temperatures for a mean mid-latitude atmosphere were obtained (WW, SST, LWP and cloud thickness as shown above). Random noise (between +0.5K and -0.5K) was then added to each of the brightness temperatures. These were then used to calculate a LWP value for each of the algorithms. This method was repeated two hundred times to obtain a standard deviation for each algorithms. This standard deviation is a measure of the algorithm's overall sensitivity to noise.

The above investigation was repeated two times, with the LWP value held constant at 0.6kg/m^2 and 0.9kg/m^2.

3.7 Notes on the Algorithms

The following table shows the main features of the algorithms I used in this study - the actual algorithms can be found in appendix A.

ALGORITHM AUTHORS	ALGORITHM TYPE	APPLICATION AREAS	LWP RANGE kg/m^2
Alishouse et al. 1990	statistical, based on ground based radiometers.	off Californian coast	0 - 0.3
Petty and Katsaros 1990	semiphysical, based on a radiative transfer model.	off Californian coast (marine stratus)	0 - 0.5
Grody and Ferraro 1992	statistical, based on a radiative transfer model and tuned using clear sky SSM/I data.	mid-latitudes and tropics	0 - 0.5
Hargens et al. 1992	statistical, based on a radiative transfer model.	mid-latitudes, sub-tropics and tropics	0 - 1.0
Liu and Curry 1993	physical, calibrated using a radiative transfer model and tuned using clear sky SSM/I data.	mid-latitudes, sub-tropics and tropics	0 - 0.5 (non-precip) 0.5 - 3.0 (precip)
Greenwald et al. 1993	physical, calibrated using clear sky SSM/I data.	mid-latitudes, sub-tropics and tropics	0 - 0.5
Weng and Grody 1993	statistical, based on a radiative transfer model, tuned using clear sky SSM/I data.	global	0 - 3.0

ALGORITHM AUTHORS	CHANNELS USED							OTHER INPUTS
	19H	19V	22V	37H	37V	85H	85V	
Alishouse et al.	Y		Y		Y	Y		
Petty and Katsaros	Y	Y	Y	Y	Y	Y	Y	
Grody and Ferraro		Y			Y			
Hargens et al.			Y		Y			
Liu and Curry	Y	Y	Y	Y	Y			sea surface temp cloud top temp
Greenwald et al.	Y	Y	Y	Y	Y			sea surface temp
Weng and Grody		Y	Y		Y	Y		

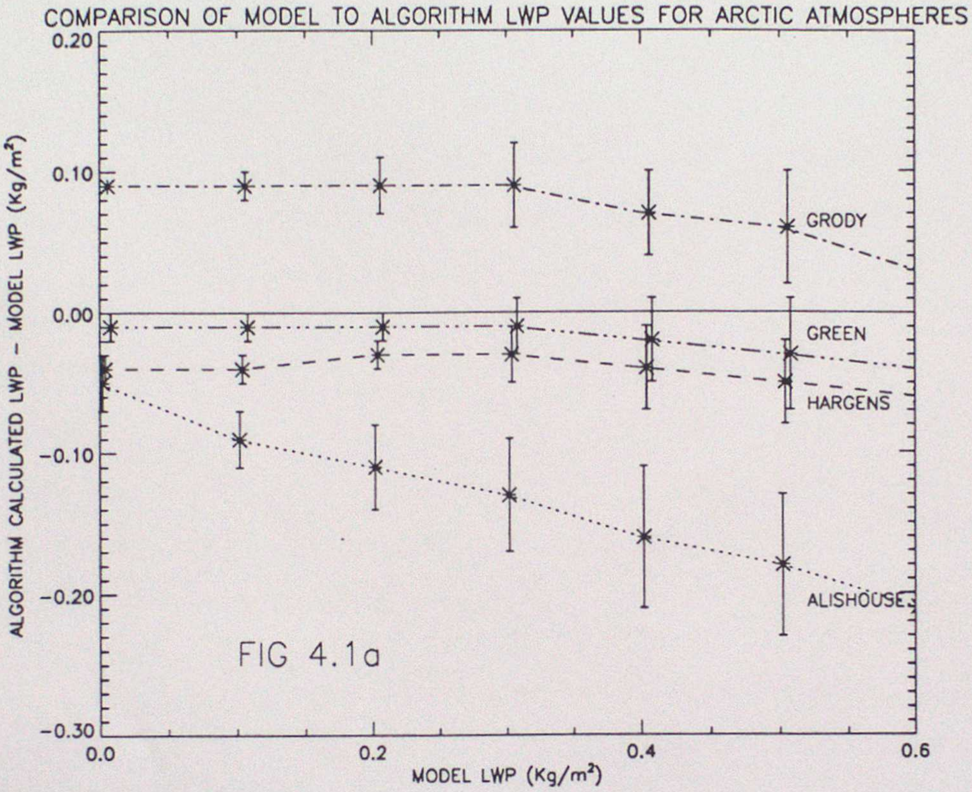
3.8 Notes on the Model

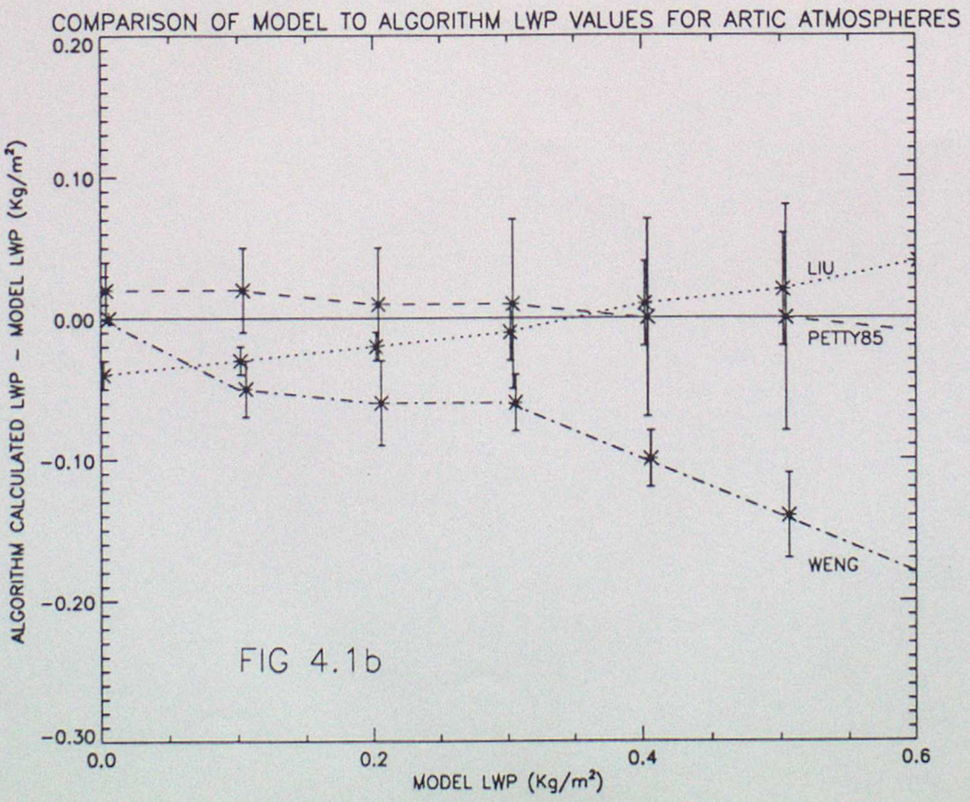
The radiative transfer model used was taken from English (1991). It is based on the solution of the polarized radiative transfer equation and it operates between 10-200GHz. A plane parallel liquid cloud model is used and the particles are assumed to be small enough for the Rayleigh approximation to be valid. The dielectric constant of water is found using a fast fit to a single Debye formula, based on Ray's (1972) data. Sea surface emission and reflection are calculated using fresnel coefficients for the geometric facet distribution determined by Cox and Munk (1955). Foam emission is also included following Wilheit (1979). Water Vapour and Oxygen absorption is modelled using Liebe (1989). This model has been validated for clear skies in English (1994a), for cloudy skies in English (1994b) and for sea surface reflectance in Guillou (1994).

4 Results

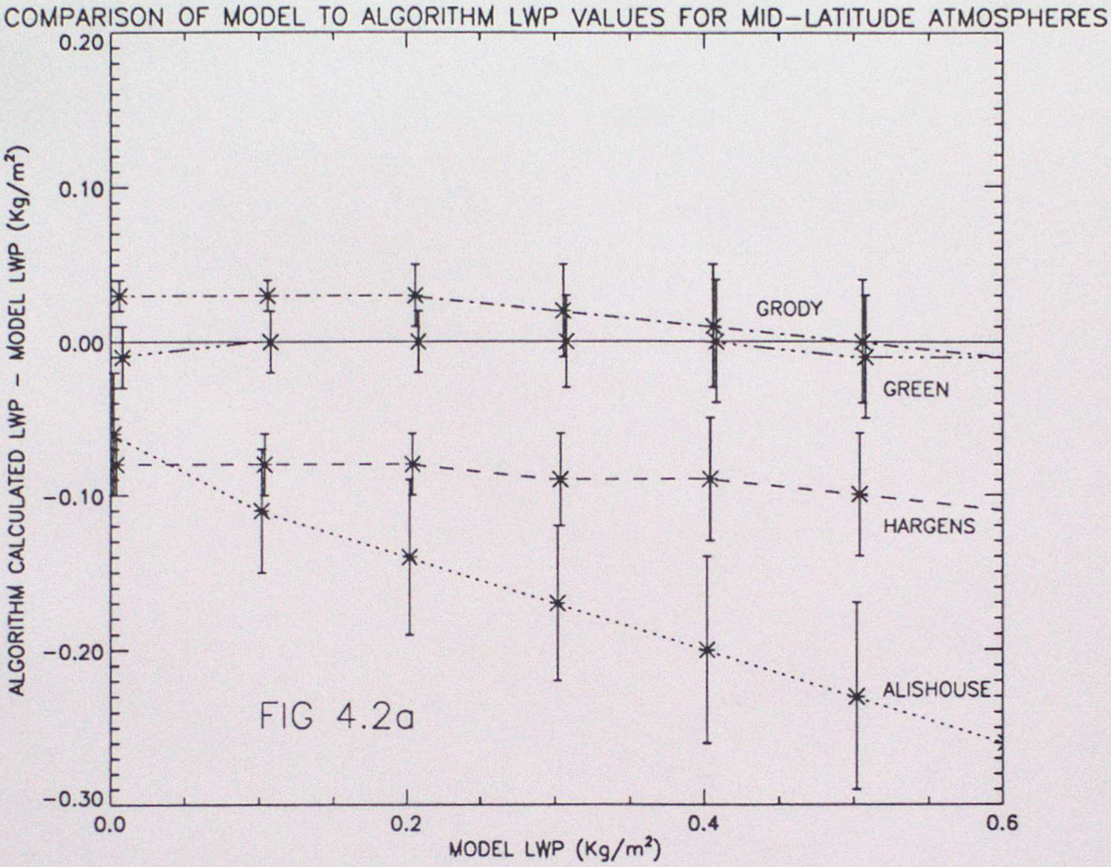
4.1 A Comparison Between Model and Algorithm LWP Values

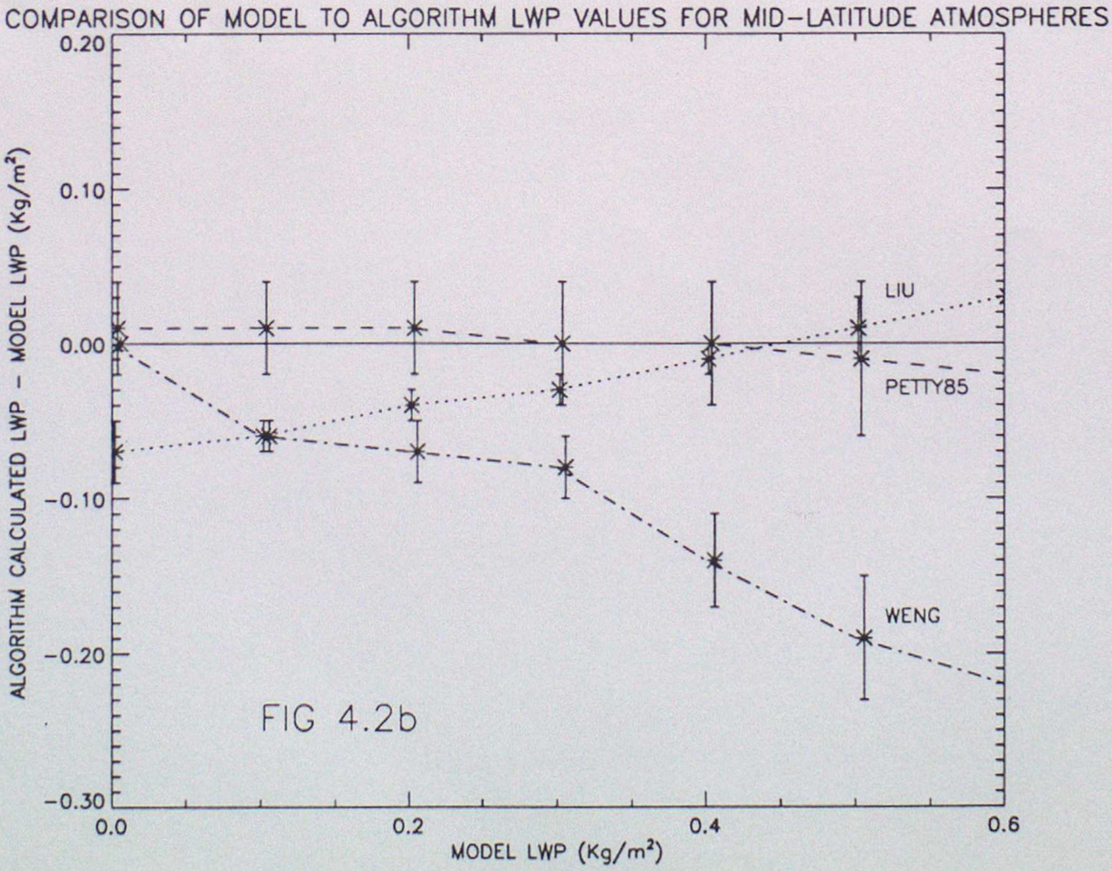
4.1.1 Artic Atmospheres





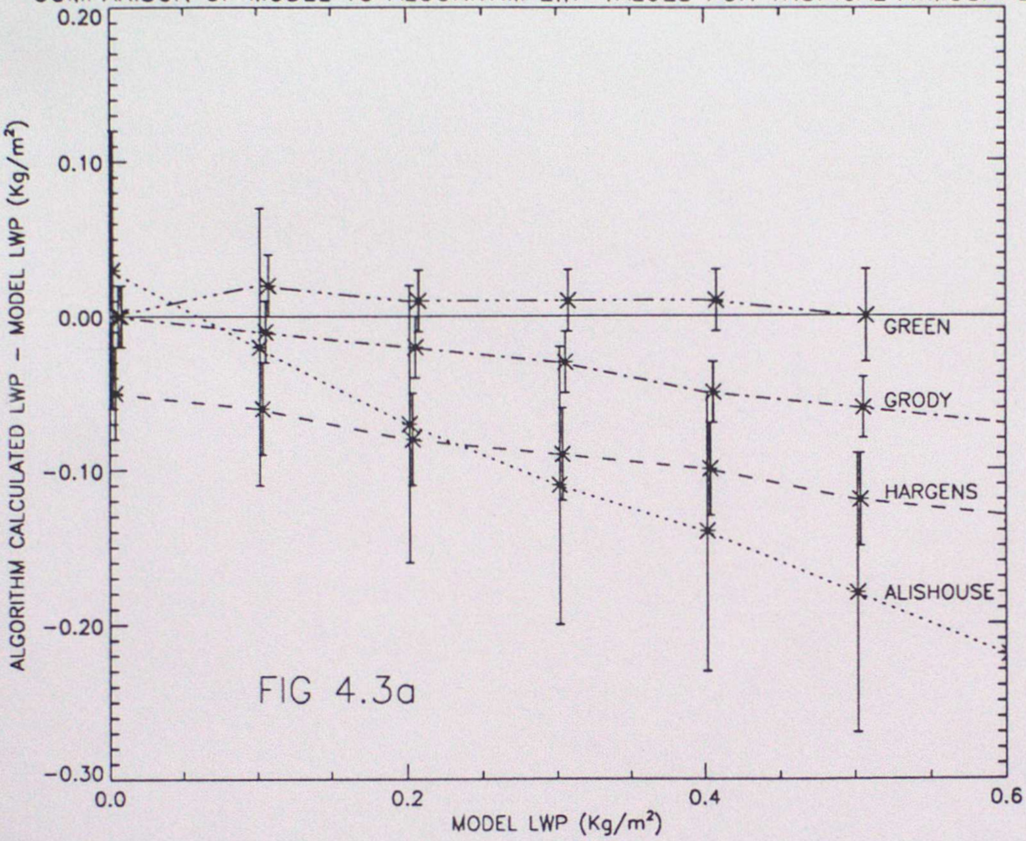
4.1.2 Mid-Latitude Atmospheres



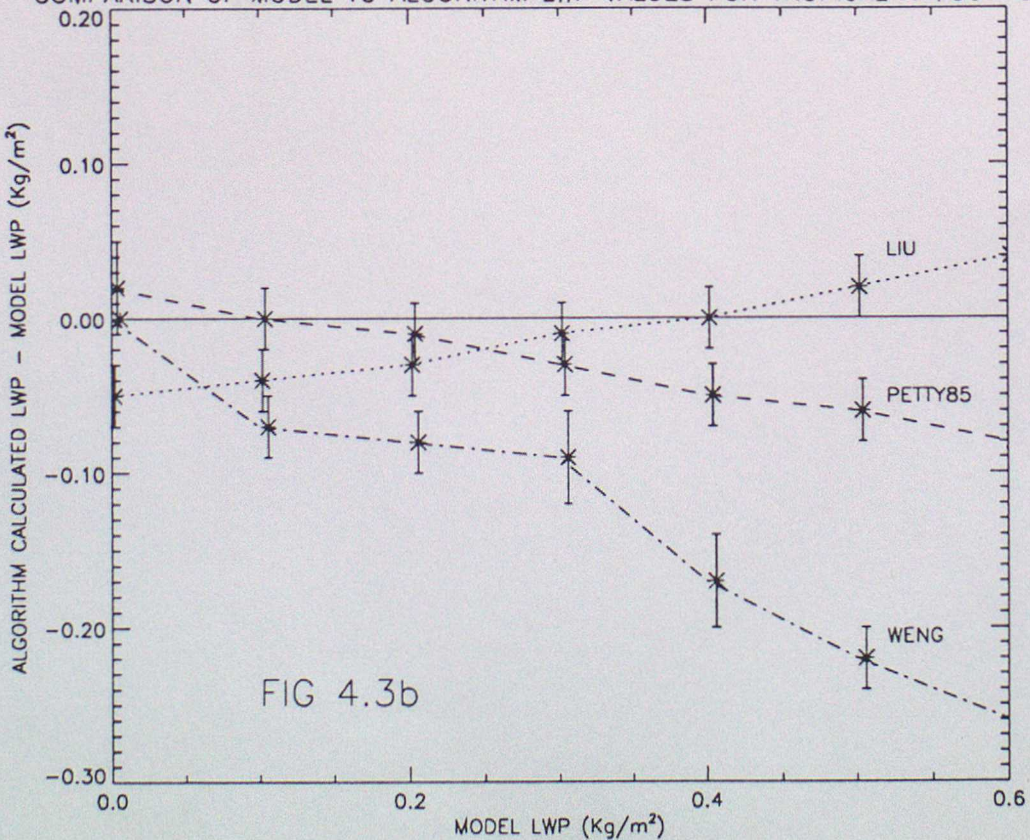


4.1.3 Tropical Atmospheres

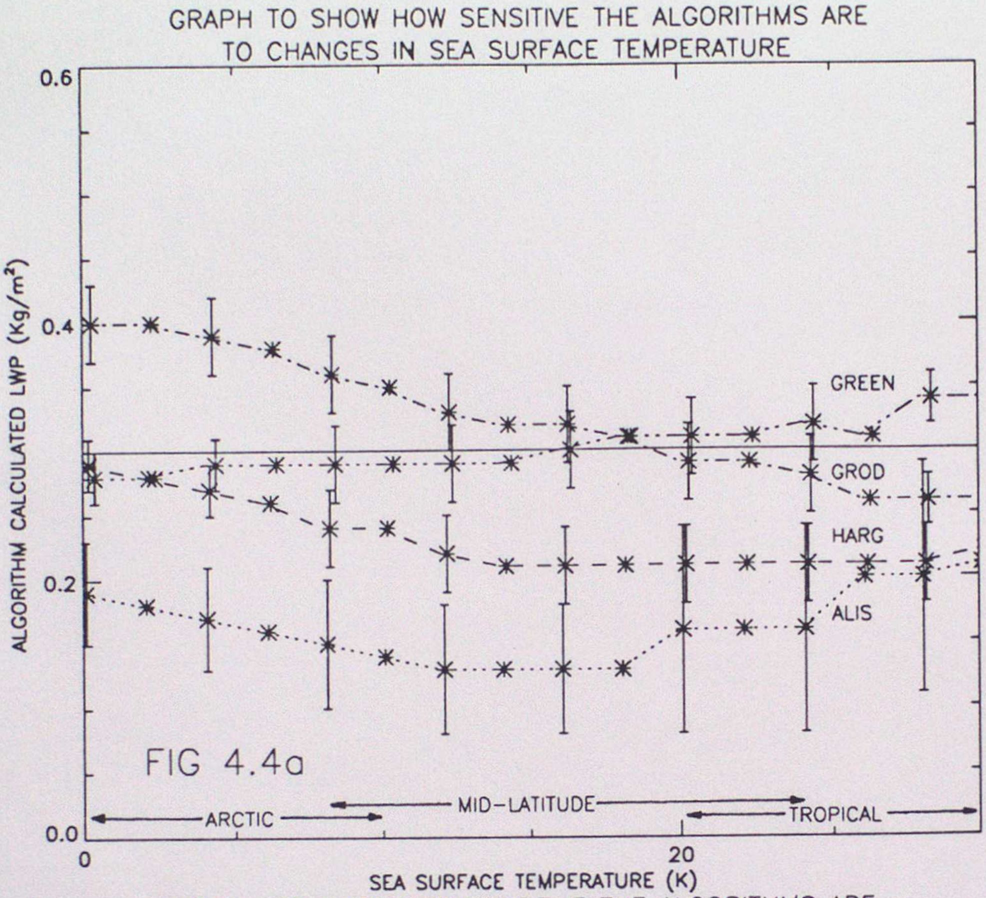
COMPARISON OF MODEL TO ALGORITHM LWP VALUES FOR TROPICAL ATMOSPHERES

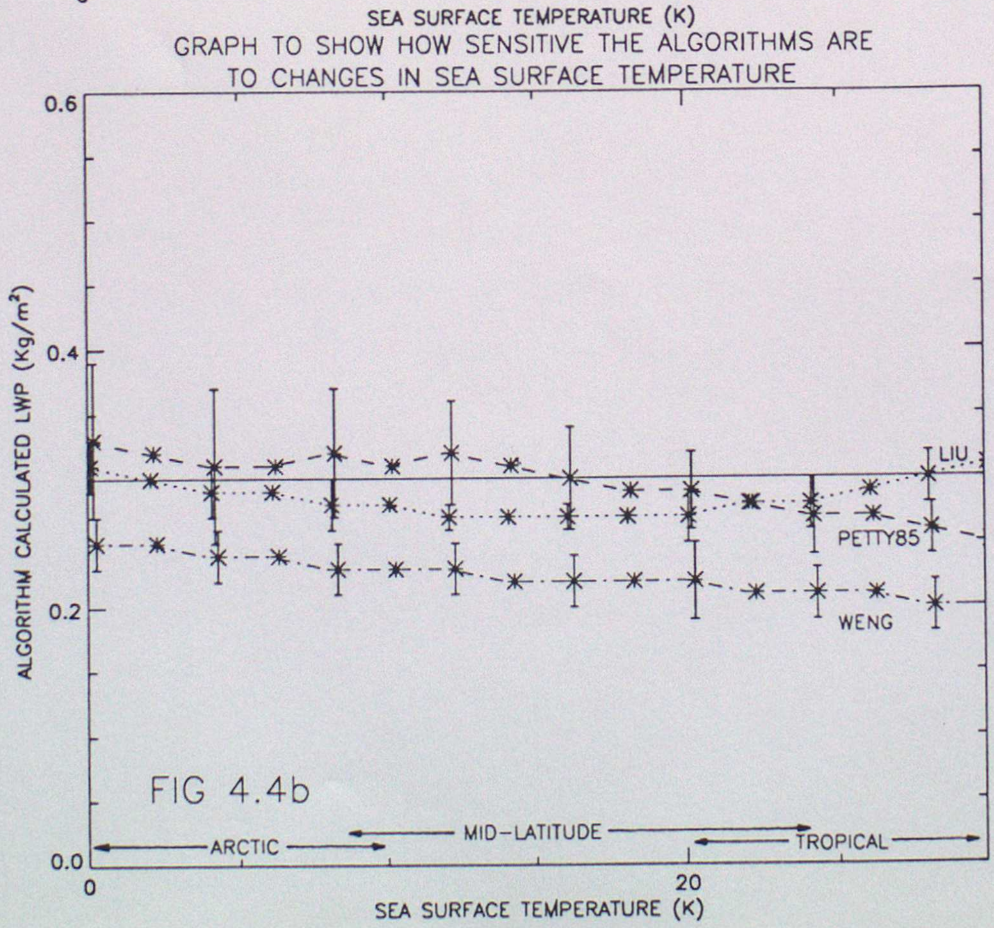


COMPARISON OF MODEL TO ALGORITHM LWP VALUES FOR TROPICAL ATMOSPHERES



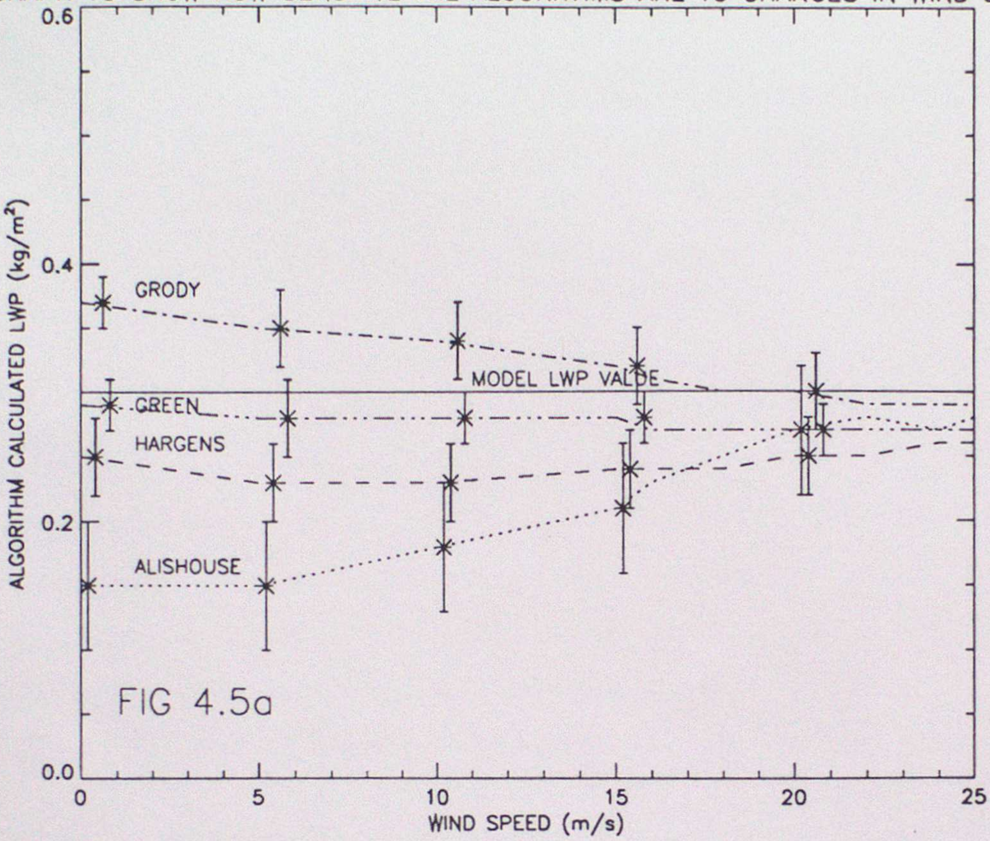
4.2 Sensitivity to Changes in Sea Surface Temperature



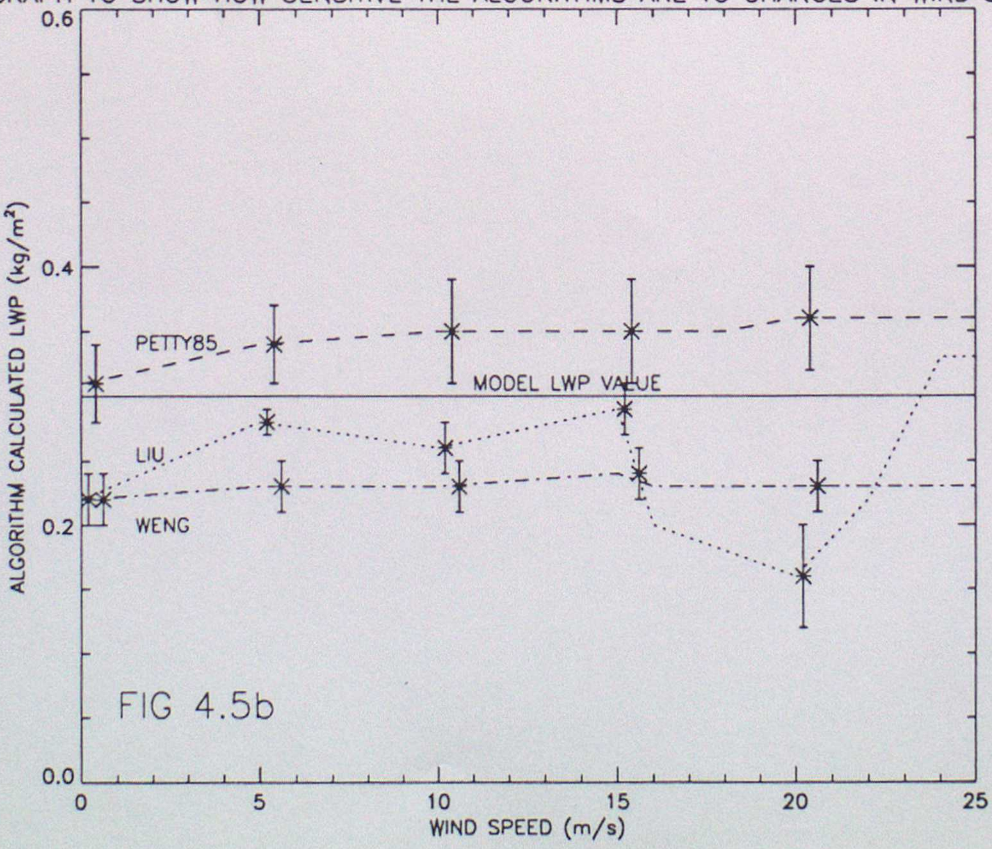


4.3 Sensitivity to Changes in Wind Speed

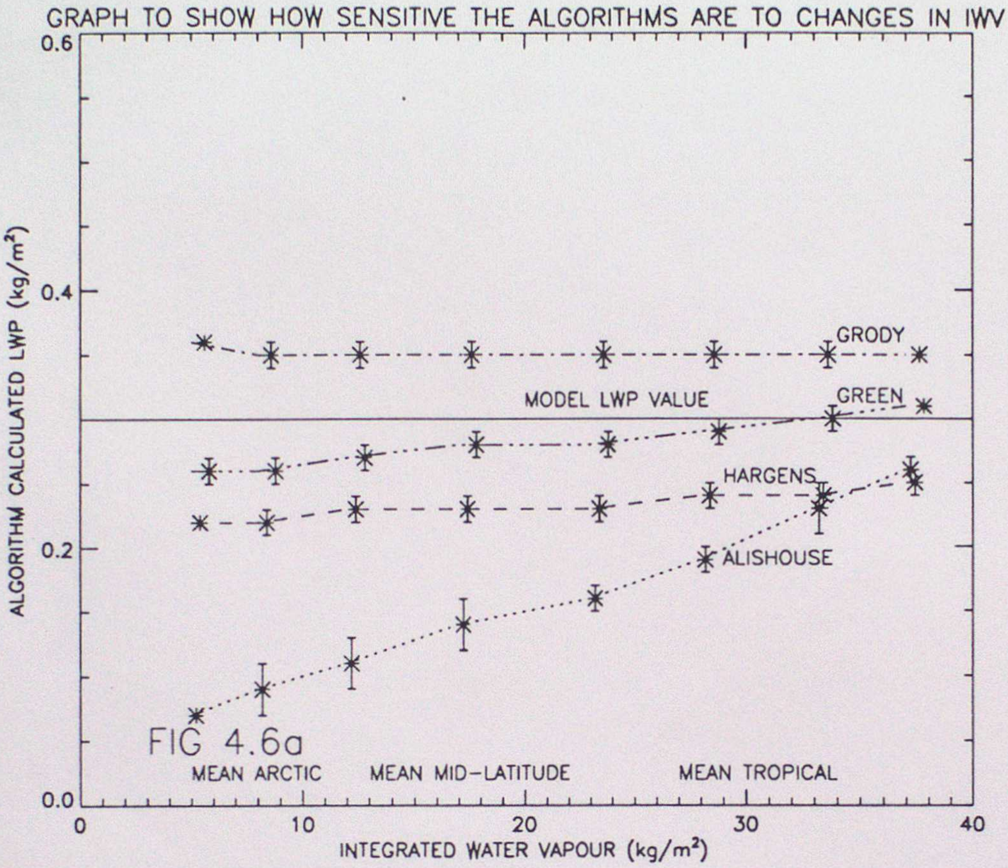
GRAPH TO SHOW HOW SENSITIVE THE ALGORITHMS ARE TO CHANGES IN WIND SPEED

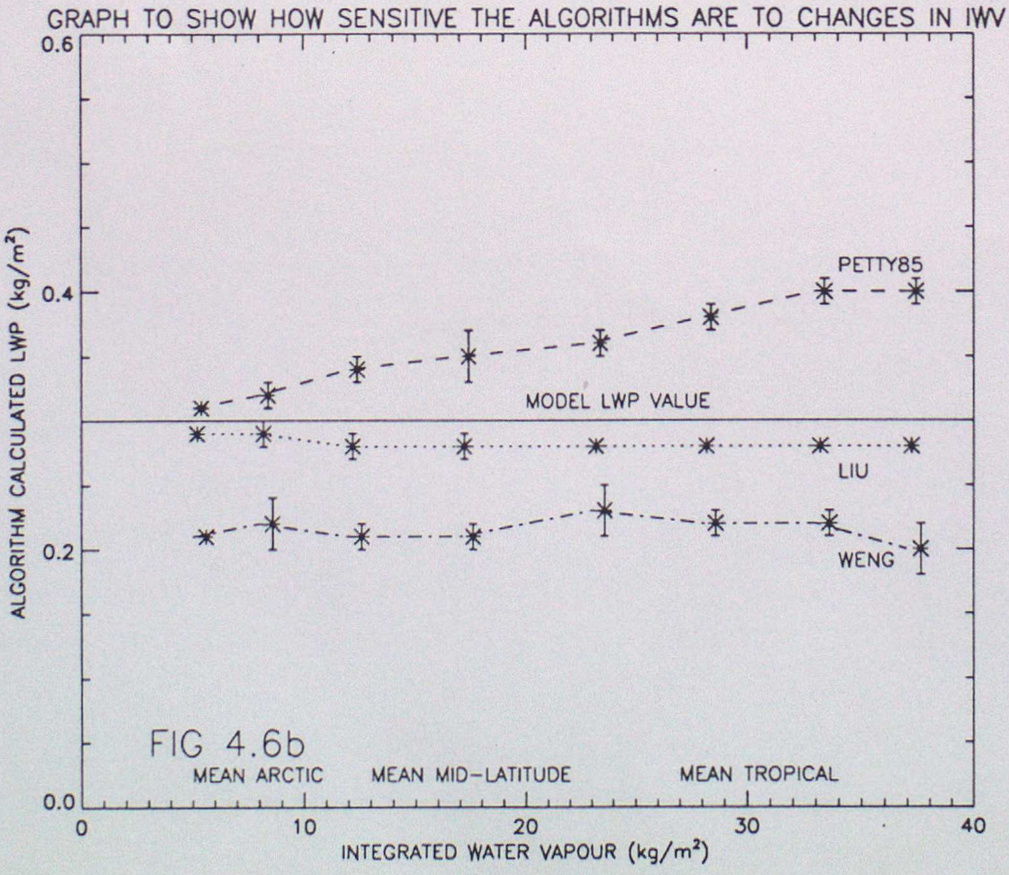


GRAPH TO SHOW HOW SENSITIVE THE ALGORITHMS ARE TO CHANGES IN WIND SPEED



4.4 Sensitivity to Changes in Integrated Water Vapour





4.5 Sensitivity to Changes in Cloud Temperature

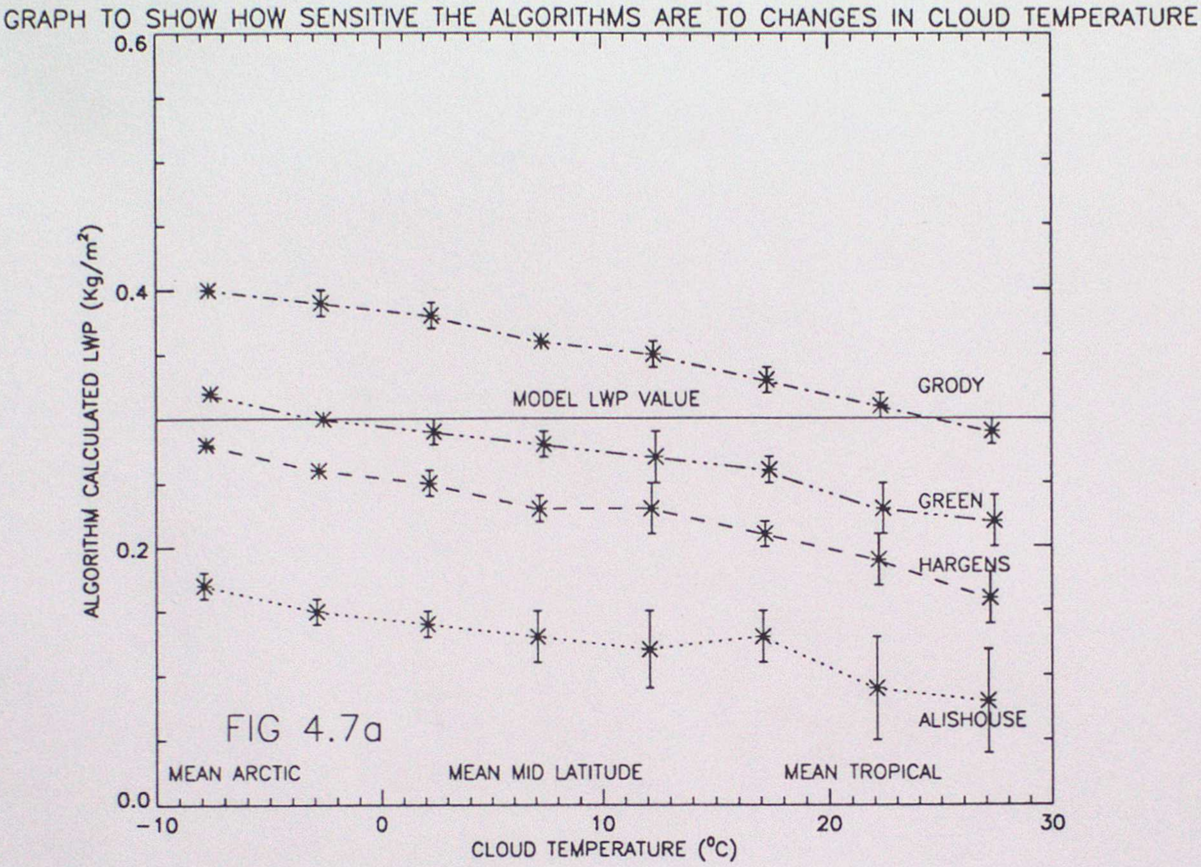


FIG 4.7a

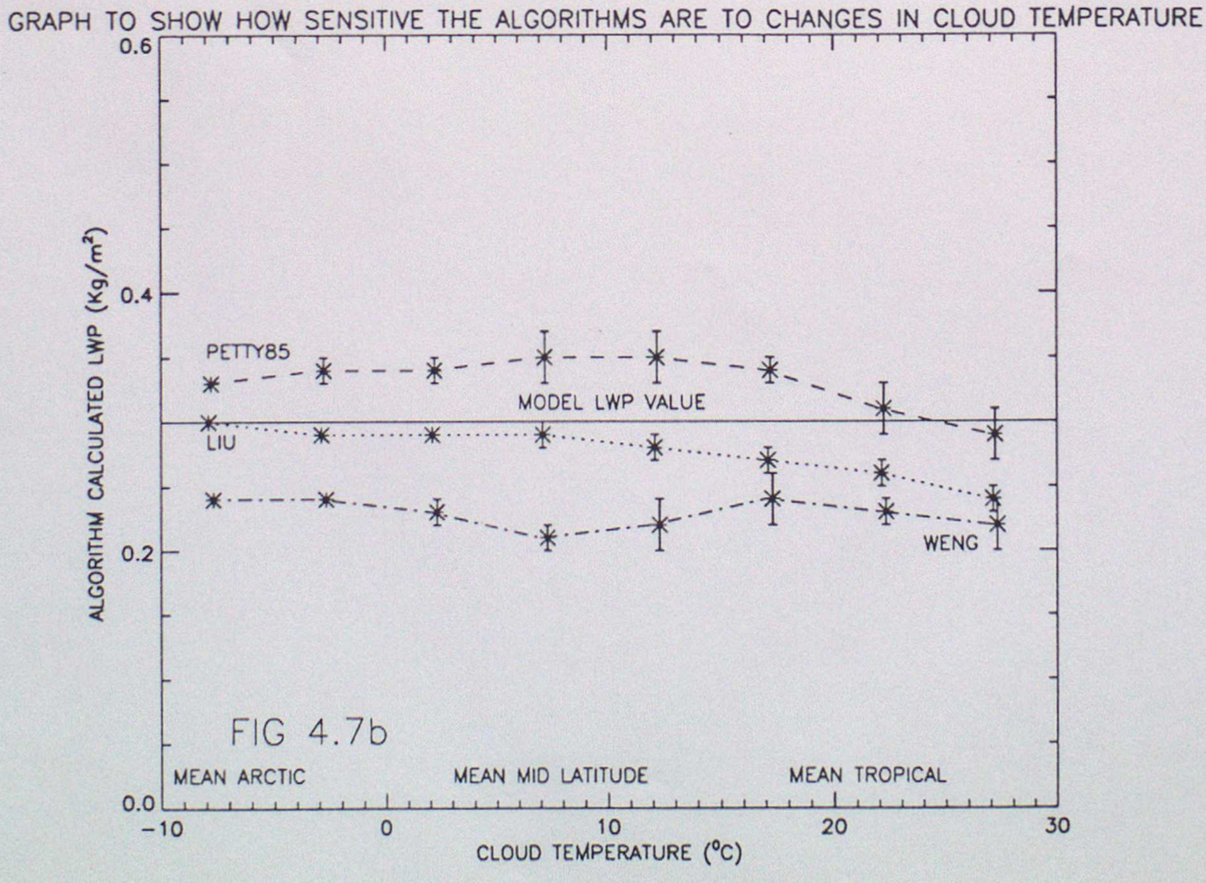


FIG 4.7b

4.6 Sensitivity to Noise in the SSM/I Brightness Temperatures

TABLE 4.6A : Model LWP = 0.3kg/m^2

ALGORITHM AUTHORS	CHANNEL SENSITIVITIES (kg/m^2) 19H	19V	22V	37H	37V	85H	85V	OVERALL
Alishouse et al.	0.006	-	0.005	-	0.020	0.003	-	0.007
Petty and Katsaros	0.002	0.008	0.004	0.006	0.014	0.018	0.018	0.009
Grody and Ferraro	-	0.018	-	-	0.028	-	-	0.010
Hargens et al.	-	-	0.006	-	0.022	-	-	0.008
Liu and Curry	0.031	0.021	0.005	0.029	0.017	-	-	0.014
Greenwald et al.	0.000	0.011	0.001	0.003	0.022	-	-	0.007
Weng and Grody	-	0.000	0.005	-	0.001	0.006	-	0.006

TABLE 4.6B : Model LWP = 0.6 kg/m^2

ALGORITHM AUTHORS	CHANNEL SENSITIVITIES (kg/m^2) 19H	19V	22V	37H	37V	85H	85V	OVERALL
Alishouse et al.	0.006	-	0.005	-	0.020	0.003	-	0.007
Petty and Katsaros	0.002	0.008	0.004	0.006	0.014	0.047	0.047	0.019
Grody and Ferraro	-	0.019	-	-	0.035	-	-	0.012
Hargens et al.	-	-	0.006	-	0.030	-	-	0.009
Liu and Curry	0.034	0.023	0.005	0.037	0.018	-	-	0.016
Greenwald et al.	0.000	0.011	0.001	0.003	0.029	-	-	0.009
Weng and Grody	-	0.000	0.005	-	0.020	0.000	-	0.007

TABLE 4.6C : Model LWP = 0.9 kg/m^2

ALGORITHM AUTHORS	CHANNEL SENSITIVITIES (kg/m^2) 19H	19V	22V	37H	37V	85H	85V	OVERALL
Alishouse et al.	0.006	-	0.004	-	0.020	0.003	-	0.007
Petty and Katsaros	0.003	0.007	0.005	0.007	0.015	0.116	0.116	0.049
Grody and Ferraro	-	0.020	-	-	0.040	-	-	0.013
Hargens et al.	-	-	0.008	-	0.036	-	-	0.011
Liu and Curry	0.038	0.025	0.005	0.047	0.020	-	-	0.019
Greenwald et al.	0.000	0.012	0.001	0.002	0.038	-	-	0.011
Weng and Grody	-	0.000	0.006	-	0.024	0.000	-	0.007

dashes indicate that channel is not used

5 Discussion

5.1 A Comparison Between Model and Algorithm LWP Values

FIG.s 4.1, 4.2 and 4.3 show the comparison between algorithm calculated values of LWP and LWP values inputted into the radiative transfer model. These are shown for arctic, mid-latitude and tropical atmospheres. The first thing to note is how similar the graphs are. In all three, Alishouse's and Weng's algorithms have a fairly large negative slope and are below the zero line. Liu's algorithm starts too low and ends up too high, crossing the model LWP value between 0.3 - 0.5 kg/m^2. The other algorithms all have reasonable slopes and are usually within 0.1 kg/m^2 of the model value.

Comparing Alishouse's and Grody's algorithms is interesting. Both are statistical fits, and Alishouse's algorithm uses more channels, but the results from Grody's compare far better with the model's LWP. The difference comes from Alishouse being a simple linear fit, whereas Grody's is linear in log(280-T_B) - this equation is theoretically a much better linear fit and results appear to back this up.

It was surprising that the results from Liu's did not agree more favourably with the model. The algorithm was fairly complex and required the input of two physical parameters and so it was expected to perform better than most of the other algorithms, but analysis of the graphs shows this not to be the case.

Hargens' and Grody's algorithms were both of the same type - two channel statistical fits, linear in log(280-T_B); both use the 37v channel, but for the second channel Grody uses 19v, while Hargens uses 22v. A great deal of similarity can be seen in their performance; although there is a vertical offset, their slopes are comparable in all three graphs.

Weng's algorithm is of a similar type to Grody and Hargens, but it uses different channels and coefficients depending on the LWP and IWV. This explains the discontinuities in the graph where new equations are used.

The algorithms which best compared with the model were Greenwald's and Petty's. It is interesting that both these algorithms work on the polarization difference principle. Out of the two, Greenwald's compares better, with Petty's showing signs of saturation in tropical atmospheres.

The standard deviations calculated in this experiment were quite small. A wide variety of atmospheres were used which contained a wide spread of cloud temperatures and water vapour amounts, and yet most of the algorithms were able to cope with this and come up with fairly consistent results. The average standard deviation of all the algorithms was 0.04 kg/m^2.

Most of the algorithms showed some signs of saturation which can be detected by a negative slope. Alishouse's began to saturate almost immediately, while most of the others started tailing off between 0.2 - 0.4 kg/m^2. The exception to this is Liu's algorithm which starts with a positive slope and curves upwards as LWP increases.

It should be noted that the algorithms differ as to the situation in which they are expected to perform. They have all been tested using the same model, simulating a layer of low, warm cloud in a variety of atmospheres. These are situations which all the algorithms should be able to cope with, but it still may not be a fair test of all the algorithms. An area of contention arises when comparing algorithms which take scattering effects into account with a model which does not. Various studies associate a LWP of 0.5 kg/m^2 with the onset of rain (Liu and Curry,1992). At LWPs greater than 0.5 kg/m^2, precipitation size particles would be expected, which would cause scattering. It might be the case that algorithms which were developed to account for scattering such as Hargens and Weng are doing so at large LWPs, even though no scattering is being modelled. But this would still not explain offsets at low LWP values.

5.2 Sensitivity to Changes in Sea Surface Temperature

FIG. 4.4 shows how LWP retrievals are effected by changes in sea surface temperature (SST). The first thing to notice is that the results may be effected when sets of atmospheres are changed. This is most probably the cause of the increase in Alishouse's algorithm at 20°C (as tropical atmospheres are included) and 24°C (as mid-latitude atmospheres are removed). But this does not seem to have effected the other algorithms to a large degree.

Nearly all the algorithms have a similar variation in LWP, between 0.04 - 0.08 kg/m^2, over the 30°C range. The exception is Grody's algorithm which has roughly double this variation. Hargen's algorithm hardly varies at all for SSTs above 15°C. Petty's and Greenwald's algorithms show the opposite; these are roughly constant for SSTs below 15°C. Weng's and Liu's algorithms had the least variation. Both the Liu and Greenwald algorithms require SST to be input, so it was surprising that these did not have a significantly lower sensitivity than the other algorithms.

5.3 Sensitivity to Changes in Wind Speed

FIG. 4.5 shows how the algorithm calculated LWP values vary when surface wind speed is altered. Most of the algorithms showed little variation; Hargens', Weng's and Greenwald's algorithms were the least sensitive with variations of less than 0.03 kg/m^2 - then came the algorithms by Petty and Grody which had roughly double this variation. Liu's algorithm can be seen to behave strangely in the 15 - 25 m/s wind speed range. This, it is believed, is due to the way rough ocean geometry is set up in the radiative transfer model. The model represents a rough ocean with a limited number of discrete facets and problems arise when a slope gets pushed beyond the limits of the distribution. The effects of this are most clearly seen in the 37(H) GHz channel and because Liu's algorithm relies heavily upon this channel (see 5.6), this would seem to explain its erratic behaviour at large wind speeds.

5.4 Sensitivity to Changes in Integrated Water Vapour

Fig 4.6 shows the sensitivity of the algorithms to changes in IWV. Most of the algorithms performed well, varying by less than 0.05 kg/m^2 over the IWV range. A couple, Grody's and Liu's, performed very well (varying only 0.01 kg/m^2); and a couple, Petty's and Alishouse's, showed a much larger variance.

The error bars in Fig 4.6 are significantly smaller than those seen in the previous investigations. This is most probably because atmospheres were selected for a particular IWV and temperature, rather than being a random sample. Therefore, the algorithms would not have to cope with such a wide variety of atmospheres, so it is not surprising that their results were more consistent.

Nearly all the graphs have a positive slope. This would imply that the algorithms are not able to totally filter out the effects of IWV. Therefore when IWV is increased, some of this increase will be mistakenly identified as LWP, and so calculated LWP will increase.

5.5 Sensitivity to Changes in Cloud Temperature

Fig 4.7 shows how sensitive the algorithms are to changes in cloud temperature. Weng's shows little variation, less than 0.03 kg/m^2; Petty's and Liu's varies by 0.06 kg/m^2 and the other four all vary by about 0.1 kg/m^2.

The general trend appears to be a reduction in LWP retrieved values as cloud temperature increases. There is usually a strong correlation between areas of high humidity and areas with a high temperature - the warmest low level clouds are usually found in humid areas. Because humid areas seem to increase LWP retrievals (Fig 4.6) and high cloud temperatures to decrease LWP retrievals (Fig 4.7) there may be some cancelling out of these two effects.

5.6 Sensitivity to Noise in the SSM/I Brightness Temperatures

Table 4.6a shows the sensitivities of the algorithms to each of the SSM/I channels and polarizations, and an overall sensitivity. Tables 4.6(b and c) show the same as 4.6a, but for different values of LWP. The results showed Weng's and Alishouse's algorithms to be the least sensitive to noise; then came Hargens', Greenwald's and Grody's; the most sensitive algorithms were those of Liu's and Petty's - Petty's is particularly sensitive at large LWPs.

When the LWP was increased from 0.3 kg/m^2 to 0.9 kg/m^2, on average, the sensitivities increased. The reason for this can be seen on fig 5.1. Because of the curve on this graph, a 1K variation in brightness temperature at large brightness temperatures has a larger effect on LWP than at low brightness temperatures - and because large brightness temperatures are caused by large LWPs, an increase in LWP would therefore cause an increase in an algorithms sensitivity to noise.

Liu's algorithm can be seen to be the only algorithm which is particularly sensitive to the 37GHz horizontal channel. This would explain why it alone behaved strangely in the wind speed investigation (5.3).

The sensitivity of Petty's algorithm to the 85GHz channels increases substantially when LWP is increased. These high frequency channels are the first to saturate as LWP increases. At a LWP of 0.3 kg/m^2 the difference between vertical and horizontal brightness temperatures would be around 20K, while at 0.9 kg/m^2 it would be around 4K. A change in brightness temperature of 1K therefore becomes more important in percentage terms as LWP increases. So it is not surprising that this algorithm is very sensitive to noise in these channels at high LWPs.

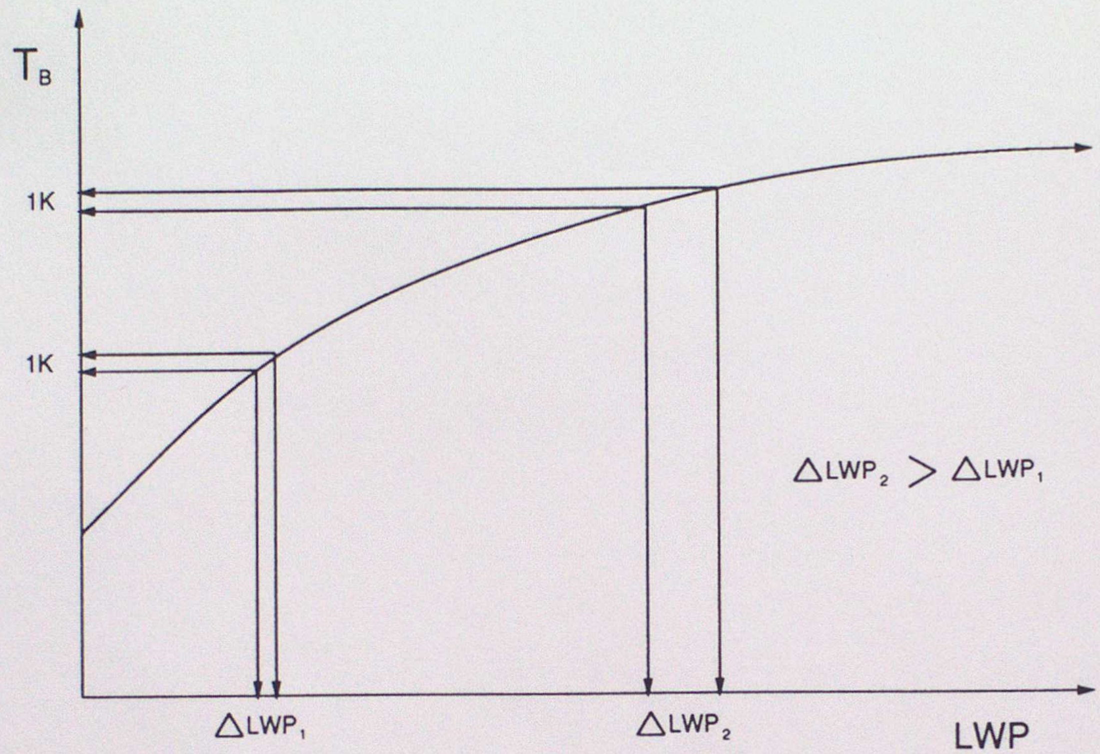


FIGURE 5.1 : Graph to Show the Typical Response of a Microwave Brightness Temperature to Increases in LWP.

6 Summary and Conclusions

An investigation into the accuracy and sensitivity of a number of LWP algorithms has been presented. A radiative transfer model was used and by varying input atmospheres, a number of experiments were carried out. The results of these are shown in Fig.s 4.1 - 4.7 and table 4.6. Using Fig.s 4.1 to 4.3 the root mean square (RMS) difference between model and algorithm LWP results were calculated. The error bars in these figures represent the spread of LWP values resulting from different atmospheres being used in the calculations, these are expressed in terms of one standard deviation from the mean value. From these figures the average standard deviation(SDs) for each of the algorithms were also calculated. Using fig.s 4.4 to 4.7 the maximum variation in LWP due to variations in SST, WW, IWV and cloud temperature were measured. This value was found by taking each of the figures in turn and, for a particular algorithm, subtracting the minimum LWP value from the maximum LWP value. These values are all shown in table 6.1.

Using this table, it is possible to see how well each of the algorithm's LWPs compared with the model's LWP. It is interesting that the two algorithms which best agreed with the model were both of the polarization difference type. Then came Liu's algorithm, which was physically based and required the input of two physical parameters. The next three were all of the same type; two channel algorithms linear in log(280 - T_B). And finally came Alishouse's algorithm which was linear in T_B.

These results show that something more sophisticated than a linear combination of T_Bs is required for an accurate algorithm. A better algorithm is one which is linear in log(280 - T_B). These algorithms generated fairly large RMS errors mainly due to significant constant biases. The polarization difference algorithms did not show such large biases; this may be due to their working on the difference between two T_Bs rather than on the absolute T_B value.

The sensitivity studies showed that no one factor caused significantly larger variations in all the algorithms. Different algorithms are sensitive and insensitive to different factors. For example; Grody's is sensitive to changes in SST, but insensitive to changes in IWV; while Greenwald's is sensitive to changes in CT, but insensitive to changes in WW. It should be noted that an accurate algorithm needs to be relatively insensitive, but if an algorithm is insensitive it does not necessarily make it accurate. Therefore the foremost criteria is an accurate algorithm.

The sensitivity to brightness temperature noise investigation showed that some algorithms were much more sensitive than others. Also as the LWP increased, sensitivities increased (in all but one case), this was especially noticeable in results from Petty's algorithm.

The best algorithm has an average RMS error of 0.013 kg/m^2. This error was calculated using the average of forty ascents over various LWP values and in various atmospheres. In considering this error, account should also be made of the standard deviations which occurred in obtaining this average value. This was around 0.03 kg/m^2. It should be noted that the conditions modelled were very nearly optimum for these algorithms to work in. When working on real data, they would encounter a much larger variety of conditions and their average errors would most probably be larger. Bearing this in mind, the results from this study show that the minimum average error for current LWP algorithms is around 0.05 kg/m^2.

6.1 Summary of Results

ALGORITHM	AVERAGE RMS ERROR			MAXIMUM VARIATION				SDs
	kg/m^2			kg/m^2				kg/m^2
	ARCTIC	MID-LAT	TROPICAL	SST	WW	IWV	CT	
ALISHOUSE	0.142	0.179	0.130	0.08	0.13	0.19	0.09	0.06
PETTY	0.013	0.011	0.045	0.08	0.05	0.09	0.06	0.04
GRODY	0.077	0.022	0.042	0.14	0.07	0.01	0.11	0.02
HARGENS	0.043	0.091	0.094	0.08	0.03	0.03	0.12	0.03
LIU	0.027	0.042	0.032	0.04	0.17	0.01	0.06	0.04
GREENWALD	0.022	0.007	0.010	0.06	0.02	0.05	0.10	0.03
WENG	0.127	0.130	0.153	0.05	0.02	0.03	0.03	0.02

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APPENDIX A: THE ALGORITHMS

ALISHOUSE ET AL. 1990

$$LWP(kg/m^2) = -3.14559+0.0060257T_{19H}-0.0048803T_{22V}+0.019595T_{37V}-0.0030107T_{85H}$$

PETTY AND KATSAROS 1990

$$LWP(kg/m^2) = -0.339log_e(P_{85})$$

$$P_{85} = (T_{85V} - T_{85H})exp(0.0241WW + 0.0271IWV - 4.44)$$

$$WW(m/s) = 1.0969T_{19V} - 0.4555T_{22V} - 1.76T_{37V} + 0.7860T_{37H} + 147.90$$

$$IWV(kg/m^2) = 11.98log_e(280-T_{19V})+42.06log_e(280-T_{19H})-54.36log_e(280-T_{22V})-20.5$$

GRODY AND FERRARO 1992

$$LWP(kg/m^2) = -0.359 - 0.882log_e(290 - T_{19V}) - 1.98(log_e(290 - T_{37V}))$$

HARGENS ET AL. 1992

$$LWP(kg/m^2) = 4.29930 + 0.399635log_e(280 - T_{22V}) - 1.40692log_e(280 - T_{37V})$$

LIU AND CURRY 1993

$$LWP(kg/m^2) = \frac{1}{\Omega} log_e \left(\frac{1}{1 - \varepsilon_c} \right) cos(53.1)$$

$$\Omega = exp(-1.35 - 0.0234(T_c - 273.15) - 0.122 * 10^{-3}(T_c - 273.15)^2 + 0.548 * 10^{-5}(T_c - 273.15)^3)$$

$$A\varepsilon_c^2 + B\varepsilon_c + C = 0$$

$$A = \alpha T_c$$

$$B = T_{B0} - (1 + \alpha)T_c$$

$$C = T_{37H} - T_{B0}$$

$$\alpha = 1 - \frac{T_{B0}}{2} \left(\frac{1}{SST - 15} + \frac{1}{SST} \right)$$

$$T_c = T_{ct} + 44.7 - 10.36 log_e(280 - T_{19H}) + 13.53 log_e(280 - T_{19V}) + 1.70 log_e(280 - T_{22V})$$
$$+ 14.33 log_e(280 - T_{37H}) - 30.56 log_e(280 - T_{37V})$$

$$T_{B0} = T_{B0}^R + 4.8 + 0.1206(T_{19H} - 100)$$

$$T_{B0}^R = 280 - exp(-0.988 + 2.943 log_e(280 - T_{19H}) - 1.240 log_e(280 - T_{19V}) - 0.183 log_e(280 - T_{22V})$$
$$- 1.131 log_e(280 - T_{37H}) + 0.686 log_e(280 - T_{37V})$$

GREENWALD ET AL. 1993

$$LWP(kg/m^2) = \frac{\tau_2 \kappa_{w19} - \tau_1 \kappa_{w37}}{\delta}$$

$$\delta = \kappa_{w19}\kappa_{l37} - \kappa_{w37}\kappa_{l19}$$

$$\tau_1 = -\frac{\mu}{2} ln\left[\frac{\Delta T_{19}}{T_s r_{19V}(1 - F_{19}) T_{ox19}{}^2}\right]$$

$$\tau_2 = -\frac{\mu}{2} ln\left[\frac{\Delta T_{37}}{T_s r_{37V}(1 - F_{37}) T_{ox37}{}^2}\right]$$

κ_w - water vapour mass absorption coefficient (m^2/kg)

κ_l - liquid water mass absorption coefficient (m^2/kg)

$\Delta T_{19} = T_{19H} - T_{19V}$

μ - cosine of incidence angle

T_s - sea surface temperature

r_{19V} - sea surface reflectivity at vertical polarization

$F_{19} \approx \frac{r_{19H}}{r_{19V}}$

T_{ox} - oxygen transmittance

WENG AND GRODY 1994

$$LWP = \begin{cases} LWP_{19V} \text{ if LWP}_{19V} \geq 0.6mm \\ LWP_{37V} \text{ if LWP}_{37V} \geq 0.2mm \text{ or WVP} \geq 30mm \\ LWP_{85H} \text{ otherwise} \end{cases}$$

$$LWP_{19V} = -2.8 - 2.7log_e(290 - T_{19V}) - 0.42log_e(290 - T_{22V})$$
$$LWP_{37V} = -2.9 - 1.15log_e(290 - T_{37V}) - 0.349log_e(290 - T_{22V})$$
$$LWP_{85H} = 1.6 - 0.44log_e(290 - T_{85H}) - 1.354log_e(290 - T_{22V})$$

$$IWV = 219.2 - 0.419T_{37V} - 1.83T_{22V} + 0.00597\,T_{22V}{}^2$$