EUMETSAT Cloud resolution study

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Chapter 1

Introduction

1.1 Clouds influence on the radiation budget

Clouds play a critical role in the Earth’s hydrological cycle and in the energy balance of the climate system. They have a strong effect on solar heating by reflecting part of the incident solar radiation back to space. An increase in the average albedo of the Earth-atmosphere system by only 10 percent could decrease the surface temperature to that of the last ice age. Clouds affect the thermal cooling by intercepting part of the infrared radiation emitted by the Earth and atmosphere below the cloud, and re-emitting part of this radiation back to the surface. Global change in surface temperature is highly sensitive to cloud amount and type. Increasing low-level and middle-level clouds has a net cooling effect because they reflect more solar radiation and have a relatively small effect on infrared radiation. On the other hand, increased high clouds will have a warming effect by virtue of their low temperature and reduced cooling to space. High cirrus also acts as a natural cloud seeder and strongly modulates the radiatively-important upper tropospheric water vapor budget. Given the sensitivity of the global climate to clouds, it is not surprising that the largest uncertainty in model estimates of global warming is due to clouds. It is for this reason that cloud will be the subject of much further study. Data from MSG amongst other instruments will provide an important source for these studies.

1.2 Observing Clouds

Many cloud studies have concentrated on observing clouds from ground based sites e.g radar, lidar or during aircraft campaigns. This type of data provides valuable insights into the vertical and horizontal variability of clouds at high resolution but is limited in its application to global climate modeling by the sparsity of sites. Satellite data can provide global coverage but is limited by the resolution of the observations. Polar orbiting satellites such as ATSR-2 and MODIS have relatively high resolution of 1km or greater on the ground, but with poor temporal resolution. In the case of ATSR only observing the same place once every 3 days. Geostationary satellites such as MSG and Meteosat have high temporal coverage but poorer spatial resolution. Each satellite or ground based instrument has its disadvantages and advantages depending on the quantity being studied. The production of information is also complicated by more technical requirements to process large amounts of data in a timely and manageable manner. In such a case it might be desirable to process the data at a lower resolution but faster e.g in near real time. In this study the ATSR-2 instrument can be used to look at the variation in the cloud properties retrieved at different resolutions for application such as utilising MSG or more importantly designing future satellite instruments in order to ascertain the loss of information incurred and low resolutions which could directly affect the
The aims of this work are to:

- Investigate cloud parameter retrievals for potential new satellite instruments.
- Investigate the variance of cloud parameter retrieval with changing resolution.
- Investigate the variance of cloud parameter retrieval with different cloud fraction estimate methods.
- Investigate the effects on cloud properties when the high resolution cloud retrievals are converted to low resolution products.
- Assess the validity of the cloud parameters under different geometry as a function of different retrieval resolutions.
- Assess the significance of any differences seen.

1.3 The ATSR-2 Instrument

The ATSR-2 instrument (an imaging radiometer on board the ESA/ERS-2 polar orbiting satellite), figure 1.1, produces images of the Earth at three visible/near infrared wavelengths (0.55, 0.67, and 0.87µm) and four infrared wavelengths (1.6, 3.7, 11 and 12µm). The instrument has been designed to observe the same scene in the 'nadir' view (zenith angle between 0° and 25° and in the 'forward' view (zenith angle between 52° and 55°). The spatial resolution at nadir is about 1 x 1km² and the repeat cycle 3 days. The main features of the ATSR-2 instrument are

- The use of low noise infrared detectors cooled to near optimum temperatures.
- Continuous on board radiometric calibration.
- The use of the along track scanning technique to provide enhanced atmospheric correction.
- The use of the multi channel approach to SST retrievals previously demonstrated by AVHRR.

Owing to the spectral and dual view of ATSR-2, the instrument has a wide variety of applications, one of which is to detect sea surface temperature. Watts[1] has also pointed out the possibilities for retrieval of cloud parameters. The following section describes the cloud retrieval algorithm.

1.3.1 Analogy with MSG

The SEVIRI(Spinning Enhanced Visible and Infra Red Imager) is a 50 cm diameter line by line scanning radiometer which is one of the main instruments on MSG. The MSG satellite and the SEVIRI instrument are shown in figure 1.2. It provides data in four visible and near infra red channels and eight infrared channels. 6 of these channels are analogous to the ATSR-2/AATSR channels see table 1.1. The resolution is 3x3km².
Figure 1.1: The ATSR Instrument

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<th>MSG $\mu$m</th>
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<td>2</td>
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<td>0.64</td>
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<tr>
<td>3</td>
<td>0.87</td>
<td>0.81</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>1.64</td>
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<td>7</td>
<td>12.0</td>
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</tbody>
</table>

Table 1.1: Comparison of ATSR and MSG channels

Figure 1.2: The MSG satellite and the main instrument SEVIRI.
Chapter 2

Cloud Retrieval Algorithm

2.1 Cloud retrievals from ATSR-2 data

Cloud product information from ATSR-2 radiances originates from the interaction of solar and terrestrial emitted radiation with the cloud. In an ideal situation each channel of ATSR-2 would be sensitive to just one cloud parameter. In reality each measurement is the result of many complex interactions within the cloud and between the cloud, the atmosphere and the surface. In general however, cloud effects at the wavelengths measured (which are in atmospheric 'windows') are stronger than the other effects. By combining the information available we are able resolve most cloud parameters in most situations.

The cloud parameters studied in this report with definitions and a short description of the reason ATSR-2 is able to retrieve them is given below.

- **Cloud Optical Depth:** At visible wavelengths (0.55, 0.67 and 0.87 μm) there is no absorption of radiation by liquid or water drops and the total reflected radiance is related directly to the total number of scattering objects in the scene. There is a small drop size dependence and also small effects from the atmosphere.

- **Cloud Effective Radius:** The radiatively effective size of the cloud particles, \( R_e \); All clouds contain particles of a range of sizes with a size distribution that ranges from reasonably well known (e.g. stratus water clouds) to poorly known (e.g. cirrus). No current or planned remote sensing instrument can measure this distribution but a single size with; radiatively equivalent effect can be retrieved. Fortunately, for climate and other applications, this effective radius is virtually all that is required to determine radiative effects. effective radius affects the measurements by changing the effectiveness of which an ensemble of particles scatter radiation. In the 1.6 and 3.7 μm channels where there is a small amount of absorption of radiation by liquid and solid water, both scattering and absorption are important the balance between the two leads to a sensitivity to effective radius - smaller particles scatter more effectively than larger ones. These two channels are the most important channels for daytime estimation of effective radius. They are both affected to some extent by the cloud optical thickness and surface effects (and temperature in the 3.7 μm case). Therefore it is necessary to use the information (simultaneously in our case) from the visible wavelength channels to account for this. The 1.6 μm channel is especially useful in phase estimation because, at this wavelength, solid water absorption is significantly higher than liquid water absorption leading to much lower reflectance over ice cloud.

- **Cloud top Pressure:** The IR thermal emission has a strong dependence on pressure since the pressure determines the temperature of the clouds.; Therefore the 11 and 12 μm channels are the most useful determinants of cloud pressure although at night the
3.7 μm channel is almost as useful. All thermal channels are affected, especially in thin cloud cases by the optical depth and fractional coverage and this again suggests that best results are obtained when visible channel information on optical depth is incorporated into pressure retrieval. It should be stressed that because the ATSR:thermal channels are all relatively clean; windows, the essential measurement we make is of cloud top temperature. This is effectively translated into cloud pressure through the NWP: model profiles.

- Cloud Fraction: The cloud fraction affects measurements in all channels since the response to cloudy and clear scenes is generally very different. The only exceptions are thin cloud over highly reflective land and low cloud with a similar temperature to the surface. Thus all channels are important in estimating the fractional cover.

2.2 Variational Analysis

In the variational analysis scheme a fast radiative transfer model of water and ice cloud is used to estimate cloud optical depth, phase effective radius and fractional cover from 0.67, 0.87, 1.6, 11 and 12 micron channels of ATSR-2. ECMWF temperature and humidity profiles are used to characterise the clear atmosphere. The visible wavelengths channels provide the most information on optical depth, the 1.6 micron channel is a robust indicator of phase and effective radius and the infrared channels indicate cloud top temperature from which pressure is obtained.

We use an ‘Optimal Estimation’ (OE) approach to the retrieval of parameters enabling us to extract information from all channels simultaneously. The OE method also allows us to characterise the error in each parameter in each individual observation (or ‘pixel’) under the assumption that the cloud observed is consistent with the modeled cloud (i.e., reasonably plane-parallel in nature). A second diagnostic (the solution cost, J) indicates whether in fact this assumption is true. The OE framework also allows us to use any prior information on the pixel observed. In terms of retrieved products we presently only have significant priori information on cloud fraction and skin temperature, however, all the clear atmospheric (i.e., non-cloud) effects on the IR measurements are derived from prior information in the form of NWP profiles (courtesy of ECMWF through the BADC). The ice crystal properties, stored in look up tables, are based on those calculated by Baran et al[3]

The Optimal Estimation (OE) described here is essentially that based on that described by Rogers[4]. The method allows for the simultaneous inversion of all products using all measurements and a weighted apriori with appropriate levels of confidence. The probability of the retrieved state is given by

\[ P(x|y_m, x_b, b) \]

where \( y_m \) are the measurements, (.67, 0.87, 1.6, 3.7, 11, 12um). \( x_b \) is the measurement error covariance and \( b \) are the model parameters.

Maximising the probability is the same as minimising \( J \), the cost function where \( J \) is defined by

\[ J = (y(x) - y_m)S_y^{-1}(y(x) - y_m)^T + (x - x_b)S_x^{-1}(x - x_b)^T \]  

(2.1)

The solution to \( J \) is found by iterating with

\[ x_{n+1} = x_n - (\delta^2 J/\delta x^2 + aI)^{-1} \delta J/\delta x \]  

(2.2)

until \( J = (J_{n+1} - J_n) < e \)  

(2.3)

The quality of fit is given by \( J(x_{solution}) \). The error estimate is given by

\[ S = D_yS_yD_y^T + (D_y K - I)S_x (D_y K - I)^T; D_y = (S_x - 1 + KS_yK^T)^{-1}KS_y^{-1} \]  

(2.4)
Where the retrieved $x = [\tau, r_c, P_c, f, T_b]$ is the retrieved state, comprising, optical depth, drop size, cloud top pressure, cloud fraction and skin temperature, $y(x)$, the radiative transfer model, $x_b$ the a priori information, $x_b$, the first guess, $S_y$ the measurement error covariances, $S_x$, the a priori error covariance, $K(x) = \delta y(x) / \delta(x)$ the gradient and $D_y$, the inversion operator, which describes the response of the retrieval estimator to a change in the measurements.

For a more complete description of the algorithm see Watts[3]
Chapter 3

Background Information

3.1 Cloud Horizontal Scales

Clouds exhibit dramatic variabilities at spatial scales smaller than typical grid cells of large scale models used to study climate and weather. These unsolved cloud fluctuations are potentially important for parameterizations of both cloud radiative effects and cloud microphysical processes. It is now well accepted that neglect of cloud sub scale variability can seriously bias model estimates of radiative energy budget in the Earth-atmosphere system. We will try to address some aspects of this bias in this report.

Different types of clouds have different horizontal variabilities. Stratus clouds have typically low horizontal variability and may stretch for 10s even 100s of km. Convective 

Cumulonimbus clouds have typically much shorter scales of 1-5km (typically 1-2km) in which optical depths and effective radius can vary[6](the vertical particle distribution, varies much more significantly). To give an idea of the variation in cloud parameters in time and distance. Figure 3.1 shows the variation in an alto cumulus cloud field as a function of reflectivity from the 94GHz radar at Chilbolton over a 24 hour period. The reflectivity is proportional to the size of the particles in the atmosphere and the images give an indication of the cloud top height and depth. Clouds traveling at 10m/s typically travels 60km per hour. Cloud systems such as fronts develop in stages but in general ATSR-2 cloud retrievals with a resolution of 1km will capture most of these features.

Figure 3.1: Chilbolton 94GHz radar image of an Alto Cumulus cloud system
3.2 Cloud type definitions

For the purpose of this study we have found it useful to break down the cloud into different classes. The classes selected are based on the ISCCP[7] cloud classes shown in figure 3.2 and are categorised according to optical depth and cloud top pressure. This classification is by no means perfect and in reality the thresholds are much more blurred and should perhaps be viewing with some skepticism. However it was used in order to gain deeper insights into the changes induced by changing the resolution, the results in the following sections are often broken down in to cloud types in order to identify specific behavior.

3.3 Characteristics of the data set and limitations

3.3.1 What data was used

The data used in this analysis was a globally representative set of ATSR-2 scenes from the 23rd of July 1996. The distribution of this data can be seen in figure 3.3. As the data set is only for a single day the solar zenith angle is latitudinally dependent and peaks at around 70° at the poles, see figure 3.4. The distribution of azimuth angle is less localised. The view zenith angle is almost constant according to the ATSR-2 viewing geometry.

3.3.2 Quality control

A basic quality control was applied to the data. Retrievals with a 'cost' (see equation 2.1) greater than 50 and cloud top pressure greater than 1000hPa were removed from the data set. This had the effect of removing retrievals particularly over land identified as a cloud which the cloud mask misidentified. The cloud mask used is an empirical NDVI scheme used at Rutherford Appleton laboratory on ATSR-2 data[8].
Figure 3.3: Cloud optical depth for the data sample used on the 23rd of July 1996. The data is plotted in a one degree grid.

3.3.3 Cloud distribution

In order to accurately assess the results it is important to understand any biases in the system. One such bias is the predominance of different cloud types at certain latitudes. The distribution for this data set is given in figure 3.5. Low cloud types that occur most frequently, while mid-level and high cloud most commonly occur in the storm tracks and tropics.
Figure 3.4: Distribution of cosine solar zenith angle and azimuth angle as a function of resolution for the analysis data set.

Figure 3.5: Cloud type as a function of latitude.
Chapter 4

Results

4.1 Resolution Analysis

In this chapter the methodology behind the analysis is described. The results for two case studies are presented. This section is then wrapped up with the results for the whole data set.

4.1.1 Calculation of cloud fraction

In this study the cloud fraction is estimated using three methods. The first method estimates cloud fraction using no prior knowledge of the super-pixel (a super-pixel is comprised of many sub-pixels) e.g. a 3x3km pixel is assumed to be either cloudy or clear. The second uses sub pixel information, e.g. if the cloud parameter is being retrieved at 3x3km resolution then the cloud fraction is estimated from the nine individual sub pixels, the apriori cloud fraction is two thirds if six pixels are cloudy and three pixels are clear. With this technique it should be possible to get a more accurate cloud fraction, for the super-pixel before the retrieval takes place. In both cases the error on the apriori is dependent on the neighboring super-pixels. If all the neighboring super-pixels are cloudy the apriori error is 0.01, i.e. it is assumed that the super-pixel most likely has a cloud fraction very close to one. If any of the neighboring super-pixels are clear then the apriori error is 0.1 which gives the retrieval more flexibility to change the cloud fraction. One of the main advantages of using an optimal estimation method to retrieve cloud fraction is that the scene under study can have cloud fraction less than one. A third scenario is also considered, that of retrieving the cloud property at high resolution but spatially averaging up that result to lower resolutions. This will simulate the cases where high resolution cloud parameters are averaged to large grid boxes for comparison with weather prediction models.

4.1.2 Normalisation

In the aggregated results a reduction in the possible number of clouds that can be retrieved occurs at lower resolution because of the reduction in the number of super-pixels. The lower resolution cloud retrievals have been normalised to that of the higher resolution retrievals for ease of comparison. This normalisation was applied by multiplying the end retrieved product by the resolution squared. In theory this should result in the same number of total retrieved cloud parameters. However in practice 1x1km retrievals are more successful than larger resolution retrievals leading to a slight discrepancy. Figure 4.1 shows the number of clouds in each cloud class retrieved as a function of resolution. For the majority of cloud types, cirrus, stratus, deep convection the number retrieved do not vary with resolution however the number of stratocumulus cloud retrieved increases by 10%. The percentage of cumulus cloud decreases
slightly. This suggests that as the resolution decreases these cloud types become mixed in a super-pixel.

Figure 4.1: Fraction of cloud scenes as a function of resolution, for the total data set and broken down according to cloud type.

4.2 Case study 1: Cloud parameters retrieved for mid latitude clouds over England and Ireland.

This section investigates a cloud scene for the 23rd of July 1996 over England and Ireland. Figure 4.2 shows a false colour image of a broken cloud scene with many different cloud types. The image is a composite of the 1.6, 0.87 and 0.67 μm, (R,G,B) channels. The blue areas show high cold cloud while the red areas indicate lower warmer cloud banks. In the right hand corner is a bank of high thick cloud while at the bottom of the scene is a bank of lower broken cloud.

Each cloud parameter was retrieved at 1x1km (upper left), 3x3km (upper right), 5x5km (lower left) and 8x8km (lower right) resolution. Figures 4.3 to 4.18 show results for when the cloud fraction apriori has a value of one. Figures 4.19 to 4.31 show the same parameter but when the sub pixel information is used to determine the cloud fraction apriori.

4.2.1 Optical Depth

Figures 4.3 to 4.6 show the optical depth retrieved at different resolutions. As the resolution is decreased the finer details are lost however the general pattern remains the same. Areas that in the 1x1km resolution retrieval were relatively clear at 1x1km resolution such as the Isle of Man between England and Ireland slowly become more cloudy, over this small area the optical depth as the resolution decreases seems to decrease only very slightly. Between the 1x1km and higher resolutions the optical depth in the top right hand corner seems to increase.

4.2.2 Effective radius

Figures 4.7 to 4.10 show the particle effective radius as the resolution decreases. The patches of high effective radius in the right hand corner slowly blur as the cloud is retrieved over a
Figure 4.2: This RGB false colour image is composed of the 1.6, .87 and .67μm channels respectively. The blue areas show high cold cloud while the red areas indicate lower warmer cloud banks. This cloud scene shows a variety of cloud types and much broken cloud.

larger areas.

4.2.3 Cloud Top Pressure

Figures 4.11 to 4.14 shows the cloud top pressure for different resolutions. As the resolution decreases there is no significant change in cloud top pressure. Except once again as the resolution decreases over the Isle cloud top pressure decreases, i.e clouds appear lower.
Figure 4.3: Optical depth for 1x1 km, apriori cloud fraction one
Figure 4.4: Optical depth for 3x3 km, apriori cloud fraction one

Figure 4.5: Optical depth for 5x5km, apriori cloud fraction one
Figure 4.6: Optical depth for 8x8 km, apriori cloud fraction one
Figure 4.7: Effective radius for 1x1km, apriori cloud fraction one
Figure 4.8: Effective radius for 3x3km, apriori cloud fraction one
Figure 4.9: Effective radius for 5x5km, apriori cloud fraction one
Figure 4.10: Effective radius for 8x8km, apriori cloud fraction one
Figure 4.11: Cloud top pressure for 1x1km, apriori cloud fraction one
Figure 4.12: Cloud top pressure for 3x3km, apriori cloud fraction one
Figure 4.13: Cloud top pressure for 5x5km, apriori cloud fraction one
Figure 4.14: Cloud top pressure for 8x8km, apriori cloud fraction one
4.2.4 Cloud Fraction

Figures 4.15 to 4.18 shows the estimated fraction as a function of resolution. The change in fraction is perhaps the most obvious of all the cloud parameters. As the resolution decreases the number of super-pixels that are cloud-free decreases. The effective cloud coverage increases but only at the edges of cloud banks. This effective will be most significant for broken cloud banks. This confirms what has previously been studied by Wielicki et al[9], that as the the super-pixel size increases the cloud coverage will be overestimated. There is an odd side effect of the retrieval technique visible in the cloud fraction images. Over very high cloud the the cloud fraction decrease this is because of the difficulty in correctly modeling the ice cloud properties.

4.2.5 Changing the cloud fraction apriori technique

Figure 4.19 to 4.34 show the same case study results as in the previous section but for retrievals which use sub-pixel information to calculate the cloud fraction apriori. At first glance there are no obvious differences.
Figure 4.16: Cloud fraction for 3x3km, apriori cloud fraction one
Figure 4.17: Cloud fraction for 5x5km, apriori cloud fraction one
Figure 4.18: Cloud fraction for 8x8km, apriori cloud fraction one
Figure 4.19: Optical depth for 1x1 km, sub pixel cloud fraction apriori
Figure 4.20: Optical depth for 3x3km, sub pixel cloud fraction apriori
Figure 4.21: Optical depth for 5x5km, sub pixel cloud fraction apriori
Figure 4.22: Optical depth for 8x8km, sub pixel cloud fraction apriori
Figure 4.23: Effective radius for 1x1km, sub pixel cloud fraction apriori
Figure 4.24: Effective radius for 3x3km, sub pixel cloud fraction apriori
Figure 4.25: Effective radius for 5x5km, sub pixel cloud fraction apriori
Figure 4.26: Effective radius for 8x8km, sub pixel cloud fraction apriori
Figure 4.27: Cloud top pressure for 1x1km, sub pixel cloud fraction apriori

Figure 4.27 to figure 4.30 shows the cloud top pressure as the resolution decreases there is no significant change in cloud top pressure.
Figure 4.28: Cloud top pressure for 3x3km, sub pixel cloud fraction apriori
Figure 4.29: Cloud top pressure for 5x5km, sub pixel cloud fraction apriori
Figure 4.30: Cloud top pressure for 8x8km, sub pixel cloud fraction apriori
Figure 4.31: Cloud fraction for 1x1km, sub pixel cloud fraction apriori
Figure 4.32: Cloud fraction for 3x3km, sub pixel cloud fraction apriori
Figure 4.33: Cloud fraction for 5x5km, sub pixel cloud fraction apriori
Figure 4.34: Cloud fraction for 8x8km, sub pixel cloud fraction apriori
The differences become clearer when the difference between the two techniques is plotted as in figures 4.35 to 4.38.

To interpret this information it is necessary to have a basic knowledge of the cloud mask. The cloud mask in this retrieval is based on NDVI ratios and was developed in house. In order to process as many cloudy pixels as possible the ranges to identify the cloud are quite loose, hence more cloudy scenes are identified than are actually present. Later on using the quality control information the non cloudy scenes become easy to identify having high cost, equation 2.1. However this is going to bias the results. The cloud mask is used to identify clear or cloudy sub-pixels so using this cloud mask we are going to underestimate the percentage of cloudy pixels with cloud fractions less than one. This is immediately obvious in the bottom right corner of the image where the scene is relatively cloud free but no differences are seen between the cloud fraction techniques. Nevertheless we can still see some important trends.

These figures show the difference between the two retrieval techniques, ‘cloud fraction one - sub-pixel cloud fraction’. Figures 4.35 to 4.38 show that the majority of the differences occur at the edges of cloud banks.

The differences are more obvious when they are plotted as a histogram in figures 4.39 to 4.42. Assuming the ‘true’ cloud fraction is that estimated from the sub pixel information the optical depth of clouds will be underestimated when a cloud fraction of one for the super-pixel is assumed. Interestingly the difference between the two retrieval techniques decreases as the pixel size increases. The cloud effective radius shows the opposite effect perhaps compensating for the change in optical depth. The cloud effective radius shows a slight positive bias indicating that over estimating the cloud fraction will over estimate the effective radius. While the bias is small, less than 0.3μm the standard deviation can be as high as 4μm. The cloud top pressure shows a more significant positive bias, i.e. as cloud fraction is over estimated the average cloud top height will be lower. Cloud fraction shows the most predictable response, at high resolutions the difference in the two techniques shows a digitized effect corresponding to a fraction of the super-pixel. This is smoothed as the resolution decreases. Again the bias seems to decrease as the resolution increases. The area that the differences encompass has increased but the individual super-pixel differences decrease, particularly in areas where the cloud is very patchy or broken and as the super-pixel size increases it encroaches on more cloud.

These changes are understandable because as the fraction decreases some cloud parameter has to compensate. Optical depth is the likely because changes the cloud top pressure will only really affect the infrared channels and the effective particle radius has little effect on the visible channels.
Figure 4.35: Optical depth difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.36: Effective radius difference between two cloud fraction apriori techniques, from clockwise 3x3 km, 5x5 km and 8x8 km resolution
Figure 4.37: Cloud top pressure difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution.
Figure 4.38: Cloud fraction difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.39: Optical depth difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.40: Effective radius difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.41: Cloud top pressure difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution.

It should be noted that the areas that show a difference is biased by the cloud flagging method and to an extent by the quality control. The super-pixels that show the greatest difference are super-pixels that incorporate clear flagged pixels. The cloud flagger used in these retrievals over flags cloud. These misidentified pixels are rejected later using the quality control however the cloud fraction used in the apriori does not take this into account. Hence the extent of these differences will be underestimated.
Figure 4.42: Cloud fraction difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Difference between high and low resolutions

Figure 4.43 shows the probability distribution functions of difference in the cloud parameter retrievals for 8x8km resolution minus the 2x2km (All the other corresponding difference functions have a similar shape). The mean bias for all resolutions and all cloud types is shown in figure 4.44. All the distributions are centered close to zero, the mean bias in all cases is less than 1%, however the bias is different for different cloud types. The largest bias occurs for the altocumulus and cirrus clouds, both clouds are thin and have some ice cloud component. Given the statistics used in this plot it is difficult to form any conclusions.

![Frequency Distributions](image)

Figure 4.43: Case study: Difference between retrievals at 8x8km and 2x2km resolution

4.2.6 Spatially averaging high resolution images to produce low resolution products

Figures 4.45 to 4.60 shows cloud parameters averaged to different resolutions. The averages are calculated using the 1x1km resolution retrievals and a cloud fraction for the super-pixel provided by the sub-pixel information. This is the scenario one might envisage to provide spatially averaged products for comparison with weather prediction models. Many of the changes described in the previous section are visible in this case. The high effective radius areas blur and the cloud fraction decreases around the edges of the cloud.
Figure 4.44: Case study: Difference between retrievals for different resolutions, relative to the 2x2km super-pixels, e.g. 3 means super-pixel 3x3km - 2x2km resolution, 4 means 4x4km - 2x2km resolution
Figure 4.45: Optical depth for 1x1km, high to low resolution spatial averaging
Figure 4.46: Optical depth for 3x3km, high to low resolution spatial averaging
Figure 4.47: Optical depth for 5x5km, high to low resolution spatial averaging
Figure 4.48: Optical depth for 8x8km, high to low resolution spatial averaging
Figure 4.49: Effective radius for 1x1km, high to low resolution spatial averaging
Figure 4.50: Effective radius for 3x3 km, high to low resolution spatial averaging
Figure 4.51: Effective radius for 5x5km, high to low resolution spatial averaging
Figure 4.52: Effective radius for 8x8km, high to low resolution spatial averaging
Figure 4.53: Cloud top pressure for 1x1km, high to low resolution spatial averaging
Figure 4.54: Cloud top pressure for 3x3 km, high to low resolution spatial averaging
Figure 4.55: Cloud top pressure for 5x5km, high to low resolution spatial averaging
Figure 4.56: Cloud top pressure for 8x8km, high to low resolution spatial averaging
Figure 4.57: Cloud fraction for 1x1km, high to low resolution spatial averaging

**Difference between high and low resolutions when spatially averaging.**

Figures 4.61 to 4.64 show the location of the differences in the two techniques i.e retrieval calculated at resolution X (where X is 3x3km, 5x5km or 8x8km) resolution minus the resolution calculated by averaging the 1x1km pixels to lower resolutions. Unlike the previous section the differences are global. For optical depth the difference are greatest and show the most positive bias where the cloud is thickest, this is an artifact of the retrieval algorithm. Else the optical depth differences do not seem significant. The effective radius differences are greatest at the edges of the clouds as is the case for cloud top pressure and cloud fraction. In all cases he differences at the edges of the cloud show the sub pixel method estimating values higher than the spatially averaged products. I.e using the sub pixel technique the effective radius can be 30% higher, the cloud top pressure up to 260HPa closer the the ground and the cloud fraction up to 25% higher. I.e the clouds are much warmer.
Figure 4.58: Cloud fraction for 3x3 km, high to low resolution spatial averaging
Figure 4.59: Cloud fraction for 5x5km, high to low resolution spatial averaging
Figure 4.60: Cloud fraction for 8x8 km, high to low resolution spatial averaging
Figure 4.61: Optical Depth difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Figure 4.62: Effective radius difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Figure 4.63: Cloud top pressure difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Figure 4.64: Cloud fraction difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Figure 4.65: Optical Depth difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging

Figures 4.65 to 4.68 illustrate the differences with histograms. The positive bias in optical depth is clear. The bias in the effective radius, cloud top pressure and cloud fraction seen at the edges of the cloudy banks is mitigated by the opposite negative bias over the thick clouds. Since the negative bias is due to the retrieval technique rather than the change in reresolution in all cases the spatially averaged value is smaller than the sub-pixel technique. It is difficult to say at this point if the cloud fraction is correct or underestimated in this case.

Difference between high and low resolution spatially averaged cloud parameters

Figures 4.69 to 4.72 show the difference between the 1x1km and lower spatial resolutions. These maps are most interesting to see that the differences occur at the borders between clear and cloudy pixels. In the spatially averaged case the cloud fraction is too low in the in the cloud closest to the edge and too high just outside the edge.

As expected figures 4.73 to 4.76 show the bias is zero but the standard deviation is significantly high for all cloud parameters and increasing as the resolution decreases.
Figure 4.66: Effective radius difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Figure 4.67: Cloud top pressure difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Resolution 1x1km – 3x3km Cloud Fraction
Resolution 1x1km – 5x5km Cloud Fraction
Resolution 1x1km – 8x8km Cloud Fraction

Figure 4.68: Cloud fraction difference 3x3km, 5x5km and 8x8km, sub-pixel fraction - spatial averaging
Figure 4.69: Optical Depth difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.70: Effective radius difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.71: Cloud top pressure difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.72: Cloud fraction difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.73: Optical Depth difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging

4.2.7 Retrieval error

Figure 4.77 and 4.78 show the cloud retrieval error for cloud property retrievals at 2x2km resolution and 8x8km resolution for the case with a cloud fraction apriori of one. Figures 4.79 and 4.80 show the same plots but when the cloud fraction apriori uses sub pixel information. The two techniques have very similar error distributions. The errors are highest over the high cloud where the difficulty in modeling the ice crystal behaviour evident. There is little difference in the distribution of errors.
Figure 4.74: Effective radius difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.75: Cloud top pressure difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.76: Cloud fraction difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.77: Cloud property error, 2x2km resolution, cloud fraction apriori of one. Optical depth top right, effective radius top left, cloud top pressure bottom right, cloud fraction bottom left.
Figure 4.78: Cloud property error, 8x8km resolution, cloud fraction apriori of one. Optical depth top right, effective radius top left, cloud top pressure bottom right, cloud fraction bottom left.
Figure 4.79: Cloud property error, 2x2km resolution, cloud fraction apriori uses sub pixel information. Optical depth top right, effective radius top left, cloud top pressure bottom right, cloud fraction bottom left.
Figure 4.80: Cloud property error, 8x8km resolution, cloud fraction apriori uses sub pixel information.

4.3 Case study 2: Cloud parameter retrieval of a tropical convective cloud scene.

Figure 4.81 shows the false colour image of a totally different cloud scenario to that of case one, that of a tropical convective cloud. Figures 4.118 to 4.129 show the cloud parameters retrieved at different resolutions for the three different retrieval scenarios.

4.3.1 Optical Depth
Figure 4.81: This RGB false colour image is composed of the 1.6, .87 and .67μm channels respectively. This cloud scene has a large convective cloud in the top right hand corner.
Figure 4.82: Optical depth for 1x1 km, cloud fraction apriori uses sub-pixel information
Figure 4.83: Optical depth for 3x3km, cloud fraction apriori uses sub-pixel information
Figure 4.84: Optical depth for 5x5km, cloud fraction apriori uses sub-pixel information
Figure 4.85: Optical depth for 8x8km, cloud fraction apriori uses sub-pixel information
Figure 4.86: Optical depth for 1x1km, apriori cloud fraction one
Figure 4.87: Optical depth for 3x3km, apriori cloud fraction one
Figure 4.88: Optical depth for 5x5km, apriori cloud fraction one
Figure 4.89: Optical depth for 8x8km, apriori cloud fraction one
Figure 4.90: Optical depth for 1x1km, high to low resolution spatial averaging
Figure 4.91: Optical depth for 3x3km, high to low resolution spatial averaging
Figure 4.92: Optical depth for 5x5km, high to low resolution spatial averaging
Figure 4.93: Optical depth for 8x8km, high to low resolution spatial averaging
4.3.2 Effective radius

![Effective radius for 1x1km, cloud fraction apriori uses sub-pixel information](image)

Figure 4.94: Effective radius for 1x1km, cloud fraction apriori uses sub-pixel information
Figure 4.95: Effective radius for 3x3km, cloud fraction apriori uses sub-pixel information
Figure 4.96: Effective radius for 5x5km, cloud fraction apriori uses sub-pixel information
Figure 4.97: Effective radius for 8x8km, cloud fraction apriori uses sub-pixel information
Figure 4.98: Effective radius for 1x1km, apriori cloud fraction one
Figure 4.99: Effective radius for 3x3km, apriori cloud fraction one
Figure 4.100: Effective radius for 5x5km, apriori cloud fraction one
Figure 4.101: Effective radius for 8x8km, apriori cloud fraction one
Figure 4.102: Effective radius for 1x1km, high to low resolution spatial averaging

4.3.3 Cloud Top Pressure
Figure 4.103: Effective radius for 3x3 km, high to low resolution spatial averaging
Figure 4.104: Effective radius for 5x5 km, high to low resolution spatial averaging
Figure 4.105: Effective radius for 8x8 km, high to low resolution spatial averaging
Figure 4.106: cloud top pressure for 1x1 km, cloud fraction apriori uses sub-pixel information
Figure 4.107: Cloud top pressure for 3x3km, cloud fraction apriori uses sub-pixel information
Figure 4.108: Cloud top pressure for 5x5km, cloud fraction apriori uses sub-pixel information
Figure 4.109: Cloud top pressure for 8x8km, cloud fraction apriori uses sub-pixel information
Figure 4.110: Cloud top pressure for 1x1km, apriori cloud fraction one

4.3.4 Cloud Fraction
Figure 4.111: Cloud top pressure for 3x3 km, apriori cloud fraction one
Figure 4.112: Cloud top pressure for 5x5km, apriori cloud fraction one
Figure 4.113: Cloud top pressure for 8x8 km, apriori cloud fraction one
Figure 4.114: Cloud top pressure for 1x1km, high to low resolution spatial averaging
Figure 4.115: Cloud top pressure for 3x3km, high to low resolution spatial averaging
Figure 4.116: Cloud top pressure for 5x5km, high to low resolution spatial averaging
Figure 4.17: Cloud top pressure for 8x8 km, high to low resolution spatial averaging
Figure 4.118: Optical depth for 1x1km, cloud fraction apriori uses sub-pixel information
Figure 4.119: Optical depth for 3x3 km cloud fraction apriori uses sub-pixel information
Figure 4.120: Optical depth for 5x5 km, cloud fraction apriori uses sub-pixel information
Figure 4.121: Optical depth for 8x8 km, cloud fraction apriori uses sub-pixel information
4.3.5 Retrieval Error

Figure 4.130 shows the cloud retrieval error for cloud property retrievals at 8x8km resolution for the a case with a cloud fraction apriori of one. Figure 4.131 shows the same plots but when the cloud fraction apriori uses sub pixel information.
Figure 4.123: Cloud fraction for 3x3km, apriori cloud fraction one
Figure 4.124: Cloud fraction for 5x5 km, apriori cloud fraction one
Figure 4.125: Cloud fraction for 8x8 km, apriori cloud fraction one
Figure 4.126: Cloud fraction for 1x1km, high to low resolution spatial averaging
Figure 4.127: Cloud fraction for 3x3km, high to low resolution spatial averaging
Figure 4.128: Cloud fraction for 5x5km, high to low resolution spatial averaging
Figure 4.129: Cloud fraction for 8x8km, high to low resolution spatial averaging
Figure 4.130: Cloud property error, 8x8km resolution, cloud fraction apriori of one. Optical depth top right, effective radius top left, cloud top pressure bottom right, cloud fraction bottom left.
Figure 4.131: Cloud property error, 8x8km resolution, cloud fraction apriori uses sub pixel information.

**Difference between the cloud fraction techniques**

Figures 4.132 to 4.135 show the difference between the cloud fraction techniques for this convective scene as a function of location. Figures 4.136 to 4.139 show the differences as a histogram. Once again the differences are displayed as the retrieval using cloud fraction of one minus the retrieval using a sub-pixel cloud fraction. There are many similarities with the first case study, the differences are all at the boundaries between clear and cloud scenes. Cloud fraction 4.135 is overestimated using a cloud fraction of one, the cloud fraction differences show a digitisation effect related to the super-pixel size. Optical depth, figure 4.132 and effective radius figure...
Figure 4.132: Optical depth difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.133: Effective radius difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.134: Cloud top pressure difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.135: Cloud fraction difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.136: Optical depth difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution.
Figure 4.137: Effective radius difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution
Figure 4.138: Cloud top pressure difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution

**Difference between spatially averaging from high to low resolution**

Figure 4.140 to 4.143 show the difference between a retrieval estimated at different resolutions using a large super-pixel minus the result of averaging 1x1km pixels to low resolution as a function of location. Figure 4.144 to 4.147 The largest changes in optical depth are concentrated where the clear and cloudy areas meet and also where low cloud edges on high cloud. Overall there is a positive bias that increases slightly as the resolution decreases. The cloud top pressure changes are also concentrated at these edges and show a significant standard deviation. The cloud fraction and effective radius changes seem to be tied together. The cloud fraction shows a significant negative bias over the deep convective cloud core. Coincident with this is a larger than normal change(negative bias) in the effective radius and high standard deviation. Since this cloud should have a cloud fraction of one with small error then this change can be explained by the incorrect modeling of the ice crystals associated with the convective cloud. The changes may also be associated with a strong inhomogeneity of cloud effective radius in this type of cloud.
Figure 4.139: Cloud fraction difference between two cloud fraction apriori techniques, from clockwise 3x3km, 5x5km and 8x8km resolution.
Figure 4.140: Optical Depth difference (sub-pixel cloud fraction - averaged), 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.141: Effective radius difference 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.142: Cloud top pressure difference (sub-pixel cloud fraction - averaged) 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.143: Cloud fraction difference (sub-pixel cloud fraction - averaged), 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.144: Optical Depth difference 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging

**Difference between High and low resolution when averaging high resolution to low resolution cloud parameters**

Figures 4.148 to 4.151 and the corresponding histograms, figures 4.152 to 4.155 show the difference between retrieving at single pixel resolution and averaging to lower resolutions.

Significant differences i.e. those not pale green or yellow occur where the cloud and clear areas meet and at the edges of the high convective cloud and the surrounding lower cloud. There are no significant changes within the clouds. The standard deviation at very low resolutions could become significant.
Figure 4.145: Effective radius difference (sub-pixel cloud fraction - averaged), 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.146: Cloud top pressure difference (sub pixel cloud fraction - averaged) 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.147: Cloud fraction difference (sub-pixel cloud fraction - averaged), 3x3km, 5x5km and 8x8km, high to low resolution spatial averaging
Figure 4.148: Optical Depth difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.149: Effective radius difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.150: Cloud top pressure difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.151: Cloud fraction difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.152: Optical Depth difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.153: Effective radius difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.154: Cloud top pressure difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
Figure 4.155: Cloud fraction difference 1x1km - 3x3km, 1x1km - 5x5km and 1x1km - 8x8km, high to low resolution spatial averaging
4.4 Averaged cloud parameters

In this section the results are analyzed using all the data in the global sample.

4.4.1 Variation of cloud parameters within a super-pixel

The standard deviation of the cloud parameters was estimated by super pixelling the results from the highest resolution (1km) case and calculating the average variance for each super-pixel in turn.

![Graphs showing the relationship between resolution and standard deviation of optical depth, particle size, cloud top pressure, and cloud fraction](image)

Figure 4.156: Standard deviation of cloud parameters as a function of retrieval resolution for all cloud types
The standard deviation of all cloud parameters increases with lower spatial resolution see figure 4.156. The thickest clouds have the highest optical depth variances. The mid level cloud has the highest effective radius deviation this is an indicator of the increased likelihood of these clouds being mixed phase and the retrievals oscillating between ice and water phases and effective radius. The cloud top pressure standard deviation by comparison is relatively small compared to the absolute values of cloud top pressure. This indicates that the cloud top pressure is probably the least varying cloud parameter across a cloud scene. The fraction standard deviation, appears to show unusual behavior and is highest for the cumulus cloud cases at low resolution. However when you consider the scale the variance is quite low and there is a high uncertainty in the cloud fraction retrieval. The phase standard deviation, figure 4.158 is highest for alto cumulus and cumulus type clouds. The overall standard deviation of the phase rises rapidly to 10% at 8x8km resolution.

![ATSR-2 Resolution vs Stdev. optical depth](image1)

![ATSR-2 Resolution vs Stdev. particle size](image2)

![ATSR-2 Resolution vs Stdev. cloud top pressure](image3)

![ATSR-2 Resolution vs Stdev. cloud_fraction](image4)

Figure 4.157: Standard deviation of cloud parameters as a function of retrieval resolution for different cloud types

### 4.4.2 Fraction of clear scenes as a function of resolution

Figure 4.159 shows the fraction of cloudy pixels as a function of resolution for each of the three techniques investigated. Using a cloud fraction apriori of one there is very little variation as the resolution changes indicating an over estimate of cloudy scenes. The sub pixel technique
Figure 4.158: Standard deviation of Phase as a function of resolution

Figure 4.159: Fraction of cloudy scenes as a function of resolution for all cloud types and the full data set, top right cloud fraction apriori of one, to left cloud fraction apriori uses sub pixel information and bottom spatially averaged 1x1km data.
dects slightly more partially cloudy scenes. The spatial averaging more partially cloudy scenes although to some extent the difference between the two last graphs is a function of the cloud mask. This is basically telling you that as the super-pixel size increases it is more likely to contain a lower amount of cloud as it begins to encompass previously cloud free areas. For the correct retrieval of cloud properties in this scheme it is necessary to know this cloud fraction as accurately as possible. Although this is not always possible and more difficult as the super-pixel size increases.

**4.4.3 Averaged cloud properties**

The average cloud property is calculated by

\[
\text{average}(x) = \frac{\sum_{j=1}^{n_{\text{retrieved}}} x_j \cdot \text{cloud fraction}}{n_{\text{retrieved}} \cdot \text{cloud fraction}}
\]  

(4.1)

except for the cloud fraction which is calculated by

\[
\text{average}(x) = \frac{\sum_{j=1}^{n_{\text{retrieved}}} x_j}{n_{\text{retrieved}}}
\]  

(4.2)

in order to identify the trends more clearly. Where \( x \) is the cloud parameter e.g. cloud top pressure and \( n_{\text{retrieved}} \) is the number of cloudy scenes retrieved. The averaged cloud parameters are only calculated for super-pixels which are cloudy.

The results for each cloud parameter are documented in this section. The results shown in the first section are for the case when the sub-pixel information is used to calculate the cloud fraction a priori. Figure 4.160 shows the average cloud property as a function of cloud type and decreasing resolution. The average values for all clouds types are shown in figure 4.161.

The optical depth overall increases slightly as the resolution decreases, when this is broken down into cloud type, mid level clouds have constant optical depth. Thick convective cloud shows a slight increase and there is a corresponding decrease in the optical depth of thin cirrus.

Cloud top pressure is relatively constant for most cloud types except cumulus cloud which shows a slight increase in cloud top pressure as the resolution decreases, and convective clouds showing an increase.

The effective radius shows the most distinctive trends. As the resolution decreases the effective radius for predominantly ice clouds decreases as the resolution increases. This is slightly but not totally compensated for by an increase in effective radius for cumulus clouds. In the case study this was occurring at the edges between different cloud types.

The cloud fraction decreases as the resolution decreases as more clear pixels become included in the super-pixel. The decrease in the fraction of cirrus and convective cloud is more significant than other cloud types. This could be due to three reasons, one, the increased probability that these cloud types form on scales smaller than a super-pixel or two, these cloud types have an increased probability of overlapping lower cloud types such as cumulus within a super-pixel and hence become 'washed' out. The third reason is an issue of the technique rather than cloud formation. Validation of the optimal estimation technique with ATSR-2 have shown that ATSR-2 has reduced sensitivity to thin cirrus. This is because the weighting functions of the ATSR-2 channels dominate at the surface, hence very thin cirrus will be undetected by the algorithm.

Because of the nature of the retrieval in optimal estimation, i.e all cloud properties are retrieved simultaneously it is also likely that some of the effects on the cloud effective radius as a response to changing resolution is incorrect due to incorrect modeling of the ice cloud properties in the look up tables. Since modelling ice crystal properties is a hotly debated research topic this cannot be dismissed.
Figure 4.160: Averaged cloud parameters as a function of retrieval resolution
Figure 4.161: Averaged cloud parameters as a function of retrieval resolution for all cloud types
Phase should not change significantly with resolution, if it did this would indicate that clouds of different phase, ice or water were being mixed in a super-pixel. Mixed phase clouds could occur in a super-pixel, for example, in the case of high cirrus cloud partly overlapping lower water clouds. The average phase as a function of resolution for each cloud type and for all the clouds inclusive is shown in figure 4.162. Phase equal to one indicates water, phase equal to two is ice. There is no mixed phase cloud flag in the cloud retrieval algorithm but a phase between one and two will mean some pixels were ice and some were water. The average phase is approximately 1.4 indicating a predominance of water clouds. Satisfyingly high clouds such as cirrus and deep convective clouds are nearly always identified as being ice at 1x1km resolution. This is an indication that for ice clouds at 1x1km resolution there is very little cloud phase inhomogeneity. However as the resolution decreases the high ice clouds become mixed with lower water clouds. Cumulus clouds show the opposite behaviour. Suggesting that they are a cloud type which will often be in a mixed cloud type super-pixel with ice cloud.

![ATSR-2 Resolution vs Phase](image1)

![ATSR-2 Resolution vs Phase](image2)

Figure 4.162: Averaged phase as a function of retrieval resolution, First for different cloud types and secondly for all cloud types.

In theory decreasing the retrieval resolution should result in the cloud scene under investigation becoming more plane parallel like. The cost parameter from equation 2.1 gives an indication of how well the cloud being viewed fits the plane parallel assumption and should decrease with decreased resolution. The cost for the different cloud types and the overall cost is shown in figure 4.163. From the data set under investigation there is no clear indicator that the cost is decreasing. For most cloud type the cost is constant while for cirrus and to a lesser extent deep convective and cirrostratus clouds this value increases. Along with the information about phase. This information indicates that the ice clouds are mixing with other cloud types in a super-pixel.

### 4.4.4 Probability distribution functions

Figures 4.164 to 4.167 show the probability distribution functions for cloud when the fraction is calculated using sub-pixel information. The different retrieval resolutions are shown in different colours. There are not many different features evident when all cloud cases are considered together. The differences are more evident when the high clouds are considered separately see figures 4.168 to 4.171. While low cloud shows very little variation in cloud properties there are significant difference between the different retrieval resolution for high cloud.
Figure 4.163: Averaged cost as a function of retrieval resolution first for different cloud types and secondly for all cloud types
Figure 4.164: Probability distribution function optical depth
Figure 4.165: Probability distribution function effective radius
Figure 4.166: Probability distribution function cloud top pressure
Figure 4.167: Probability distribution function for high cloud and cloud fraction
Figure 4.168: Probability distribution function for high cloud and optical depth
Figure 4.169: Probability distribution function for high cloud and effective radius
Figure 4.170: Probability distribution function for high cloud and cloud top pressure
Figure 4.171: Probability distribution function for high cloud and cloud fraction
The optical depth shows an increase as the resolution decreases, at high resolution there is evidence that the retrieval is finding it more difficult to find a solution as the frequency of greater than 2.4 optical depth retrievals increases. This is most likely due to the presence of multi layer cloud. This is also reflected in the increase in effective radius retrievals that have an effective radius less than three. There is evidence from the cloud top pressure retrievals that the clouds are getting lower. The cloud fraction retrievals show a steady decrease in cloud fraction as the resolution decreases.

**Error on cloud parameters as a function of resolution**

Figures 4.172 and 4.173 show the error retrieving the different cloud parameters for different cloud types, when the fraction is calculated using sub-pixel information. The error calculated is outlined in equation 2.4. The largest optical depth errors are for the thick cloud types, only cirrus and cumulus clouds shows any appreciable increases as the resolution decreases. The errors on the effective radius are almost constant with resolution except for ice clouds which show marked increases. The cloud top pressure shows only slight changes with resolution as does cloud fraction.

Figure 4.172: Averaged retrieval error for each cloud parameters as a function of retrieval resolution for all cloud types
Figure 4.173: Averaged retrieval error for each cloud parameters as a function of retrieval resolution for all cloud types
4.4.5 Equivalent results for a cloud fraction apriori of one

All the following graphs are estimated using a cloud fraction apriori derived from the sub-pixel information.

![Fraction of cloud scenes vs resolution](image1)

**Figure 4.174:** Total number of Cloud retrievals

Figure 4.174 shows the total number of cloud retrievals as a function of resolution. Once again the cloud fraction is folded into this number. The total number of clouds retrieved increases slightly with resolution, and the is approximately 15% more cloud at 8x8km resolution, than in the previous example when cloud fraction was estimated using sub-pixel information. When the number is broken down into cloud types. The fraction of cumulus cloud increases. This could indicate a problem determining the cloud fraction of low lying broken clouds or mixed cloud types being designated cumulus cloud.

![ATSR-2 Resolution vs Cost](image2)

**Figure 4.175:** Cloud cost as a function of resolution

Figure 4.175 shows the cost is invariant for changing resolution.

The phase, figure 4.176 is also invariant as the resolution decreases. This is different to the previous case which had evidence of cloud types mixing.
Figure 4.176: Cloud phase as a function of resolution

Figure 4.177: Averaged cloud parameters as a function of retrieval resolution for all cloud types
Figure 4.178: Averaged cloud parameters as a function of retrieval resolution for all cloud types
Figure 4.177 and 4.178 show the cloud parameter retrievals as a function of resolution, the key differences from the previous technique is the relative invariance as the resolution decreases. The cloud fraction does not decrease at all. This is primarily because the retrieval algorithm is setup such that the cloud fraction does not have much freedom to move away from one. This technique will lead to an over estimation of cloud fraction which is reflected in the increased number of cloud retrievals than when using the previous cloud fraction technique. Few differences are apparent in 4.178. Overall the cloud optical depth decreases slightly as the resolution decreases. Similarly the clouds become slightly warmer/lower. The effective radius also shows a slight decrease. These changes are of the order of 5% or less.

**Error on cloud parameters as a function of resolution**

Figures 4.179 and 4.180 show the error on the cloud parameters as a function of resolution. The main differences from the previous technique is the smaller error on cirrus clouds for optical depth. The invariant effective radius error for ice clouds.

![ATSR-2 Resolution vs Error optical depth](image1)

![ATSR-2 Resolution vs Error particle size](image2)

![ATSR-2 Resolution vs Error top pressure](image3)

![ATSR-2 Resolution vs Error cloud fraction](image4)

Figure 4.179: Averaged retrieval error for each cloud parameters as a function of retrieval resolution for all cloud types
Figure 4.180: Averaged retrieval error for each cloud parameters as a function of retrieval resolution for all cloud types.
4.4.6 Spatially averaging high resolution images to produce low resolution products

The graphs in this section are produced by spatially averaging the retrievals made at 1x1km resolution. This technique produces some quite different results that are difficult to interpret. Figure 4.181 shows the cloud fraction as a function of resolution. The fraction of cloud is relatively constant as the cloud fraction is calculated using the 1x1km pixels.

![Graph of Fraction of Cloudy Scenes](image)

Figure 4.181: Cloud fraction as a function of resolution

Figures 4.182 and 4.183 show the variation in the cloud parameters as a function of resolution, nearly all the cloud parameters are constant with changing resolution, only nimbostratus cloud shows evidence of any variation and only in particle size. Cumulus cloud shows the smallest cloud fraction once again showing that is cloud often is part of broken cloud banks.

Figure 4.184 shows the cloud phase as a function of resolution the phase remains constant although mid level clouds so some slight variations. Figures 4.185 and 4.186 show the error increasing for all parameters as the resolution decreases.

4.5 Conclusion and Recommendations

The variance of cloud properties over different resolutions has been analyzed.

The standard deviation of the cloud parameters shows that on average cloud effective radius and optical depth have a much higher variance within a super-pixel (i.e. differences occur on much smaller spatial scale) than cloud top pressure or cloud fraction.

The proportion of totally clear pixels decreases as the resolution decreases.

The variation in retrieved cloud parameter was analysed over different resolutions using three techniques:

- Retrievals that assume a cloud fraction apriori of one for all resolutions.

- Retrievals that use sub-pixel information to assign cloud fraction.

- Cloud parameters derived from spatially averaging cloud parameters at the lowest resolutions.
Figure 4.182: Averaged cloud parameters as a function of retrieval resolution
Figure 4.183: Averaged cloud parameters as a function of retrieval resolution for all cloud types

Figure 4.184: Cloud phase as a function of resolution
Figure 4.185: Averaged cloud parameters as a function of retrieval resolution
Figure 4.186: Averaged cloud parameters as a function of retrieval resolution for all cloud types
From these three cases we can begin to discover some of the biases induced by retrieving cloud parameters at different resolutions. The main observations to come from this study are outlined below.

In a comparison of the first two methods estimating the cloud fraction incorrectly, i.e. assuming a scene is 100% cloudy will overestimate all the cloud parameters. Retrieving the scene with a cloud fraction almost one made very little difference to the average optical depth at each resolution hence an overestimation of the average cloud property of up to 15% is possible at high resolutions such as 8x8 km resolution. This is value is most likely underestimated due to deficiencies in the cloud masking technique used.

If the cloud fraction is well identified then as the resolution decreases the clouds that become the most variant are the high clouds, cirrus, deep convective clouds and cirrostratus. As the resolution decreases the fraction of these clouds in a super-pixel decreases dramatically. Other cloud types are more homogeneous. The cloud parameter this affects the most is the effective radius. While the effective radius for high clouds decreases the effective radius of low cumulus cloud increases indicating high and low clouds often overlap or accompany each other within a super-pixel. This effect is often accompanied by corresponding changes in cloud top pressure(lower ice clouds and higher cumulus) and lower optical depth. This phenomena is substantiated by the reduction of ‘pure ice’ high clouds as the resolution decreases, and an increase in the percentage of ice clouds in a box designated cumulus.

Overall different trends blur some of the individual cloud results and may not be linearly related, this is due to impart to the behaviour of the retrieval algorithm at different resolutions. There is evidence that as the resolution decreases the cloud scenes become more difficult to retrieve, this is indirect proof that the clouds within a scene are becoming more inhomogeneous and multi-layered.

Low lying cloud such as cumulus are difficult to retrieve as the resolution increases as the cloud fraction is often less than one, the clouds are close to the surface resulting in a poor contrast, and they often accompany other cloud types within a pixel.

Spatial averaging of high resolution results to lower resolutions does not introduce any positive or negative biases with respect to the highest resolution result. However, local difference can be quite high particularly at the edges of cloud banks and at the borders of different cloud types.

Finally here is still some uncertainty in the results due to the retrieval technique rather than the resolution effect. More statistics would go some way to relieving this confusion.

4.6 References


[8] RSG, Remote Sensing Group, Atmospheric Science Division, Rutherford Appleton Laboratory.