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Sky analysis from CCD images: cloud cover

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One of the tasks in sky modelling is the determination of the location and amount of cloud coverage in the sky. Analysis using digital camera systems is possible but requires an automated method of separating sky images into clear sky and cloud regions. Two segmentation approaches have been used in this research, one based purely upon the colour characteristics of sky regions, the other a neural network approach using a wider range of variables. A convolution technique was developed to reduce classification errors prior to defining cloud outlines using polylines. Sensitivity analysis shows that this can be carried out efficiently with little loss of accuracy.

1. Introduction

One of the basic tasks to be faced by daylight modellers and meteorologists concerns the determination of the location and amount of cloud coverage in the sky. This task of segmenting the sky into clear sky and cloud regions has largely been a matter of visual judgment with inevitable inaccuracies.[1] However, it can be approached in a number of more quantitative ways depending on the availability of measuring devices including satellites e.g., Smith *et al*.[2] Conventional photographic imaging has been used in the past, such as by Nakamura and Oki,[3] but was limited by the length of time required to analyse the images. Digitizing these images potentially speeds up this process and a number of studies, including this one, have been carried out on them. For example, Davis *et al*.[4] have shown that with a quite simple approach of working from coloured photographs a reasonable attempt can be made to isolate out the cloud patches in an image of the sky.

Direct digital imaging using cameras with a charge coupled device (CCD) has been proposed and used for both interior and exterior studies, e.g., Berrutto and Fontoynont.[5] The most sophisticated of these has, probably, been carried out by Shields *et al*.,[6] using a CCD camera, with neutral density (ND) filters to extend the dynamic range of the recorded images and red and blue filters to selectively record the image in these wavelengths. They use a cooled CCD system which allows images to be recorded in very low light levels, and probably during darkness. The resources involved in this project were not insignificant but lower cost systems, using conventional digital cameras, can be created to achieve many of the same results. Uetani *et al*.,[7] have shown the viability of this approach using images captured from a CCD video camera. Advances in digital camera technology, for example the Nikon E2 Series camera used in this study, mean that much higher resolution images can be captured and cloud coverage accurately assessed.

The digital image that this system generates is 1000×1280 pixels of 24 bits depth with the effective image being a circle about 1000 pixels in diameter which is an equiangular transformation of the sky dome onto the image plane of the CCD. At each pixel there are 256 levels of information

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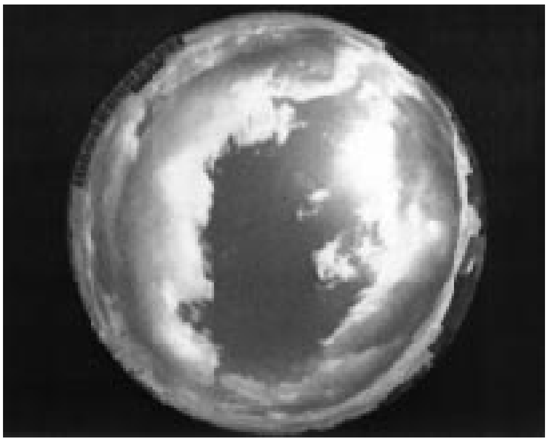


Figure 1 A typical digital image

for each of the red, green and blue (RGB) light levels producing a ‘realistic’ image as shown in Figure 1. The essential task is to be able to process this digital image and to describe the edges of the clouds that appear. Two approaches to this segmentation have been explored in this research along with a number of image refinement techniques.

2. Segmentation approaches

The colour temperature of the whole sky could be used as a measure[7] but the task of sky segmentation is essentially quite simple at face value in that anything that is ‘blue’ must be sky and the rest ‘cloud’, that is a method based upon the simple colour dimension of parts of the sky. Davis *et al.*,[4] based upon analysis of scanned sky images, have proposed that the segmentation can be effectively achieved from a partitioning of the Hue-Saturation-Value (HSV) colour space on the saturation dimension alone i.e., depth of blueness alone. They suggest that two thresholds on the saturation value can be used where a value above 54% would result in a ‘sky’ classification, below 47% ‘cloud’ and in between values ‘uncertain’. This approach is not clearly demonstrated in the data from our camera and it would appear that the Hue dimension is a better discriminator. This approach has been taken by Shields *et al.*[6] who have proposed that the segmentation is best achieved from colour difference, specifically the red/blue ratio based on the proposition that the light emanating from clouds has a larger red component than that for clear sky. In this system a value above some threshold results in cloud classifications while a value below is considered sky. When analysed in this manner, pixel by pixel, test images from the Nikon system showed good separation of sky and cloud, as shown in Figure 2. From this diagram it appears that a red/blue ratio of about 0.95 would segment this data set rather well with cloud above and sky below this line.

Given these indications two empirical segmentation filters were implemented:

- An HSV filter which does a primary partitioning on the basis of hue dimension i.e., blueness, where if it lies between 120 and 300, and has a saturation greater than 10, it is defined as ‘sky’ otherwise it is ‘cloud’.
- An RGB ratio filter which does a primary partitioning on the basis of red/blue ratio using the results from Figure 1 i.e., ratios less than 0.95 are ‘sky’ otherwise they are ‘cloud’.

In addition, if points were located where the sun and the solar corona were expected to be located, using the algorithm proposed by Roy *et al.*,[8] then

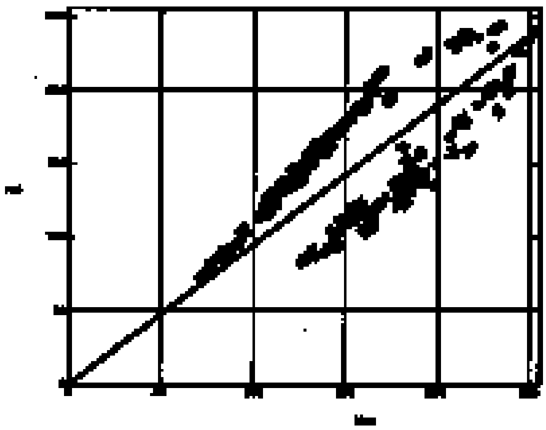


Figure 2 Plot of red versus blue dimensions of colour for sky and cloud pixels

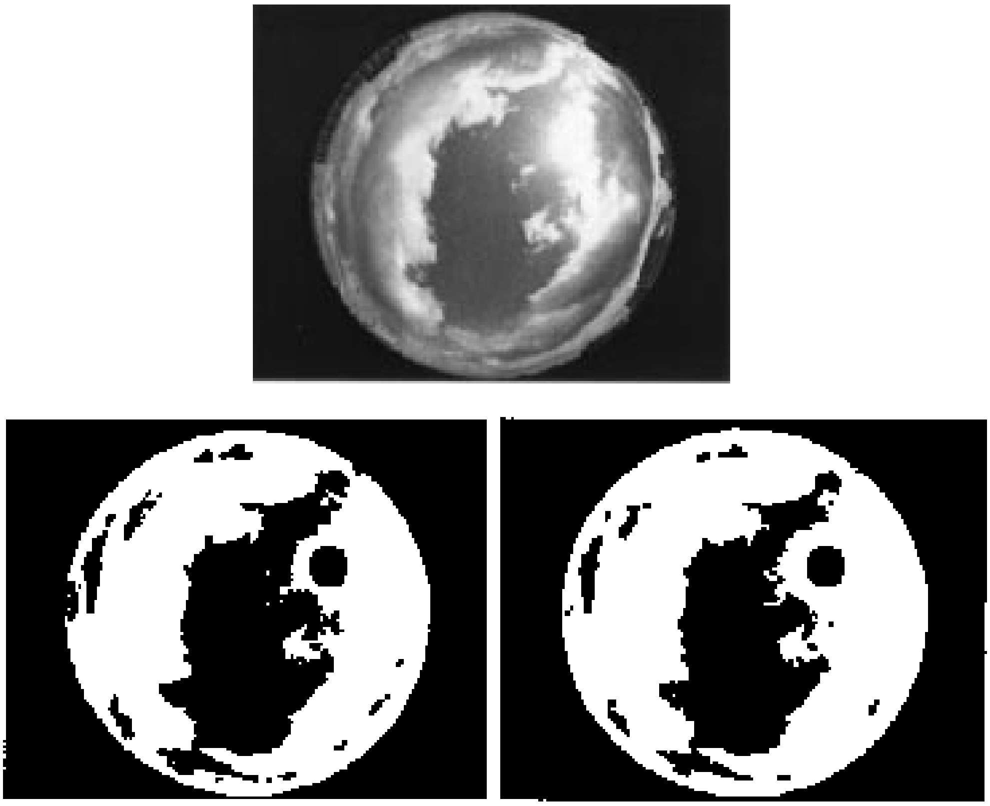


Figure 3 Comparison of colour segmentation algorithms

extra filters were included which assume that any high value pixels are likely to be the 'sun' if the pixel falls within a region where we expect to find the sun. For cloud cover estimation purposes, 'sun' is taken as 'sky' which introduces a small error when very bright clouds actually mask the sun.

From the sets of images acquired examples were chosen to cover the range of sky conditions, from clear skies through to fully overcast, with both 'thin' and 'dense' clouds, to assess the performance of the various algorithms. An example is shown in Figure 3 with regions of cloud shown in white and sky in black. From this analysis a number of initial observations were made:

1) Both the HSV and RGB ratio filters give very similar results.
2) The segmentation seems, in general, quite reasonable with clear sky and cloud regions being effectively segmented.
3) The presence of the sun, and its corona, does cause some problems. The black disk results when the algorithm detects that the high value pixels fall within a region where the sun is expected for that time of day . Where the sun is actually visible the sun is effectively masked, though parts of the corona are not.
4) With very bright, and thin, cloud coverage the algorithms conclude that the sun is visible.
5) Images with dense clouds result in good segmentations including those best described as partially cloudy.
6) Where the cloud is thin it is handled quite well but segmentation does becomes less effective for very thin clouds.

7) A number of image artefacts result from the penetration of direct sunlight into the lens system of the camera. These do not appear to generate significant errors in the computations but could be predicted and filtered, if absolutely necessary, from relative solar position and lens optics.

An alternate approach involves the application of Analogue Neural Networks (ANNs) which can be readily applied to pattern recognition tasks.[9] In this case the training task was quite simple using the RGB data for each pixel of the digital image, the exposure settings from the camera and, by human judgment, whether a pixel should be classified as cloud or sky. In addition, it was possible to include the presence of horizon obstructions in the image.

The ANN used was a conventional feed-forward back-propagation network consisting of four input nodes, a hidden layer of nodes and one output node. The input nodes corresponded to:

1) The red value of the pixel in the range 0–255, scaled to the range –1 to +1.
2) The green value of the pixel in the range 0–255, scaled to the range –1 to +1.
3) The blue value of the pixel in the range 0–255, scaled to the range –1 to +1.
4) The exposure value for the image defined as the ratio of Tf^{-2}, where T is the shutter speed (seconds) and f is the aperture setting (f-stop number) which is constant for a given amount of light entering the lens. Typically, for images in this work, the exposure value ranges from 2.7 to 11.1×10^{-6} [10] and was scaled to –1 to +1 where –1 represents a ratio of 0 and +1 a value of 20×10^{-6}.

The number of nodes in the hidden layer requires experimentation. A sufficient number of nodes is necessary to provide enough degrees of freedom for the solution searching process, but not too many to ‘over fit’ the network on the data provided for training. The number of nodes in the hidden layer required at least three but did not significantly improve as the number was increased to five or six. The output node value ranged from –1 to +1 and was used as the segmentation filter based upon the values shown in Table 1.

Table 1 Classification of the output node for the ANN

Output value	Interpretation
–1.0	Horizon obstruction
–0.25	Sky
+0.25	Cloud
+1.0	Sun

The data for the training and testing of the ANN was obtained by extracting representative sets of small sample patches from a number of images. From the collected data, the ANN was trained on half the data points, and then tested on the other half. Approximately the same number of sample points were made for each type of output response i.e., sun, sky, cloud and obstruction. Various data sets have been tried from small, with a few hundred points, to quite large, with many thousands of sample data points, with similar results. The solution converged quite quickly and the ANN was able to classify the data points reasonably accurately where a prediction error in excess of about 0.25 generates an incorrect classification in about 6% of cases. A typical result of the application of the resulting ANN filter to a sky image is shown in Figure 4.

Results are similar to those obtained with the other filters but there are some differences in individual images where the ANN model has not correctly classified some cloud regions. In Figure 4, for example, it has misclassified clouds at the edge of the bright cloud area but it has done a better job on the rather ‘thin’ cloud regions than the other two filters did. It has similar problems with the sun’s corona region, as well as classifying regions of bright cloud that fall in the region of the sun’s corona, but provides a formal segmentation of the horizon effects.

From the images analysed, all filter models appear to offer some potential. Both ANN and the two explicit colour space filters are based on the premise that the sky/cloud segmentation can be derived from the colour information from the

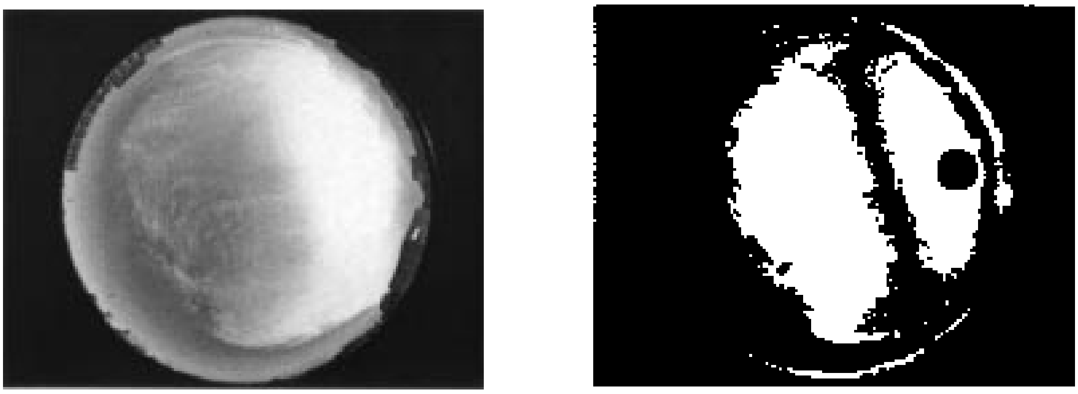


Figure 4 Performance of ANN segmentation algorithm

pixels in the digital image. Both use some additional information of the position of the sun to discriminate cloud from clear sky conditions where the sun is exposed to view. The empirical models are very simple and appear to give marginally better results overall, though this may not be the case in other situations (different CCDs, cameras and locations). In addition, they are more intuitive models appearing to rely upon 'real' information on how we discriminate clouds from sky. The ANN model, however, could improve with better approaches to selecting training and test data sets and additional data e.g., sky radiances.

3. Image correction

For all segmentation filters, but perhaps more so for the ANN model, the classification process produces local variations and regions of cloud and sky are often dotted by classification errors. Image correction is, therefore, necessary to assist in any subsequent cloud classification analysis and prevent the process from becoming unnecessarily complex due to large numbers of very small patches of cloud or sky.

To perform this tidying-up process a convolution mask is passed over the whole image which makes an assessment about each pixel of an image and determines if the classification of the pixel should remain or be changed. The convolution mask works on a voting principle where for any given pixel, if there are sufficient numbers of neighbouring pixels that have a common value (cloud or sky) then it is most probable that the selected pixel should also have the same value. It consists of a square of a fixed number of pixels which is placed over each pixel in the image and focused on the central pixel.

The mask size must be an odd number of pixels so that the centre pixel is defined for each position of the mask. If the mask is too small there is not a 'big' enough picture of the local conditions i.e., mix of cloud and sky pixels, and if too large the mask becomes ineffective as the decision rules become less well defined. In addition, the computational cost also increases with the square of the size of the mask. Experience has shown that a 5×5 mask works quite effectively on images of 500×500 pixel resolutions and for much lower resolutions (less than 100×100) a 3×3 mask may be better suited.

A decision making strategy is used by considering the voting pattern for each pixel being considered i.e., the pixel at the centre of the mask. For each position of the mask, a cloud pixel is counted as 1 and a sky pixel as 0 and the cell at the centre, of a 5×5 mask, can thus

Table 2 Classification of the output node for the ANN

Vote value	Decision
< = 7	Sky
> 7 & < = 16	No change
> 16	Cloud

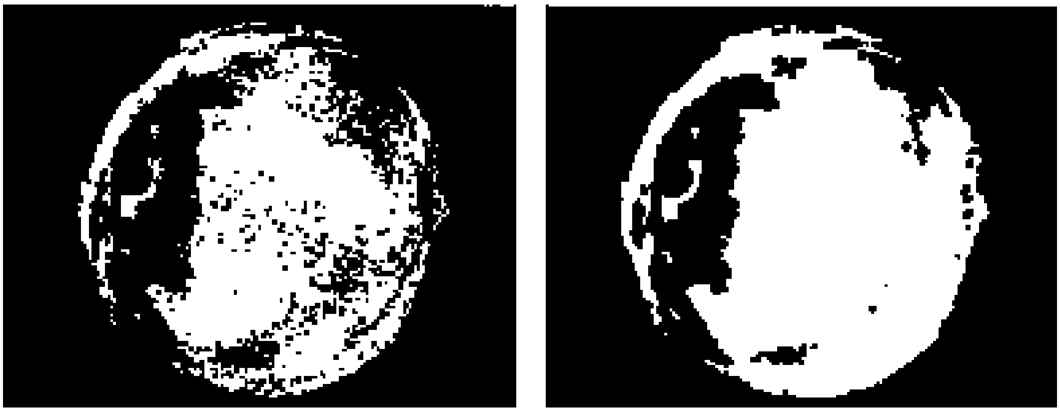
receive a vote somewhere between 0 and 25. If the vote is 25 then the cell is, and remains, a cloud type; if the vote is 0 then cell is, and remains, a sky type. Decision rules are needed to assess the status of intermediate points.

If the voting level decision points are not well chosen, the convolution process may have the effect of moving cloud edges and, perhaps, increasing or decreasing the size of the cloud patches. Based upon experimentation, by repeatedly applying the mask and assessing distortion in real images, decision rules for intermediate possibilities were found, as shown in Table 2. The mask always operates on the existing image and a new image is created to contain the modified pixel values.

A typical result for complete digital images is shown in Figure 5 which shows the raw segmented image and then the image after the convolution mask has been processed across the image. This appears to generate the desired effect with many of the small clusters of pixels eliminated and the cloud edges better defined (compare with original image in Figure 4).

For meteorological studies, an ideal situation is where the full sky dome can be seen, as nearly as possible, from horizon to horizon. For example, the images shown were taken from the roof of the School of Architecture, University of Sydney and horizon obstructions account for only about 3% of the images. Apart from very special locations this is unlikely to be the case and if a study is focussing on the daylighting conditions for a particular façade of a particular building in a particular location then horizon effects are very important. In this case the impact of vegetation, buildings, etc needs to be represented as accurately as possible, including all luminance properties. Consequently, an assumption is needed on how to handle this effect, either removing horizon effects from the analysis or assuming, possibly ‘intelligently’, cloud or clear sky behind the obstructions.

Any decision on this issue will be context based e.g., the scale of the possible errors introduced by the horizon effects. However, for automated analysis the horizon extent needs to be identified. Given that the colour of the horizon obstructions could be anything, colour segmentation schemes may not lead to useful results but,



After Segmentation　　After Convolution

Figure 5 Image correction steps

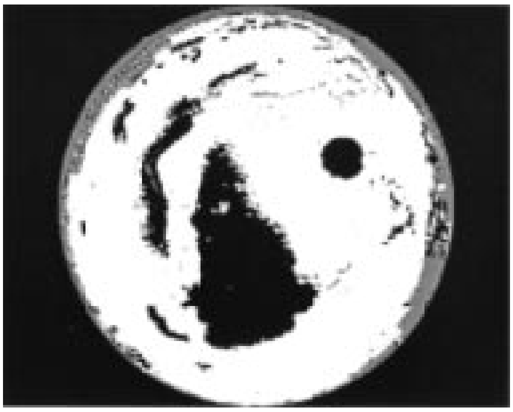


Figure 6 Segmentation showing horizon obstructions from ANN

as indicated above, the ANN model does a reasonable job at identifying the obstructions as shown in Figure 6 where pixels classified as horizon obstructions are grey. Results, however, vary considerably with lighting conditions such as bright sunlight versus dull overcast, etc.

A pragmatic solution for the problem, on the basis that for a given location the position horizon effects do not change at least in the medium term, is to construct an horizon mask from a, visually validated, segmented image such as Figure 6. The use of the 'paint' type application to create this mask enables corrections to the automatically generated image and to clean up the image where the ANN segmentation has failed to correctly discriminate the obstructions. Once constructed the same mask can be applied to all images captured at a location (at least until there is some change in the horizon obstructions). It is normally loaded into the analysis sequence after completing the convolution process and prior to any cloud area calculations.

4. Cloud outlining

Once a 'clean' image has been created it is then possible to undertake further analysis to provide a concise way of describing where the clouds are and to compute the cloud coverage over the whole sky on designated regions of the sky dome. Drawing upon the Standard Data Format (SDF) technique,[11] clouds are represented by sets of polylines describing the outer edge of each cloud patch as a set of vectors across the sky dome. This offers an efficient way of describing the complex boundary conditions, including clouds with 'sky holes'. The same geometric representation can also be used to compute the areas of the cloud patches, and thus the total cloud coverage.

In summary, the cloud outlining algorithm proceeds as follows:

```
Mark the outer boundary of the image with
sky pixels.
For each pixel in image:
   If the pixel is at a cloud/sky edge
      Mark pixel (e.g. change colour to red)
      Move to next edge pixel and mark it
      as an edge pixel
      Add pixel to edge list
   Until back at starting pixel
   Mark all cloud pixels inside edge as
   processed (by a flood fill)
      Until all pixels are processed.
```

Figure 7 shows this algorithm in process where the outer edges of the image are marked as sky pixels. The first edge (processing the image from the top left, across then down) has been found and flood filled. The next edge has also been found and the cloud pixels to be filled. Finally the hole in the cloud has to be found and then marked. Once all the pixels are marked all the cloud edges have been found.

Even with a relatively clean image a quite complex edge description results containing several hundred (if not thousand) edge segments, where many edge segments will be just one, or two, pixels long. While this might be considered thorough it is most likely quite unnecessary in terms of the accuracy of the image, the segmentation process and provides edge polyline definitions with far too much detail. The next step simplifies, or smooths, the edges to some acceptable level via a vertex dropping technique.[12]

The decision to drop a vertex will depend on the area of the polygon shape to be cut off by the

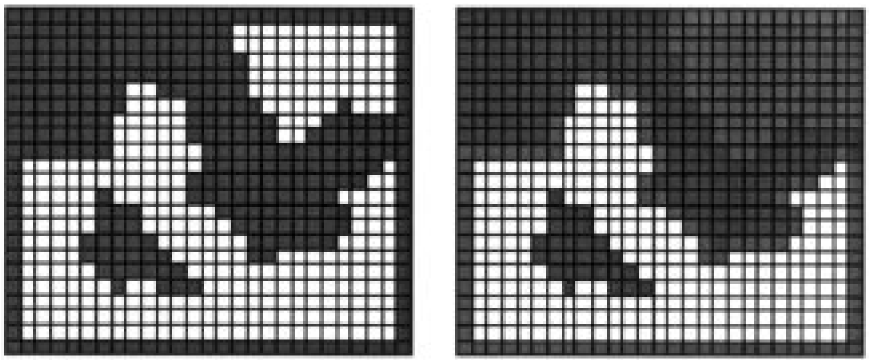


Figure 7 Marking the cloud edges

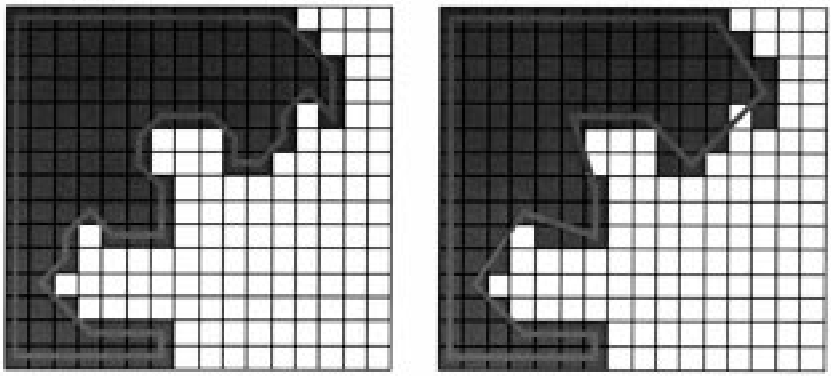


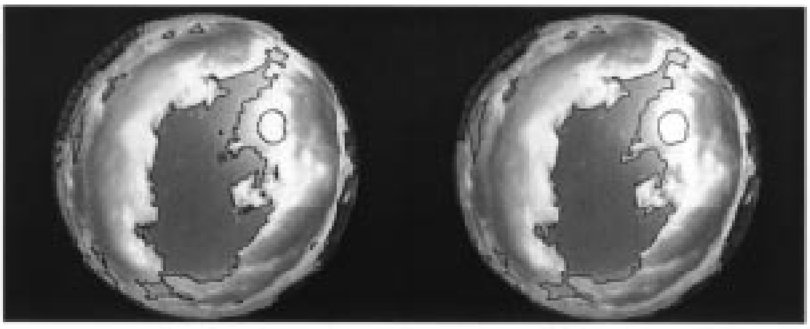
Figure 8 Smoothing the edge polyline

approximation. The number of pixels in each triangular shape is computed at each step, and using a (variable) pruning factor the level of reasonable approximation is controlled for each application. An example is shown in Figure 8 where the first image shows the type of edge generated from the above process, whilst the second image shows a reasonable approximation with many fewer edge segments and little loss of detail.

A further form of simplification concerns the presence of degenerate polygons, such as polygons with two sides, which can be eliminated. In addition, it is possible to consider eliminating polygons with three or four sides given their extremely small size as they are likely to be artefacts of the image analysis process. From experience, a degenerate limit of four, has proved satisfactory.

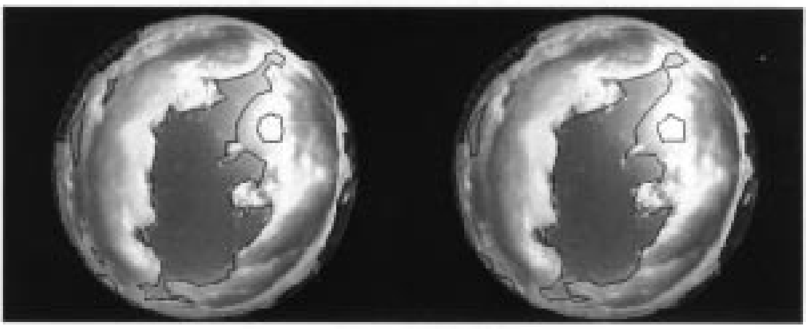
Once the outlines of the clouds are known we can compute the area of each polygon shape (on the sky dome) using the functions from the SDF[11] modelling package, see Roy *et al.*[13] Summing these for each cloud patch gives the estimated total cloud coverage.

To demonstrate the operation of the above algorithm and various values for the pruning factor a typical analysis is shown in Figure 9 with the cloud outlined. The first case has a pruning factor set to 0 i.e., no pruning is done, producing very detailed edge definition with a large number (1576) of edges and 27 different polygons being found. The second case shows what happens when the pruning factor is set at



Pruning factor = 0
Degenerate limit = 4
Number of polygons = 27
Number of edges = 1576
Cloud coverage = 65%

Pruning factor = 50
Degenerate limit = 4
Number of polygons = 8
Number of edges = 356
Cloud coverage = 66%



Pruning factor = 200
Degenerate limit = 4
Number of polygons = 6
Number of edges = 176
Cloud coverage = 66%

Pruning factor = 400
Degenerate limit = 4
Number of polygons = 4
Number of edges = 117
Cloud coverage = 67%

Figure 9 Example of cloud edge analysis for varying pruning factors

50 i.e., the maximum area of polygon pruned is five square pixels in area. The number of edges is less (356) and most of the very small polygon shapes have been removed. The other cases show results for pruning factors of 200 and 400, respectively. At a pruning level of 400 some obvious approximations appear but this still may be acceptable, depending on what accuracy of results is required. In fact, if cloud coverage estimation is the only criterion then a pruning factor of 400 would probably be satisfactory.

5. Conclusion

The hardware (Nikon E2 based) and software system, using fairly simple algorithms based upon simple colour information (HSV or RGB) alone to separate cloud from sky, provides the potential for 'real time' automated cloud coverage assessment over a wide range of sky conditions. The process of segmentation, convolution and cloud outlining takes approximately one minute on a relatively modest (180 MHz) computer. Other steps in the image process, described elsewhere[10] mean that the overall time is of the order of 2 min. This is perfectly satisfactory for many daylight applications such as the requirements of the International Daylight Measurement Programme and is more than adequate for meteorological usage since cloud cover is generally measured at several hour intervals. (In fact, it could encourage the collection of such data at more frequent intervals.)

There are, however, a number of factors that should be addressed before the method can be generalized to any CCD based system or situation:

1) *Overall response of camera-lens systems*
   The experimental work was carried out using one specific model of digital camera, Nikon E2, and lens, Nikkor 8mm *f* – 2.8, without comparison with the performance of other camera-lens systems. (A number of other, lower cost, options have become available since the original work in this paper was carried out. For example, the Nikon D1 camera, released in late 1999, offers the same features as the E series at a lower price and the Nikon Coolpix 990. The latter is a non-professional style digital camera and supports a full-field adaptor lens, FC-E8, that appears to have the same geometry as the Nikkor lens.) In addition, any system characterized must include all components that might affect the transmission of light e.g., ultra-violet filters and transparent weather proof housings as serious errors in measurement of available light can occur.[14]
2) *Any losses, distortions which may occur in getting the image from camera to computer*
   The images from the camera are compressed using a JPEG (Joint Photographics Expert Group) algorithm after exposure which may produce some errors though they are not likely to be significant.
3) *The exposure setting on the camera (shutter speed and aperture)*
   For the sequence of images, used for calibration and testing, the exposure setting varies (by the camera's automatic exposure algorithm). If it is assumed that this adjustment process has been optimized to use the effective dynamic response range of the CCD then it is possible to argue that the changing exposure settings may tend to cancel out the potential variations in light quanta actually reaching the CCD so that the colour rendition is retained. For example, if the camera had no exposure adjustments then high levels of light falling on the CCD will quickly exceed its response range and the recorded saturation values will fall as the CCD saturates.
4) *The dynamic range of the CCD is limited*
   It is to be expected that digital images have a limited dynamic range. From the camera calibration described elsewhere[15] it was observed that the CCD is limited to a dynamic range of about 25 000 cdm^{-2}. It is possible to extend the dynamic range with the use of multiple images with different exposure settings which is the subject of current research. For the purposes of sky segmentation, however, it is probably not necessary though it may improve the results of the algorithm in some circumstances e.g., in the case of considerable numbers of close-to-white clouds, or a very large and bright circumsolar region.
5) *Sky samples used were under 'normal' daylight conditions*
   Images were not taken at night or close to dawn and sunset to eliminate the need to consider colour change effects. Furthermore, other conditions that could seriously affect the presence or colour characteristics of a sky, such as fog, heavy pollution from particulate matter and other chemical components, such as nitrous oxides, have not yet been studied. However, for the wide range of skies used in this study, from low turbidity clear to fully overcast, the system appears to work remarkably well.

Acknowledgement

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Discussion

Comment on 'Sky analysis from CCD images: cloud cover' by G Roy, S Hayman and W Julian

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The paper presents an interesting approach to how cloud cover determination might be made less subjective than the visual observation methods used by meteorologists. It has the potential to give indications of cloud cover by, say, quadrant and time of day. For example, in some locales, cloud cover can build up during the day in a particular direction (for example, around mountains). There is great potential for the technique to assist in automated cloud cover assessment but it would need the support of the World Meteorological Organisation to produce a standard method.

What would have been a useful addition to the paper might have been the inclusion of a meteorologist's assessment of the cloud cover, say, for the discussion of Figure 9 which shows a typical analysis with the cloud outlined and where a difference between 65, 66 and 67% is negligible between pruning factors. However this should agree with a traditional assessment of, presumably, 5 octas. Similarly, with the thin cloud shown in Figure 4, (using analogue neural networks (ANNs)), where blue sky is 'visible'. What would be the meteorological assessment and would a large number of meteorologists agree?