A comparison of satellite-retrieved parameters with mesoscale model analyses

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SUMMARY

A scheme to retrieve quantitative products from radiances recorded by the AVHRR (Advanced Very High Resolution Radiometer) on NOAA satellites over the same area as the Meteorological Office mesoscale model is outlined. Satellite products and model fields are both averaged over fifth of a degree latitude/longitude grid squares. Results for one satellite overpass over the British Isles on 21 June 1986 are described in detail. Fields of surface temperature over land and sea, fractional cloud cover and cloud top temperature retrieved from the AVHRR data are compared with the corresponding model-analysed fields nearest in time to the satellite overpass. The AVHRR and model sea surface temperatures are in reasonable agreement (≈0.7 K), although the satellite data provide the more detailed field. The satellite land surface brightness temperatures could not be easily compared with the model ground temperatures as the former are radiative skin temperatures whereas the latter are related to screen temperatures and near-surface lapse rates. Differences of up to 10 K are noted in clear sky situations. The satellite and model fractional cloud cover fields are in reasonable agreement though the satellite fields did highlight one or two areas where the model analysis is in error. This is mainly in areas devoid of conventional observations. Fields of satellite cloud top temperatures show more detail and are more realistic than the corresponding model fields. This is not surprising as cloud top temperatures cannot be easily inferred from the surface observations analysed by the model. Satellite products, such as the ones described here, could in the future be used operationally to improve mesoscale or regional model analyses.

1. INTRODUCTION

In recent years there have been a number of mesoscale forecast models developed with a grid point spacing between 15 and 40 km (e.g. Golding 1984; Imbard et al. 1987). Conventional surface observations used to define the initial state of the atmosphere are not normally made at such a high spatial resolution, even over well populated areas such as the British Isles. Therefore independent surface observations will not be available at all of the model grid points. One potential solution to this lack of conventional data is to make use of high resolution satellite data either from NOAA polar orbiters (i.e. currently NOAs 10 or 11) or from geostationary satellites (i.e. METEOSAT for Europe and Africa) which make radiance measurements over the area covered by the European mesoscale models.

The current utilization of satellite data in numerical weather prediction (NWP) models is poor. This is partly due to errors of the satellite product being unacceptably large and partly due to satellite data being a different kind to that conventionally used by NWP models. Cloud motion vectors, vertical temperature profiles and sea surface temperatures are the primary satellite parameters currently being used for NWP (Isaac et al. 1986). For example, a range of quality-controlled METEOSAT products are derived at the MIEC (Meteosat Information Extraction Centre) in Darmstadt for dissemination to forecasting centres over the global telecommunication network (MEP 1987). The MIEC cloud motion vectors and sea surface temperatures are both used operationally in European NWP models. Sea surface temperatures averaged over 2.5°×2.5° latitude/longitude squares are derived by NOAA/NESDIS in Washington from the Advanced Very High Resolution Radiometer data (AVHRR/2) as described by McClain et al.

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They are disseminated for use by NWP models. The NOAA temperature sounder data are also processed to give vertical atmospheric temperature profiles for use by NWP models, both globally at NOAA/NESDIS, and locally for higher resolution soundings (e.g. Turner et al. 1985). In the future it is likely that sounder radiances will be used directly in new multivariate analysis schemes (Eyre and Lorenc 1989). The spatial resolution of these data, however, are more suited to regional or global NWP models than to mesoscale models. As the grid lengths of models become smaller the high resolution satellite data become potentially more valuable to improve the model analyses (Austin 1987). There is also a variety of other satellite parameters not described above which could provide additional useful information.

The aim of this paper is to show how quantitative parameters retrieved from AVHRR/2 data might improve the initial analysis for NWP models. The parameters described here are intended primarily for the mesoscale model being developed at the Meteorological Office (Golding 1987a). The AVHRR/2 has a nominal resolution of 1·1 km at the sub-satellite point increasing to over 3 km in the across-track direction at the edge of the pass. For model grid points with a spacing of 15 km, AVHRR/2 can provide about 185 independent radiances measurements, close to the sub-satellite track, for each grid point at five different wavelengths. For the nominal two polar orbiter system, measurements can be made four times a day with overpass times for the British Isles around 03, 08, 14 and 19 GMT though these times can vary by up to ±50 minutes. Measurements from the European geostationary satellite METEOSAT are also valuable as, for a given area, a measurement is made once every half hour. This enables measurements to be analysed every three hours close to the model analysis times. The field of view for the METEOSAT radiometer gives a resolution of approximately 5·5×10 km² at 52°N 0°E which provides about four independent radiances measurements for each mesoscale model grid point at three wavelengths.

This study has concentrated on using AVHRR/2 data to provide parameters for assimilation into the model analysis in preference to METEOSAT data for the following reasons. The AVHRR has been on board every NOAA operational satellite since 1979. Future satellites are planned until at least the mid 1990s (with a slightly improved AVHRR). After this a derivative of AVHRR called AMRR (Advanced Medium Resolution Imaging Radiometer) is planned for the proposed polar platforms and so this type of instrument should provide an uninterrupted flow of data for many years. The major advantage of AVHRR/2 data over METEOSAT data is the higher spatial resolution, allowing many more measurements to be made per model grid square. Over partly cloudy areas the smaller AVHRR fields of view (referred to as pixels in the image) allow accurate surface measurements to be made through small (~1·5 km) gaps in the clouds, whereas for the METEOSAT data the gaps would have to be much bigger (~10 km) to obtain accurate surface parameters from the satellite data. This factor becomes important over persistently cloudy areas such as north-western Europe. Also the smaller pixel size means that a more detailed structure in cloud tops can be observed, resulting in more accurate cloud parameters. Another advantage is that whereas METEOSAT has only three spectral channels (VIS: 0·4–1·1 μm; IR: 10·5–12·0 μm; and WV: 5·8–7·3 μm) the AVHRR/2 has five spectral channels as described below. These additional channels allow a more accurate correction to be made for atmospheric absorption and scattering effects, resulting in better estimates of surface parameters. They also enable low cloud at night and thin cirrus to be more effectively detected. Finally the AVHRR infrared channels have a low noise-equivalent temperature and are well calibrated, ensuring that measured radiative temperatures have an uncertainty of less than 0·2 K (Lauritson et al. 1979).
Although these advantages currently suggest the use of AVHRR data in preference to METEOSAT data for obtaining the most accurate surface and cloud parameters it should be noted that the second generation METEOSAT due for launch in the mid 1990s will have many of the advantages of the AVHRR outlined above. In addition, the advantage of having data closer to the analysis times suggests that ultimately the scheme described here should be applied to second generation METEOSAT data. For parameters which can vary rapidly with time (e.g. fractional cloud cover, cloud top temperature) the advantages of timely METEOSAT-retrieved parameters which are more representative of the conditions at the analysis time are still valuable despite their greater uncertainties.

The retrieval scheme outlined below, to extract surface and cloud parameters from AVHRR/2 data, has been applied to many passes both day and night and for all seasons. Results for one day are described in detail and compared with the corresponding mesoscale analysed fields derived from conventional surface and upper air observations and a forecast field from the previous analysis. Problems in both the satellite and model analyses are emphasized. Validation of the satellite parameters is also discussed with some comparisons of surface observations and the corresponding parameters retrieved from the AVHRR/2 data.

2. Description of retrieval scheme

The technical details of the retrieval scheme have been described elsewhere and the interested reader is referred to references given below. However, a short description of the main elements of the retrieval scheme, outlined in Fig. 1, is given to give the reader some idea of the methods used for retrieving the satellite parameters.

(a) Preprocessing AVHRR data

AVHRR/2 data are received from the NOAA spacecraft as part of the High Resolution Picture Transmission (HRPT) data stream. HRPT data can be received whenever the satellite is above the local horizon of a receiving station. For stations in

```
Extract AVHRR data from HRPT frame

\downarrow

Compute location of pixels

\downarrow

Compute infrared brightness temperatures and visible reflectances

\downarrow

Identify cloud-free, cloud-filled and partly cloudy pixels

\downarrow

Remap image data on to model grid

\downarrow

Compute mesoscale surface and cloud parameters from AVHRR data
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Figure 1. A schematic flow diagram showing the necessary processing steps required to retrieve quantitative mesoscale parameters from raw HRPT data.
Britain this gives an approximate area of coverage of 30°N–70°N, 40°W–40°E which more than covers the present mesoscale model area, shown in Fig. 2.

AVHRR data extracted from the HRPT data stream consist of radiometer counts in four or five spectral bands of the earth and space views, and calibration information (i.e. black-body temperatures and radiances) for the three infrared channels. The spectral bands in which the AVHRR measures radiances are in the following wavelength ranges: 0.58–0.68 μm, 0.72–1.10 μm, 3.52–3.93 μm, 10.3–11.3 μm and 11.5–12.5 μm (the last band only for the AVHRR/2 on NOAA 7, 9 and 11) hereafter referred to as channels 1 to 5 respectively. More details of the AVHRR instrument and data characteristics can be found in Schwalb (1978) and Kidwell (1985). For this study, for which data were not processed in real time, the HRPT data were obtained on tapes from either the Lasham receiving station in Hampshire, southern England, or the University of Dundee receiving station in Scotland. The data are processed using the APOLLO software (Saunders and Pescod 1988) developed in the Meteorological Office. Figure 1 outlines the basic processing steps which are applied to the data to derive quantitative parameters. All five channels are used, channels 1, 2, 4 and 5 (when available) during the day and channels 3, 4 and 5 at night. The basic preprocessing steps are reading the raw data from tape, calibrating the data by conversion of raw instrument counts into physical quantities and earth location of the data to an accuracy of better than 2 km.

For channels 1 and 2 the calibration consists of converting the instrument counts to top-of-the-atmosphere (TOA) bidirectional reflectance using the method described by Rao (1987) and the coefficients supplied in the appendices of Lauritson et al. (1979). For the infrared channels (i.e. 3, 4 and 5) counts are converted to brightness temperatures (equivalent black-body temperatures integrated over the channel response function) using the procedure recommended by Brown et al. (1985) with the coefficients taken from the appendices of Lauritson et al. The correct application of the nonlinearity correction factor is a key factor in getting accurate infrared brightness temperatures over a wide range of values (i.e. 200–320 K).
The images are then 'navigated' (i.e. pixel positions in the image are assigned a latitude/longitude) by computing the position of the spacecraft above the earth from a Brouwer–Lyddane orbital model developed by NOAA/NESDIS. This model requires orbital elements which are updated daily. They are received as part of the TBUS part IV message over the global communications system. Once the position of the spacecraft is known, the scanning geometry of the AVHRR allows the location of any pixel along a scan line to be computed. Errors in the orbital elements, the satellite clock time and the orbital model can lead to errors in the satellite position of tens of kilometres (Nagle 1986). To correct for these errors a coastline computed from the calculated pixel locations is overlaid on to the image on an interactive display and then shifted to match the actual coastline in the image. Normally the errors are <20 km in the along-track direction and <5 km in the across-track direction. The corrected pixel locations which are then computed are accurate to <2 km (along and across track) and allow the image to be remapped as described below.

(b) Cloud analysis and remapping

The next step is to perform a series of tests to each pixel to ascertain whether it is cloud free, partially cloud covered or completely cloud covered (i.e. cloud filled). The cloud-free pixels are used to determine surface parameters (e.g. surface albedo over land and surface temperature over land and sea). Cloud-filled pixels are used to determine cloud top parameters (e.g. cloud top temperature). At the present time the partially cloudy pixels are only used to determine fractional cloud cover. The details of this cloud analysis scheme are described in Saunders (1986) and Saunders and Kriebel (1988). It requires channels 1, 2, 4 and 5 during the day and channels 3, 4 and 5 at night and consists of five tests applied to each pixel to test for cloud-contaminated radiances and cloud-filled radiances. These tests vary with underlying surface type (sea, land or coast) and with time of day (day, night or dawn/dusk). They are most accurate over the sea, and during daylight (i.e. solar zenith angle <80°) and least accurate over coastal areas especially during dawn or dusk (i.e. solar zenith angle >80° and <95°). Over the British Isles typically 20% of the pixels in a pass are assigned cloud free, 20% cloud filled and 60% partly cloudy.

Up to this point in the processing the pixels are stored along a scan line as viewed by the AVHRR. The preprocessing steps are simplified if the data are kept in this format because calibration and time information are conveniently related to each scan line. The products, however, are required on a projection suitable for assimilation into a model analysis. The mesoscale model is on a transverse Mercator projection with grid points approximately 15 km apart and ultimately it is planned to remap the satellite data into the same projection. For this study however, to retain flexibility, the satellite data are remapped into a latitude–longitude projection so that each record contains data from a grid square 1/5°×1/5° latitude/longitude. All the radiances and associated cloud flags are remapped into these 1/5° lat./long. arrays.

(c) Retrieval of surface parameters

The surface parameters presently derived and listed in Table 1 are sea surface temperature (s.s.t.), land surface temperatures (l.s.t.), and surface albedo over the land. These surface parameters are derived only from pixels identified as cloud free. The method developed by Llewellyn-Jones et al. (1984) is used to determine s.s.t. from the calibrated AVHRR channels 4 and 5 brightness temperatures. Only the so called 'split window' algorithm is used, owing to persistent noise in channel 3:

\[ T_s = a_0(a) + a_1(a)T_4 + a_2(a)T_5 \]
TABLE 1. SURFACE AND CLOUD PARAMETERS RETRIEVED FROM THE AVHRR DATA FOR THE MESOSCALE ANALYSIS AND THEIR REQUIRED ACCURACIES AND RESOLUTION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required accuracy</th>
<th>Spatial resolution lat./long.</th>
<th>Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l.s.t.</td>
<td>±2 deg C</td>
<td>0.2°</td>
<td>Every pass</td>
</tr>
<tr>
<td>s.s.t.</td>
<td>±1 deg C</td>
<td>0.2°</td>
<td>Every pass</td>
</tr>
<tr>
<td>Reflectance</td>
<td>±5%</td>
<td>0.2°</td>
<td>Monthly</td>
</tr>
<tr>
<td>Clouds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fractional cover</td>
<td>±10%</td>
<td>0.2°</td>
<td>Every pass</td>
</tr>
<tr>
<td>Top temp.</td>
<td>±3 K</td>
<td>0.2°</td>
<td>Every pass</td>
</tr>
<tr>
<td>Liquid water</td>
<td>±1 K (low cloud)</td>
<td>0.2°</td>
<td>Every pass</td>
</tr>
<tr>
<td></td>
<td>±20%</td>
<td>0.2°</td>
<td>Every pass</td>
</tr>
</tbody>
</table>

where \( T_4 \) and \( T_5 \) are the AVHRR channels 4 and 5 brightness temperatures in K and \( T_s \) is the retrieved s.s.t. in K. In this case the coefficients, \( a_n \), are varied with satellite zenith angle \( \alpha = \sec(\theta) \) and with different types of air mass (e.g. mid-latitude, polar or tropical). They were taken from the North Atlantic set in Table 2 of Llewellyn-Jones et al. as representative of conditions around the British Isles.

Currently the same algorithm and set of coefficients are used to derive the surface temperature over the land. There are a number of sources of error in this approach. Firstly, the surface emissivity over land is no longer uniform and close to one for some surfaces. A change in emissivity of 0.01 results in a change in retrieved l.s.t. of about 0.5 K. Secondly, the coefficients \( a_n \) used were for maritime conditions and it would be expected that they should be different over land due to the different structure and greater variability in the atmospheric boundary layer. The root-mean-square deviation due to atmospheric variability over land is estimated to be about 1 K, reducing to 0.6 K over the sea (Llewellyn-Jones et al. 1984). The height of the land surface above sea level also becomes important as the higher the surface the less water vapour there is in the path and hence a lower atmospheric correction is required. Over the British Isles the latter two sources of error would not be expected to be large as the air masses are normally maritime and there are only a few areas where the mean surface (averaged over 1.2 km²) is significantly above the boundary layer where most of the atmospheric absorption/emission occurs. The errors introduced by assuming the same emissivity over land as over the sea may sometimes amount to a few kelvin. Work is currently underway to develop an improved temperature retrieval algorithm over land.

The other surface parameter which is retrieved is the albedo of the land surface integrated over all wavelengths. However, as the mesoscale model currently assumes a constant albedo of 18% over land, comparisons between satellite and model values are not meaningful. A dataset of surface albedos for each grid square of the model over land for eight cloud-free passes during the summer months has been derived from the AVHRR data. A description of the procedure employed to compute surface albedo and a discussion of the results are given in Saunders (1988b). In the future it is hoped to use this albedo dataset in the radiation scheme of the model. An extension of this method would be to retrieve snow cover, another potentially valuable parameter for the model.

(d) Retrieval of cloud parameters

The cloud parameters retrieved are listed in Table 1. For the comparison with model cloud parameters only fractional cloud cover and cloud top temperature are considered here.
The effective fractional cloud cover $N$ (the product of actual cloud cover and cloud top emissivity) is computed for each pixel by using the relation

$$N = \frac{(I_s - I_m)}{(I_s - I_c)} \quad (2)$$

where $I_s$ is the clear sky radiance computed from the mean of all the cloud-free pixels in the grid square, $I_c$ is the mean cloud top radiance computed from the cloud-filled pixels in the grid square and $I_m$ is the measured radiance of each pixel. Channel 4 radiances are used since they are available both day and night and are unaffected by shadows. The fractional cloud cover for each pixel is then averaged over the grid square to give a mean cloud cover for that grid point. A more detailed discussion of the retrieval of fractional cloud cover from AVHRR data is given in Saunders and Kriebel (1988).

Cloud top temperature is only computed from the pixels identified as cloud filled and optically thick by the cloud analysis scheme. For optically thick cloud and neglecting scattering effects we have

$$I_{11} = \tau_{0c}^{11}(\psi, \theta)B(T_c) + \int_{h_c}^{H} B(T(h)) \frac{\partial \tau_{h}^{11}(\psi, \theta)}{\partial h} dh \quad (3)$$

where $I_{11}$ is the measured channel 4 radiance, $B(T)$ is the Planck function integrated over the channel 4 filter response, $T_c$ is the temperature of the cloud top at height $h_c$, $T(h)$ is the temperature of the layer at height $h$, $\psi$ is the atmospheric state (e.g. humidity and temperature profiles etc.), $\tau_{h}^{11}$ is the atmospheric transmission from height $h_1$ to $h_2$ and $H$ is the top of the atmosphere.

To determine $T_c$, the temperature of the cloud top, from $I_{11}$ we only need to know the atmospheric transmission and emission of the atmosphere between cloud top and the satellite sensor. As the atmospheric correction term is small at mid-latitudes and normally reduces the measured cloud top brightness temperature $T_c$, it was converted into a brightness temperature deficit $\Delta T$ which allows the cloud top temperature to be computed simply from the measured brightness temperature $T_{11}$:

$$T_c = T_{11} + \Delta T(T_{11}, \alpha). \quad (4)$$

$\Delta T(T_{11}, \alpha)$ was computed from Eq. (3) by using a line-by-line atmospheric transmission model for five different satellite viewing angles ($\alpha$ is defined above). The values of $T_c$ for each cloud-filled pixel are averaged over the grid square. More details of the method and examples of high resolution cloud top temperature products are given in Saunders (1988a).

Other cloud parameters, such as cloud top reflectance and cloud liquid water content derived from the reflectance, are also retrieved but comparisons with equivalent model parameters have not yet been undertaken with the U.K. mesoscale model. There are other comparisons underway between AVHRR-derived cloud liquid water amounts and model representations of the same quantity, as described by Kriebel (1989).

3. Validation of retrieved satellite parameters

In order to have some confidence in the accuracy of the parameters retrieved from the AVHRR data it is desirable to compare them with equivalent parameters measured by conventional means. One way of doing this is to compare the satellite fields with a model analysis of the same parameter. This comparison is described in the following sections but first a few results are presented in this section comparing conventional synoptic observations with the satellite parameters.

The satellite parameter most easily validated is sea surface temperature (s.s.t.) since
this does not normally vary within a single pixel or rapidly in time and an equivalent in situ measurement can be made from a ship or buoy. There are small differences (≈0.2 K) between bulk water temperatures and radiative skin temperatures but nevertheless a validation accurate to a few tenths of a degree is adequate for our purposes. The s.s.t. retrieval scheme used here was validated over the North Atlantic by comparisons with 49 good quality ship measurements, giving a bias of 0.13 K and standard deviation of 0.58 K (Llewellyn-Jones et al. 1984). A comparison between the conventional s.s.t. charts available to forecasters and the satellite s.s.t. product is described by Pescod et al. (1986), again showing good agreement in absolute values. Therefore s.s.t.s derived from AVHRR data should have uncertainties less than 1 K, which is adequate for NWP applications.

Land surface temperature (l.s.t.) is a much more difficult quantity to validate for a number of reasons. Firstly, the quantity measured by the satellite is a radiative skin temperature averaged over a pixel (typically an area of 1.5 km²). This skin temperature is only representative of the uppermost few micrometres of the surface (or vegetation canopy) and often varies markedly within a pixel. Also for clear sky conditions it can change rapidly, for instance owing to a sudden clearance of cloud. The only conventional measurements readily available and close to the satellite overpass times are air temperatures recorded in a screen at a height of 1.2 m (T_screen). Hence there are problems of comparing a pixel-averaged quantity with a point measurement and also with comparing screen temperatures with surface skin temperatures. Tables 2 and 3, which list both the conventional and AVHRR observations for one week for the grid squares containing Heathrow airport, London (51°29’N 0°27’W) and Manchester airport (53°30’N 2°15’W), illustrate the problem. During the night the satellite l.s.t.s are usually less than the air temperatures and during the day they are higher. This would be expected for clear sky radiative situations where at night the ground cools down to below T_screen and during the day the ground heats up to above T_screen. These are the only conditions in which the AVHRR can make surface temperature measurements. Even if ground-based radiative skin measurements are made, to validate the satellite l.s.t., the radiating surface would need to be uniform over the area of one AVHRR pixel. At the present time it can only be assumed that the expected error in l.s.t., due to uncertainties in surface emissivity of

<table>
<thead>
<tr>
<th>Date and overpass time (GMT)</th>
<th>Observed screen temp. (°C)</th>
<th>AVHRR surface temp. (°C)</th>
<th>Observed cloud cover (%)</th>
<th>AVHRR cloud cover (%)</th>
<th>AVHRR cloud top temp. (°C)</th>
</tr>
</thead>
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<tr>
<td>14 Apr. 0348</td>
<td>8</td>
<td>-2</td>
<td>87</td>
<td>73</td>
<td>-4</td>
</tr>
<tr>
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<td>12</td>
<td>62</td>
<td>64</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
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<td>13 Apr. 1332</td>
<td>11</td>
<td>10</td>
<td>100</td>
<td>98</td>
<td>-3</td>
</tr>
<tr>
<td>16 Apr. 0327</td>
<td>9</td>
<td>10</td>
<td>100</td>
<td>97</td>
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<td>50</td>
<td>65</td>
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<tr>
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<td>10</td>
<td>19</td>
<td>75</td>
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<td>8</td>
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<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>18 Apr. 1300</td>
<td>17</td>
<td>20</td>
<td>50</td>
<td>71</td>
<td>2</td>
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<td>7</td>
<td>3</td>
<td>50</td>
<td>81</td>
<td>-19</td>
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<tr>
<td>20 Apr. 1249</td>
<td>20</td>
<td>23</td>
<td>12</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>20 Apr. 0246</td>
<td>9</td>
<td>87</td>
<td>100</td>
<td>99</td>
<td>-21</td>
</tr>
</tbody>
</table>
less than 0.04, is about 2 K. This latter assumption may be valid over the British Isles, which is mainly covered by vegetation, but will not be true over desert areas where significant uncertainties in surface emissivity exist because the restrahlung effect in quartz can reduce the channel 4 emissivity to about 0.85.

The problems of validating satellite-derived fractional cloud cover are discussed by Sèze et al. (1986) and by Saunders and Kriebel (1988) specifically for the retrieval scheme used in this study. Validation of clear sky and overcast conditions can be done with some confidence but partly cloudy situations are more difficult to compare. Tables 2 and 3 show comparisons of cloud cover at Heathrow and Manchester for 14 satellite overpasses. The AVHRR cloud cover is averaged over a 1° latitude/longitude grid square. In general the agreement is reasonable which, together with the results described in Saunders and Kriebel, suggests that satellite-derived fractional cloud cover is normally within 2 oktas of the observed cloud cover. The larger differences for the pass at 0256 GMT on 19 April 1985 are probably due to the fact that both the Heathrow and Manchester observations were reporting cirrus cloud. The satellite-retrieved effective fractional cloud cover tends to underestimate the coverage of thin cirrus owing to the lower emissivity of the cloud top. The same is true for the retrieved cloud cover over Manchester on 17 April 1985 at 0318 GMT.

Finally a validation of satellite cloud top temperatures has been carried out for one case study by Kriebel et al. (1983) by making coincident satellite and airborne lidar measurements of cloud top heights. For optically thick high cloud they reported a mean difference of 0.4 km (~3 K). Over fog some recent comparisons of aircraft, radiosonde and satellite measurements reported by Findlater et al. (1989) show agreement to within 1 K between the different measurements. These results suggest that satellite-derived cloud top temperatures are accurate to within 3 K for high cloud and 1 K for low uniform cloud. The current retrieval scheme does not attempt to determine the cloud top temperatures of semi-transparent cloud.

4. Description of mesoscale model fields

A mesoscale, non-hydrostatic, numerical weather prediction model covering the
British Isles (see Fig. 2 for approximate area covered) has been under development in the Meteorological Office for a number of years now (Tapp and White 1976; Carpenter 1979; Golding 1987a). The model currently has a 15 km grid point spacing, and 16 levels from a height of 10 m to 12 010 m. Its purpose is to provide local area forecasts up to 24 hours ahead. The regional ‘fine-mesh’ model provides the boundary conditions for the model (Bell and Dickinson 1987). To initialize the model, the main sources of information at the present time are the previous 3-hour forecast, the regional model analysis for the upper air data, and the surface synoptic observations. In the future it is planned to make use of high resolution satellite and radar data by interactively modifying the conventional analysis (Golding 1987b).

For comparison with the fields derived from AVHRR data the model fields on a 15 km grid were resampled on to a 1/5°×1/5° latitude/longitude grid to match the AVHRR products averaged over this grid. Three model-analysed fields were compared with the AVHRR products: the surface temperature ($T_s$), the fractional cloud cover, and the cloud top temperature, derived from the cloud top height field.

The surface-temperature-analysed field consists of an s.s.t. field over sea, which is interpolated from the Meteorological Office global model s.s.t. analysis (Smith 1987), and a corrected forecast surface temperature field over land. The latter is computed by first taking 3-hour model forecast fields of $T_s$ and $T_{10m}$. A forecast field of $T_{\text{screen}}$ is computed by taking the average of $T_s$ and $T_{10m}$ if the boundary layer is unstable, or by linearly interpolating between $T_{10m}$ and $T_s$ if not. The forecast field of $T_{\text{screen}}$ is then compared with an analysed field of observed screen temperatures and modified to agree with the observations. Finally the forecast $T_s$ field is modified by the same amount to give the analysed field for $T_s$.

The model carries cloud water and turbulent kinetic energy as prognostic variables and fractional cloud cover is diagnosed for each time step from the joint distribution of moisture and temperature implied by the turbulent kinetic energy. The model initial fields of fractional cloud cover are derived from a 3-hour forecast. The fractional coverage of each model layer is then modified to be consistent with the surface observations at the analysis time. Cloud layers visible from the ground are set to the observed cloud cover at the nearest model level to the observed base. Those hidden by low cloud retain the forecast information. If Cb clouds are observed at the analysis time the cloud top is assigned to a level at 9 km and Cu(cong) to a level at 5–6 km. If layer cloud is observed which is not present in the forecast it is assigned to the height of the reported cloud base. The upper layers will always be from the forecast field unless they can be seen from the ground. The overall cloud cover should therefore agree with the observations. The model fields of cloud top temperature are predominantly determined from a 3-hour model forecast field of cloud top height. More recently the cloud top heights for the 12 GMT analysis have been compared with the most recent METEOSAT infrared image and then interactively modified to give better agreement with the satellite image. This was not done for the model fields used in this study.

5. COMPARISON OF SATELLITE AND MODEL PARAMETERS

The satellite-retrieved parameters have been compared with model fields on several days but for the purposes of this paper results from one day (21 June 1986) will be described in detail; the conclusions are the same for the other days studied. The AVHRR data processed for 21 June were from the early afternoon NOAA-9 overpass at 1350 GMT.

The conventional visible (channel 2) and infrared (channel 4) AVHRR imagery for the 21 June are shown in Fig. 3. The synoptic situation for 12 GMT is shown in Fig. 4.
Figure 3. AVHRR images recorded over the British Isles at 1350 GMT on 21 June 1986. Both the channel-2 reflectance image (a) and the channel 4 thermal infrared image (b) are shown.
The British Isles was under the influence of a weak north-easterly airstream at this time. An occluded front was analysed lying to the south-west of the British Isles and was clearly evident in the satellite imagery as a well defined band of thick cloud. This front moved very slowly north-east during the afternoon to cross a line from South Wales to Southampton by midnight. Thunderstorms were reported over Cornwall and the Channel Islands associated with this front. An area of high pressure centred to the north of Scotland resulted in most of Scotland being cloud free with screen temperatures reported in the range 11–15°C. Further south, screen temperatures as high as 22°C were reported in the London area. An area of low stratocumulus cloud was reported along the east coast of England and this is clearly evident in the visible image of Fig. 3 extending well into the North Sea.

The AVHRR data were processed as described in section 2 and then both the model and satellite products were displayed in the format shown in Fig. 5. Each square corresponds to a 1/5°×1/5° latitude/longitude area over which the satellite data are averaged. The colour scale at the bottom provides the key to relate colour to the value of the parameter.
Figure 5. 21 June 1986, 1350 GMT. The upper plot shows the satellite-derived surface skin temperature; the lower plot shows the corresponding values of the land/sea temperature ($T_s$) in the model analysis. The colour scale along the bottom relates the colour in the plot to temperature in °C.
(a) Surface temperature

A comparison of surface temperatures derived from the AVHRR data and the corresponding model field (interpolated between the 12 and 15 GMT analyses) for 21 June at 1350 GMT is shown in Fig. 5. Over the sea, the satellite and model s.s.t.s are in good agreement generally, though the satellite s.s.t.s are consistently colder than the analysis, especially in the Irish Sea. An alternative way of comparing the model-analysed s.s.t.s and the satellite s.s.t.s is to plot them as shown in Fig. 6. There are comparisons for three days in 1986 included on this plot (20 May at 0257 GMT, 21 June at 1350 GMT and 16 November at 1412 GMT) with s.s.t.s at over 2000 grid points plotted. On average the satellite s.s.t.s are biased 0.7 K cooler than the model values. This suggests that the coefficients $a_n$ in Eq. (1) could be further optimized for s.s.t. retrievals around the British Isles for these atmospheric conditions. The skin effect (Robinson et al. 1984) may also contribute to the bias here as the model analysis will be based mainly on ship or buoy measurements at depths of several centimetres. The points with AVHRR temperatures much colder (>2 K) than the model temperatures are probably due to residual cloud

![Figure 6. A comparison of AVHRR and model-analysed sea surface temperatures for three different overpasses (for times see text). Each point is an average over a 1/5° grid square.](image-url)
contamination. Good coverage is obtained with the satellite data, which allows a more detailed s.s.t. field to be determined than that derived from ship and buoy measurements alone.

Over land the differences between the satellite ($T_{\text{sat}}$) and model surface temperatures ($T_s$) can be much greater, as shown in Figs. 5 and 7. Figure 5 shows that over the Scottish Highlands $T_{\text{sat}}$ is up to 10 K warmer than the corresponding model $T_s$ values. Large cities (e.g. London, Manchester) also show up as significantly warmer in the satellite data. Areas which have recently been cloud covered (i.e. most of England) have smaller differences (~2 K). Figure 7, like Fig. 6, includes points from the two other days, one of them (20 May) being a nighttime overpass. For 20 May and 16 November data $T_{\text{sat}}$ is on average 3 K colder than the model $T_s$ values, whereas for 21 June $T_{\text{sat}}$ is on average 4 K warmer than $T_s$.

One reason for these differences is that the satellite is measuring a radiative skin temperature whereas the model $T_s$ values are related to the screen temperature and the
Figure 8. 21 June 1986. The upper plot shows the satellite-derived fractional cloud cover at 1350 GMT. The lower plot shows the model-analysed fractional cloud cover at 1500 GMT. 100% cloud cover is represented by a white grid square, whereas clear areas are represented by a blue (sea), green (coast) or yellow (land) square.
lapse rate near the surface, as described in section 4. For clear sky radiative conditions the skin temperature would be expected to be greater than $T_s$ when there is appreciable solar heating of the surface, and colder than the model $T_s$ values at night due to radiative cooling of the surface. The comparisons in Fig. 7 show that for 21 June $T_{sat}$ is greater than $T_s$ in most cases, due to solar heating. The reverse is true for 16 November where the solar heating is small and the l.s.t. values were less than the s.s.t.s around the British Isles at this time. Similarly for the nighttime overpass on 20 May, $T_{sat}$ was on average 3 K less than $T_s$. It is interesting to note that Diak et al. (1986) also show similar differences over the United States between satellite and model surface temperatures. They used the 11 and 12-6μm wavelength VAS (VISSR atmospheric sounder) channels on the GOES geostationary satellite and a retrieval algorithm of the same form as Eq. (1). Over regions which were near areas of cloud the differences were small but during the day over large cloud-free areas the satellite surface temperatures were up to 15 K warmer.

These results demonstrate that $T_{sat}$ is essentially a different physical parameter to $T_s$ and so it cannot simply be used to update or correct the model's $T_s$ field. However, fields of $T_{sat}$ may be another useful variable to define the radiative skin temperature ($T_{rad}$) for the model's radiation scheme. For cloud-covered areas, where $T_{rad}$ cannot be obtained from the infrared satellite data, $T_s$ would normally be a good approximation for $T_{rad}$. Analysed fields of $T_{sat}$ may also provide improved horizontal fields of the model $T_s$ values by including the information about the relative changes in $T_{sat}$ fields in the analysed $T_s$ fields.

(b) Cloud cover

A comparison of cloud cover derived from the AVHRR data at 1350 GMT and the model-analysed cloud cover at 15 GMT is shown in Fig. 8. The extensive layer of cloud associated with the occluded front is well represented both in the satellite cloud cover and the model analysis. In general the overall agreement is reasonable; however, the satellite cloud field does appear to be more realistic in a few areas. Over the English Channel the satellite product indicates clear skies, which is consistent with the visible imagery in Fig. 3 and synoptic reports at 14 GMT from a few coastal stations on both sides of the channel. The model analysis, however, shows complete cloud cover along the south coast of England for both the 12 and 15 GMT analyses. Secondly, the satellite-derived cloud fields show the clearing behind the front whereas the model analysis (which has no surface observations in this area) still shows complete cloud cover. Both the satellite cloud cover and model analysis give a reasonable representation of the low stratuscumulus cloud over the east coast and North Sea. The low cloud further north, to the east of Scotland, is somewhat overestimated in the model analysis. The other significant area of disagreement between the satellite cloud field and model analysis is to the north-west of Ireland. The cloud in this area reported as thin cirrus appears to be overestimated by the model analysis when compared with the satellite product.

(c) Cloud top temperature

The comparison between the model-analysed cloud top temperature and the satellite cloud top temperatures is shown in Fig. 9. Satellite cloud top temperatures are displayed only when there are some cloud-filled pixels in the grid square. The satellite product shows the cloud tops associated with the front to be at 230–240 K along the line of the front with a small area of higher clouds (cloud top temperatures below 225 K) over the north Cornish coast. This latter area of high cloud shows up not only as being colder in the infrared imagery but also by the shadow of the high cloud on the lower cloud behind
Figure 9. 21 June 1986. The upper plot shows the satellite-derived cloud-top temperature at 1350 GMT; the lower plot the corresponding model-analysed cloud-top temperature at 1500 GMT. The scale along the bottom relates the colour to cloud-top temperature in kelvin.
it in the visible image of Fig. 3. The cloud ahead of the front is lower and hence warmer with tops around 265 K. The low stratocumulus cloud over the North Sea had cloud tops measured by the satellite around 279 K. The thick cirrus clouds over Northern Ireland had tops as cold as 230 K.

The corresponding model cloud top temperatures for 15 GMT are also shown in Fig. 9. They are displayed only if the fractional cover of the grid square is greater than 50%. The frontal cloud was assigned a cloud top temperature of 223 K along most of the front. The satellite data showed that most of the frontal cloud tops were in fact 10 K warmer (∼1.2 km lower) than this. The cirrus cloud over Northern Ireland was assigned a temperature of 224 K, 6 K colder (∼0.7 km higher) than the satellite value. It is possible that in this case the satellite cloud top temperature should be higher than was actually measured owing to the radiation emanating from within the cirrus rather than the cloud top. The tops of the stratocumulus cloud over the North Sea were at 285 K, 6 K warmer (∼0.4 km lower) than the satellite values. It is interesting to note that the model analysis includes some high cirrus clouds over the layer of stratocumulus which are not evident in the satellite product. The infrared imagery in Fig. 3(b) does show a few streaks of thin cirrus over this area which were also seen by observers on the ground. However, they are very thin (negligible as far as the model is concerned) and further south than in the model analysis. The determination of the cloud top temperature of thin cirrus from the satellite data is not attempted at present.

6. DISCUSSION AND CONCLUSIONS

It has been demonstrated that radiances measured by the AVHRR over the British Isles can be processed to retrieve a range of meteorological parameters potentially useful for NWP applications. A scheme for retrieving quantitative products from the AVHRR data, such as the one described here, could be implemented operationally to provide satellite products within an hour of receipt of the data. Data for many satellite overpasses (both daytime and nighttime) have now been processed giving realistic fields of surface skin temperature, surface albedo, fractional cloud cover and cloud top height. Surface parameters are retrieved only in cloud-free areas but the cloud parameters for the uppermost layers are obtained over the mesoscale model area. The complete coverage obtained is the principal advantage of the satellite product with retrievals made every fifth of a degree in contrast to the non-uniform distribution of surface observations.

Some attempts have been made to validate the satellite s.s.t., l.s.t., fractional cloud cover and cloud top temperature observations by comparing them with conventional in situ observations. However, there are no routine surface observations which are measuring exactly the same physical parameter as the satellite. This paper has demonstrated a different way to approach this problem, by comparing satellite parameters with an analysis from a mesoscale NWP model.

Comparison of satellite s.s.t.s with the corresponding model values shows the satellite values to be on average 0.7 degC colder than the model analyses. This may be due to a bias in the s.s.t. analysis or due to the retrieval coefficients not being optimized for the atmospheric conditions around the British Isles, and also the skin effect. The satellite s.s.t. field does reveal more detailed structure than is evident in the model analysis. Comparisons between satellite l.s.t. and the model $T_\star$ values clearly show the difference between the two parameters. However, the relative changes in the satellite field could provide useful information to include in the model $T_\star$ field. It is suggested that the satellite radiative skin temperatures could be used as the lower boundary of the model’s radiation scheme.
The satellite-derived cloud cover fields were in good qualitative agreement with the cloud cover observed in the original visible radiance image. When compared with model cloud fields the satellite product clearly showed areas where the model analysis was in error owing to the lack of conventional observations. Similarly, comparison between cloud top temperatures derived from the AVHRR data and those inferred from the model analysis suggests that the model's representation of the cloud tops could be improved. This is hardly surprising as the model's representation of cloud top temperature is based only on a 3-hour forecast field modified by a few surface observations of cloud type. As far as improving the model analysis is concerned the AVHRR cloud top temperature product is probably the most valuable product as it is this parameter which is the least well represented in the model. However, as Golding (1987b) points out, care is needed in deducing the corresponding cloud top height when the temperature profile is, or may be, multivalued as, for instance, when introducing an area of fog under an inversion. In that situation the corresponding vertical temperature profiles in the model must also be modified so that there is an inversion to contain the fog. Although comparisons for only one day (21 June 1986) are presented here, comparisons on four other days were also carried out and the conclusions presented above are the same for each day.

There are a number of possible ways to use the AVHRR data to improve the model's analysis. The easiest, though rather inefficient, way is to display the satellite products in the same format as the model analysis (as illustrated in this paper) and then to modify the model analysis interactively to fit the satellite observations better. For instance the analyst would recognize areas of cloud incorrectly analysed by the model and then add or delete them to improve the agreement with the satellite data. Eventually, after experience with the above method, objective techniques for incorporating the retrieved satellite parameters could be developed and the products then directly assimilated into the model's analysis.

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