Interpretation of 8–13μm measurements of sea-surface temperature

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(Received 8 December 1975; revised 15 March 1976)

SUMMARY

The difference between the true sea-surface temperature and that inferred from satellite measurements of infrared radiances when viewing vertically through a cloud-free atmosphere may be estimated to a useful accuracy for the 8–13μm radiometers of Defense Meteorological Satellite Program satellites. A simple parametric formula is developed that gives the difference to within ±0.6 K of that computed by a numerical method of solving the equation of radiative transfer. A comparison with data suggests that accuracies <1.3 K may be achieved relative to the actual value. Further work is necessary to confirm this accuracy because of an apparent discrepancy in the satellite data.

1. INTRODUCTION

Digital infrared ‘measurements’ of sea surface temperature ($T_s$) from Defense Meteorological Satellite Program (DMSP) satellites represent a source of data not often used by the non-military meteorological and oceanographic communities. Present DMSP radiometers operate in the so-called ‘window’ extending from 7.7 to 13.15μm (about 1300 to 760cm$^{-1}$) and have instantaneous fields-of-view (IFOV) of about 4 and 0.6 km respectively for the high and very high resolution sensors. In this interval the most significant attenuators in a cloud-free atmosphere are water vapour, ozone, carbon dioxide, and aerosols. CH$_4$ and N$_2$O also attenuate at wavelengths below about 8.2μm. Blankenship and Savage (1974) describe the radiometer in general terms, while Spangler (1974) and Dickenson et al. (1974) provide more detailed descriptions.

A drawback to the use of these data is the lack of a means to compute rapidly and accurately the difference ($D$) between $T_s$ and the temperature ‘seen’ by a satellite when viewing vertically through a cloud-free atmosphere, herein called the deficit. In this paper $D$ is computed by a numerical technique, and a parametric formula is developed that gives $D$ in terms of total water vapour content ($M$) and total ozone content ($U$). The numerical and parametric values are compared with each other and with a limited set of observations. Ship data and satellite (4km) data were supplied through the Environmental Prediction Research Facility (EPRF) of the Naval Post-Graduate School in Monterey, California, and covered the area of the Mid-Ocean Dynamics Experiment (MODE) centred near 28°N 70°W during June 1973.

2. ATMOSPHERIC ATTENUATION

(a) Numerical method

Numerical computations were performed by a program that utilized transmittances computed by LOWTRAN-2 developed by Selby and McClatchey (1972) and McClatchey et al. (1972), at a spectral resolution of 20cm$^{-1}$. Temperature ($T$), pressure ($p$), and vapour density ($\rho_v$) were extracted from radiosonde data for kilometre levels from the surface to 4 km. For levels from 7 to 25 km, and for seven additional levels to 100 km, these variables were provided by McClatchey et al. for a typical ‘Mid-Latitude Summer’ atmosphere. Values for intermediate levels were interpolated from the 4 and 7km values. McClatchey et al. also provided climatological data for other atmospheric constituents such as ozone, carbon dioxide, and aerosols.
(b) Parametric formula

The numerical method may require excessive time if applied to mapping $T_x$ over large areas. Since atmospheric profiles of temperature, humidity, and ozone frequently assume characteristic shapes over sub-tropical and mid-latitude oceans a parametric formula may be derived that gives $D$ in terms of $M$ and $U$. The contribution ($D_{we}$) arising from continuum absorption by water vapour may be estimated by the method of Cogan and Willand (1976), but in the present paper for a mean wavenumber of 1024 cm$^{-1}$. As in their paper $B \approx B_p P^4$, where $B_p$ is the surface value of the Planck function and $P$ is atmospheric pressure in atmospheres, but $I_{1ow}$ has the value of 0·9. From their method we have for a representative $T_x$ of 290 or 300 K

$$D_{we} \approx 0·81M + 0·105M^2$$

(1)

where $M$ is in g cm$^{-2}$ and $D_{we}$ is in K.

Computations using the numerical method suggest that water vapour lines account for only about an additional 0·5 K of $D$ for the cases studied. A very crude estimate of the contribution ($D_0$) from absorption by water vapour lines may be obtained by $D_1 \sim 0·1M$. Adding this expression to (1) we have $D_w \approx 0·91M + 0·105M^2$, where $D_w$ is the contribution from water vapour, in K.

The contribution ($D_0$) to $D$ arising from absorption by ozone may be approximated by a formula in terms of $U$. Fig. 1 shows a curve of $D_0$ as a function of $U$, where $U$ was varied by multiplying ozone densities at all levels of the Mid-Latitude Summer atmosphere by a constant (profile shape did not change). A straight line was fitted to the curve of $D_0$ that is good to ±0·1 K for 0·23 $<$ $U$ $<$ 0·43 atm. The line is given by $D_0 = 5·7U + 2·8$, where $D_0$ is in K and $U$ is in cm atm. This formula is only valid for the climatological region represented by the chosen atmosphere.

![Figure 1](image)

Figure 1. Values of the deficit ($D_0$) arising from ozone absorption computed for various values of total ozone content ($U$). Dashed line gives approximate values for 0·23 $<$ $U$ $<$ 0·43 cm atm. Both curves were drawn for the typical Mid-Latitude Summer atmosphere of McClatchey et al. (1972).

Computations by the numerical technique without haze and with the two haze distributions of McClatchey et al. for the Mid-Latitude Summer atmosphere suggest that extinction by aerosols may have contributed slightly less than 0·4 K to $D$ in the MODE area. The contribution by carbon dioxide and other uniformly mixed gases was computed numerically, with water vapour, ozone, and haze removed, to be about 1·0 K. These values may be regarded as constants for most atmospheres over a middle latitude or sub-tropical ocean.

Summing the several expressions and constants, we have for the 'parametric' value ($D_p$) of $D$

$$D_p \approx 0·91M + 0·105M^2 + 5·7U + 4·2$$

(2)

where $D_p$ is in K. In practice daily measurements of $U$ are not made over the oceans and therefore an appropriate climatological value should be selected. Dobson meter measurements for Tallahassee in June 1973 and climatological values from Grobecker (1975) and Dütsch (1974) suggest a value of $U$ that nearly coincides with the value, 0·324 cm atm,
Figure 2. The deficit \((D)\) as a function of total integrated water vapour content \((M)\). The curve gives the parametric values \((D_p)\), and the dots the numerical values \((D_s)\). Attenuation by ozone, aerosols and uniformly mixed gases is treated as a constant \((=6.05, \text{see text})\).

from the Mid-Latitude Summer atmosphere. Fig. 1 gives a value of 4.65K for this value of U, and (2) may now be written

\[ D_p \approx 0.91M + 0.105M^2 + 6.05 \]  

(3)

Fig. 2 compares \(D_p\) with values \((D_s)\) computed by the numerical method for 13 soundings. In all cases \(D_p\) approximates \(D_s\) to \(\leq \pm 0.6\)K. However, (2) may not have this accuracy for profiles of \(T\) and \(\rho_a\) that depart far from assumed shapes, or for large deviations in \(U\) or the profile of ozone from that of the atmosphere.

3. Comparison with Observations

\(D_p\) and \(D_c\) were compared with the deficit \((D_p)\) derived from a comparison of ship measurements of \(T_s\) with satellite values of equivalent black body temperature \((T_b)\). Four research vessels participating in the MODE and three ships-of-opportunity provided \(T_s\) data. A method of selecting cloud-free scan spots and a discussion of possible errors when comparing ship and satellite measurements are given in Cogan and Willard (1976). Mean values of \(T_b\) for areas of 10 x 10 scan spots were subtracted from \(T_s\) to obtain the temperature difference \((\Delta T)\).

Normally, \(D_s \approx \Delta T \cos Z\) where \(Z\) is the zenith angle and \(Z < 75^\circ\), but no apparent relationship appeared between \(\Delta T\) and \(Z\) in these DMSP data. This discrepancy may have arisen from variation of the emissivity of the ocean surface with \(Z\), slight contamination from very thin cirrus or scattered small cumulus, use of a \(T_b\) limit to aid the elimination of cloud filled scan spots that was too high, or use of a standard correction technique for \(Z\) on the data before delivery to EPRF. A large variation in emissivity would tend to increase \(\Delta T\).

<table>
<thead>
<tr>
<th>Date (June 1973)</th>
<th>(M)</th>
<th>(D_s) (average value)</th>
<th>(\Delta D_s) ((D_s - D_a))</th>
<th>(\Delta D_p) ((D_p - D_s))</th>
<th>(\sec Z) (average)</th>
<th>(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>2.91</td>
<td>9.80</td>
<td>9.59</td>
<td>10.85</td>
<td>-0.95</td>
<td>1.30</td>
</tr>
<tr>
<td>14</td>
<td>4.91</td>
<td>11.44</td>
<td>11.71</td>
<td>10.90</td>
<td>0.55</td>
<td>0.85</td>
</tr>
<tr>
<td>15</td>
<td>3.54</td>
<td>10.20</td>
<td>10.59</td>
<td>10.20</td>
<td>0.00</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Comparison of computed with observed values of \(D\) assuming that \(\Delta T = D_s\). All values of \(D\) and \(\Delta D\) are in K. Sounding of 14 June may have passed through a cloud near 750mb. Values of \(D_s\), \(\Delta D_s\), and \(\Delta D_p\) are to the nearest 0.05K. \(N\) is the number of ships providing measurements of \(T_s\) for each day.
at high $Z$, and slight cloud contamination probably would only cause an error of 1 or 2 K. Only in the 13 June data where $sec Z \sim 3.1$ did values of $T_R$ occur less than the $T_R$ limit of 285 K, six temperatures of 283-4 K out of 360 individual values. Application of the standard correction (Dickenson et al.) could not be verified either way despite considerable effort. As a consequence of these uncertainties, it was assumed that $D_s = \Delta T$. This assumption is reasonable for $sec Z$ not much greater than 1,0, such as for the 15 June data.

The results shown in Table 1 suggest that $D_s$ estimated $D_s$ to about $\pm 1.3$ K. However, because of the aforementioned discrepancies, only the 15 June data may be useful. Nevertheless, the 15 June results tend to support the contention that (3) can estimate the deficit to about the precision, 1-7 K (Dickenson et al.), of the satellite data even if $D_s$ of Table 1 overestimated the real deficit by 1 or 2 K.

4. CONCLUSIONS

The parametric formula appears capable of estimating the deficit for DMSP data to an accuracy of $< \pm 0.6$ K compared with results from numerical computations for atmospheres typical of the MODE area. A limited comparison with observations suggests that it may estimate the actual deficit to about $\pm 1$ K. Unfortunately some unresolved uncertainties make this comparison inconclusive, and further work is necessary using additional DMSP data. Nevertheless, from the results of this paper it appears that the parametric method should be a useful tool for interpretation of digitized data from the 8-13 $\mu$m radiometer of DMSP satellites.

ACKNOWLEDGMENTS

The author wishes to acknowledge the support and assistance provided by Roland Nagle and others of the EPRF (Contract No. N77856-4120-5502). Recognition also should be given to James Willand, Nancy Tripp, and Ronald Isaacs for their invaluable help in processing the data and for their advice on programming.

REFERENCES


* K. W. Ruggles noted in a very recent private communication (1976) that a standard correction for zenith angle is imposed on DSMP data of the type used for this work. Therefore, in Table 1 the computed deficits are probably accurate to about the precision of the system for all days, since the assumption of $D_s = \Delta T$ now has some validity for all the satellite data.