4.19 IMPROVING MERCHANT SHIP AIR TEMPERATURES USING AN ANALYTICAL MODEL OF HEATING ERRORS

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1. INTRODUCTION

Observations of the marine air temperature (MAT) made by Voluntary Observing Ships (VOS) are known to contain significant biases which depend on both environmental factors, such as solar radiation, and on the exposure of the instruments. These biases can be greater than 2 °C when the solar radiation is strong and the instruments poorly sited (e.g. Goerss and Duchon, 1980; Kent *et al.*, 1993). The existence of such large errors has lead to the development of MAT climatologies based only on the night time observations (e.g. Parker *et al.*, 1995). Previous studies of the heating errors in the MAT have assumed a steady state (e.g. Kent *et al.*, 1993): relating the heating errors to the incident shortwave radiation and the relative wind speed at the time of measurement. However this type of correction is likely to over correct the air temperature in the morning, under correct in the afternoon (Aiguo Dai, pers. comm.) and cannot remove biases which persist after sunset. Figure 1 shows a plot of the diurnal variation in North Atlantic MAT in June 1996 from the International-Comprehensive Ocean Atmosphere Dataset (I-COADS, Woodruff et al. 1998). Much of this variation is due to heating errors in the ship data, the true diurnal variation of the marine air temperature is thought to be much smaller. Also shown is the MAT after the correction of Kent *et al.* (1993) has been applied. The over correction before midday and under correction in the afternoon can be clearly seen, with residual errors of up to 0.6°C still present at 1800 local solar time. The residual bias after sunset can also be seen with a heating error of up to 0.2°C at midnight.

We are therefore developing a new correction based on an analytical model of the heat budget of the ship and sensor environment, making a number of assumptions and approximations about the different environmental conditions and ship characteristics. Making these approximations and assumptions allows us to simplify and solve the heat budget analytically. In doing so we allow for a time varying incoming solar radiation and use the solution to give estimates of the difference between the ship environmental temperature and the ambient air temperature, and hence the error in the ship measured air temperature. The analytical model contains empirical constants which are determined by fitting the correction to data from the I-COADS.

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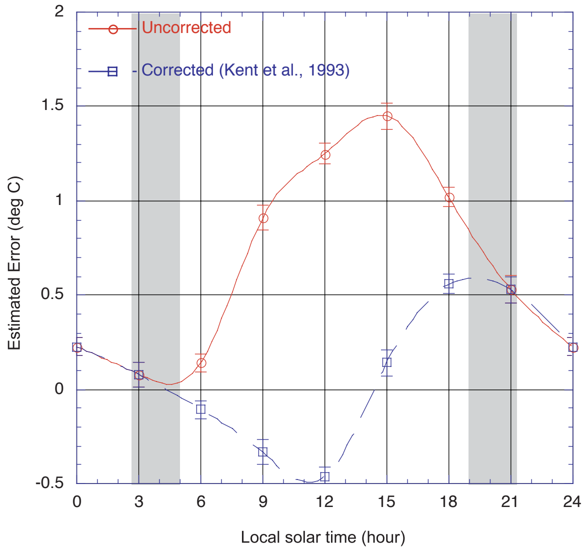

Figure 1. Estimated errors for VOS observations of the MAT from the North Atlantic (30N – 60N) for June 1996 before and after the correction of Kent et al. (1993). The vertical bands indicate the range of times for sunrise and sunset for June. The error bars show the standard deviation of the mean.

2. DEVELOPMENT OF THE HEATING MODEL

We have modelled the radiative heating errors by using the principles of conservation of energy. In modelling the heat budget we have made a number of approximations to simplify and to solve the heat budget analytically. We follow a similar approach to Anderson and Baumgartner (1998) who modelled the radiative heating errors in MAT measurements made by buoys. Our approach, however, differs in that we have allowed for the storage of heat by the ships structure, a term they could neglect due to the small heat storage by the buoys.

We assume that the net longwave radiative heating or cooling is negligible compared to the other terms. The heat budget can then be written as

$$mc\frac{dT_{ship}}{dt} = Q_{SW} + \left(Q_1 + Q_2\right) \qquad (1)$$

Where m is the mass of the ship [kg]; c is the specific heat capacity of the ship [J kg^{-1} K^{-1}]; T_{ship} is the temperature of the ship and sensor environment [K]; t is time [seconds]; Q_{SW} is the rate of solar energy absorbed [W]; Q_1 is the rate of energy transfer between the ship and the atmosphere and ocean through convection [W]; Q_2 is the rate of energy transfer between the ship and the atmosphere and ocean through conduction [W].

In this study we have used the okta model (Dobson and Smith, 1988) to calculate the average hourly solar radiation. Using the okta model the rate of solar energy absorbed, Q_{SW}, can be written as

$$Q_{SW} = \alpha_S A_S R_{top}(a + b\sin\theta)\sin\theta \qquad (2)$$

Where α_S is solar absorptivity of the ship and sensor environment; A_S is the area normal to the solar radiation [m^2]; R_{top} is the solar radiation [W m^{-2}] at the top of the atmosphere; a and b are constants fitted for the okta model and sinθ is the sine of the solar elevation. The sine of the solar elevation can be written as

$$\sin\theta = \sin(lat \cdot dr)\sin(dec) + \cos(lat \cdot dr)\cos(dec)\cos(hang) \qquad (3)$$

Where lat is the latitude [degrees N]; dr is a constant to convert from degrees to radians [π/180]; dec is the declination of the sun [radians]; and hang is the hour angle [radians]. It should be noted that in this model we have assumed the change in the surface area normal to the solar radiation is negligible throughout the day. We have also assumed that the position of the ship and the declination are constant throughout the day.

The convective and conductive cooling terms, Q_1 and Q_2, will both be proportional to the temperature difference between the atmosphere and the ship and to the convective and conductive heat transfer coefficients respectively. i.e.

$$(Q_1 + Q_2) = (T_{air} - T_{ship})A_c(h_\mu + h_o) \qquad (4)$$

Where T_{air} is the air temperature [K]; A_c is the surface area of the ship/sensor in contact with the atmosphere; and h_μ and h_o are the convective and conductive heat transfer coefficients respectively [W m^{-2} K^{-1}]. h_o is assumed constant in this paper over the range of temperatures encountered in the MAT measurements and h_μ will be dependent on the geometry of the ship and the relative wind speed. In this paper we have approximated the geometry of the ships environment and sensors as a block. The convective cooling can be then be approximated by $h_\mu = x_3 V^{x_4}$. x_3 and x_4 are empirically determined coefficients and V is the relative wind speed [m s^{-1}]. It has been assumed that the sensor is sufficiently far above the sea surface that the effect of the ocean on the radiative heating errors is negligible.

Assuming that the diurnal variation in the MAT is negligible compared to the radiative heating errors as a first approximation, letting hang = αt + β and substituting Equations 2 – 4 into Equation 1 the heat budget becomes

$$\frac{d(\Delta T_{est})}{dt} + h_1(\Delta T_{est}) = h_2 + h_3\cos(\alpha t + \beta) + h_4\cos^2(\alpha t + \beta) \qquad (5)$$

Where $\Delta T_{est} = T_{ship} - T_{air}$ is the estimated radiative heating error [deg C]; $h_1 = x_2(h_\mu + h_o)$; $h_2 = x_1 R_{top}(ak_1 + bk_1^2)$; $h_3 = x_1 R_{top}(ak_2 + 2bk_1k_2)$; $h_4 = x_1 R_{top} bk_2^2$; $x_1 = \alpha_S A_S / mc$; $x_2 = A_c/mc$; $k_1 = \sin(lat \cdot dr)\sin(dec)$ and $k_2 = \cos(lat \cdot dr)\cos(dec)$.

During the night time the solar radiation terms can be dropped from the heat budget and Equation 5 simplifies to

$$\frac{d(\Delta T_{est})}{dt} = -h_1(\Delta T_{est}) \qquad (6)$$

The solution of Equation 5 is given by

$$\begin{aligned}(\Delta T_{est}) = {} & \frac{h_2}{h_1} + \frac{4\alpha^2 h_4}{4\alpha^2 + h_1^2}\left(\frac{\cos(\alpha t + \beta)\sin(\alpha t + \beta)}{2\alpha}\right) \\ & + \frac{4\alpha^2 h_4}{4\alpha^2 + h_1^2}\left(\frac{h_1\cos^2(\alpha t + \beta)}{4\alpha^2} + \frac{1}{2h_1}\right) + \\ & + \frac{\alpha h_3}{\alpha^2 + h_1^2}\left(\sin(\alpha t + \beta) + \frac{h_1}{\alpha}\cos(\alpha t + \beta)\right) \\ & + k_{day}\exp(-h_1 t)\end{aligned} \qquad (7)$$

And the solution of Equation 6 by

$$(\Delta T_{est}) = k_{night}\exp(-h_1 t) \qquad (8)$$

The constants k_{day} and k_{night} can be found by solving (7) and (8) at sunrise and sunset respectively. In Equation 7, t is the time after sunrise and when calculating k_{day} it has been assumed that the radiative heating error is zero at sunrise (i.e. ΔT_{est} = 0 at time t = 0). To calculate k_{night} (7) and (8) are solved simultaneously at sunset, with t equal to the time after sunset in (8). Assuming the area normal to the solar radiation is constant throughout the day and letting $h_\mu = x_3 V^{x_4}$ and $h_o = x_5$ we have five unknown constants in our solution to the heat budget, x_1 to x_5. The other terms in Equations 7 and 8 can be calculated from the ships location and the time of observation or are known constants (e.g. R_{top} = 1368 W m^{-2}). The constants x_1 to x_5 have been fitted using a non-linear least squares regression (see Section 3). It should be noted that this correction is expected to apply to the means of a large number of observations rather than to individual observations due to the approximations and assumptions it has been necessary to make.

3. FITTING THE HEATING MODEL TO THE I–COADS

3.1 Method

The I-COADS (Woodruff *et al.*, 1998) contains observations of surface marine meteorological variables from a variety of sources for the period 1980 – 1997. We have used only the observations made by ships (platform types 1- 5 within I-COADS). The radiative heating errors for the I-COADS observations have been estimated by first calculating the night time monthly mean air temperature on a 5° by 5° grid. This monthly mean air temperature is then subtracted from the individual observations to give an estimate of the heating errors. It should be noted that only observations made between midnight and sunrise have been used to calculate the monthly mean air temperature since it has been shown that the heating errors persist for several hours after sunset (see Figure 1).

The solution of the radiative heating model has then been fitted to these estimates of the heating errors using a non-linear least squares regression, minimizing the sum of the squared differences between the estimated heating errors and the errors calculated using Equations 7 and 8. i. e.

$$\text{Minimize } F(x) = \sum \left(\Delta T - \Delta T_{est}\right)^2 \qquad (9)$$

Where ΔT is the difference between the observed air temperature and the monthly mean air temperature and ΔT_{est} is the estimated radiative heating error from Equation 7 or 8 depending on the time of day.

3.2 Results

Figure 2 shows the corrected and uncorrected estimates of the radiative heating errors for June 1996 using the solution of the heat budget fitted to these data. Also shown are the residual estimated errors after the observations have been corrected using the correction of Kent *et al.* (1993). From Figure 2 it can be seen that we are underestimating the size of the correction needed in the mid morning and afternoon, with residual errors of up to 0.7 °C at 0900 and 1800 local solar time. This double peak is probably due to the assumption that the change in surface area normal to the solar radiation is negligible throughout the day and indicates that that this variation needs to be included in the model. A similar double peak was found by Anderson and Baumgartner (1998) in uncorrected MAT observations from buoys due to the changes in the surface area of the radiation shields normal to the solar radiation throughout the day.

Figure 3 shows the estimated errors for December 1996 before and after correction using the solution of the heat budget fitted to the data for December 1996. From Figure 3 it can be seen that we also underestimate the size of the correction needed in the morning and afternoon during the winter. However, we are estimating the size of the correction needed more accurately than a correction based only on the incident shortwave radiation and relative wind speed at the time of measurement. The double peak in the residual errors due to the assumption that the variation of the surface area normal to the solar radiation is negligible can also be seen in Figure 3. The residual errors in the data corrected using the correction of Kent et al. (1993) also contain a double peak, confirming the need to allow for a variable surface area in the heat budget.

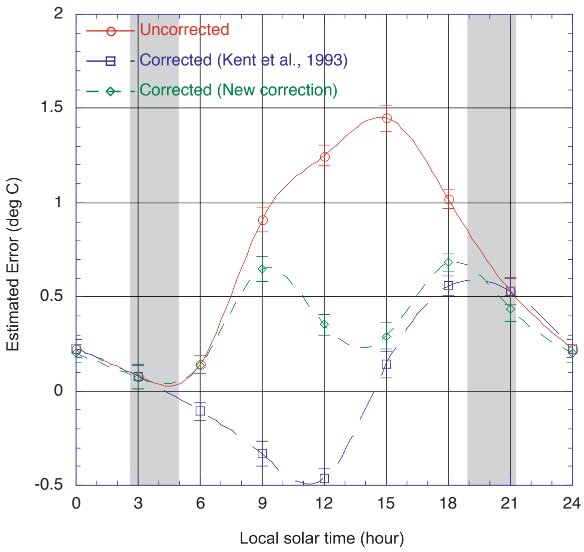

Figure 2. Estimated errors for VOS observations of the MAT from the North Atlantic for June 1996 before and after the solution of the heat budget has been applied.

The increase in the estimated errors towards midnight seen in Figure 3 is probably due to differences in the observing practices of different countries and to the spatial distribution of the data from different types of ships and from different countries. For example, Figure 4 shows the estimated errors for observations made west of 40 W in the North Atlantic during December 1996. From Figure 4 it can be seen that by excluding the data east of 40 W the increase in the estimated errors towards midnight has been removed. This suggests that a subset of ships in the eastern North Atlantic are consistently biased warm and that this subset needs to be identified. Possibly hand held psychrometers are being brought inside the wheelhouse to read during night time hours. Identifying and removing this subset or treating the subset separately from the observations should lead to an improvement in the fit of the solution of the heat budget to the observations. It should be possible to identify this subset using the metadata contained in the World Meteorological Organisation (WMO) Report No. 47 the “List of Selected, Supplementary and Auxiliary Ships”. The

WMO Report No. 47 gives information on the type of ship, the instrumentation used and country of recruitment and has been published in paper form for most years since 1954 (e.g. WMO, 1994). The WMO Report No. 47 is also available in digital form for individual years since 1973. The metadata can be linked to the individual reports within I-COADS based on the call sign of the ships, which is recorded in both the I-COADS and the WMO Report No. 47.

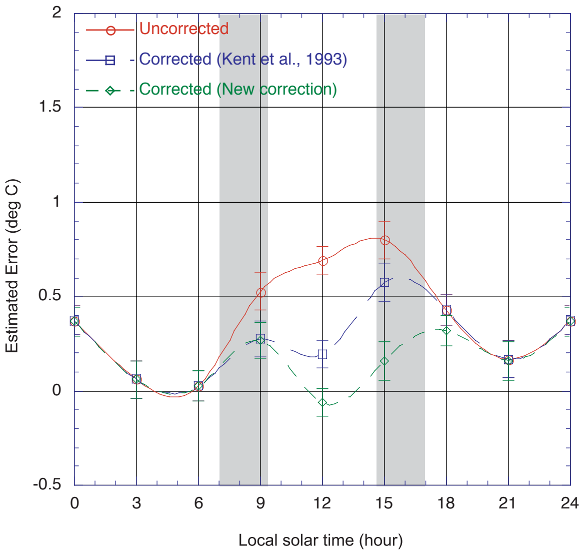

Figure 3. Estimated errors for VOS observations of the MAT from the North Atlantic for December 1996 before and after the solution of the heat budget has been applied.

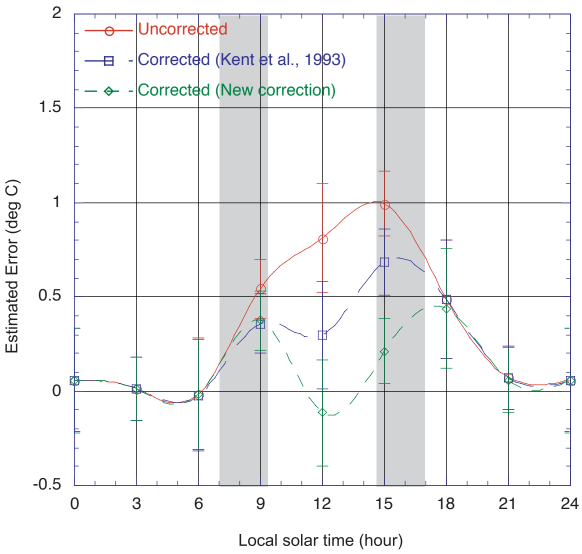

Figure 4. As for Figure 3, but using only observations made west of 40 W.

4. CONCLUSIONS

The results presented in this paper show the radiative heating errors to persist for several hours after sunset, with errors of a couple of tenths °C still present at midnight during the summer. Also shown is the under correction of the heating errors during the afternoon by a correction based on the incident shortwave radiation and the relative wind speed at the time of measurement. In this paper we have also presented the initial development of a new correction for the MAT observations from VOS based on an analytical model of the heat budget for the ships sensors and environment. The new correction allows for the storage of heat by the ships environment and sensors and appears to be an improvement on a correction based only on the incident shortwave radiation and relative wind speed at the time of observation. However, there are a number of issues which need to be resolved and further work is needed before the correction can be used.

Future work will involve the investigation of the double peak seen in the residual heating errors and the inclusion of a time varying area normal to the solar radiation into the model. The increase in the estimated error at midnight during the winter (see Figure 3) also needs to be investigated further and the subset containing the observations which are biased warm at midnight identified. This will be done by using the WMO Report No. 47 to identify and examine different subsets of the I-COADS observations based on the instrument type, country of recruitment and ship type. Other subsets will also be examined.

5. REFERENCES

Anderson, S. P., and M. F. Baumgartner, 1998: Radiative heating errors in Naturally Ventilated Air Temperature Measurements Made from Buoys. *J. Atmos. Oceanic Technol.,* **15**, 157 – 173.

Dobson, F. W. and S. D. Smith, 1988: Bulk models of solar radiation at sea, *Quart. J. Roy. Meteor. Soc.*, **114**, 165 – 182.

Goerss, J. S., and C. E. Duchon, 1980: Effect of Ship Heating on Dry-Bulb Temperature Measurements in GATE. *J. Phys. Ocean.*, **10**, 478 – 479

Kent, E. C., R. J. Tiddy and P. K. Taylor, 1993: Correction of the marine air temperature observations for solar radiation effects, *J. Atmos. Oceanic Technol.*, **10**, 900 – 906.

Parker, D. E., C. K. Folland and M. Jackson, 1995: Marine surface temperature: Observed variations and data requirements, *Climatic Change*, **31**, 559 – 600.

WMO, 1994: International List of Selected, Supplementary and Auxiliary Ships, WMO Report No. 47, WMO, Geneva, various pagination.

Woodruff, S. D., H. F. Diaz, J. D. Elms, and S. J. Worley, 1998: COADS Release 2 Data and Metadata Enhancements for Improvements of Marine Surface Flux Fields. *Physics and Chemistry of the Earth*, **23**, 517-527.