# Corrections to Pre-1941 SST Measurements for Studies of Long-Term Changes in SSTs

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## 1. Introduction

Many factors can influence a sea surface temperature reading (Barnett, 1985; Jones et al., 1986; Bottomley et al., 1990; Jones et al., 1991). Some of these introduce random errors while others result in systematic, non- cancelling errors. The most important factor is the method of collecting the sample, with the two basic methods being to haul a sample on deck with a bucket, or to measure the temperature of the intake water used for engine cooling. Here, we are concerned with bucket measurements. These are affected by the kind of bucket used, the exposure of and physical conditions surrounding the bucket, how long the bucket was left before reading the thermometer, and ship speed.

In COADS we do not have detailed information concerning the methods of measurement, nor any indication of what method was used for the individual readings that make up the data. There is, nevertheless, strong evidence that readings before 1940 were predominantly bucket measurements, while those since 1945 were predominantly intake measurements (Jones et al., 1986). Furthermore, it is likely that the major difference between the data for these two periods is the non-climatic bias due to the evaporative cooling of the canvas bucket, an effect which would clearly cause pre-1940 data to be cooler than post-1945 data (Jones et al., 1991).

In order to derive correction factors for the bucket-derived temperatures, we have modified the model developed by Folland and Hsiung, 1987 and Bottomley et al., 1990, to estimate the cooling of an un-insulated canvas bucket. The main difference between our work and that of Folland and Hsiung (1987) is that we have solved the governing equations analytically. This makes application of the model less demanding computationally, and it allows us to perform a variety of analyses.

## 2. The bucket model

### *2.1 Theory (following Folland and Hsiung, 1987)*

Terminology:

| | | |
|---|---|---|
| $b$ | = | $\partial e_{sA}/\partial T$ |
| $C$ | = | specific heat capacity of water |
| $C_p$ | = | specific heat of air at constant pressure |
| $e_A$ | = | vapour pressure of air |
| $e_{sB}$ | = | saturation vapour pressure at $T_B$ ($e_{sA}$ similarly) |
| $h$ | = | depth of water in bucket (approximately 15cm) |
| $k_c$ | = | convective heat transfer coefficient |

| | | |
|---|---|---|
| $k_r$ | = | radiative heat transfer coefficient |
| $\tilde{k}$, k* | = | water vapour mass transfer coefficients |
| L | = | latent heat of vaporization |
| p | = | atmospheric pressure |
| $Q_B$ | = | shortwave radiation input adjusted for interception area |
| $Q_H$ | = | heat transport away from bucket |
| r | = | bucket radius (approximately 9cm) |
| R | = | atmospheric relative humidity = $e_A/e_{sA}$ |
| $T_A$ | = | air temperature |
| $T_B$ | = | bucket water temperature |
| $T_S$ | = | sea surface temperature = $T_B$(t=O) |
| $T_\infty$ | = | asymptotic bucket temperature |
| $\underline{U}$ | = | wind velocity in vicinity of bucket |
| $\underline{v}$ | = | ship velocity |
| $\underline{V}$ | = | velocity of air flow past bucket |
| | = | resultant of $\underline{v}$ and $\underline{U}$ |
| $\Delta$ | = | correction = $T_S$ - $T_B$ |
| $\rho$ | = | mean density of water plus bucket |
| $\phi$ | = | angle between $\underline{U}$ and $\underline{v}$ |
| $\tau$ | = | relaxation time for evaporative cooling. |

The equation for $T_B(t)$ derived by Folland and Hsiung (1987) is

$$r^2 hC\frac{dT_B}{dt} = (2rh + r^2)[Q_B - Q_H]$$

$$= (2rh + r^2)[(k_c + k_r)(T_A - T_B) + k^*L(e_A - e_{sB}) + Q_B] \tag{1}$$

This is simplified using the following (SI units)

$$k_c = 2.34\sqrt{V/r} \qquad (Wm^{-2}K^{-1}) \tag{1a}$$

$$k_r = 5.4 \qquad (Wm^{-2}K^{-1}) \tag{1b}$$

$$k^* \cong (k_c + k_r)/AL \qquad (Wm^{-2}hPa^{-1}) \tag{1c}$$

where A is the psychrometer coefficient ($\cong 0.7 hPaK^{-1}$), together with the above values of h and r to give

$$\frac{dT_B}{dt} \cong a[Q_B + (7.8\sqrt{V} + 5.4)(T_A - T_B + 1.4(e_A - e_{sB}))] \tag{2}$$

where a = 6.902 $10^{-6}$ for t in seconds or a = 4.141 $10^{-4}$ for t in minutes.

The trick in solving equ. (2) is to note that $T_A \cong T_B$. This means that $e_{sB} \cong e_{sA} + b(T_B - T_A)$ where b - $\partial e_s/\partial$ T at $T_A$ (strictly, at $(T_A+T_B)/2$, but the difference is negligible). If we write

$$u = 7.8\sqrt{V} + 5.4 \tag{3}$$

then equ. (2) becomes

$$\frac{dT_B}{dt} \cong au(1 + 1.4b) + (T_B - T_A) = a[Q_B - 1.4(1 - R)ue_{sA}] \tag{4}$$

The solution to this is

$$T_B = T_S - (T_S - T\infty)(1 - \exp(-t/\tau)) \tag{5}$$

where

$$T_\infty = T_A - (1.4(1 - R)e_{sA} - Q_B/u)/(1 + 1.4b) \tag{6}$$

is the asymptotic bucket-water temperature (i.e. an effective “wet bulb” temperature for the bucket) and

$$\tau = 2410/(u(1 + 1.4b)) \tag{7}$$

is the time scale for relaxation of $T_B$ towards $T_\infty$ (in minutes).

*2.3 The ship speed effect*

The value of $\underline{V}$ used above is the resultant of the wind velocity $\underline{U}$ and the ship velocity $\underline{v}$, so that

$$V = (a + b\cos\phi)^{1/2} \tag{8}$$

where

$\phi$ is the angle between $\underline{U}$ and $\underline{v}$
a = $v^2 + U^2$
b = 2vU

Since $\phi$ is unknown, it may be considered a uniform random variable on $(0,2\pi)$. The mean value of V is therefore

$$\bar{V} = \frac{1}{\pi}\int_{0}^{\pi}(a + b\cos\phi)^{1/2}d\phi$$

i.e.,

$$\bar{V} = \frac{2}{\pi}(v + U)E(m) \tag{9}$$

where

$$m = 2b/(a + b) = 4vU/(v + U)^2$$

and E is the complete Elliptic Integral of the Second Kind (for solution see Abramowitz and Stegun, 1965).

If $\beta$ is the ship speed expressed in terms of the wind speed, i.e.

$$V = \beta U \tag{10}$$

then the ship speed effectively inflates the wind speed by a factor

$$\bar{V} = \alpha U \tag{11}$$

where $\alpha$ varies from 1 when $\beta = 0$, through $4/\pi$ for $\beta = 1$, upwards, with $\pi$ tending to $\beta$ for large $\beta$.

Variations in ship speed through time, therefore, can only have an appreciable effect if ship speed, v, noticeably exceeds wind speed, U. Over the period for which data exist, average ship speed has increased from around 4 $ms^{-1}$ (≅8kt) to 7 $ms^{-1}$ (≅14 kt.). Mean wind speed at ship deck height is probably around 5 $ms^{-1}$, so that V has changed from 5.8 $ms^{-1}$ to 7.9 $ms^{-1}$ implying a 17% change in $\Delta$.

*2.4 A more correct bucket equation*

In Folland and Hsiung's (1987) development of the bucket model, they employ a relationship between the heat and mass transfer coefficients which is only approximate. We have followed their method above, but it is worth noting the correct version. Equ. (1) involves sensible, radiative and latent heat transport terms which we combine here as $Q_H$

$$Q_H = (k_c + k_r)(T_B - T_A) - k^* L(e_A - e_{sB}) \tag{12}$$

Folland and Hsiung simplify this using the approximate relationship $Lk^* \cong (k_c + k_r)/A$ where A is the psychrometer coefficient and L is latent heat. The correct way to do this is relate $k^*$ and $k_c$. This require writing $Q_H$ in terms of specific humidity

$$Q_H = (k_c + k_r)(T_B - T_A) - \tilde{k} L(q_A - q_{sB}) \tag{13}$$

In this form, the mass transfer coefficient is related to the convective heat transfer coefficient by

$$\tilde{k} = k_c Le^{2/3} / C_p \tag{14}$$

where Le is the Lewis number (i.e. Prandtl number divided by Schmidt number) and $C_p$ is the specific heat of moist air at constant pressure (Spalding, 1993). For moist air, Le ≅ 1.2. Since q ≅ e/p where ε = 0.622 and p is atmospheric pressure, equ. (14) implies

$$k^* = \frac{\varepsilon}{pC_p}(Le)^{2/3} k_c = k_c / A^* \tag{15}$$

where $A^* = 0.58$.

Using the approximations earlier, $e_{sB} \cong e_{sA} + b(T_B - T_A)$ where $b = \partial e_s / \partial T$, together with the $k_c$ and $k_r$ equ. (12) becomes

$$Q_H = (T_B - T_A)\left[u + \frac{b}{A^*}(u - 5.4)\right] + \frac{e_{sA}}{A^*}(u - 5.4)(1 - R) \tag{16}$$

where u - 7.8√V + 5.4. This should be compared with the previous result which is equivalent to

$$Q_H = (T_B - T_A)\left[u + \frac{b}{A}u\right] + \frac{e_{sA}}{A}(u)(1 - R) \tag{17}$$

The difference lies solely in the terms involving A* or A. To go from equ. (16) to equ. (17) requires replacing (u-5.4)/A* by u/A. The solution given by equ. (5) and its variants is unaltered except that $T_\infty$ and τ become

$$T_\infty = T_A - \frac{(u - 5.4)(1 - R)e_{sA} - A^* Q_B}{A^* u + b(u - 5.4)} \tag{18}$$

$$= \frac{2410 \quad A^*}{A^*u + b(u - 5.4)} \qquad (19)$$

If the relaxation times and asymptotic temperatures of the approximate and correct solutions are compared, one finds that, for $V < 11.2$ $ms^{-1}$, $\tau$(correct) < $\tau$(approx.) and $T_\infty$(correct) > $T_\infty$ (approx.). The differences. for all practical cases, are less than 5% (expressing the $T_\infty$, difference in terms of $T_S - T_\infty$). For small exposure times (t: ≤ 8 minutes) the two solutions differ by only a few hundredths of a degree Celsius for most situations. In all calculations that follow, we have employed the correct solution (i.e. equ. (5a) together with equs. (18) and (19)).

## 3. Application of the bucket model

### *3.1 Model input data*

Application of the bucket model (equ. (5a)) requires knowledge of $T_B$, $T_A$, R, V (and its components U and v) and $Q_B$. ($e_{sA}$ and $b = \partial e_{sA}/\partial T$ values were calculated from $T_A$ using the formula of Murray, 1967.) For R, U, $T_B$ and $T_A$ we used climatological values derived for the period 1950-79 from COADS: R and U values were derived by A.H. Oort (personal communication), while for $T_B$ and $T_A$ we derived our own 1950-79 climatology. Representative ship speeds were taken from the shipping literature (e.g. Kirkaldy, 1919) and are the same as suggested by Folland and Hsiung (1987), and $Q_B$ values were as used by Folland and Hsiung (1987) and supplied by D.E. Parker (.personal communication, 1989). The use of climatological values can be justified by sensitivity analyses.

### *3.2 Seasonal cycles in the uncorrected data*

The gridded COADS SST data are expressed as anomalies from the appropriate 1950-79 monthly-mean field. This means that, for the base period, virtually the whole of the seasonal cycle of SST at each grid point has been removed. If the intra-annual variations at a grid point are examined for any other period, however, there will be a seasonal cycle, due partly to natural variability in the seasonal cycle and partly to the fact that instrumentally introduced “errors” also have a seasonal cycle.

To measure the magnitude of the seasonal cycle we fitted equations of the form

$$T = A\sin(\pi m/6 - \phi) \qquad (20)$$

where m is the month number (1, 2, 3.... 12) and A and $\phi$ are the best-fit values of the amplitude and phase of the annual cycle in the anomaly data obtained using standard harmonic analysis methods. These analyses were carried out using mean values over the periods 1860-79 and 1905-40, periods during which we expect the correction factors to be roughly constant.

In Figure 1 we show for 10° zones the residual seasonal cycle for the period 1905-40 (with respect to 1950-79). For this period, there is a strong residual cycle in the mid- latitude NH zones, around 20-50°N. It is this kind of spurious, instrument-based cycle that the temperature corrections have to remove, or, at least, minimize (remembering, of course, that some fraction of the cycle may be due to natural climatic change).

*3.3 Minimizing the spurious cycle*

The bucket model is now used to estimate correction factors, grid point by grid point, for a variety of exposure times up to 8 minutes. The data are then corrected and, for each exposure time, residual annual cycles are calculated. The amplitude of the residual annual cycle will depend on the assumed exposure time.

Figure 2 shows results for COADS for 1905-40. Some of these show a clear minimum in the residual seasonal cycle, representing the optimum exposure time for that combination of ship speed, wind speed fraction and latitude band. The optimum exposure time is in the range 3 to 6 minutes. There is little effect in the equatorial bands of 10°N to 10°S, but the residual seasonal cycles are weak in these regions to begin with.

## 4. Correcting SSTs using the bucket approach

*4.1 Optimum exposure time*

For 1905-40, SSTs may be corrected using the evaporating bucket model. Although average ship speed probably varied over this period, within the range of likely values ship speed does not noticeably affect the implied exposure time. We have used a ship speed of $7 ms^{-1}$. Wind speeds of 60% of the anemometer speed produce slightly better results than the 40% reduction case, and lead to slightly lower optimum exposure times (by less than 1 minute on average) so we have used this value. As the most likely exposure time lies in the range 3-6 minutes, we use 4 1/2 minutes in making final corrections.

For the nineteenth century data, the evaporating bucket model produces results which are noticeably less internally consistent compared with those for 1905-40. Based on somewhat sketchy evidence, wooden buckets were probably dominant up to 1870-1880, with a transition to un-insulated buckets occurring between then and the early twentieth century. We have assumed that canvas buckets, or their equivalent, accounted for 25% of all buckets prior to 1880, and that this fraction increased linearly to 100% in 1905. For ship speed we have used $4\ ms^{-1}$ prior to 1880, increasing linearly to $7\ ms^{-1}$ in 1905, and assumed wind speed on deck to be 60% of anemometer speed. The exposure time was kept at 4.5 minutes.

*4.2 The final correction factors*

Final correction factors depend on the location, month and year. These variations are summarized in Figures 3 to 5. Correction factors vary slightly from year to year depending on coverage changes. Figure 3 shows mean correction factors for the Northern Hemisphere. Southern Hemisphere mean corrections are shown in Figure 4. The transition from small corrections in the early decades to larger corrections after 1905 is due to the change from wooden (i.e., better insulated and assumed to require no correction) to un-insulated buckets. Correction factors are largest in the winter half year. Northern Hemisphere corrections show slightly larger season-to-season variations. Figure 5 shows how the “winter” (JFM) and “summer” (JAS) - using Northern Hemisphere seasonal labels - corrections vary with latitude. Correction factors are lower in higher latitudes in general, particularly in the 45-75°N band where the “summer” corrections are near zero. The average annual hemispheric correction factors derived are consistent with previous experimental results (James and Fox, 1972).

*4.3 The corrected SST data set*

Time series for the corrected, hemispheric-mean SST data are shown in Figures 6. For the Southern Hemisphere, the seasons are remarkably consistent. The time series also show a steady warming trend over the whole period after the mid 1900s, with no long-term trend prior to that. For the Northern Hemisphere, there is some divergence between the seasons prior to 1890. Such seasonal differences could be reduced by modifying the correction procedure, either by changing the exposure time, or by changing the assumed fraction of un-insulated buckets prior to 1905. However, this would increase the seasonal differences in the Southern Hemisphere and tend to make both hemispheric means less consistent with the land data.

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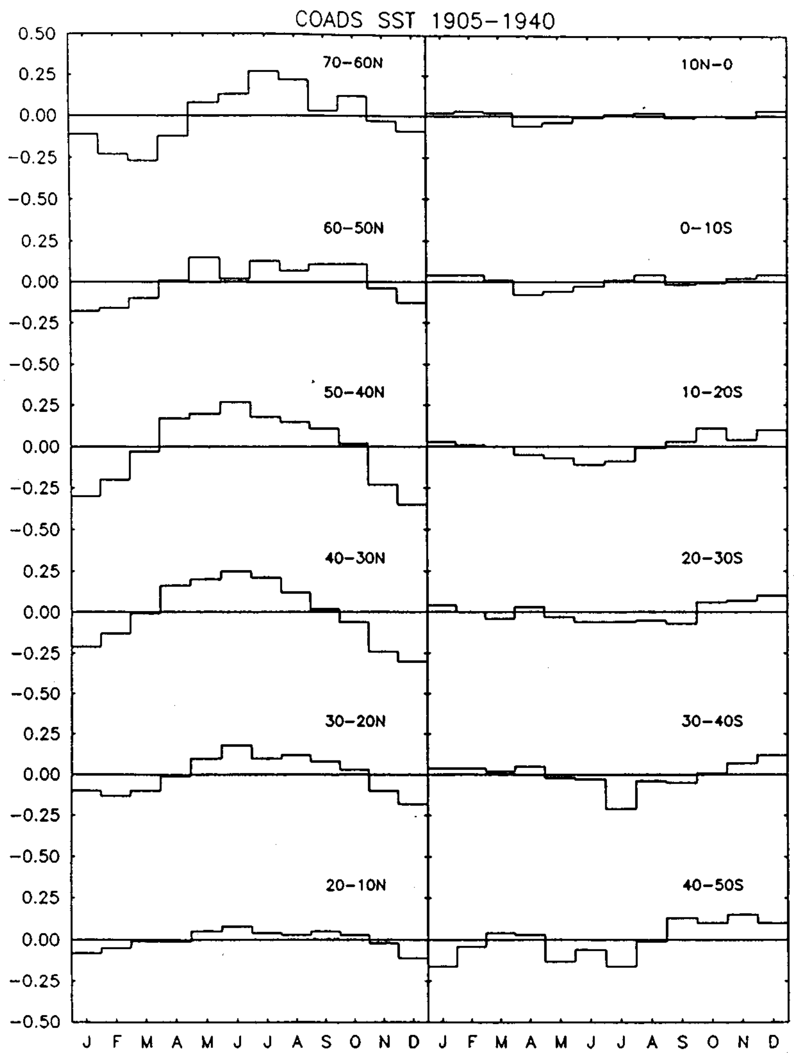


Figure 1. Mean residual (with respect to 1950-79) annual cycle for COADS SST data over 1905-40.

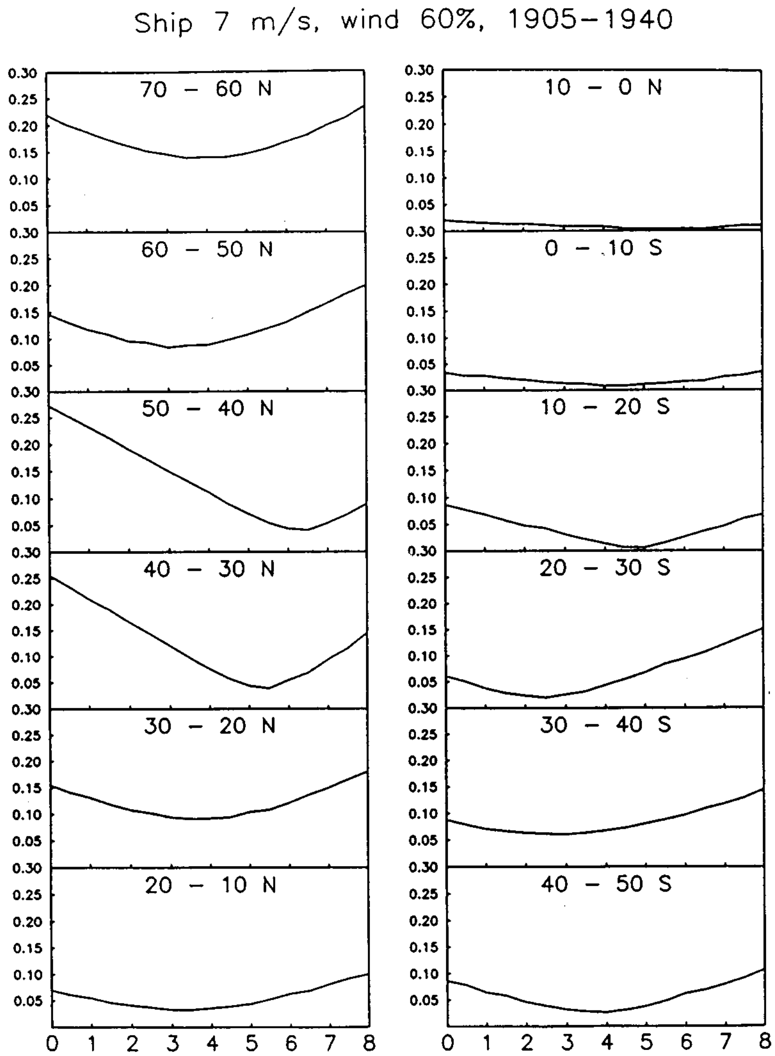


Figure 2. Minimizing the spurious annual cycle. Zonal averages for the period 1905-40 using a ship speed of 7 $ms^{-1}$, 60% anemometer wind speed. Calculated exposure times are from 0 to 8 minutes in half minute steps.

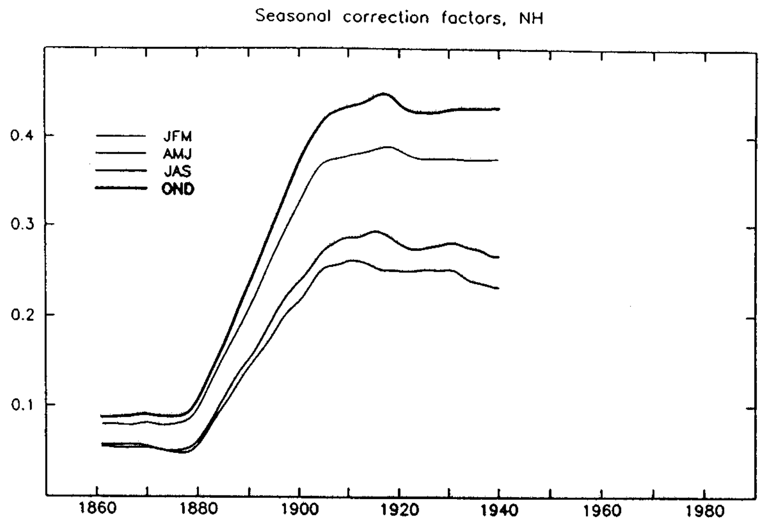


Figure 3. Smoothed seasonal bucket model corrections: Northern Hemisphere. Data are smoothed using a 10-year Gaussian filter.

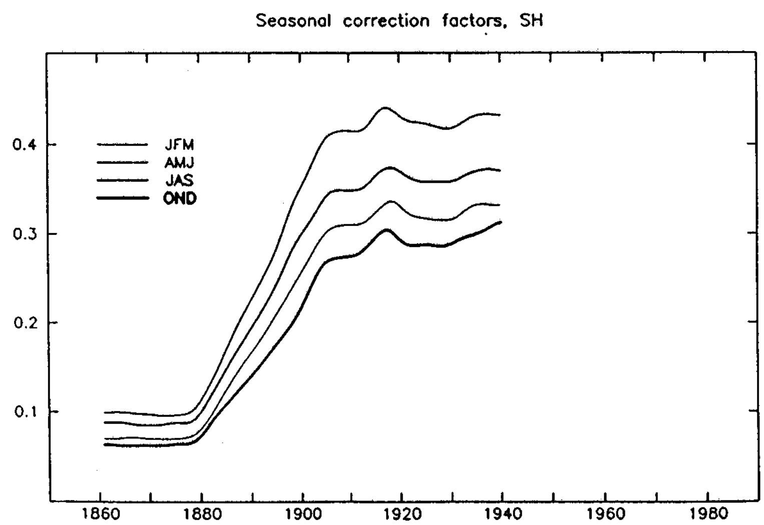


Figure 4. Smoothed seasonal bucket model corrections: Southern Hemisphere.

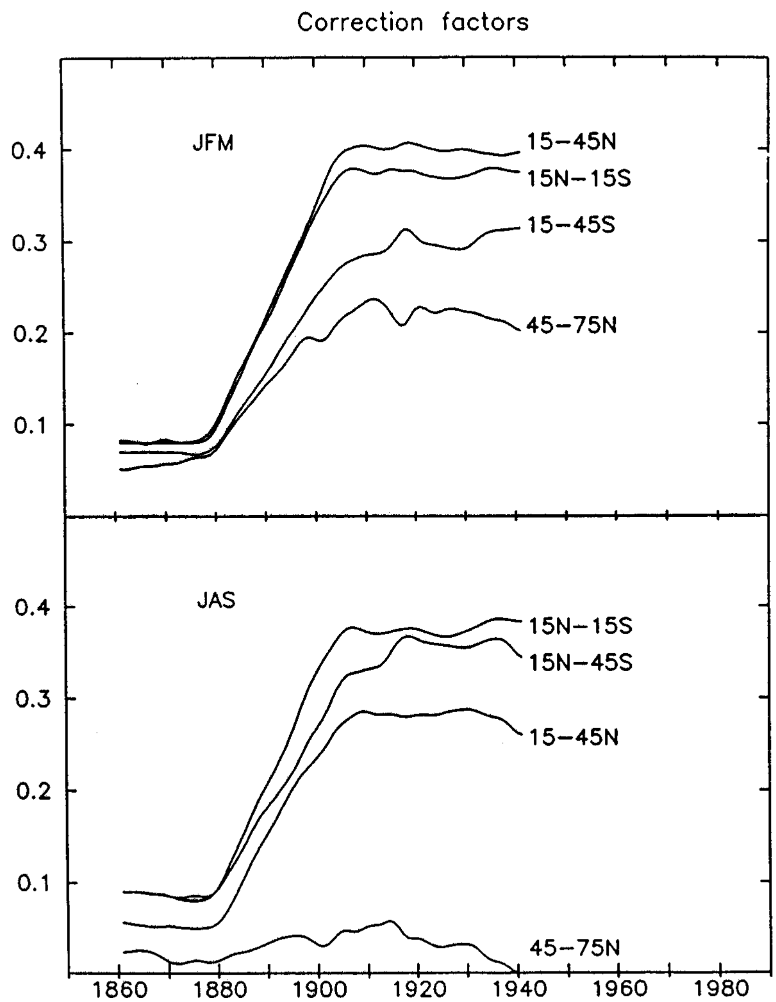

Figure 5. Smoothed bucket model corrections for various latitude zones for JFM (January-March) and JAS (July-September).

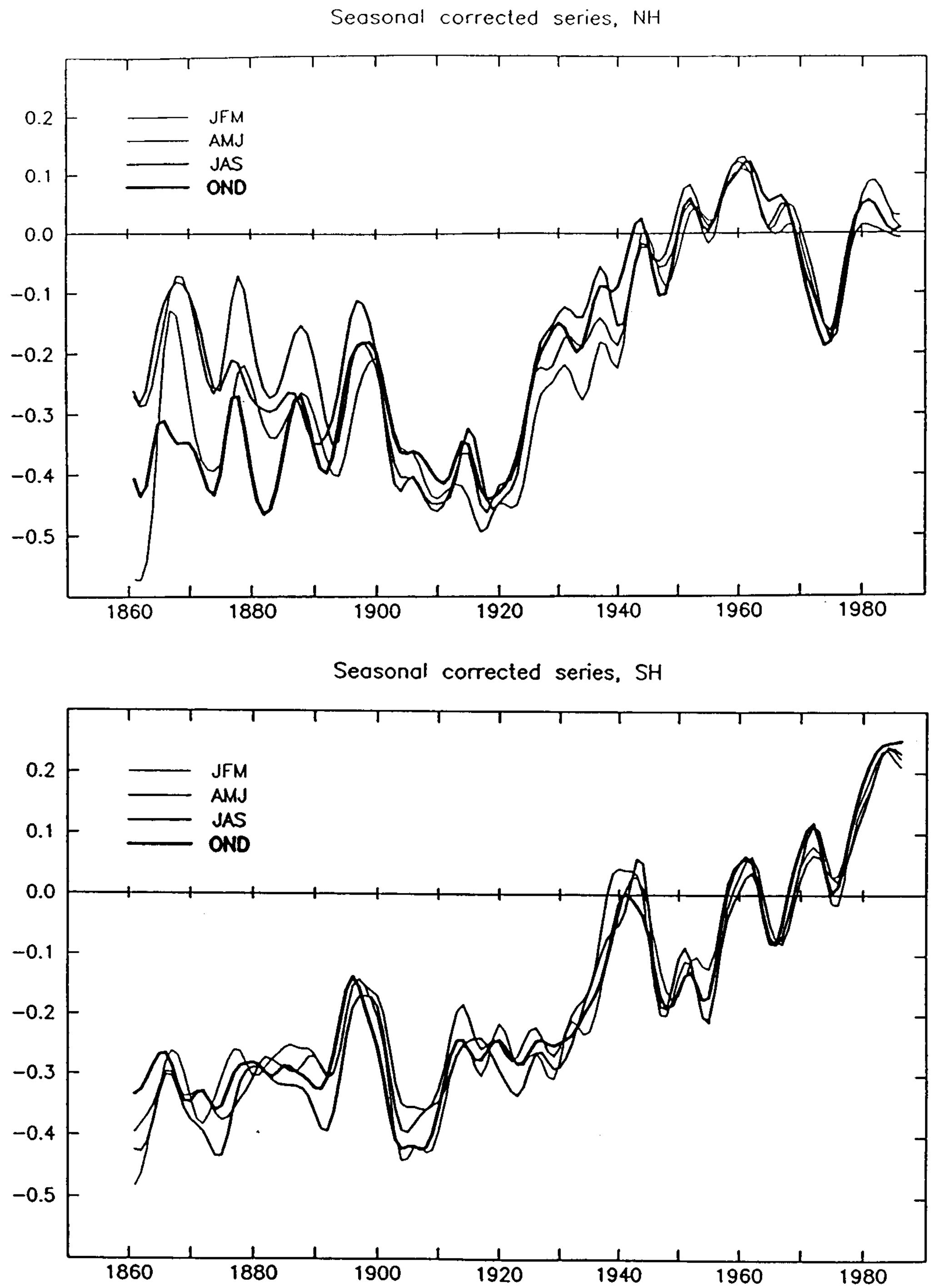


Figure 6. Smoothed seasonal COADS SST time series after bucket model corrections.