A global climatology of the diurnal variations in sea-surface temperature and implications for MSU temperature trends

J.J. Kennedy

Met Office, United Kingdom

P. Brohan

Met Office, United Kingdom

S.F.B. Tett

Met Office, United Kingdom

J.J. Kennedy, Met Office, FitzRoy Road, Exeter, EX1 3PB, United Kingdom (john.kennedy@metoffice.gov.uk)

A global climatology of diurnal variations in sea-surface temperature based on *in situ* drifting-buoy data has been created. The diurnal warming signal derived from these data correlates well with estimates from a version of the *Stuart-Menteth* [2004] model, which parametrises the diurnal cycle based on incoming short-wave radiation, wind speed and time of day, that has been modified to accept monthly inputs. An estimate is also made of the bias in estimates of tropospheric temperature derived from the Microwave Sounding Unit instruments that is due to the drift in local equator crossing time of the satellite orbits. In the tropics, this contribution is approximately 13% of the observed trend in tropospheric temperatures.

1. Introduction

Diurnal cycles in the temperature of the sea surface are an important component of the variability of sea-surface temperature. Solar heating of the sea surface in low-wind conditions can lead to the development of a stable warm layer in the top metres of the ocean and temperature excursions in excess of 3°C have been observed. Near-surface warm layers can affect air-sea fluxes and therefore models using only bulk-SST are likely to misestimate fluxes (*Schiller and Godfrey* [2005]) and diurnal variability (*Tian et al.* [2004]) in the tropics.

Diurnal warming has been observed *in situ* at a number of locations (*Stramma et al.* [1986], *Fairall et al.* [1996], *Clayson and Weitlich* [2005], *Ward* [2006]). However, these studies have all been limited in their coverage by their use of research vessel or mooring data. To overcome these limitations, a number of studies have exploited satellite data to gain a broader view of the extent of diurnal warm events, which have been shown to extend over many hundreds of square kilometres (*Stramma et al.* [1986]).

Satellite data have also provided a more global view of diurnal warming (*Gentemann et al.* [2003]; *Stuart-Menteth et al.* [2003]; *Stuart-Menteth* [2004]). Yet, infrared instruments are unable to gather data under cloudy conditions and microwave instruments have problems during heavy precipitation. In addition, satellites offer only limited sampling of the diurnal cycle due to orbital constraints. Polar-orbiters - such as the NOAA series of satellites - cross the equator twice a day at fixed local times separated by 12 hours. The crossing time changes during the satellite's lifetime, which means that the sampling of the diurnal cycle is neither continuous - only two points in the diurnal cycle are measured - nor homogeneous - the exact timing of these two points will drift. The Tropical Microwave Instrument (TMI) is in an equatorial orbit and is capable of sampling the full diurnal range at any given point. Even so, it takes 23 days to do so and SST observations are confined to the region between $40°S$ and $40°N$. Instruments placed in geostationary orbits, such as VISSR on GMS (*Tanahashi et al.* [2003]) can provide the necessary sampling of the diurnal cycle, but are still confounded by cloud in the satellite's view.

Characterisation of the diurnal cycle is valuable in a number of applications. One problem with measuring SST is that it is not a well defined quantity. Satellite retrievals measure water temperature in the upper microns of the water column, where microscopic effects such as the cool skin are important, whereas buoys and ships measure water temperature at depths between 25cm and several metres. All of these measurements are referred to as SST and each can give a biased estimate relative to the definition of SST needed for a particular application. To reconcile SST records from in situ and satellite sources it is essential to know not only how temperature varies with depth, but also how diurnal variations can affect these measurements.

Surface temperature fluctuations affect retrievals from atmospheric sounders. The drift in local equator crossing time (LECT) of the NOAA polar-orbiting satellites (*Ignatov et al.* [2004]) leads to a non-climatic trend in tropospheric temperatures as measured by the Microwave Sounding Instruments (MSU) due to changes in the sampling of the diurnal cycle of the underlying surface (*Mears et al.* [2003]).

In the analysis presented here, measurements from drifting buoys, which measure water temperature at a depth of around 25cm, were used to calculate a global climatology of diurnal temperature range (DTR) that drew on hourly *in situ* observations taken from 15 years of data between 1990 and 2004. This climatology was then used to estimate the surface contribution to retrievals of tropospheric temperatures made by the MSU series of instruments.

Section 2 describes the *in situ* data used to make the climatology. Section 3 focuses on the processing applied to extract the DTR. In Section 4 the DTR calculated in Section 3 is compared to empirical models driven by monthly-average wind and insolation fields and an estimate of its contribution to MSU tropospheric retrievals is made. There follows a brief discussion of the results and finally the conclusions of the work are presented and the results summarised in Section 5.

2. Data

Drifting buoy observations of SST made between 1990 and 1997 were taken from the International Comprehensive Ocean Atmosphere Data Set (ICOADS, *Worley et al.* [2005]). Drifting buoy observations made after 1997 were downloaded from the NCEP-GTS web site. Although drifting buoy observations were taken before 1990 as well, they were not used in this analysis because of their poor geographical coverage in the pre-1990 period.

Drifting buoy data were used in preference to SST observations taken by ships because many drifting buoys report hourly, whereas ships most often report every six hours. Moreover, ship observations are taken at a variety of depths ranging from the surface to around 25m below it (*Kent et al.* [2006]), whereas the drifting-buoy measurements are taken at a uniform depth of around 25cm. Because drifting buoys take frequent SST readings it was possible to estimate not only the size, but also the shape of the diurnal cycle.

3. Method

The aim was to use the drifting buoy data to produce a dataset that isolates the daily variations of the water temperature at a depth of 25cm and removes the inter-annual and inter-monthly variability. To this end, the observations were sorted according to the local time of the observation and separated into 24 groups containing observations taken in each hour (00:00-00:59, 01:00-01:59...). Each of the 24 sets was then processed in the following way.

The drifting-buoy data were quality controlled and processed following the procedure described in *Rayner et al.* [2006]. Each observation was turned into an anomaly relative to the 1961-90 average by subtracting the pentad climatological SST value in that 1 degree grid box and the individual anomalies were averaged on to a grid with monthly temporal resolution and a spatial resolution of $5°$ in latitude and longitude.

This process created 24 hourly fields for each calendar month between 1990 and 2004 and each field represents the average monthly SST anomaly at a different time of the day. For a single month, the average of all 24 fields was then removed from each of the 24 fields to isolate the diurnal variations, ensuring that the buoy average anomaly over all 24 hours was zero for any month. This removes the temperature difference between the 1990-2004 and 1961-1990 periods and the small cool bias due to the exclusive use of drifting buoy data in this paper.

A composite of the data from the tropics (Figure 1(a)) indicates that the empirical formula described in *Stuart-Menteth* [2004] and Equation 1 below, which describes the average shape of the diurnal cycle as a function of time as calculated from moored buoy observations, gives a reasonable fit to the data. Data from the full period (1990-2004) were averaged to give 24 hourly fields representing the climatological average at each hour of the day. At each 5° grid point, a function of the form,

$$f(t) = (a_0 + \sum_{k=1,5} a_k \cos(k\omega t) + b_k \sin(k\omega t))c_0, \tag{1}$$

was scaled to fit the 24 hourly data points by varying c_0 from location to location. $\omega = 2\pi/24\text{hr}^{-1}$, t is the local time in hours and the coefficients, a_k and b_k, are listed in Table 1. A simpler model, using only coefficients up to $k = 1$, was also fit to the data. The RMS error of the fit of this reduced model to the data was worse in all areas except the high latitudes, where the diurnal variation is expected to be small, and in a small region of the western Indian ocean, implying that the data are sufficiently accurate to describe the higher harmonics of the full model, which are used in Section 4 and Figure 1(b).

The DTR was found by taking the difference between the maximum and minimum of the fitted function. Seasonal and annual climatologies were produced. The map of annual average DTR calculated in this way is shown in Figure 2(a) along with the boreal Summer (c) and Winter (e) averages.

4. Results and Discussion

Figures 2(a), 2(c) and 2(e) depict the geographical variation of the DTR. The largest values are found in the Western Pacific Warm Pool, the summer-hemisphere subtropics and the Indian Ocean. In the Indian Ocean, the size of the diurnal cycle peaks in boreal spring (MAM, not shown), but is much reduced in the summer following the onset of the southwest monsoon (Figure 1(a)). Minima are seen in the DTR in the winter hemisphere, where wind speeds are highest and insolation is at a minimum, and in regions affected by the trade winds.

4.1. Comparison with models

Long-term average fields of monthly-average wind speed were taken from the NCEP NCAR reanalysis (*Kalnay et al.* [1996]) and monthly-averages of observed net short wave radiation were taken from the National Oceanography Centre Southampton (NOCS) flux climatology (version 1.1a, *Grist and Josey* [2003]). These were used to estimate the expected size of the diurnal cycle based on a parameterisation described in *Stuart-Menteth* [2004], which was derived from a fit to NDBC moored-buoy data. Because the model was developed using daily average wind speeds, an adjustment had to be estimated to account for the use of monthly-average wind speeds. This multiplicative coefficient was calculated using one year of daily wind speeds taken from the NCEP reanalysis. Daily values of the DTR were calculated and their monthly average was compared to the value for the DTR calculated using monthly-average wind speeds to obtain the adjustment factor.

Figures 2(b), 2(d) and 2(f) show the predicted DTR from the parametrisation. There is good agreement between the model and the data. The spatial-pattern correlation, r, is 0.67 for the annual average. Removing the 47 coastal grid boxes, out of 1362 grid boxes total, where the observed diurnal temperature range is greater than 0.7°C raises the correlation to 0.80. However, the model tends to underestimate the exact magnitude of the DTR. This may be due to the difference in depth between the data used to tune the model (1m) and the average depth of drifter measurements (25cm). The correlation varies with season and is highest in boreal summer ($r = 0.84$) and lowest in boreal autumn ($r = 0.66$). Replacing the net short-wave flux by the clear-sky downward short wave radiation leads to an overestimate of the size of the diurnal cycle suggesting that estimates of the average diurnal cycle obtained from satellite measurements under clear-sky conditions are likely to exaggerate its size.

The *Kawai and Kawamura* [2002] model based on peak solar radiation and wind speed predicts a similar geographical distribution of diurnal warming; as do the models described in *Gentemann et al.* [2003], which are derived from Pathfinder and TMI data. All these models are based on wind speed and net short wave radiation. *Smith et al.* [2001] show that the NCEP reanalysis winds tend to under- estimate wind speeds relative to research vessel measurements and *Josey et al.* [1999] suggest that there may be a low bias in the net short wave flux estimates. Both of these findings imply that there may be systematic biases in the predicted DTR, the former suggesting an overestimate, the latter an underestimate; therefore some disagreement is to be expected. Nevertheless, the models capture the major features of climatological DTR variability.

4.2. Tropospheric temperatures

Atmospheric soundings, such as those made by the MSU instruments, which measure air temperatures throughout the free atmosphere, contain a component that depends on the temperature at the surface. The Local Equator Crossing Time (LECT) of these satellites drifts by design away from local noon and hence the surface component drifts through the diurnal cycle. This is particularly noticeable in the tropics where only two overpasses, separated by 12 hours, are made each day.

To first order, the diurnal cycle can be thought of as a simple cosine function and therefore to remove its effect it would be sufficient to average observations made 12 hours apart. However, from equation 1 and Table 1 it is clear that there are significant higher-order components - chiefly the $k = 2$ component - which would not cancel in this way. Consequently, a systematic change in sampling time can add a non-climatic trend to temperature retrievals.

With the new dataset it is possible to estimate the effect of changes in LECT on the MSU temperature estimates. Other investigators have used climate models (*Mears and Wentz* [2005]) or the cross-scan views (*Christy et al.* [2003]). The former suffers from using model results driven by SSTs which have no diurnal cycle, while the latter requires unachievable accuracy in the pointing accuracy of the instrument (*Mears and Wentz* [2005]). We estimate the effect of changes in LECT on tropospheric MSU temperatures using the diurnal climatology of SST.

In the tropics the atmospheric boundary layer is at approximately 800 hPa. We assume that boundary and skin temperatures both vary throughout the diurnal cycle approximately as the climatological diurnal cycle does. It is further assumed that there is no significant diurnal cycle in the free-atmosphere - results supported for the TOGA-Core period by *Seidel et al.* [2005] (S05 from hereon). However, S05 suggest a much stronger surface diurnal cycle than we find and a smaller-than-surface DTR in the boundary layer. However, their results include several island stations as well as some research vessel data. *New et al.* [2002] find a climatological DTR of 6-8K over small and medium islands. Combining our 0.4K DTR over the oceans (5 research vessels and three atoll sites) with five island sites with a DTR of 6-8 K gives an average DTR of 2.5-3K which is consistent with the results of S05. The reduction with height found by S05 could be explained by the increased mixing of oceanic air with height over the island sites used in TOGA-CORE.

Using the assumptions above we estimate the contribution to the temperature of the low-mid troposphere (TLT) and the temperature of the mid-troposphere (TMT) as seen by the MSU instruments by integrating the TLT weighting function of *Christy et al.* [2003] from 1000 hPa to 800 hPa (0.23) and then adding the surface emissivity (0.1) to give a total of 0.33. For MT the equivalent values are 0.1, 0.05 and 0.15 respectively. This is larger than a simple weighting of the surface as it includes emissions from the boundary layer, which we assume has the same diurnal cycle as the SST.

Given the observed tropical annual-average diurnal amplitude of 0.39°C (Figure 1(a)) averaging the twice-daily retrievals would lead to a surface contribution that varies according to the LECT as shown in Figure 1(b). For the NOAA-ll satellite this contribution to the TLT retrievals would lead to a trend of −0.026°C/decade, which is 13% of the observed trend in the tropics (*Mears and Wentz* [2005]). Estimates for the other NOAA satellites are shown in Figure 1(c). Our results are an improvement on that of *Mears and Wentz* [2005] in that we only use observed data and show that LECT drift over the tropical oceans generates a non-zero trend. As general circulation models develop it will be possible to drive them with observed changes in SST and our climatological diurnal cycle and then correct for changes in LECT.

5. Conclusions

A globally-complete 15-year climatology of *in situ* diurnal sea-surface temperature variations between 1990 and 2004 was created. The data set was based on hourly data from drifting buoys and the geographical distribution of diurnal warming is in agreement with an empirical model derived from moored-buoy data.

Diurnal surface temperature variations are a significant contribution to the variability of temperatures in the lower troposphere as measured by MSU instruments. The diurnal cycle of sea surface temperatures as calculated here coupled with the slow drift in LECT of the satellites can lead to systematic misestimates of lower tropospheric tropical-temperature trends. Taking the NOAA-11 satellite as an example, this drift was shown to produce a non-climatic trend of $-0.026°$C/decade, which is approximately 13% of the observed trend. Correcting MSU data, over the oceans alone, for the effect of changes in LECT would allow other corrections to be better estimated.

Estimates of the size of the diurnal cycle from drifting buoys will allow data from different platforms to be homogenised correctly, perhaps by correction to the daily SST minimum which is representative of bulk SST. Information about the diurnal variability is also likely to be of benefit to the modeling community as well as being a climatic indicator whose variability is interesting in its own right.

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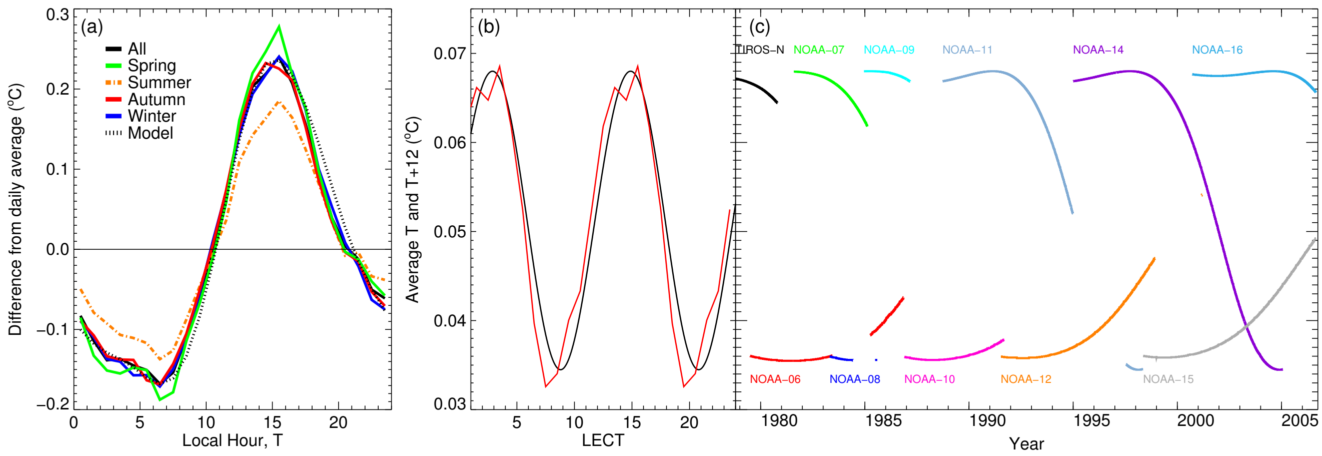

Figure 1. (a) Average diurnal cycle of SST as calculated from drifting buoy data for the Tropics 20°S-20°N. The black line shows the annual average. Also shown are spring (green), summer (orange), autumn (red) and winter (blue). A best fit to the data made using equation 1 is also shown (broken black line). (b) Contribution of the tropical ocean surface diurnal cycle to MSU TLT retrievals as a function of LECT. Results from the observed climatology are shown in red and results taken from the best fit model based on equation 1 are shown in black. (c) The drift in the contribution of the tropical ocean surface diurnal cycle to MSU TLT retrievals plotted for the 11 NOAA polar orbiting satellites.

Table 1. Coefficients for equation 1

k	a_k	b_k
$k = 0$	3.7	
$k = 1$	-2.1	-3.8
$k = 2$	0.1044	1.2
$k = 3$	-0.0759	-0.1471
$k = 4$	0.0141	-0.0159
$k = 5$	0.0278	-0.026

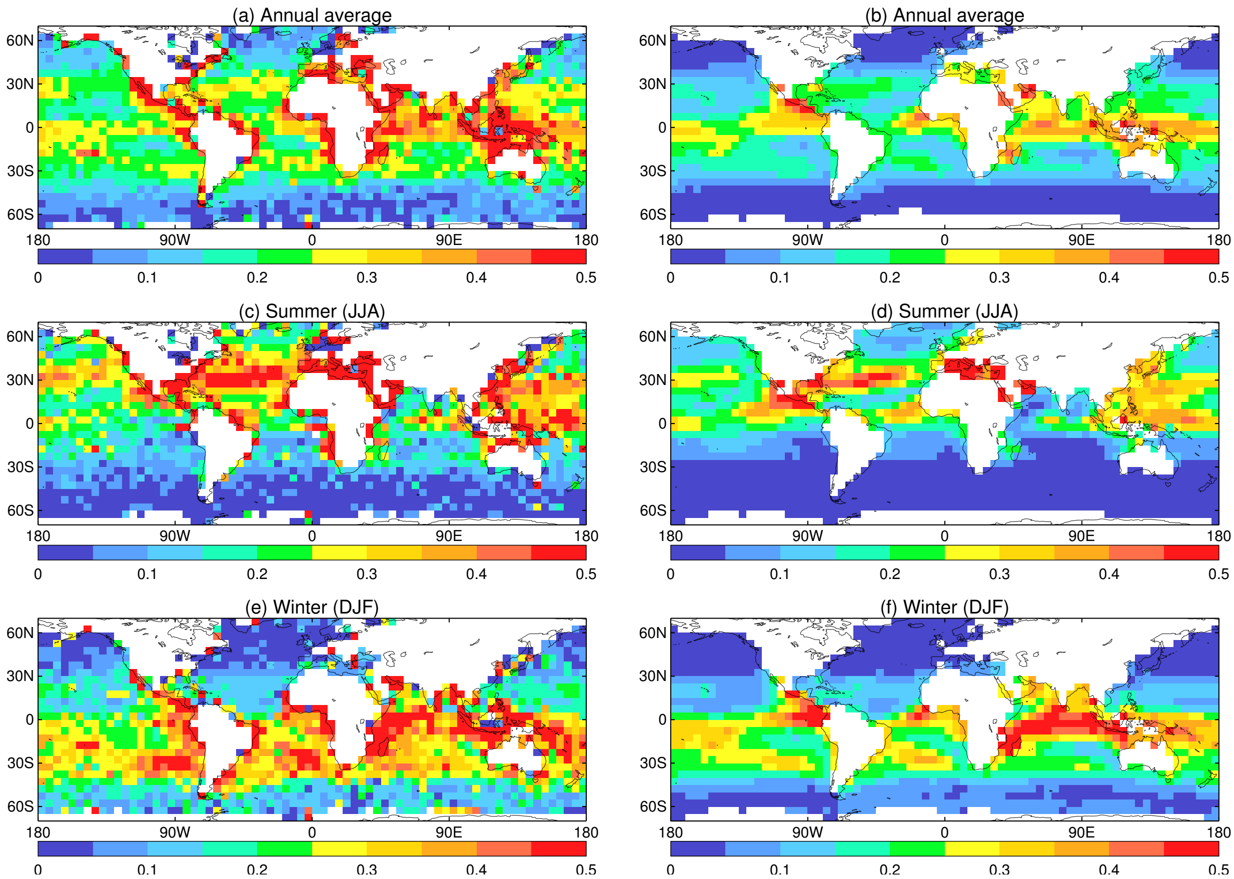

Figure 2. (left) Diurnal temperature range (°C) as calculated from drifting buoy data collected between 1990 and 2004 for (a) all seasons, (c) summer (JJA) and (e) winter (DJF). (right) Diurnal temperature range (°C) as predicted by the *Stuart-Menteth* [2004] model modified to work with monthly inputs for (b) all seasons, (d) summer (JJA) and (f) winter (DJF).