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The Effect of Diurnal Sea Surface Temperature Warming on Climatological Air–Sea Fluxes

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ABSTRACT

Diurnal sea surface warming affects the fluxes of latent heat, sensible heat, and upwelling longwave radiation. Diurnal warming most typically reaches maximum values of 3°C, although very localized events may reach 7–8°C. An analysis of multiple years of diurnal warming over the global ice-free oceans indicates that heat fluxes determined by using the predawn sea surface temperature can differ by more than 100% in localized regions over those in which the sea surface temperature is allowed to fluctuate on a diurnal basis. A comparison of flux climatologies produced by these two analyses demonstrates that significant portions of the tropical oceans experience differences on a yearly average of up to 10 W m⁻². Regions with the highest climatological differences include the Arabian Sea and the Bay of Bengal, as well as the equatorial western and eastern Pacific Ocean, the Gulf of Mexico, and the western coasts of Central America and North Africa. Globally the difference is on average 4.45 W m⁻². The difference in the evaporation rate globally is on the order of 4% of the total ocean–atmosphere evaporation. Although the instantaneous, year-to-year, and seasonal fluctuations in various locations can be substantial, the global average differs by less than 0.1 W m⁻² throughout the entire 10-yr time period. A global heat budget that uses atmospheric datasets containing diurnal variability but a sea surface temperature that has removed this signal may be underestimating the flux to the atmosphere by a fairly constant value.

1. Introduction

Although the diurnal warming of the upper ocean has been studied since the 1940s (e.g., Sverdrup et al. 1942), many of the early studies focused on the oceanographic impacts of this warming. More recently, work by groups interested in accurate determination of the sea surface temperature (SST) have focused on accurate determination of the diurnal warming in order to remove this cycle from satellite-derived SSTs (e.g., Nardelli et al. 2005). Other studies have focused on the role of diurnal SST variability on air–sea feedbacks (Lau and Sui 1997; Clayson and Chen 2002; Bernie et al. 2008). These studies have demonstrated that using a 24-hourly-mean SST or a predawn SST (roughly equivalent to a foundation SST; Donlon et al. 2007) changes prediction capability of such ocean–atmosphere-coupled phenomena as convection and the Madden–Julian oscillation (MJO) (Woolnough et al. 2007). Recent modeling studies clearly demonstrate the need to resolve diurnal SST variability even for interannual variability [e.g., Mason et al. (2012), where it is shown that not resolving instantaneous diurnal SST variability can lead to a decrease in ENSO amplitude of 15%]. Thus, evidence exists to support the contention that including the diurnal warming of the SST is a necessary component of a coupled atmosphere–ocean system. However, it is currently unclear to what extent the diurnal warming of the SST, given its extremely transient nature, may play in influencing climatological energy and water budgets.

Several researchers have estimated the change in fluxes due to the use of a diurnally varying SST, typically for very short time periods and limited areas. Schiller and Godfrey (2005) used a coupled one-dimensional ocean–atmosphere model at a mooring in the tropical

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Pacific Ocean during one week in November 1992, and found an average increase in fluxes of 10 W m\(^{-2}\). A profiler deployed in the Gulf of California for a total of 976 profiles showed net heat flux errors of up to 60 W m\(^{-2}\) were possible when using the bulk rather than the skin temperature (Ward 2006). Instantaneous errors in the tropical net heat flux associated with ignoring the diurnal warming have thus been noted, but no global ocean estimation using data has so far been described.

In this work a global reconstruction of diurnal SST warming based on satellite inputs of wind speed, solar radiation, and precipitation is used. Satellite-derived estimates of the near-surface winds, air temperature, and humidity are used to estimate the latent heat, sensible heat, and upwelling longwave fluxes using an SST with and without diurnal warming over the 10-yr period from 1998 through 2007.

2. Data description

This analysis uses the parameterization of diurnal warming of the SST (here called dSST) as found in A. S. Bogdanoff and C. A. Clayson (2013, unpublished manuscript). This is an updated version of the regression-based parameterization of Webster et al. (1996), which required daily peak solar radiation, daily-averaged wind speed, and daily precipitation. In this version of the parameterization, the length of day, initial SST, and first-guess turbulent and radiation flux are also considered. Studies using the earlier version of the parameterization include Clayson and Weitlich (2005, 2007) and Kawai and Kawamura (2002). Formulations similar to the earlier version of the parameterization include Price et al. (1986), Kawai and Kawamura (2002), and Gentemann et al. (2003).

The surface solar radiation is derived from the National Aeronautics and Space Administration (NASA)/Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB), release 3.0 dataset (Gupta et al. 2006). The near-surface winds, air temperature, and humidity are derived from the SeaFlux V1 dataset, which uses an adjusted version of the NASA Cross-Calibrated Multiplatform (CCMP) winds (Atlas et al. 2011) and the Roberts et al. (2010) algorithm for determining these quantities from the Special Sensor Microwave Imager (SSM/I) instruments.

The base SST product is the Reynolds Optimally Interpolated, version 2, using the Advanced Very High Resolution Radiometer (AVHRR) only (Reynolds et al. 2007). Since the Reynolds SST is used at sunrise as the non-diurnally varying SST, the base SST product is linearly interpolated from sunrise to sunrise. The diurnal variability in the uppermost portion of the ocean is parameterized using the methodology of A. S. Bogdanoff and C. A. Clayson (2013, unpublished manuscript), an update of the Clayson and Curry (1996) parameterization, allowing for the creation of a 1-hourly SST product. Both of the two SST datasets in this study use the same atmospheric parameters (as described above) and the same bulk flux parameterization [a neural network version of the Coupled Ocean–Atmosphere Response Experiment (COARE) 3.0 algorithm; Fairall et al. (2003)]. The SeaFlux product contains 3-hourly-average atmospheric fields and thus resolves diurnal atmospheric variability. Upwelling longwave radiation is calculated using the Stefan–Boltzmann law and a constant emissivity of 0.984 (Konda et al. 1994). The results of using an alternative approach that compares daily-averaged SST instead of the non-diurnally varying SST are shown in appendix A.

3. Instantaneous flux variability

An example of the dSST for one day (1 June 2005) is shown in Fig. 1. Note that the peak values presented on this day are near 3°C. However, conditions on other days can realize differences of up to 7°C. At very low wind speeds (where the satellite winds are most uncertain) small overestimations in the winds can substantially decrease the dSST, and thus it is possible that the dSST is underestimated in some highly localized low-wind-speed regimes. As noted by Merchant et al. (2008), the highest diurnal-warming events require sustained low winds, which may mitigate the effect of instantaneous satellite-retrieved wind errors. Gentemann et al. (2008) estimated that for instantaneous wind speeds of less than 1 m s\(^{-1}\) diurnal-warming events larger than 5°C occur 0.5% of the time. As a result, the flux field differences are likely a conservative assessment.

Estimated diurnal variability from Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) satellites is also shown in Fig. 1, in which the variability is estimated by comparison of two satellite passes at different times in the diurnal cycle (M. Filipiak 2010, personal communication). The localized and synoptic features of diurnal warming from the diurnal-warming parameterization are consistent with these observations, with noted underestimations at the very high values. An examination of typical length scales of diurnal warming in the western Mediterranean Sea and European shelf seas from satellite data by Merchant et al. (2008) also demonstrated the typical localized extent of the diurnal-warming events, with even moderate diurnal-warming (∼2°C) events having horizontal length scales on the order of only 60 km. As the magnitude of the diurnal-warming event increased, the horizontal length
A sample day’s difference between the affected heat fluxes is shown in Fig. 2. The patterns of the differences in the flux fields follow the diurnal-warming patterns exactly; regions where the sun is below the horizon have zero differences. Over much of the sunlit region, the differences are still small as the diurnal warming is low (due to clouds and/or relatively strong winds).

In regions where the diurnal warming reaches 1°C or more, instantaneous errors in the sensible heat flux can be greater than 10 W m\(^{-2}\) (as much as 100% of the non-diurnally varying flux). Overall error magnitudes are greater for the latent heat flux (localized differences can reach 60 W m\(^{-2}\) or more, as much as 50% of the total flux). It should be noted that this also means an equivalent difference in evaporation rates (i.e., up to 50% locally).

The longwave flux differences are generally on the same order as the sensible heat flux differences (maxima in the 10–15 W m\(^{-2}\) range), but as a percentage of the upwelling longwave flux are very small.

A flux dataset that does not include the existing diurnal variability is missing salient physics of the system. It was in recognition of this fact that the COARE algorithm (Fairall et al. 1996) includes a diurnal-warming effect, such that if observations below the surface were used for the SST, a correction can be made. Figure 3 shows the maximum difference during the 10-yr dataset between fluxes using diurnally varying SST and those without. Maximum errors surpass 300 W m\(^{-2}\), and there is some coherence to the regions of maximum flux difference. In addition to the large flux differences of the tropical western Pacific and Indian Oceans, as expected, the influence of frontal regions are clearly present, such
as the Gulf Stream region, the Labrador Current, and the Agulhas Current eddy region.

4. Seasonal, yearly, and decadal fluxes

The seasonal averages of the flux differences for 1998–2007 are shown in Fig. 4. Spatial patterns between the latent heat flux (generally 50%–70% of the total difference in the tropics, and 30% or less in higher latitudes, where the sensible heat flux difference can reach 50% of the total) and total heat flux are very similar. Several seasonal effects can be seen in these figures. In an analysis of the tropical diurnal SST warming, Clayson and Weitlich (2007) showed that the most dominant mode of variability in the Atlantic and Pacific basins was the seasonal shifting of the sun. In the Indian Ocean, this was the second most dominant mode of variability, with the first being related to the monsoonal cycle. In both the Atlantic and the Pacific the second mode of variability was an east–west dipole, with the western (eastern) portion of the basin being consistently higher (lower) in diurnal warming in the later (earlier) part of the calendar year. These patterns are evident in the seasonal variability of the fluxes due to diurnal warming shown here.

The average error associated with using a nondiurnally varying SST to calculate the surface fluxes over the global oceans, over all seasons, is shown in Fig. 5. Values over 5 W m$^{-2}$ lie almost entirely between the Tropics of Capricorn and Cancer, testifying to the primacy of the
seasonally varying solar radiation in determining the multyear-mean diurnal-warming response. Between those latitudes, the magnitude of the flux error is primarily determined by the differing solar radiation and wind fields associated with global atmospheric circulation patterns, as well as more regional climates.

5. Summary and discussion

Over the 10 years of this dataset, our estimate of the globally-averaged error in flux calculations between the ocean and atmosphere due to neglect of the diurnal SST warming is roughly 4.5 W m\(^{-2}\), which varies by only 0.1 W m\(^{-2}\) over these 10 years (as can be seen in Fig. 5). Thus, even though there can be substantial differences in monthly averages in specific locations (as shown by one typical year-to-year monthly difference in Fig. 5), at least during this time period the net result of these changes on the total error is very small. On an instantaneous basis, the total error from neglecting diurnal SST warming in localized regions can exceed 200 W m\(^{-2}\). The magnitude of the impact of the inclusion of a diurnally varying SST depends on several factors: the atmospheric conditions that create high diurnal warming (a combination of high solar insolation, a long length of day, light winds, and possibly morning precipitation) and the atmospheric boundary layer characteristics such as the air temperature and humidity that affect the stability and air–sea humidity difference.

The global error estimate is a measurable fraction of the recent estimates of the uncertainty or imbalance in the global annual atmospheric energy balance. In Lin et al. (2008), multiple satellite datasets of the top-of-atmosphere (TOA) and surface fluxes were used to analyze the global energy balance. The radiative and surface turbulent flux datasets used in Lin et al. (2008) are calculated from daily averages of the atmospheric properties, but the SST from the Goddard Satellite-based Surface Turbulent Fluxes (GSSTF) products is based on the Reynolds and Smith (1994) dataset, which is not a true daily-averaged value (see appendix A). Their estimated imbalance in the surface energy budget was on the order of 9 W m\(^{-2}\) (within the range of uncertainty of the datasets but only slightly larger than our estimated error of 4.5 W m\(^{-2}\)). In a more recent study including diurnal variability, Stephens et al. (2012) concluded that uncertainties in the surface energy balance were approximately ±21 W m\(^{-2}\).

The water budget is affected through the latent heat flux, which had an average error of 2.87 W m\(^{-2}\), an evaporation rate of 1.88 \times 10^{16} \text{ kg yr}^{-1}, or roughly 4% of the global-average oceanic evaporation. Note that this amount is larger than one estimation of the global ocean evaporation increase over the same time periods at 1% yr\(^{-1}\) (e.g., Schlosser and Houser 2007), but this error does not change over the time period of this dataset.

The effect of not including the diurnally varying component of the SST, as it relates to the surface heat budget on a regional scale, can be established by a comparison of an estimate of the annual-mean sea surface heat budget (e.g., Lin et al. 2008) with the average climatological error induced by omitting diurnally varying SST. Regions such as the eastern tropical Atlantic and Pacific have sea surface heat budgets of greater than 60 W m\(^{-2}\) (and even higher in the cold-tongue region), such that an error of 10 W m\(^{-2}\) may constitute at most a 10%–15% error in the fluxes. However, the western tropical Pacific has an annual surface heat budget of less than 40 W m\(^{-2}\) in many regions in which the dSST error...
reaches 8–10 W m\(^{-2}\), which can be 25% of the budget. In parts of the Arabian Sea, which has increases of fluxes from diurnal warming of nearly 10 W m\(^{-2}\), the sea surface heat budget is less than 40 W m\(^{-2}\), so omission of the dSST-induced flux can account for errors of up to 50%. Likewise, the Bay of Bengal is a region in which the omission of the dSST-induced flux can be a substantial error compared to the total sea surface heat budget.

The goal of a 10 W m\(^{-2}\) accuracy in fluxes has been cited by multiple authors, including Webster and Lukas (1992) and Curry et al. (2004), for both the tropical oceans and the global ocean. A recent study by Roberts (2011) evaluated this requirement quantitatively, with
FIG. 5. (top) A 10-yr average of the difference in surface fluxes calculated using the diurnally varying SST and a nondiurnally varying SST (as in previous figures, positive values indicate an underestimate of the fluxes from the nondiurnally varying SST). Contour lines are at 5 and 10 W m$^{-2}$. (middle) The monthly-averaged total heat flux difference between the diurnally varying SST and the nondiurnally varying SST from 1998 through 2007. (bottom) The difference between August 2004 and August 2005. Positive (red) values indicate more diurnal warming in 2005 than 2004.
a focus on the seasonal SST. In the Roberts study, data sources were combined from a number of available satellite and model analyses in order to evaluate all terms in the mixed-layer heat budget. An estimate of the flux accuracy for producing errors in SST that are less than one-half the peak-to-trough variability in seasonal SST was calculated (Fig. 6). Over nearly the entire tropical oceans, omitting the diurnally induced fluxes can lead to errors of 25% or more of the accuracy needed to produce a reasonable seasonal signal. The tropical western Pacific is particularly sensitive, with the error reaching more than 100% of the required accuracy. Omitting the diurnally induced flux can induce errors of more than 50% throughout the entire tropical warm pool. These high impacts are due to the collocation of the most sensitive regions in the tropical oceans to heat flux error with those regions where the diurnally induced fluxes are the highest.

This study specifically isolates the impact of diurnal variability (and by implication the ocean processes that drive this variability) on the surface energy balance. Inclusion of a diurnally varying SST product in turbulent flux calculations affects both instantaneous and average fluxes. For accurate flux calculations, the appropriate SST must be used, as a bulk SST at an ambiguous depth may resolve only a portion of the interfacial diurnal variability. Overall, more care on the treatment of SSTs within flux calculations and products is necessary to provide the best possible estimate of the sea surface energy and moisture budget.

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APPENDIX A

Daily-Averaged SST

A daily-averaged SST by implication describes a mean value that has been taken from an SST that resolves the diurnal cycle. This is inherently different from a predawn SST, which is the temperature that a well-mixed layer cools to prior to the sunrise. The predawn SST is analogous to a foundation SST (Donlon et al.
2007), which is defined as the depth at which diurnal warming is not present. A number of satellite SST products explicitly remove the effects of the diurnal warming from their analysis, such as the AMSR product from Remote Sensing Systems. Flux products that use SSTs from the Reynolds and Smith (1994) data or later incarnations (Reynolds et al. 2007) are using a product that is not a true daily-averaged SST, since the original data do not resolve the diurnal cycle.

It should be noted, however, that the picture is slightly more complicated by the optimal interpolation (OI) analysis that is used by Reynolds et al. (2007) and the use of the regression against a 7-day buoy value. According to Reynolds et al. (2007), “This selection ignores the diurnal cycle, which cannot be properly resolved using only one polar-orbiting instrument. Furthermore, as discussed in section 3 all satellite data are bias adjusted relative to 7 days of in situ data, which further reduces any diurnal signal. Thus, the OI analysis is a daily-average SST that is bias adjusted using a spatially smoothed 7-day in situ SST average.” The in situ data are taken from ships and buoys typically at 1-m depth or deeper, which substantially reduces the amount of diurnal warming as compared to the surface (e.g., Clayson and Chen 2002). Thus, it is difficult to support with certainty the idea that the Reynolds product is a true daily average of the surface temperature.

For comparison purposes, the mean difference between using a diurnally varying SST and a “true” daily-averaged SST on the fluxes for the time period of 1998–2007 is shown in Fig. A1. The true daily-averaged SST is a daily average of the hourly SST field. The total global-average difference is 1.21 W m$^{-2}$. Thus, if models or data sources provided an accurate SST that resolved the diurnal cycle the implication is that using a daily-averaged SST to calculate the fluxes would limit the climatological error to a little over 1 W m$^{-2}$ (although local instantaneous differences are nearly on the order of those shown for using the predawn or deeper mixed-layer temperature, and would be expected to produce different air–sea couplings and resultant ocean mixing). The noted difference of the effect of using the diurnally averaged SST flux is to be expected given the nonlinearity of the fluxes and the diurnally varying nature of the atmospheric boundary layer characteristics. The increase in effects due to using a diurnally varying SST is seen roughly everywhere except for the high-latitude regions. Regions with the highest differences are the western boundary current regions (particularly the Gulf Stream) and the ITCZ.

**APPENDIX B**

Parameterization Update

The diurnal-warming parameterization used to produce the diurnally varying SSTs is based on the Clayson and Curry (1996) formulation, as used in multiple studies (e.g., Clayson and Weitlich 2007). A comparison of the original formulation with in situ buoys was performed in Clayson and Weitlich (2007) and showed mean biases in the tropical Atlantic and Pacific of less than 0.0015°C, with standard deviations of roughly 0.25°C. The original formulation used a simple sine curve to fit
the diurnal SST variability and had no dependence on the length of day. In addition, the regression to the original model data was not entirely smooth, leading to small discontinuities in the calculated diurnal warmings, as well as underestimations at the very low wind speed conditions. The updated formulation removes these inadequacies. On an instantaneous basis this can lead to locally large differences in the flux estimates from the original version. However, for the climatological values discussed in this paper, the mean global-average difference in fluxes for the 10-yr time series between the previous and updated diurnal-warming parameterization is 0.03 W m\(^{-2}\). The differences are mainly zonal (Fig. B1), because the original parameterization was developed assuming a 12-h day. In addition, regions of very low winds such as the tropical western Pacific show a reduced effect in the new parameterization. The year-to-year differences as well as the seasonal differences (not shown) and the mean values as discussed in the body of the paper are quite consistent between the two datasets.

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