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Direct observations of Skin-Bulk SST variability

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Abstract. Skin sea-surface temperatures from the first Along Track Scanning Radiometer (ATSR) are compared with coincident bulk temperatures from the Tropical Atmosphere Ocean (TAO) moored buoy array in the equatorial Pacific Ocean. The response of the skin–bulk sea-surface temperature difference (ΔT) to variations in wind speed and surface heat flux is examined. The use of remotely-sensed skin temperatures for this purpose is enabled by ATSR's unique design which permits the independent retrieval of ocean skin temperature to an accuracy of 0.3 K. For the four-year period considered (August 1991–August 1995), almost 6000 coincident skin and bulk sea surface temperature (SST) measurements were available; at night, the mean value of ΔT is -0.20 ± 0.46K, with a daytime mean value of $+0.05\pm0.51$ K. ΔT is found to depend on both net heat flux and local wind speed as predicted by the *Saunders* [1967] model and other formulations, and an estimate of the Saunders λ parameter is obtained.

1. Introduction

Satellite infrared radiometers sense the radiant temperature of the ocean skin, whereas bulk SST as measured from ships and buoys is representative of the uppermost few meters of the water column. Skin SST is typically 0.1 – 0.5 K cooler than the immediate sub-surface water, although considerable variation in the skin–bulk difference has been observed [*e.g. Donlon et al.*, 1999]. This temperature difference is due to the vertical heat flux through the thermal boundary layer in the top millimeter of the ocean; net surface heat flux is almost always from ocean to atmosphere, resulting in a cool ocean skin. Total heat flux at the sea surface is the sum of net infrared, sensible and latent heat flux, and in daytime a contribution from the small proportion of incoming solar radiation absorbed in the skin layer. Heat transfer through the boundary layer is predominantly due to molecular conduction, as turbulent transfer is suppressed by the density difference across the ocean-air interface. The magnitude of this skin effect increases both with net surface heat flux and the thickness of the conduction layer [*Saunders*, 1967]. Wind speed influences the skin effect in two competing ways: increasing wind speed increases total surface heat flux which tends to increase the skin effect, but also thins the conduction layer, which tends to reduce the skin effect. Generally it is predicted that the magnitude of the skin effect will increase with net surface heat flux (Q) at a given wind speed (u) and decrease with increasing wind speed for a given heat flux. For example, *Saunders* [1967] and *Hasse* [1971] predicted a relationship approximately of the form $\Delta T \propto Q/u$, whereas *Wick et al.*, [1996] predicted a $Q/u^{0.25}$ dependence (both appropriate in conditions of forced convection where $u > 2\,\mathrm{m\,s^{-1}}$). In a comparison of skin effect parameterizations based on shipborne data, *Kent et al.*, [1996] reported the Saunders model best reproduced the observed skin effect variability in the wind speed range 3–7 m s^{-1}.

In this study, skin SSTs are compared with bulk SSTs measured at 1 m depth. Thermal stratification of the near-surface ocean develops in conditions of high insolation and low wind speed. This diurnal thermocline can be considerable, and surface temperatures several Kelvin warmer than water at 1 m depth have been observed on calm sunny days [*Fairall et al.*, 1996a]. After dusk, any diurnal thermocline is eroded by convective overturning, and for ATSR nighttime observations at a local solar time (lst) $\sim$ 22.30, the top meter of the ocean is well mixed, and the measured skin–bulk SST difference is due solely to the skin effect. However for daytime observations, particularly at low wind speed, the difference between skin and 1 m bulk SSTs will be due to both the diurnal thermocline and the skin effect.

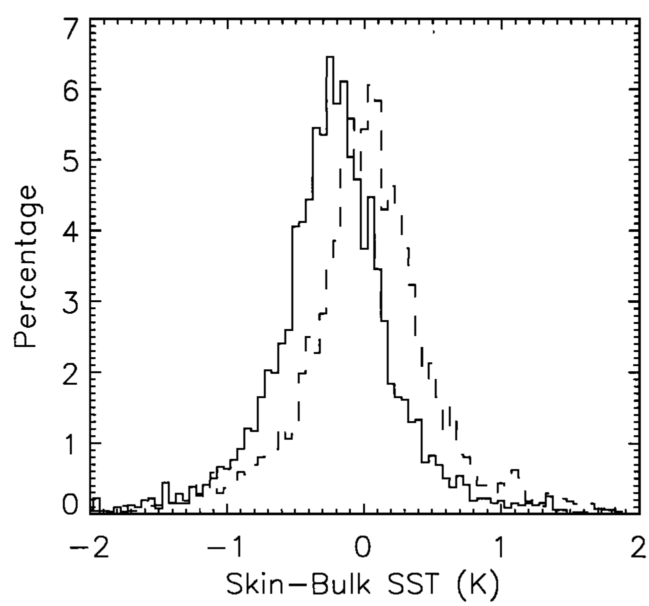

Figure 1. Histogram showing distribution of ΔT for nighttime (solid line) and daytime (dashed line) data.

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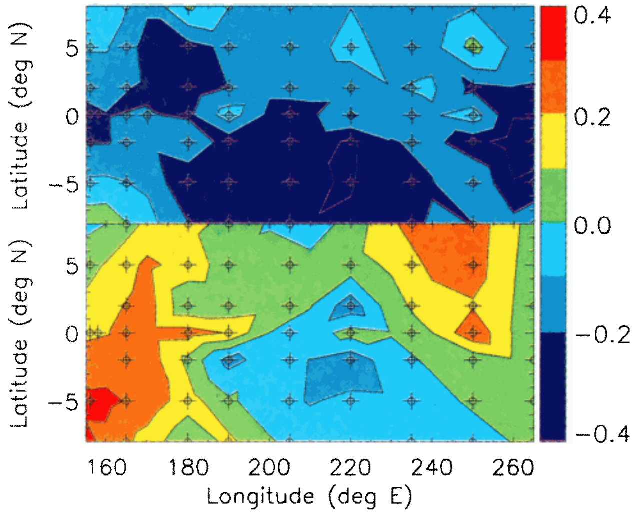

Figure 2. Geographic variation of ΔT for nighttime (upper), and daytime (lower) observations. This is based on mean ΔT for those buoy positions which provided more than 20 matchups. Buoy positions are indicated with a crossed circle.

2. Data

ATSR on board ESA's ERS-1 satellite, is a dual-view, self-calibrating, infrared radiometer with channels at 1.6, 3.7, 10.8 and 12.0 μm; this instrument delivered an independent record of global skin SST between August 1991 and July 1996 [*Mutlow et al.*, 1994; *Murray et al.*, 1998a]. ERS-1 is in a sun-synchronous orbit with day and night overpasses around 10.30 and 22.30 lst. Skin SST is retrieved by taking the linear sum of thermal brightness temperatures with associated coefficients derived from a radiative transfer model [*Zavody et al.*, 1995]. Only dual-view, 11 and 12 μm data were used for SST retrieval in this study (due to the limited availability of 3.7 μm data). The coefficient set used is a version of the *Merchant et al.*, [1999] aerosol-robust coefficients, modified to account for the ATSR detector temperature variation; comparison with AVHRR and buoy SSTs has shown the retrieved SSTs are accurate to better than 0.3 K [*Murray et al.*, 1998a, b; *Merchant and Harris*, 1999].

Hourly-averaged bulk SSTs measured at 1 m depth to an accuracy of 0.03 K, together with measurements of near-surface wind speed, air temperature, and relative humidity were available from the TAO buoy network [*Freitag et al.*, 1994]. Total (non-solar) heat fluxes were derived from the TAO data using the *Fairall et al.*, [1996b] formulation. For the four years of data considered, there were a total of 5947 cases where an ATSR SST and a collocated TAO measurement within one hour were available. For ~ 1% of these matchups, the skin–bulk difference exceeded 2 K and these data were excluded as likely to be compromised by cloud contamination or other problems, leaving 3157 nighttime and 2724 daytime matchups. Nominal buoy positions were always at the corner of four ATSR ten-arcminute cells, thus an ATSR SST represents the mean of between one and four measurements, each covering ~18 km×18 km.

3. Results and Discussion

Figure 1 shows the distribution of ΔT for both nighttime and daytime conditions. Nighttime data exhibit a mean $\Delta T = -0.20 \pm 0.46$ K, and in daytime $\Delta T = +0.05 \pm 0.51$ K. Figure 2 shows the geographic variability of observed ΔT. A ubiquitous and fairly-uniform cool skin prevails at night, whereas daytime ΔT is subject to considerable geographic variation. Considering only the western Pacific, gave nighttime $\Delta T = -0.18 \pm 0.20$ K ($n = 399$) and daytime $\Delta T = +0.20 \pm 0.26$ K ($n = 323$). This nighttime value is in close accord with the value of −0.2 K previously reported for this region [*Webster et al.*, 1996]. The increased daytime ΔT is associated with the enhanced diurnal thermocline due to the light wind conditions characteristic of the western Pacific warm pool [*Fairall et al.*, 1996a].

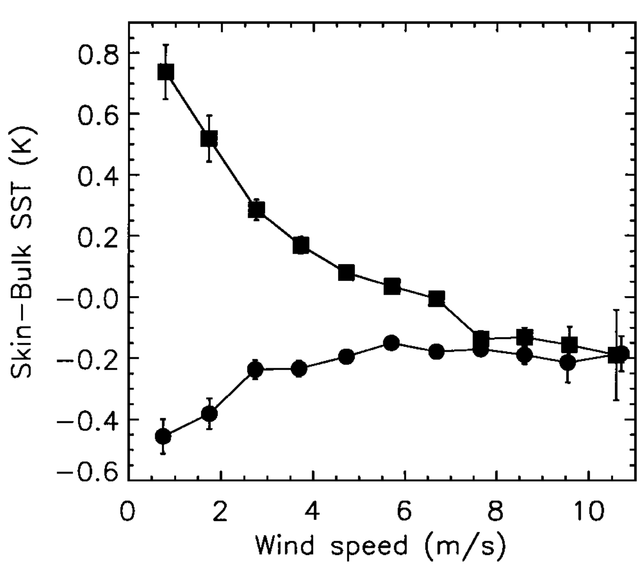

Figure 3. Response of ΔT to wind speed (with wind speed binned into 1 m s^{-1} intervals) for nighttime (circles), and daytime data (squares); the standard error in ΔT is shown.

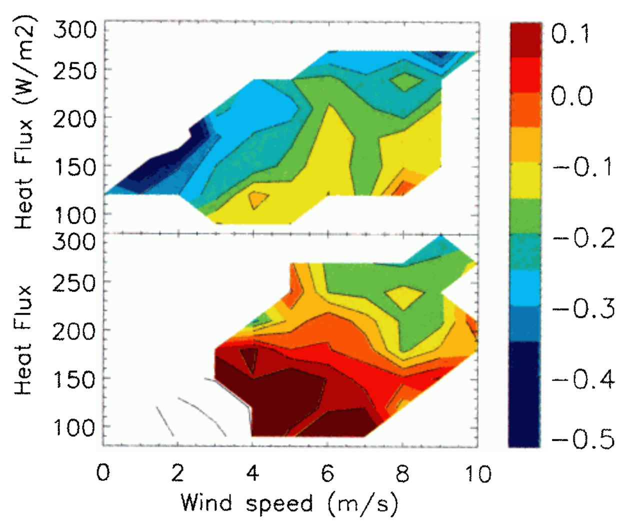

Figure 4. Contour plot of ΔT as a function of wind speed (binned into 1 m s^{-1} intervals) and total (non-solar) surface heat flux (binned into 30 W m^{-2} intervals) for nighttime (upper) and daytime data (lower). Heat flux is positive from ocean to atmosphere. Due to the large sample size, errors associated with the ΔT contours are less than 0.05 K for the entire data region.

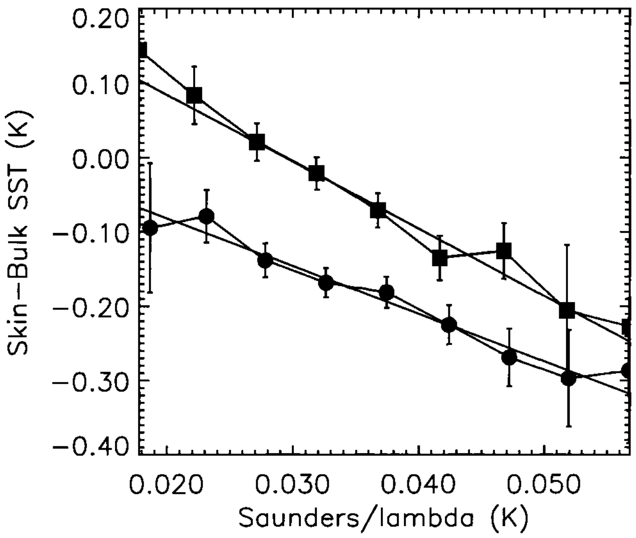

Figure 5. ΔT as a function of Saunders predicted ΔT with λ set to unity, for nighttime data (circles) and daytime data (squares). In this representation the λ parameter is given by the gradient, which is determined by a least-squares fit to individual data (although only the means of nine bins are plotted.)

Figure 3 shows ΔT against wind speed for both nighttime and daytime conditions. At night, the largest skin effect (most negative ΔT) is associated with lowest wind speeds, becoming smaller with increasing wind speed, and stabilizing around -0.2K at wind speeds above $4\,\mathrm{m\,s^{-1}}$. This behaviour suggests that in the range 4–10$\,\mathrm{m\,s^{-1}}$, the increase in sensible and latent heat flux associated with increasing wind speed, balances the effect of the wind-induced thinning of the conduction layer, rendering ΔT fairly independent of wind speed. However, at low wind speed, net longwave heat flux, which is insensitive to wind speed, is a significant fraction of surface heat flux, and the thinning of the conduction layer concomitant with increasing wind speed is the dominant effect. For daytime data, in conditions of very low wind speed ($\sim 1\,\mathrm{m\,s^{-1}}$), differential warming in the near-surface ocean leads to mean surface temperature approximately 0.8 K warmer than water at 1 m depth, as might be expected at ~10.30 lst. As wind speed increases, the top layer of the ocean is mixed, and ΔT rapidly decreases, then stabilizes close to zero in the wind speed range 4–7$\,\mathrm{m\,s^{-1}}$ as discussed below. At higher wind speeds, ΔT approaches the nighttime mean value of -0.2 K The ocean skin is expected to be destroyed by wave breaking at wind speeds above $\sim 10\,\mathrm{m\,s^{-1}}$; such conditions rarely coincide with clear skies, therefore insufficient matchups are available to confirm a transition to negligible ΔT at high wind speed. Figure 3 suggests that for validation purposes, in the absence of heat flux estimates, tropical skin SST measurements should be compared to bulk SST measurements only in conditions of moderate to high wind speed. Specifically, a skin–bulk adjustment of ~ 0.2 K is appropriate in daytime when $u > 7\,\mathrm{m\,s^{-1}}$, or at night when $u > 4\,\mathrm{m\,s^{-1}}$. *Donlon et al.,* [1999] reached a similar conclusion based on shipborne data which covered a much larger range of weather conditions.

Figure 4a is a contour plot of ΔT as a function of both wind speed and net heat flux for nighttime data. For a given wind speed, the skin effect increases (ΔT becomes more negative) with increasing heat flux, and for a given heat flux, the skin effect is reduced with increasing wind speed. This provides a clear demonstration of the individual influences of heat flux and wind speed on the skin effect. *Wick et al.,* [1996] noted similar tendencies in smaller datasets based on shipborne observations. This relationship is evident if different regions (such as the warm pool) are considered separately, showing that this result is not attributable merely to different conditions giving rise to different patterns of ΔT, Q and u with no causal relationship.

The analogous plot for daytime data is shown in Figure 4b; the surface heat flux does not include the contribution due to solar flux absorbed in the skin layer. As with the nighttime data, an increasingly cool skin is associated with higher heat flux, but the wind speed dependence is more complicated. Diurnal thermocline effects dominate at low wind speeds, with surface water almost always warmer than bulk SST for wind speeds lower than $4\,\mathrm{m\,s^{-1}}$. However, this apparent warm skin persists in the range $4 < u < 7\,\mathrm{m\,s^{-1}}$ for observations with low non-solar heat flux. For example, at $u \sim 7\,\mathrm{m\,s^{-1}}$, a wind speed which should be sufficient to mix the top meter of the ocean, a zero or positive ΔT is characteristic of data with non-solar heat flux$< 150\,\mathrm{W\,m^{-2}}$. A warm skin effect suggests net surface flux is from atmosphere to ocean, (*i.e.* surface absorption of incoming solar radiation exceeds upwelling longwave flux). This would be consistent with $\sim$ 25% of solar heat flux (typically $\sim 600\,\mathrm{W\,m^{-2}}$ at 10.30 lst) being absorbed in the skin layer. This implies a thicker skin layer than expected for this wind speed, which may be a result of turbulent mixing being suppressed by very high flux Richardson numbers in the top few millimeters due to the high solar absorption [*Simpson and Dickey,* 1981], (analogous to the suppression of turbulent kinetic energy production in more general mixed-layer schemes [*Kantha and Clayson,* 1994]).

Figure 5 shows ΔT plotted as a function of the Saunders formulation with λ set to unity (see caption), for both nighttime and daytime data where $u > 5\,\mathrm{m\,s^{-1}}$ (this wind speed minimum was chosen to reduce diurnal thermocline effects in the daytime data). Thus λ is given by the gradient of the line, implying $\lambda = 6.4 \pm 3.0$ for nighttime data, and $\lambda = 9.0 \pm 3.0$ for daytime data, values consistent with those derived from other studies [*Kent et al.,* 1996]. The linear appearance of the plot suggests that the Saunders model with a fixed λ is a reasonable fit, although the data do not exclude a wind speed dependence of $\lambda \propto u^{0.5}$ (equivalent to $\Delta T \propto Q/u^{0.5}$). Considering the data above and below 301 K separately, suggests λ is temperature dependent; for cooler SSTs ($T < 301$ K), nighttime $\lambda = 8.4 \pm 3.9$, and daytime $\lambda = 10.7 \pm 4.0$, whereas for warmer SSTs, ($T > 301$ K), nighttime $\lambda = 5.3 \pm 5.0$, and daytime $\lambda = 6.6 \pm 5.0$. (Mean wind speed is very similar, 7.0 and 6.7$\,\mathrm{m\,s^{-1}}$ for the cool and warm datasets respectively.) The difference in derived λ for cool and warm SSTs implies that the temperature dependence of ΔT on viscosity may be inadequately represented in the Saunders model. Parameterizations which extend to lower wind speeds were investigated for nighttime data with less convincing results, and will be reported in a future study, together with a more detailed analysis of the dependence of ΔT on Q, u, and water temperature.

4. Conclusion

Traditionally, skin–bulk SST comparisons have relied on skin SSTs from shipborne radiometers as satellite SST retrievals have depended on bulk SSTs for calibration purposes [*McClain et al.*, 1985]. ATSR has provided the first remotely-sensed SSTs at the accuracy required to conduct a study of the skin–bulk effect. Inevitably considerable noise derives from comparison of hourly-averaged point bulk SST measurements with instantaneous, spatially-averaged skin SSTs. Nevertheless, the large sample size enables analysis of the response of ΔT to heat flux and wind speed, and suggests the relationship between these quantities can be characterized, with the Saunders model adequately representing the skin effect variation at moderate to high wind speeds. The influence of surface heat flux on skin–bulk variability is clearly demonstrated, suggesting that this relationship may be useful in the validation of heat flux estimates whenever coincident bulk and skin temperatures, and wind speed measurements are available.

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