Improved Oceanic Cool-Skin Corrections Using a Refined Solar Penetration Model

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ABSTRACT

The oceanic near-surface temperature profile must be accurately characterized to enable precise determination of air–sea heat exchange and satellite retrievals of sea surface temperature. An improved solar transmission parameterization is integrated into existing models for the oceanic warm layer and cool skin within the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) bulk flux model to improve the accuracy of predictions of the temperature profile and corresponding heat flux components. Application of the revised bulk flux model to data from 12 diverse cruises demonstrates that the improved parameterization results in significant changes to the predicted cool-skin effect and latent heat fluxes at low wind speeds with high solar radiation due to reduced absorption of solar radiation just below the surface. Daytime skin-layer cooling is predicted to increase by 0.03 K on average but by more than 0.25 K for winds below 1 m s^{-1} and surface irradiance exceeding 900 W m^{-2}. Predicted changes to the warm-layer correction were smaller but exceeded 0.1 K below 1 m s^{-1}. Average latent and sensible heat fluxes changed by 1 W m^{-2}, but the latent flux decreased by 5 W m^{-2} near winds of 0.5 m s^{-1} and surface irradiance of 950 W m^{-2}. Comparison with direct observations of skin-layer cooling demonstrated, in particular, that use of the improved solar transmission model resulted in the reduction of previous systematic overestimates of diurnal skin-layer warming. Similar results can be achieved using a simplified treatment of solar absorption with an appropriate estimate of the fraction of incident solar radiation absorbed within the skin layer.

1. Introduction

Accurate predictions of the temperature profile immediately below the surface of the ocean are important to problems related to air–sea interactions and satellite retrievals of sea surface temperature (SST). Fairall et al. (1996b) showed that the SST must be known within an accuracy of ±0.2 K to compute the heat balance with an accuracy of 10 W m^{-2}. As a result, Fairall et al. (1996a) implemented simple models for oceanic cool-skin and warm-layer effects within their bulk flux model to enable accurate use of bulk water temperature data from ships and buoys. The resulting models have since been widely applied to estimates of the air–sea heat flux and other ocean–atmosphere interaction studies (e.g., Wu et al. 2001; Zhang et al. 2000; Godfrey et al. 1999).

Some of the most challenging and least certain corrections for surface layer effects occur during the daytime under conditions of low wind speed and high solar irradiance when diurnal warming can be significant. Under these conditions, the models are very sensitive to the assumed solar radiation absorption profiles. The original Fairall et al. (1996a) warm-layer and cool-skin

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models were based on absorption models presented by Soloviev (1982) and Paulson and Simpson (1981), respectively, and a constant surface albedo of 0.055. Comparisons of direct measurements of the skin SST with predictions from the warm-layer and cool-skin models during recent cruises indicate that the models regularly overpredict the daytime warming of the skin layer relative to measurements near 10 cm in depth. Recent independent work, however, resulted in a significantly improved solar transmission parameterization that depends on upper-ocean chlorophyll concentration, cloud amount, and solar zenith angle (Ohlmann and Siegel 2000). The new model provides an improvement in skill of order 10 W m^{-2} over existing parameterizations. Initial application of this new parameterization to a bulk flux model resulted in a 15% reduction in the solar radiation absorbed within the cool skin and warm layer and instantaneous differences in the predicted SST and net air–sea heat flux of up to 0.2 K and 5 W m^{-2}, respectively (Ohlmann and Siegel 2000). These results suggest that the new parameterization can potentially explain the errors in the predicted daytime warming of the skin layer.

In this work, the improved solar transmission parameterization is incorporated into the latest version of the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) bulk flux algorithm (Fairall et al. 2003) and the corresponding warm-layer and cool-skin models. In section 2, the implementation of the new parameterization and routines required to characterize the solar forcing are described. Section 3 presents the sensitivity of the cool-skin, warm-layer, and bulk flux models to the change in the solar radiation absorption profile as determined from a composite dataset taken from several individual cruises. A potential simplification to the treatment of solar radiation that preserves the improvements of the new transmission parameterization is also discussed. The direct impact of the changes on predicted skin temperatures is then described in detail in section 4, and the predictions are compared with direct measurements of the temperature change across the skin layer. A brief discussion of implications is presented in section 5, and conclusions from the work are summarized in section 6.

2. Implementation of the new solar transmission parameterization

The cool-skin and warm-layer models of Fairall et al. (1996a, hereinafter Fairall) require estimates of the solar flux divergence within each layer. The warm layer is defined as the region in the upper few meters of the ocean where solar radiation has caused warming relative to the deeper mixed layer, and its depth is determined from a critical value of the bulk Richardson number. The cool skin is a thin layer just beneath the ocean surface resulting from the predominance of molecular processes near the interface and the combined cooling effects of the net longwave radiation and sensible and latent heat fluxes.

The solar transmission parameterization of Ohlmann and Siegel (2000, hereinafter OS) expresses the fraction of incident surface irradiance that exists at depth as a function of a sum of four exponential terms [Eq. (3) of OS]. The parameterization uses a two-equation model to determine the corresponding coefficients and exponential terms separately for clear-sky and cloudy conditions. For clear-sky conditions, the parameters are computed as functions of the solar zenith angle and upper ocean chlorophyll concentration, while for cloudy skies they are computed from the chlorophyll concentration and a cloud index. The cloud index is defined as the difference between the clear sky (modeled) and the measured solar irradiance divided by the clear-sky irradiance. The solar transmission parameterization also directly accounts for effects of the ocean surface albedo, which varies with cloud cover and sun angle (Katsaros et al. 1985).

To implement the new solar transmission parameterization, the new expression for the average solar flux absorbed over a specified depth [Eq. (7) from OS] was applied to both the skin and warm layers, and the results were incorporated in place of Eqs. (17) and (26) from Fairall. These computations are performed at each time step of the model. Additional steps were included to determine the parameters required to compute the coefficients and exponential terms in the two-equation model. A simplified solar geometry and transmission routine (Iqbal 1988) was added to enable computation of the solar zenith angle and clear-sky solar irradiance as a function of position and time of day. Use of this routine requires the specification of basic atmospheric absorption parameters including integrated water vapor content and aerosol optical depth. Inclusion of these extra procedures added negligibly to the total computation time of the models.

3. Sensitivity of the cool-skin, warm-layer, and turbulent fluxes

Using the revised models, the sensitivity of the predicted skin cooling, near-surface warming, and sensible and latent heat fluxes to the change in solar transmission model was evaluated. An initial study of the impact of the new transmission model on the TOGA COARE bulk flux algorithm was carried out by OS for

TABLE 1. Data used to evaluate the sensitivity of the TOGA COARE bulk flux algorithm to the included solar transmission parameterization.

Cruise/experiment	Dates	Location
Tropical Instability Wave Experiment (TIWE)	20 Nov–13 Dec 1991	Equatorial Pacific Ocean just east of Christmas Island
Atlantic Stratocumulus Transition Experiment (ASTEX)	6–28 Jun 1992	Azores region of Atlantic Ocean
TOGA COARE (three cruises)	Nov 1992–Feb 1993	Western equatorial Pacific
San Clemente Ocean Probing Experiment (SCOPE)	17–28 Sep 1993	Off Southern California
Fronts and Atlantic Storm Tracks Experiment (FASTEX)	23 Dec 1996–24 Jan 1997	North Atlantic
Joint Air–Sea Interaction Experiment (JASMINE)	5–31 May 1999	Bay of Bengal
Nauru 99	15 Jun–18 Jul 1999	Tropical western Pacific, Nauru Island
Tropical Rainfall Measuring Mission Kwajalein Experiment (KWAJEX)	28 Jul–12 Sep 1999	Near Kwajalein Atoll
Moorings cruise	14 Sep–21 Oct 1999	Gulf of Alaska
Eastern Pacific Investigations of Climate Processes (EPIC99)	11 Nov–2 Dec 1999	Tropical eastern Pacific

a low wind speed period during the TOGA COARE intensive observing period. In this work, the initial study is extended to encompass a database compiled from multiple cruises in diverse regions so that the sensitivity can be shown as a function of a broad range of conditions. The sensitivity is presented in terms of the difference between predictions using the new transmission model and those using the older models.

Data from 12 individual cruises were processed into hourly averages, combined, and used to force the models. The cruises composing this dataset are summarized in Table 1. All of the cruises included measurements of the basic meteorological parameters required to compute bulk flux estimates, downwelling longwave and solar radiation, and bulk SST measurements taken at depths between 10 cm and 5 m. For several of the cruises, coincident eddy covariance measurements were also available for comparison with the bulk fluxes. Direct measurements of chlorophyll concentration were available only during the EPIC cruise, so a constant value representative of open-ocean conditions was selected (0.1 mg m^{-3}). Since all of the data were collected in the open ocean, significant variations in chlorophyll concentration are not expected. The original and modified TOGA COARE bulk flux models were run to generate predictions of the skin temperature, cool-skin effect (the temperature at the base of the skin layer minus the skin temperature), warming of the oceanic layer above 5-cm depth, total warming of the derived warm layer, and the bulk latent and sensible heat fluxes. The output was filtered to include only daytime results.

Differences in all the output quantities were observed, particularly at low wind speeds with high solar radiation. Mean differences were generally small because of the predominance of higher wind speeds, but many significant instantaneous differences exist. Distributions of the differences are plotted in Fig. 1, and the mean values are noted. On average, the predicted cooling of the skin layer during the daytime is 0.03 K greater using the improved solar transmission model, but increased cooling of greater than 0.1 K is not uncommon. The increased cooling is the result of increased solar transmission and, thus, less absorption within the skin layer and is consistent with the results of OS. The average impact on predicted warming of both the entire warm layer and that above 5 cm is very small. Instantaneous values of the change in warming above 5 cm are also small, but more significant changes are observed over a deeper layer. While most points undergo a very small increase in warming, a much larger decrease in warming is observed for a few individual points. The difference results from changes in wind speed affecting the depth of the mixed layer as will be illustrated further in the discussion of Fig. 2 below. The changes to the skin and surface layer result in mean changes to the latent and sensible heat flux of less than 1 W m^{-2}, but instantaneous differences in the latent heat flux of 5 W m^{-2} are observed.

The model allows estimation of the amount of warming occurring above a specified depth to enable computation of a surface temperature from a measurement at that depth. The warming above 5 cm was isolated to illustrate the impact of warming immediately below the surface and to represent the warm-layer correction that would be applied to various present floating SST sensors that attempt to measure the near-surface temperature. Results obtained for the warming expected above 5 m (typical of thermosalinograph or intake measurements) were very close to the computed change in total near-surface warming and are not shown. Since the warming above 5 m generally captured the total warming, the computed depth of the layer influenced by warming was less than 5 m for most cases of significant warming.

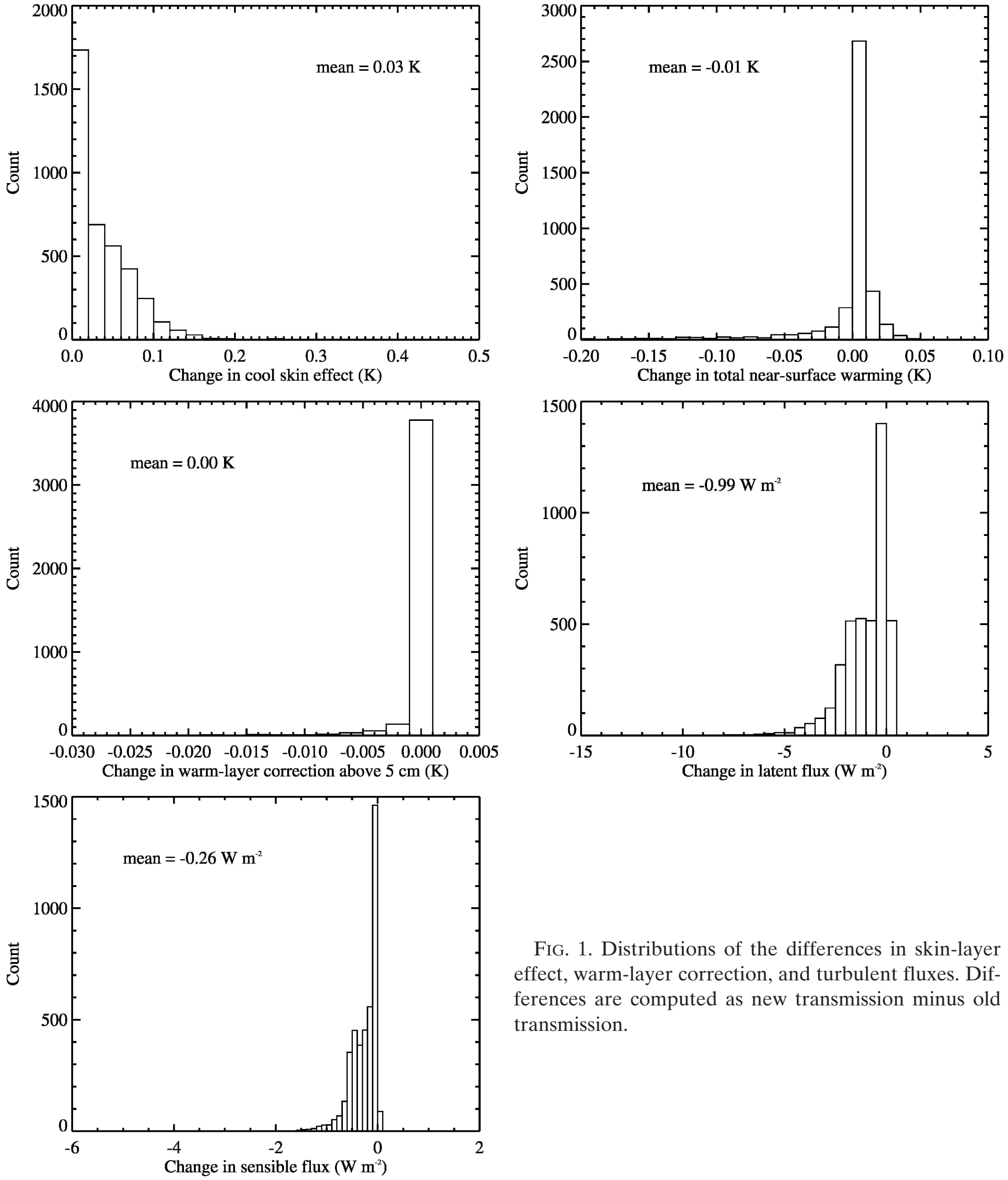

FIG. 1. Distributions of the differences in skin-layer effect, warm-layer correction, and turbulent fluxes. Differences are computed as new transmission minus old transmission.

The two environmental parameters with the greatest impact on the skin and warm-layer structure are wind speed and surface irradiance. To demonstrate the sensitivity of the differences to these variables, the results are contoured in Fig. 2. The results for skin-layer cooling clearly show that the largest impact of the new solar transmission model is at low wind speeds and high insolation. The increased cooling (or decreased warming) exceeds 0.1 K below winds of 4 m s^{-1} and can exceed 0.25 K for winds below 1 m s^{-1} and surface irradiance greater than 900 W m^{-2}. Similar results generated in terms of the percent change (not shown) illustrate that the change in the skin effect increases from 10% near a surface irradiance of 200 W m^{-2} to more than 100% for winds below 2 m s^{-1} and irradiance above 800 W m^{-2}.

Changes to the predicted warm-layer heating are a strong function of the wind speed. Below wind speeds of approximately 4 m s^{-1}, when the predicted depth of the layer influenced by warming is small, less diurnal warming is predicted because of the increased solar transmission near the surface. Within the entire layer influenced by warming, the reduction in warming exceeds 0.1 K, or about 10%, for wind speeds below 1 m s^{-1} and surface irradiance greater than 800 W m^{-2}.

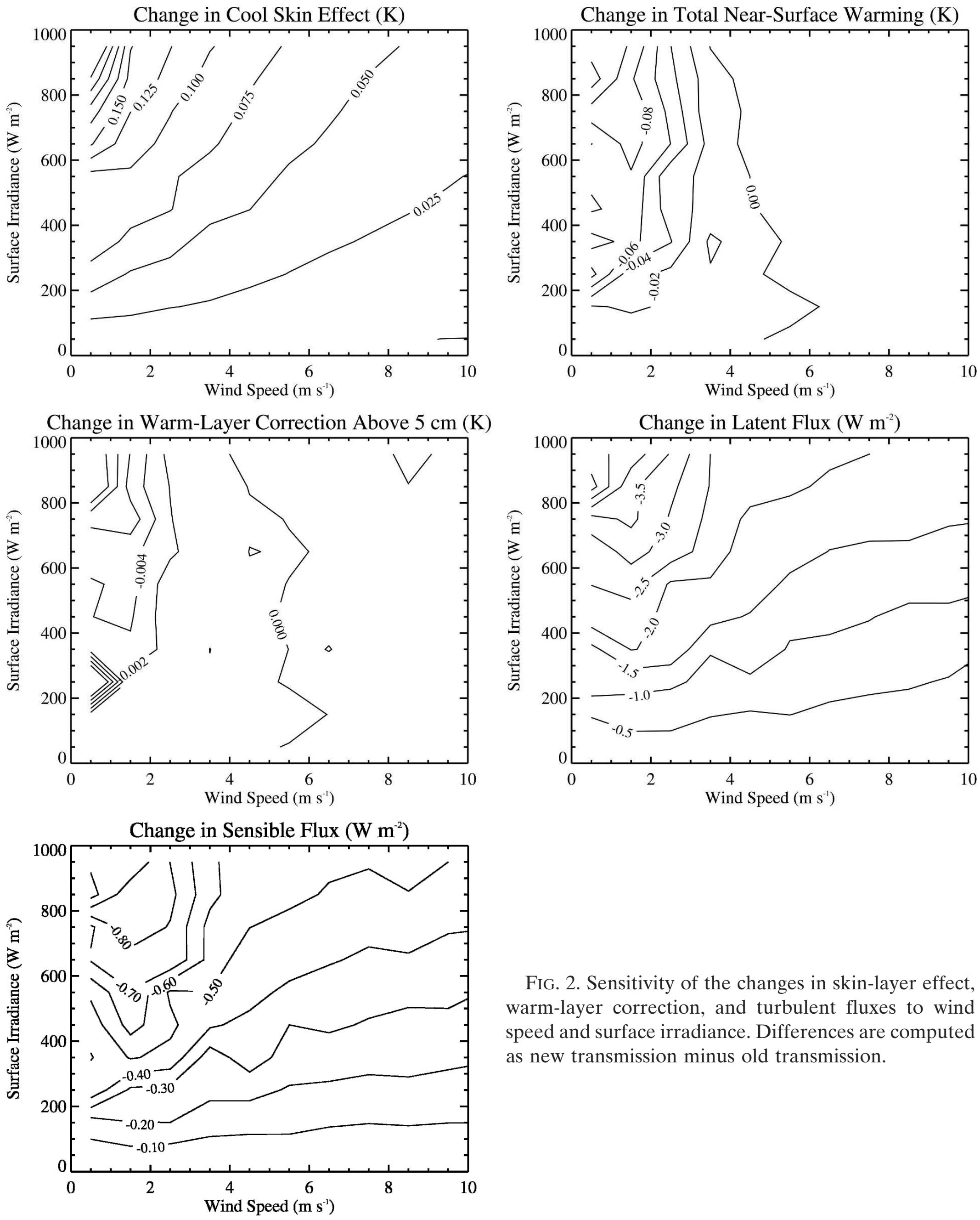

FIG. 2. Sensitivity of the changes in skin-layer effect, warm-layer correction, and turbulent fluxes to wind speed and surface irradiance. Differences are computed as new transmission minus old transmission.

For the fraction of warming occurring shallower than 5 cm, however, the change is nearly negligible. In contrast, above wind speeds of 4 m s^{-1}, when mixing forces diurnal warming to influence a deeper layer, a very slight increase in warming is predicted for the entire warm layer. The majority of points correspond to this condition, as shown in Fig. 1. These results indicate that, on average for the conditions represented by the data, while increased transmission is predicted immediately below the surface, the new transmission model predicts slightly less transmission at greater depths (several meters).

The latent and sensible heat fluxes, like the skin temperature, exhibit the greatest sensitivity to the solar absorption parameterization at low wind speeds and high insolation. The uppermost contour in the latent heat flux results at a 0.5 m s^{-1} wind speed and 900 W m^{-2} surface irradiance corresponds to a decrease of 5 W m^{-2}. This represents a decrease in the latent heat flux of over 5% under those conditions. For lower solar fluxes, the difference is largely independent of wind speed because of the relatively small temperature changes occurring when the insolation is weaker. The absolute change in the sensible heat flux is small but approaches 10% of its value. While the average impact on the turbulent fluxes is small, the fractional change is not negligible and the effect under the extreme conditions approaches a value of one-half of the often-quoted, desired accuracy of 10 W m^{-2}. A comparison with the available eddy covariance flux measurements showed that use of the improved solar transmission model resulted in improved latent flux estimates but slightly degraded sensible flux estimates.

The most significant impact of the new solar transmission model is on the skin-layer cooling where skin temperature changes exceeded 100% of the temperature change across the skin layer. A skin temperature change of more than 0.2 K is also significant when one considers that the satellite SST community is presently seeking in situ validation measurements with an accuracy of 0.1 K. The most notable aspect of this difference is that use of the earlier absorption model in the cool-skin model appears to have introduced a systematic bias in the daytime skin temperature estimates. The model frequently predicted the existence of a warm skin layer, where the skin temperature was greater than that just below the skin, while few measurements showed evidence of such a warm skin. Use of the new absorption model reduces the number of predicted warm skins by over one-third, and those that do remain are very small in magnitude.

For the cool-skin model, a simplification of the solar absorption parameterization can provide similar results without requiring the additional input of the chlorophyll content, solar zenith angle, and cloud amount. The results of OS showed that the mean decrease in the fraction of solar irradiance absorbed within the cool skin was 0.07. In Eq. (17) of Fairall describing the fraction of incident solar radiation absorbed within the skin layer, a constant term of 0.137 is included to account for the absorption of wavelength bands with scales much less than the expected skin-layer depth. This suggests that the mean difference between the absorption models could potentially be removed by reducing the constant term in Eq. (17) of Fairall by 0.07 to a value of 0.067.

This simplified skin-layer absorption model was evaluated using the 12-cruise composite dataset, and the results were compared with those using the full improved parameterization. The simplified model resulted in the same predicted mean cool-skin correction and produced only small instantaneous differences at lower wind speeds. The sign of the differences tended to vary with the surface irradiance, with the simplified model predicting less cooling for smaller irradiance and more cooling for greater irradiance. The largest differences were near 0.05 K (simplified model overcooling) at winds below 1 m s^{-1} and surface irradiance above 900 W m^{-2}.

4. Improved predictions of the cool skin

To examine more closely the impact of the solar transmission model on the skin-layer cooling and further verify the model refinements, predicted temperatures were compared with direct observations under conditions of low wind speeds and high solar flux. Detailed coincident measurements of the skin temperature, subsurface temperature at depths between approximately 5 and 10 cm, and the heat flux components were available from several recent experiments. These experiments were the Fluxes, Air–Sea Interaction, and Remote Sensing (FAIRS) Experiment aboard the Research Platform *Floating Instrument Platform* (*FLIP*) off the coast of Monterey, California, in September–October 2000, and cruises of the R/V *Ronald H. Brown* conducted as part of the EPIC program in September 2001, the North American Air Quality Study (NEAQS) in July–August 2004, and the Tropical Atmosphere–Ocean (TAO) buoy servicing in November 2004. In all cases, the skin temperature was measured with the calibrated infrared in situ measurement system (CIRIMS) radiometer (Jessup et al. 2002). During FAIRS, the subsurface temperature was measured with a wave-following thermistor at a depth of 10 cm, and the fluxes were measured by a group from the Woods Hole Oceanographic Institution. During the R/V *Ronald H. Brown* cruises the subsurface temperature was measured with a towed floating thermistor at a depth near 5 cm, and the fluxes were measured using the NOAA Environmental Technology Laboratory flux package (Fairall et al. 1997). The modeled cool-skin effect was compared with the difference between the subsurface and skin temperatures. No warm-layer effects were computed for these comparisons because the previous results showed the change in warming shallower than 5 cm to be negligible.

Because of the generally small changes resulting from the model modifications, it is important to consider the expected uncertainties in the measurements and models. Measurements of the temperature change across the skin layer are particularly challenging. An intercomparison of infrared radiometers (Barton et al. 2004) demonstrated that typical errors in skin temperature measurements from radiometers like CIRIMS are near 0.1 K. Comparison of independent subsurface temperature sensors at nighttime when vertical temperature gradients are expected to be small suggests typical random errors of 0.03 K and offsets of up to 0.02 K in the measurements. Based on these results, the expected uncertainty in the cool-skin effect can be estimated as near 0.12 K. Previous evaluations of the Fairall cool-skin calculation at nighttime have suggested rms errors of 0.13 K (Castro et al. 2003). Errors in the skin-layer model are not expected to change with the time of day except as a result of the solar penetration model. Additional errors could result from instances where the towed thermistor fell to greater depths beneath the base of the skin layer or was influenced by mixing such as by the ship wake. In these cases the perceived warming of the skin layer would be greater because of the additional solar absorption between the skin and the effective depth of the measurement.

A comparison using the original and full improved solar transmission parameterizations is highlighted for one day of data from EPIC01 in Fig. 3. This day was one of a series of days with low wind speeds and notable diurnal warming. The chlorophyll concentration was directly measured and was 0.125 mg m^{-3} on that day. Prior to sunrise, the modeled skin effect agrees quite favorably with the observations. Following sunrise, however, the skin effect predicted using the original solar transmission model decreases by over 0.2 K because of significant predicted absorption within the skin layer. No such reduction of the skin effect is observed in the direct measurements. The discrepancy is also present if the thermosalinograph measurements are used in place of the towed thermistor. While the offset exceeds the random errors of the measurements and models by only a relatively small amount, the model trend is also systematic and no systematic trend is seen within the random fluctuations of the observations. When the OS transmission parameterization is used instead, less absorption and reduction of the skin effect is predicted, and the results agree more closely with the observations. The two large downward spikes in the observed skin effect result from variations in the temperature recorded by the towed thermistor corresponding to large changes in the ship's velocity.

The tendency for improvement with the new model is further emphasized when viewing the modeled skin temperature for the four surrounding days. The modeled skin temperatures are shown with the observed skin and bulk temperature in Fig. 4. During peak heating on each day, the original transmission model results in an overestimate of the skin temperature while the new model leads to temperatures more consistent with the observations. The comparisons were also performed using the simplified skin-layer absorption model. The results for EPIC01 indicate that the predictions obtained assuming a constant shallow absorption fraction of 0.067 are similar to those from the full new parameterization.

The comparisons were extended to consider multiple days from the experiments where warming within the skin layer was predicted by the original model. The results are summarized in Fig. 5. The difference in the reduction in the skin effect between what was observed and predicted is shown for the original model, the new transmission parameterization, and the simplified absorption model. The warming of the skin layer predicted by the original model was too large on each of the days considered. The new models always result in less predicted warming and, on all but a couple of days, give smaller absolute errors in the predicted skin-layer evolution. The simplified parameterization produces similar results to the full model but with slightly less warming on most days. Overall the new models reduce the mean overprediction of the warming from 0.16 K to less than 0.03 K. These results demonstrate that improved predictions of the skin temperature and cool-skin effect can be achieved using the new solar transmission model with less absorption near the surface and provide added validation for the model.

5. Discussion

While the overall changes introduced by incorporation of the new model are small both absolutely and relative to typical measurement errors, the physically based approach does appear to reduce a systematic tendency for overestimation of skin temperatures in the presence of diurnal warming. The conditions under which these changes are most significant are relatively limited in a global sense but occur with frequency in climatologically important regions such as the western Pacific warm pool where small changes can have an effect on atmospheric circulation. Accurate treatment of the diurnal evolution of sea surface temperature is also an important challenge in current efforts to produce multisensor-based satellite sea surface temperature products (Donlon 2004).

The improvements are achieved through a reduction in the absorption of solar radiation within the skin layer. A likely reason for the overestimated absorption in the earlier model is that much of the radiation assumed to be absorbed rapidly just below the surface is absorbed passing through the moist marine atmosphere before reaching the ocean surface. The wavelengths absorbed most rapidly, thereby contributing to warming within the skin layer, correspond to the near-infrared portion of the spectrum. Significant modifications in

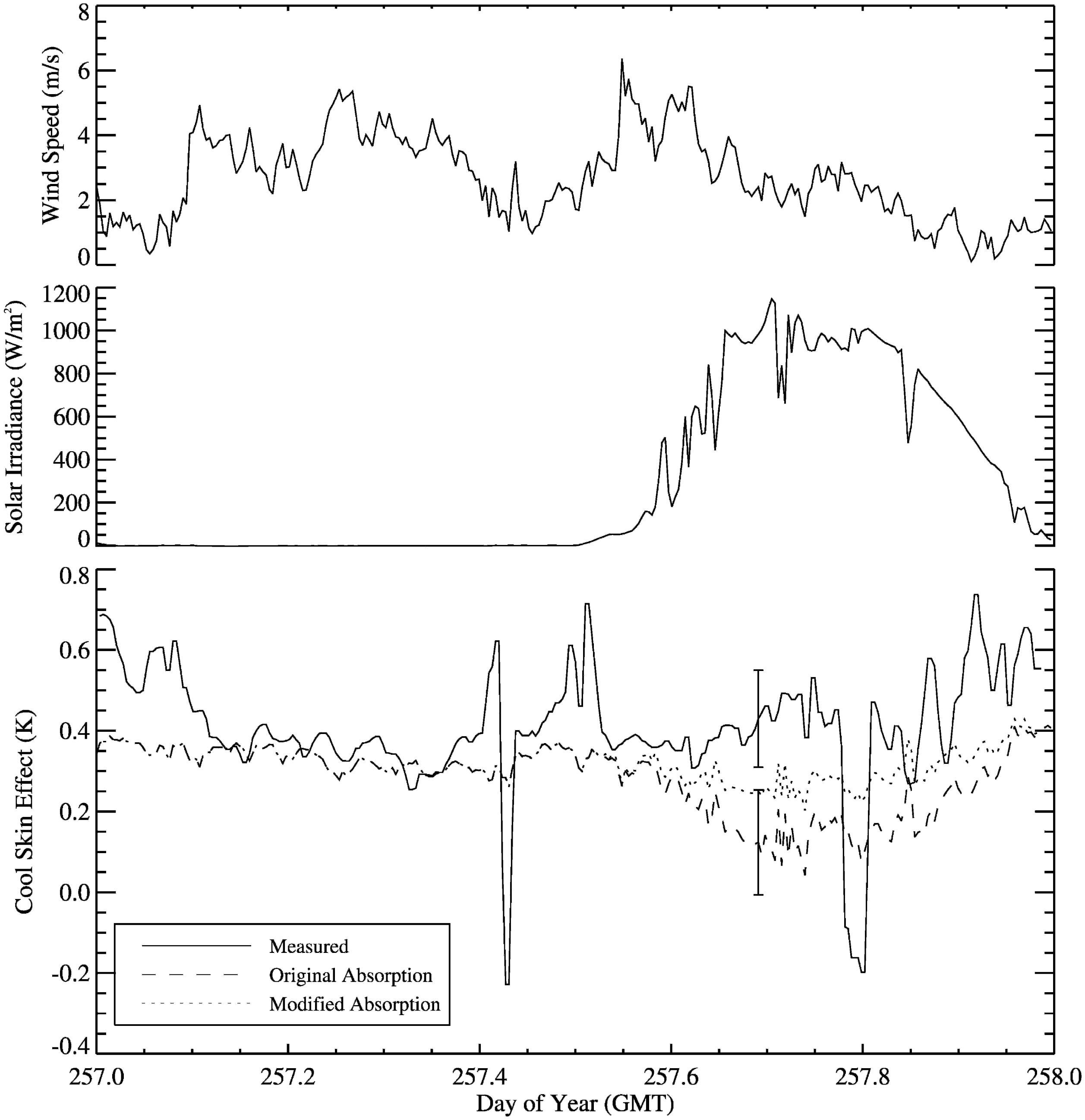

FIG. 3. Comparison of the modeled and observed cool-skin effect for 1 day during EPIC01 using both the original and modified solar transmission models. The wind speed and downwelling solar radiation are included to show the corresponding conditions and illustrate the daytime period. Representative error bars are shown for the measured and modeled skin effect. The latent, sensible, and net longwave fluxes averaged near 90, 12, and 54 W m^{-2}, respectively.

the treatment of the water vapor continuum and water vapor absorption in the infrared spectrum has occurred (e.g., Clough et al. 1992; Bennartz and Lohmann 2001), resulting in increased atmospheric absorption rates.

On average, the observed warming is still slightly less than that predicted by the new models, but there are also some instances where the warming of the skin layer is underestimated in brief wind lulls. While these remaining differences are well within the uncertainties in the measurements and models, differences could be related to such factors as the modeled depth of the skin layer and the assumed water vapor content and cloud fraction used in the new model. The calculation of skin-layer depth is a potential source of uncertainty in the

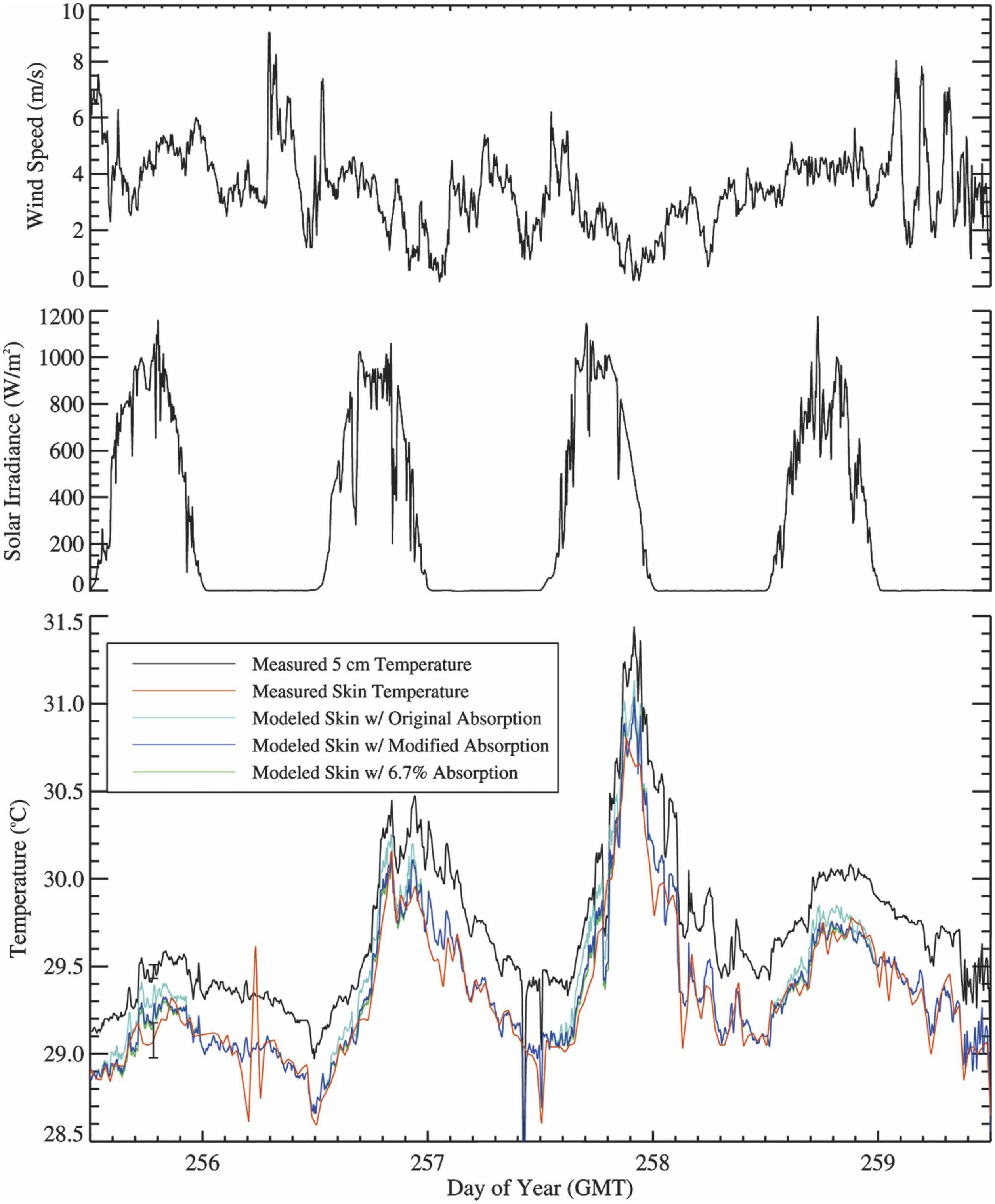

FIG. 4. Comparison of measured and modeled skin temperatures for a 4-day period from EPIC01 including the day shown in Fig. 3. The modeled temperatures include results using the original solar transmission model, the full modified model, and the simplified model assuming 6.7% absorption within the skin layer. The measured subsurface temperature is also shown for reference. Representative error bars for the measured temperatures are shown for the observations near yearday 255.8.

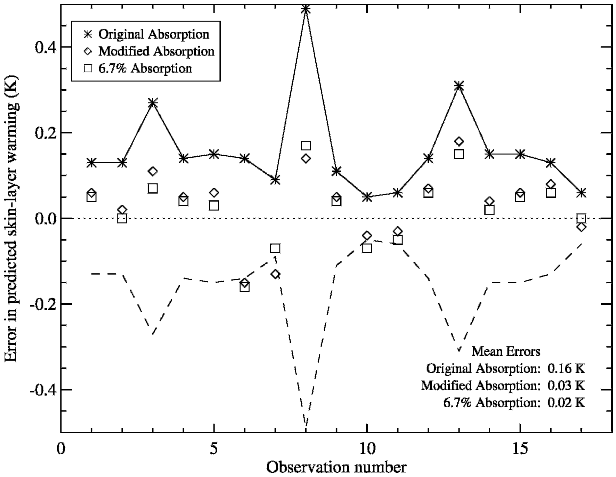

FIG. 5. Illustration of the systematic reduction in error in computed daytime warming of the skin layer resulting from use of the improved solar transmission model. The error is computed as the difference between the peak modeled daytime warming (relative to nighttime values) and the corresponding observed warming. A positive value indicates that the model is overestimating the warming while a negative value suggests an underestimate. The dashed line corresponds to the negative of the observed error to demonstrate where the errors are reduced in absolute value. Observations 1–5 correspond to EPIC01, 6–8 to NEAQS, 9–12 to TAO04, and 13–17 to FAIRS.

modeled skin-layer warming. A reduction in the modeled skin-layer depth of 0.4 mm corresponds to a reduction in the effective absorption fraction within the skin layer of 0.01. Reduced absorption fractions would also be obtained with increases to the cloud index and water vapor content. While high cloud contents were not observed, the computed cloud indices for the EPIC01 simulation did appear too low. A simplified model for clear-sky solar radiation was used in the simulations, and it consistently underestimated the net irradiance relative to direct measurements under clear-sky conditions. Further consideration of warm-layer effects would also have a small effect on the calculations. Additional warming between the base of the skin layer and the depth of the subsurface sensor would cause revised simulations to predict more warming of the skin temperature.

6. Conclusions

An improved, physically based, solar transmission model developed by OS was implemented in the latest version of the TOGA COARE bulk flux algorithm (Fairall et al. 2003) and corresponding warm-layer and cool-skin models. The new absorption model achieves improved predictions of the solar transmission in the top few meters of the ocean through parameterization of the effects of solar geometry, cloud cover, and chlorophyll concentration. The overall sensitivity of the predictions of the TOGA COARE model to the change in transmission model was evaluated using a dataset compiled from several cruises under diverse conditions. The mean effect of the change on skin-layer cooling, diurnal warming, and the turbulent heat fluxes was small, but there was a significant impact on the skin layer and fluxes under conditions of low wind speed and high surface irradiance. Under these extremes, instantaneous predictions for skin-layer cooling and the latent heat flux changed by over 0.25 K and 5 W m^{-2}, respectively. The changes are due to a reduction in the solar radiation absorbed just below the surface relative to the original absorption models. These results closely follow those found previously by OS and further support their findings.

The most significant impact of the improved solar transmission model was on the modeled skin temperature. The overestimate of absorption in the shallow skin layer in previous transmission models resulted in systematic excessive simulated warming of the skin layer during the daytime. Comparisons with direct measurements of skin-layer cooling from several different experiments demonstrated that the new model results in less predicted warming and improved estimates of skin temperature variations during the day. The illustration of improved accuracy of the modeled skin temperatures provides important additional validation for the new transmission model. The impact on the warm-layer correction was smaller, and the sign of the change varied with the wind speed. At higher wind speeds, a small increase in warming was predicted, suggesting that, while the new model gives increased transmission immediately below the surface, slightly less transmission occurs at greater depths.

Overall, the results suggest that if one is attempting to compute the air–sea heat flux or model the skin temperature at low wind speeds, improved solar transmission models that accurately predict absorption immediately below the surface should be used. If the required inputs to the OS parameterization are not available, the improvements brought about by the model can be reproduced to a large extent using the simplified expression for absorption within the skin layer presented by Fairall et al. (1996a) with a reduced constant term for absorption at depths shallower than the skin layer.

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