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 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 twelve 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 from two cruises demonstrated, in particular, that use of the improved solar transmission resulted in the reduction of previous overestimates of diurnal skin layer warming. Results using a simplified treatment of solar absorption suggested that further smaller improvements might be possible if modified solar irradiance inputs or reduced predictions of skin layer thickness resulted in even less absorption 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 models were based on absorption models presented by Soloviev (1982) and Paulson and Simpson (1981), respectively. 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 over predict 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 was found to provide 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-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) bulk flux algorithm 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 data set 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, hereafter Fairall) require estimates of the mean solar radiation absorbed within each layer. The amount absorbed is expressed as a fraction of the net radiation incident at the ocean surface. The warm layer is defined as the region in which temperature changes due to solar heating occur and its depth is determined from a critical value of the bulk Richardson number. An estimate of the sea surface albedo is also required and was previously assumed to be a constant 0.055.

The solar transmission parameterization of Ohlmann and Siegel (2000, hereafter OS) expresses the fraction of incident surface irradiance that exists at depth as a function of a sum of four exponential terms (equation 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.

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 incorporated in place of equations 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 radiative transfer and solar geometry routine 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 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 twelve individual cruises were processed into hourly averages, combined, and used to force the models. The cruises comprising this data set are summarized in Table 1. All 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. None of the datasets included direct measurements of chlorophyll concentration so a constant value representative of open ocean conditions was selected (0.1 mg m^{-3}). 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 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 due to the predominance of higher wind speeds, but many significant instantaneous differences exist. Distributions of the differences are plotted in Figure 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 surface 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. The majority of points undergo a very small increase in warming but a much larger decrease in warming is observed for a few individual points. These differences result in mean changes to the latent and sensible heat flux of near only 1 W m^{-2}, but instantaneous differences in the latent heat flux of 5 W m^{-2} are observed.

The warming above 5 cm has been isolated to illustrate the impact of warming immediately below the surface. The quantity is also representative of the warm layer correction that would be applied to various present floating SST sensors that attempt to measure the near-surface temperature. Results for the layer above 5 m that would correspond to typical thermosalinograph or intake measurements closely mirror those for the entire surface layer and are not shown. The similarity indicates that the warm layer depth is less than 5 m for most cases of significant warming.

To demonstrate the sensitivity of the differences on wind speed and surface irradiance, the results are contoured in Figure 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}. 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 warm layer is small, less diurnal warming is predicted due to the increased solar transmission near the surface. For both the entire warm layer and the layer above 5 m, the reduction in warming exceeds 0.1 K for wind speeds below 1 m s^{-1} and surface irradiance greater than 800 W m^{-2}. 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 Figure 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 950 W m^{-2} surface irradiance corresponds to a decrease of 5 W m^{-2}. For lower solar fluxes, the difference is largely independent of wind speed. While the average impact on the turbulent fluxes is small, the effect under the extreme conditions approaches half the often quoted desired accuracy of 10 W m^{-2}. Differences in the sensible heat flux are also observed at high wind speeds and low surface irradiance. Under these conditions, variability of other parameters such as air temperature influences the flux calculations and small differences are amplified by the large wind speeds. 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. A skin temperature change of 0.25 K is highly significant when one considers that the mean nighttime skin layer cooling is only about 0.2 K. In addition, 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 equation 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 equation 17 of Fairall by 0.07 to 0.067.

This simplified skin layer absorption model was evaluated using the twelve-cruise composite data set and the results 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 more closely examine the impact of the solar transmission model on the skin layer cooling, predicted cooling was 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 5-10 cm and the heat flux components were available for two recent experiments. These experiments were the Fluxes, Air-Sea Interaction, and Remote Sensing (FAIRS) Experiment aboard the Research Platform Flip off the coast of Monterey, CA in September-October 2000, and a cruise of the R/V Ronald H. Brown conducted as part of the Eastern Pacific Investigation of Climate (EPIC) program in September 2001. In both 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 EPIC 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 (ETL) 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.

A comparison using the original and full improved solar transmission parameterizations for one day of data from EPIC is shown in Figure 3. This day was selected for the presence of low wind speeds and notable diurnal warming. 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 due to significant predicted absorption within the skin layer. No such reduction of the skin effect is observed in the direct measurements. 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 correspond to large changes in the ship's velocity and are believed to be due to measurement difficulties.

A similar comparison for one day from the FAIRS experiment with notable warming is shown in Figure 4. For this day, the model predictions for the cool skin effect are offset from the observations by about 0.1 K on average. Most notably, however, the original cool-skin model again predicts significant warming of the skin layer (or a corresponding reduction in the skin effect) during the daytime that is not observed in the direct measurements. When the revised cool skin model is run using the improved transmission model of OS, the large warming of the skin layer is no longer present. 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.

The comparisons against the cruise data were also performed using the simplified skin layer absorption model. For the EPIC data, shown in Figure 5, the results with a constant shallow absorption fraction of 0.067 are similar to those obtained using the full new parameterization. Interestingly, however, an additional run, with a constant term of 0.01 produces even better agreement with the observations. For the FAIRS data, shown in Figure 6, the simplified model produces results different from the OS model as use of the 0.067 absorption term results in greater predicted warming. The formal model predicts less absorption for the specific conditions. Further assumption of less absorption through use of a shallow absorption fraction constant of 0.01 again provides seemingly good results. Possible reasons for the improved results with less absorption are discussed in the following section.

5. Discussion

Improved predictions of skin layer cooling have been achieved with a new solar transmission model that results in less absorption of solar radiation within the skin layer than in the original models. 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 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.

Comparisons against direct measurements of the skin effect suggest, however, that there may be even less absorption within the skin layer than predicted by the OS transmission model. There are several possible factors that could contribute to this. The neglecting of warm-layer effects in the calculations does not likely contribute to the observed discrepancy because additional warming between 5-cm depth and the base of the skin layer would cause the model results to be even further from the observations. Near-surface attenuation within the water appears to be accurately reproduced given the assumed incident radiation on the surface. Additional simulations with the OS model demonstrated that absorption fractions as low as 0.01 within the skin layer are possible if there cloud index is sufficiently large. For a skin layer thickness of 1.0 mm and a cloud index of 0.9, the predicted absorption fraction ranged between 0.0073 and 0.0112 depending on solar angle and chlorophyll content. While high cloud contents were not observed, the computed cloud indices for the EPIC 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.

As with the earlier absorption models, underestimates of atmospheric absorption by water vapor could also lead to overestimated absorption within the skin layer. The OS model was developed using an incident radiance distribution computed with the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi et al. 1998). Since creation of the model, however, other studies have found increased absorption rates of solar energy in clear skies due to water vapor (Arking 1999; Belmiloud et al. 2000; Bennartz and Lohmann 2001). If the spectral content of the input radiation is incorrect and there is too much infrared radiation, then the absorption at the shallowest depths would be too high. It is still unclear, however, what amount of the observed discrepancy can be explained by possible increased absorption.

Overestimated skin layer depths would also contribute to overestimates of absorption within the skin layer. The modeled skin layer depth in the FAIRS simulation increases to near 2.3 mm whereas estimates derived from the observed cooling approach only 1.5 mm. This change in depth corresponds to a change in the absorption fraction of 0.02. A reduction in the modeled FAIRS skin layer depth would also lead to better agreement in the predicted cool skin amplitude. Within the EPIC simulation, however, the skin layer depth appears to be well-predicted.

Conclusive determination of causes of the apparent absorption discrepancies will require additional work including examination of measurement uncertainties. Because of difficulties in determining the spectral irradiance immediately above and below the ocean surface, direct measurements of the skin effect may be valuable for verifying the amount of solar absorption within the skin layer.

6. Conclusions

An improved solar transmission model developed by OS was implemented in the latest version of the TOGA COARE bulk flux algorithm 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 excessive simulated warming of the skin layer during the daytime. Comparisons with direct measurements of skin layer cooling from two different experiments demonstrated that the new model results in less predicted warming and improved estimates of skin temperature variations during the day. 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, they should use improved solar transmission models that accurately predict absorption immediately below the surface. 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.

The direct observations of skin layer cooling indicate that there may be even less absorption within the skin layer than predicted by the OS transmission model. Possible reasons include further increased atmospheric attenuation of solar radiation at near-infrared wavelengths in clear sky conditions due to water vapor and overestimated thicknesses of the skin layer. Any further reduction in the absorption of solar radiation within the skin layer would tend to amplify the changes from the original bulk flux model.

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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)	11/21-12/13/1991	Equatorial Pacific just east of Christmas Island
Atlantic Stratocumulus Transition Experiment (ASTEX)	6/06-6/28/1992	Azores region of Atlantic
TOGA COARE (3 cruises)	11/1992 – 2/1993	Western Equatorial Pacific
San Clemente Ocean Probing Experiment (SCOPE)	9/17-9/28/1993	off Southern California
Fronts and Atlantic Storm Tracks Experiment (FASTEX)	12/23/1996–1/24/1997	North Atlantic
Joint Air-Sea Interaction Experiment (JASMINE)	5/05-5/31/1999	Bay of Bengal
Nauru 99	6/15-7/18/1999	Tropical Western Pacific, Nauru Island
TRMM Kwajalein Experiment (KWAJEX)	7/28-9/12/1999	near Kwajalein Atoll
Moorings Cruise	9/14-10/21/1999	Gulf of Alaska
Eastern Pacific Investigations of	11/11-12/2/1999	Tropical Eastern Pacific

Climate Processes (EPIC)

Figures

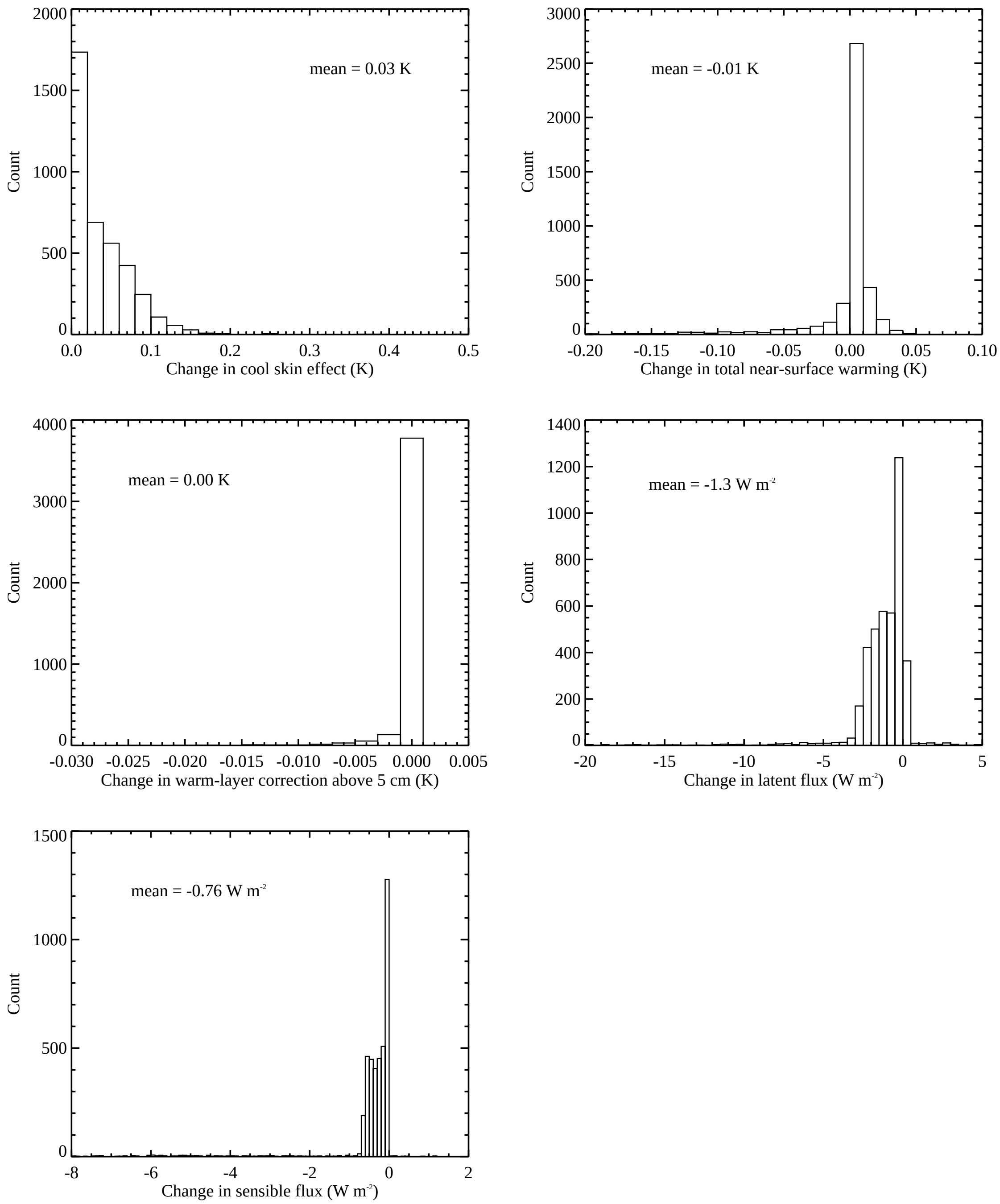

Figure 1. Distributions of the differences in skin layer effect, warm layer correction, and turbulent fluxes. Differences are computed as new transmission minus old transmission.

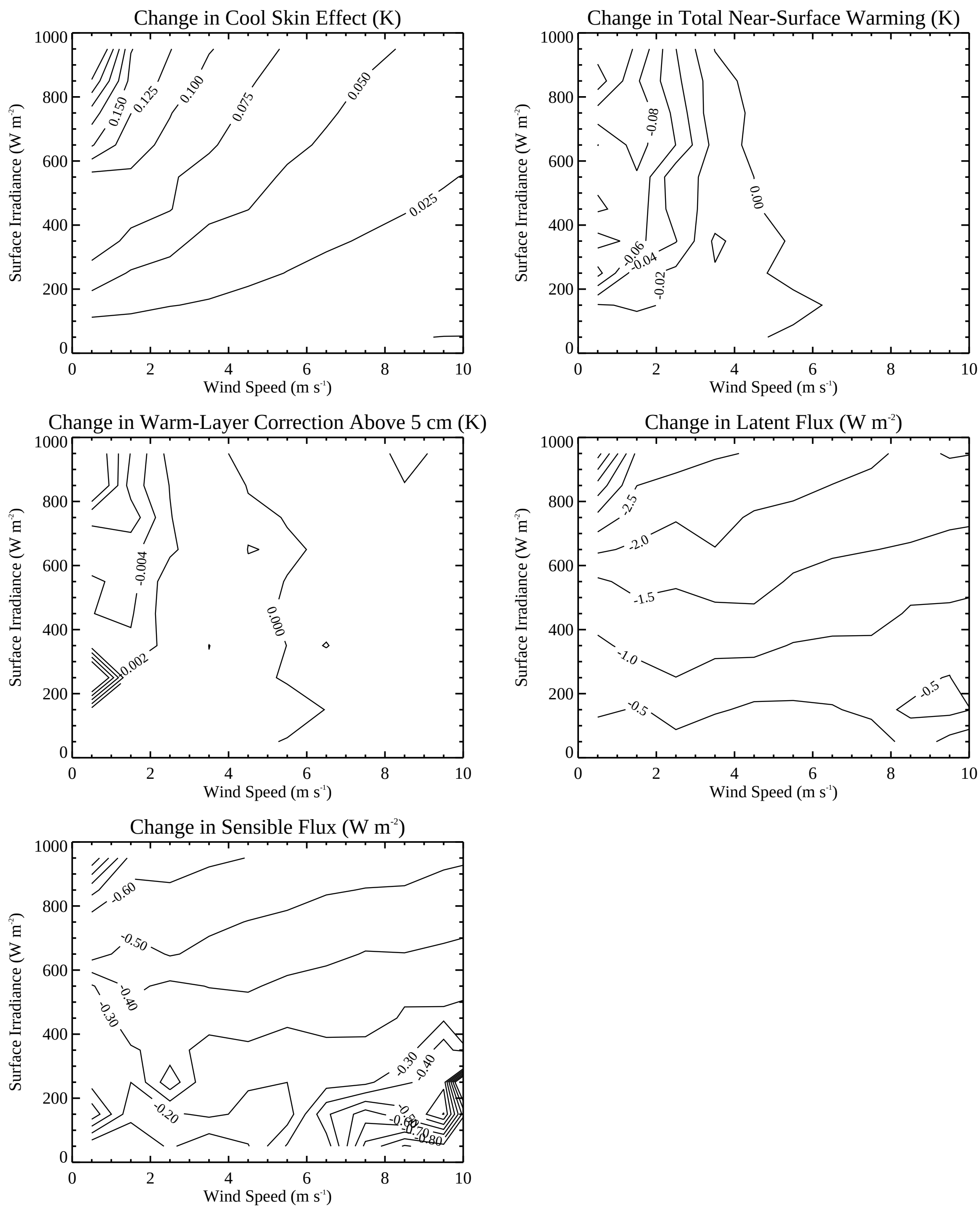

Figure 2. Sensitivity of the changes in skin layer effect, warm layer correction, and turbulent fluxes to wind speed and surface irradiance. Differences are computed as new transmission minus old transmission.

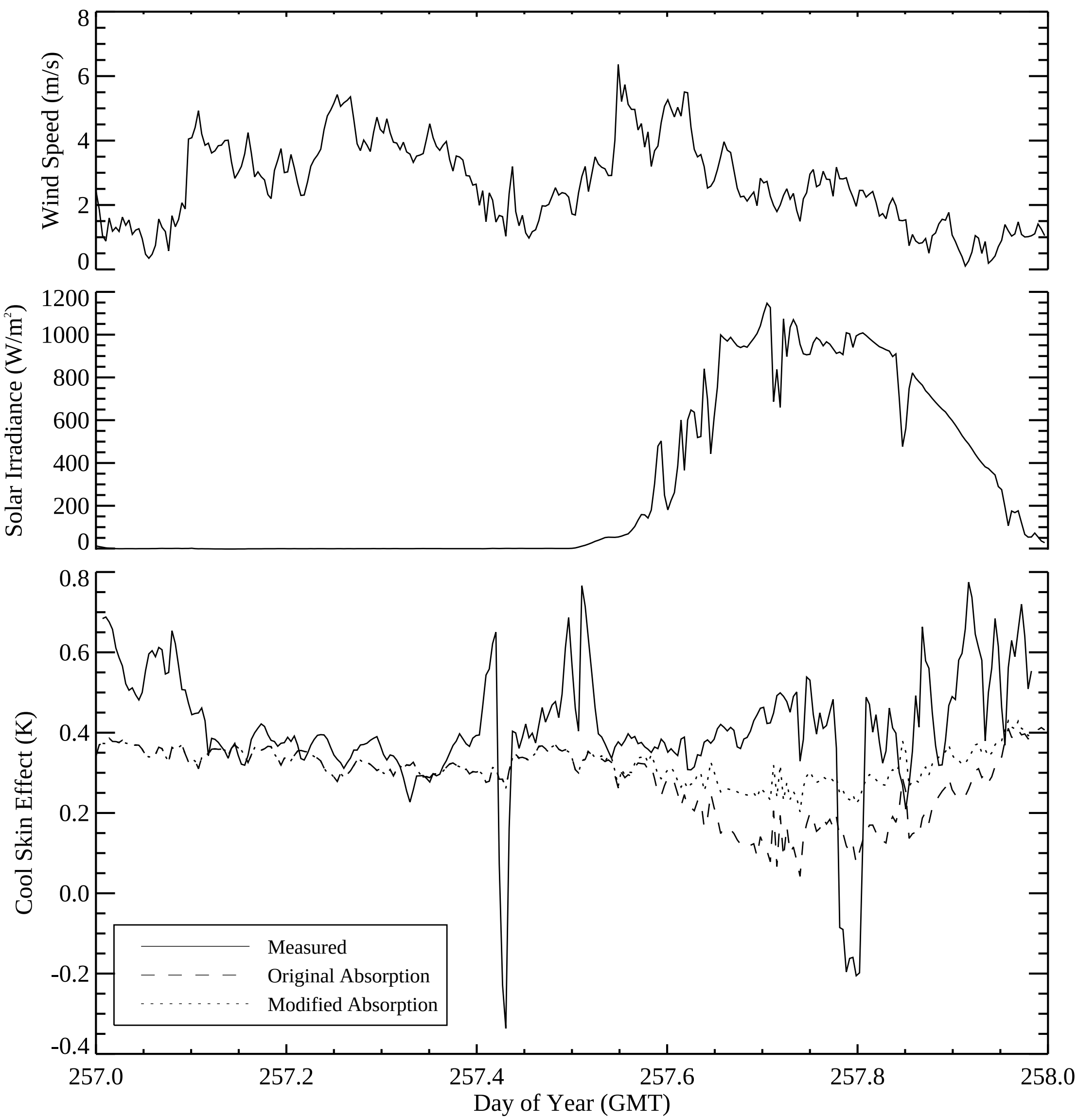

Figure 3. Comparison of the modeled and observed cool skin effect for one day during EPIC using both the original and modified solar transmission models. The wind speed and downwelling solar radiation are included to show the corresponding conditions and illustrate the daytime period.

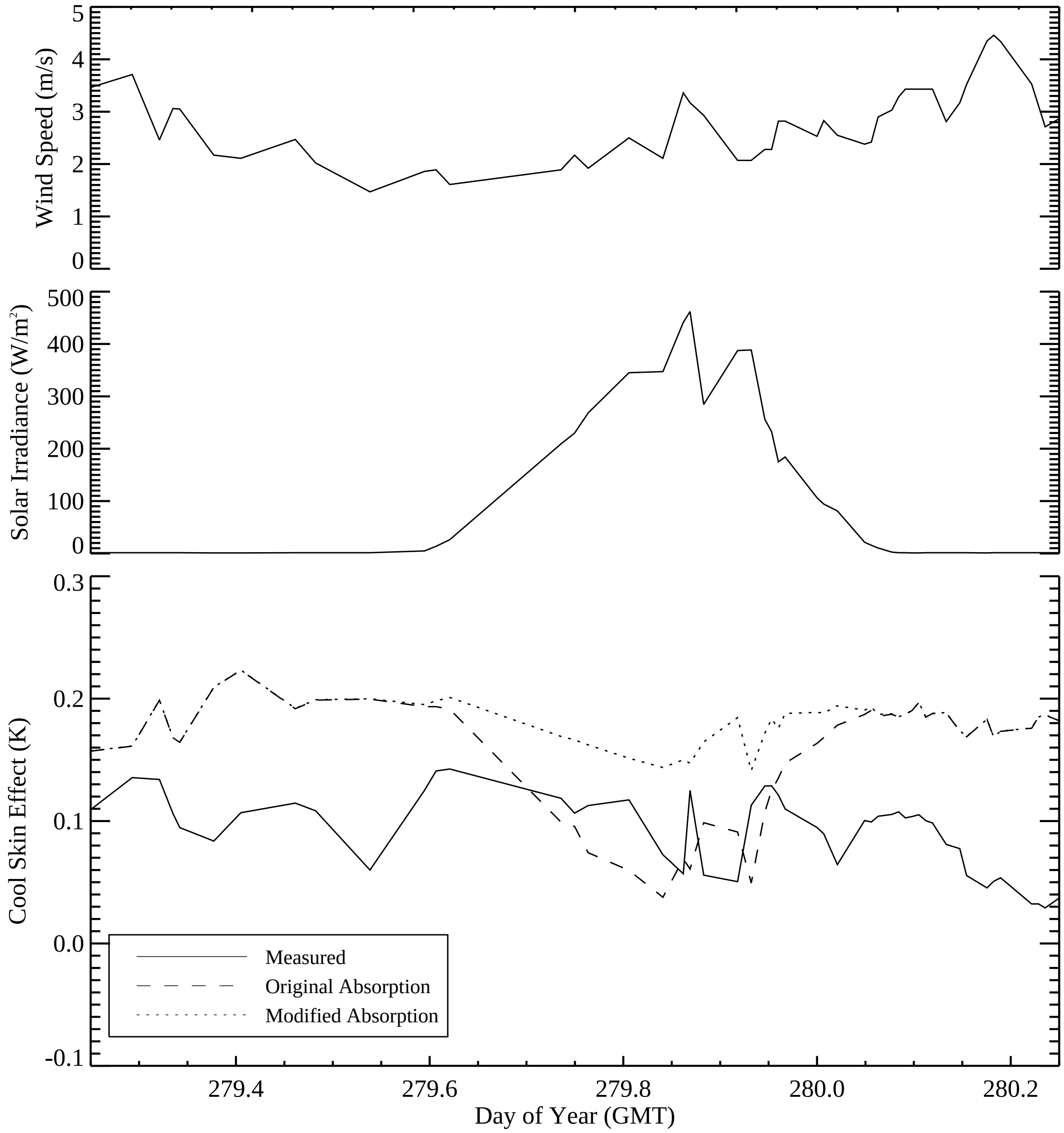

Figure 4. Comparison of the modeled and observed cool skin effect for one day during FAIRS using both the original and modified solar transmission models. The wind speed and downwelling solar radiation are included to show the corresponding conditions and illustrate the daytime period.

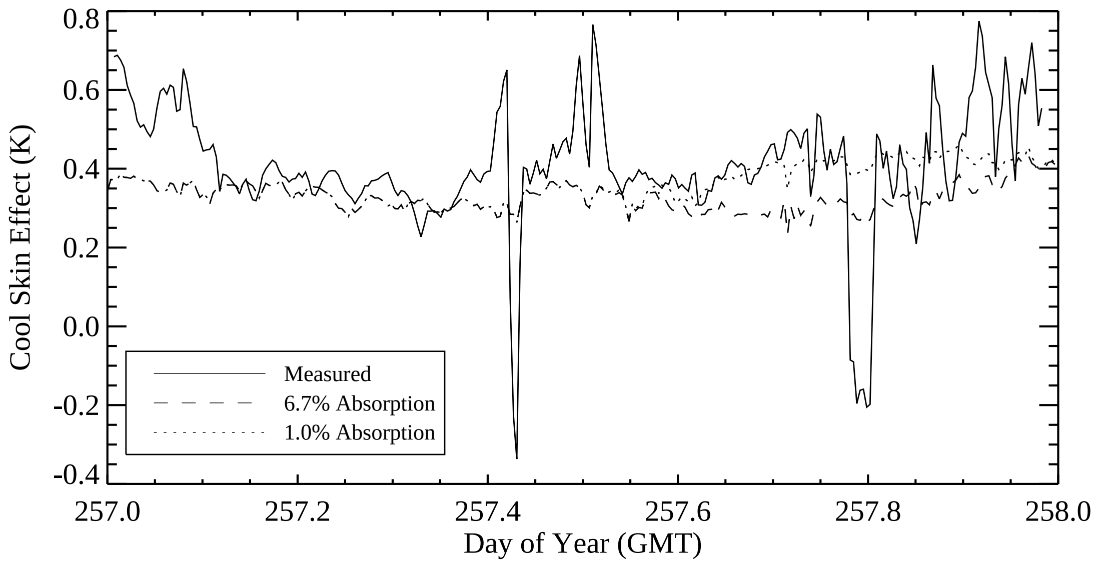

Figure 5. Comparison of the cool skin effect observed during one day of EPIC with predictions obtained using a simplified solar transmission model and different assumptions about the fraction of solar irradiance absorbed at depths shallower than the skin layer. The best results are obtained assuming very little absorption.

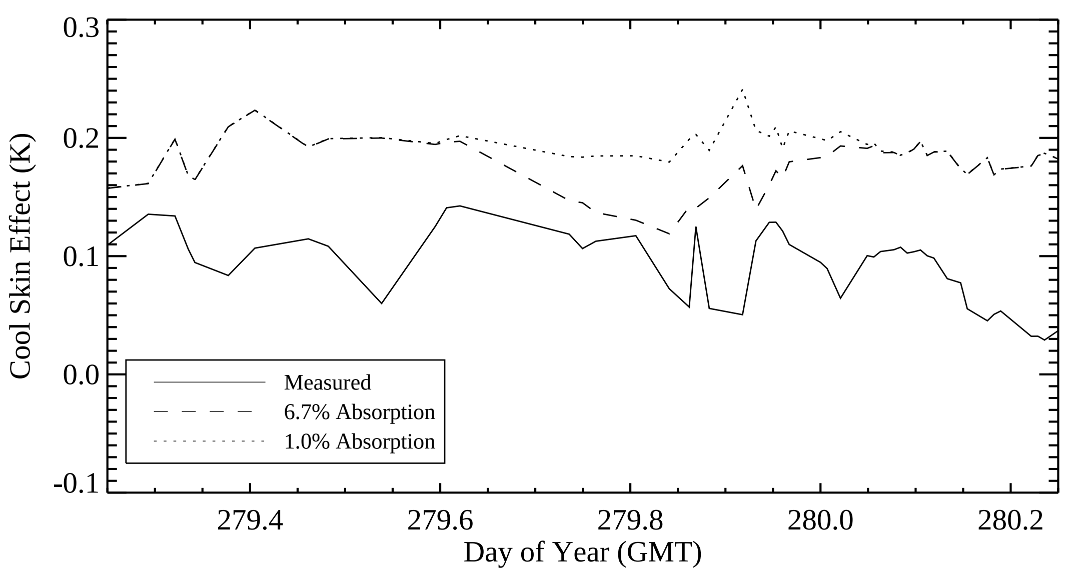

Figure 6. Comparison of the cool skin effect observed during one day of FAIRS with predictions obtained using a simplified solar transmission model and different assumptions about the fraction of solar irradiance absorbed at depths shallower than the skin layer.