Analysis of ECMWF Prognostic Cloud Forecasts Using ARESE October 30, 1995, Data

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Introduction

Understanding the complex, non-linear role that clouds play in the earth's climate system hinges upon a better characterization of their spatial, temporal, and microphysical distributions and properties on the global scale. Of fundamental importance is the interaction of clouds with both solar and terrestrial radiation; providing for differential heating and cooling of the atmospheric column, which in turn influences atmospheric circulation on much larger scales. Representing closure of the hydrological cycle, the formation and dissipation of cloud may be regarded as the most readily observable signature of the underlying moisture and circulation fields. The degree to which a numerical weather prediction (NWP) model can reproduce the observed cloudy/clear field, then, is a very important indirect measure of its ability to characterize atmospheric circulation on all scales. Surprisingly, very few marriages to date have been consummated between the cloud modeling and cloud measurement communities, and it is of no doubt that the focus and development of both have suffered for it.

The Atmospheric Radiation Measurement (ARM) Program provides a unique opportunity to investigate model forecasts of cloudiness with an instrument-rich data base. As an extension to the spatial distribution analyses (Miller et al. 1999) performed using global cloud profile data from the Lidar In-space Technology Experiment (LITE), the global forecast model of the European Centre for Medium-Range Weather Forecasting (ECMWF) was selected for analysis in this study. While the ECMWF cloud forecasts (which apply the prognostic scheme of Tiedke 1993) have been found to perform admirably in comparison to observed spatial distributions for short-range (~30-hour) global forecasts at the meso- and synoptic scales, the equally relevant question of microphysics (e.g., liquid/ice water content, cloud droplet distribution, and extinction) has yet to be addressed formally. If systematic biases in the model water content fields do exist, a comprehensive model/retrieval intercomparison (multiple retrieval cases spanning a wide array of cloud types and geographic locations) campaign will succeed in identifying them. In this context, radiative and in situ measurements collected during the ARM intensive observation period (IOP) experiments will play an integral role in model cloud validation and refinement.

ARESE October 30, 1995, Case Study

The ARM Enhanced Shortwave Experiment (ARESE) took place in October 1995. Among the instruments flown aboard the Egrett aircraft during this IOP was the Colorado State University Scanning Spectral Polarimeter (SSP) instrument and a cloud detection lidar (CDL). The former provided spectral radiance and flux measurements (40 channels) spanning the range of 0.4 to 1.1 microns (for use in cloud property retrievals), and the latter provided a two-dimensional slice of the cloud profile along the Egrett flight track (for cloud cover comparisons).

On October 30, the aircraft flew above a two-layer cloud field comprised of thin cirrus at 10 km and a thick low-level stratus cloud between 1 and 2.5 km. Figure 1 shows the flight path spanning the period 1700-1945 Universal Time Coordinates (UTC). The high optical depth of the lower layer attenuated completely the CDL signal before reaching the surface. As a result, rawinsonde data launched from the Cloud and Radiation Testbed (CART) site were used to infer an approximate cloud base from the condensation level (roughly 1 km).

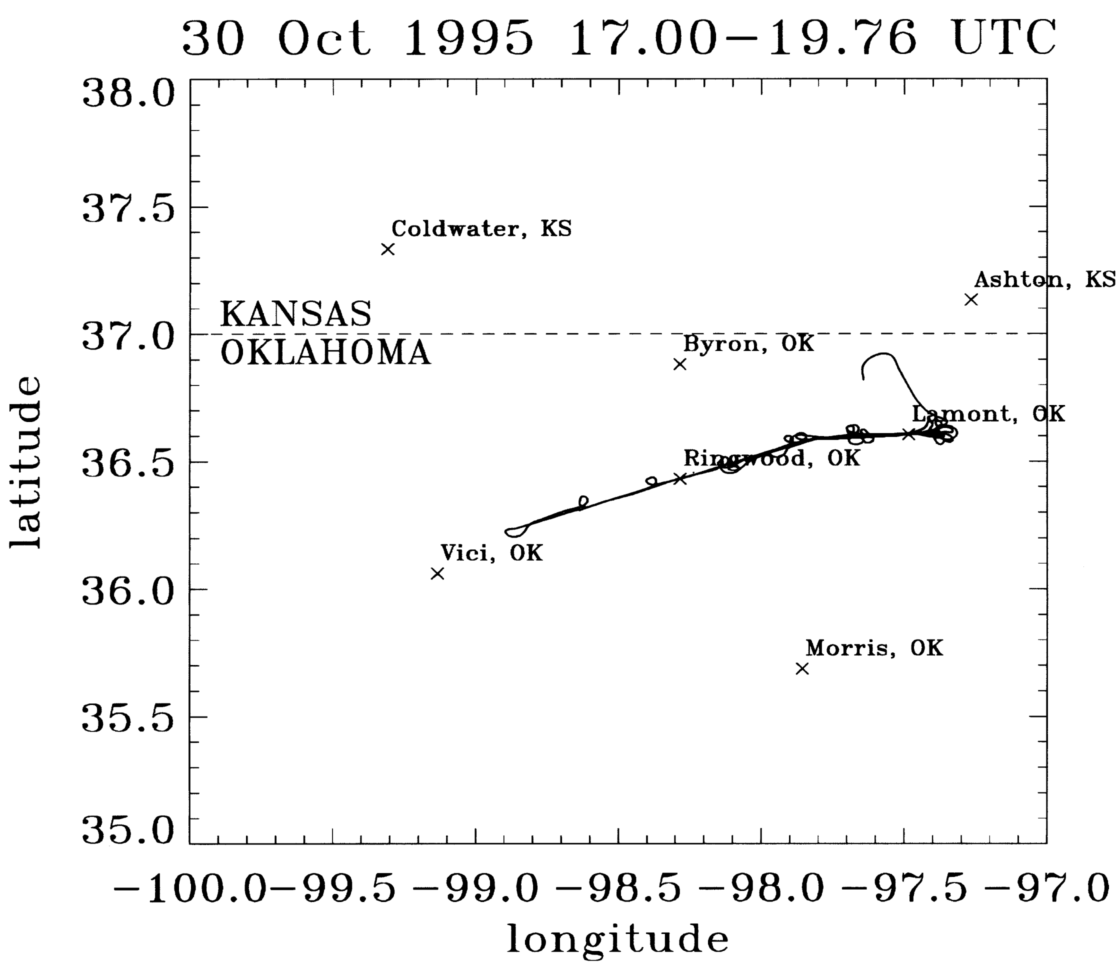

Figure 1. The Egrett flight track from 1700 Z to 1945 Z during ARESE October 30, 1995.

Spatial/Temporal Comparison

Discrete-grid ECMWF forecasts (encompassing the Egrett flight track) at T319 resolution interpolated to 1-degree grid spacing (~100 km horizontal resolution) and 31 hybrid flux levels were produced for the ARESE October 30, 1995, case. Initialized at 00 UTC, forecast steps between 17 and 20 hours at 20-minute temporal resolution were extracted for the comparisons. Model output fields included cloud cover (0-1 fraction), specific liquid water content (kg/kg) and specific ice water content (kg/kg), along with profiles of temperature, pressure, and humidity. In order to obtain a one-to-one comparison between model and observations, the CDL data were binned to the spatial and temporal resolution of the model. Figure 2 illustrates the rebinning of the CDL data to model resolution.

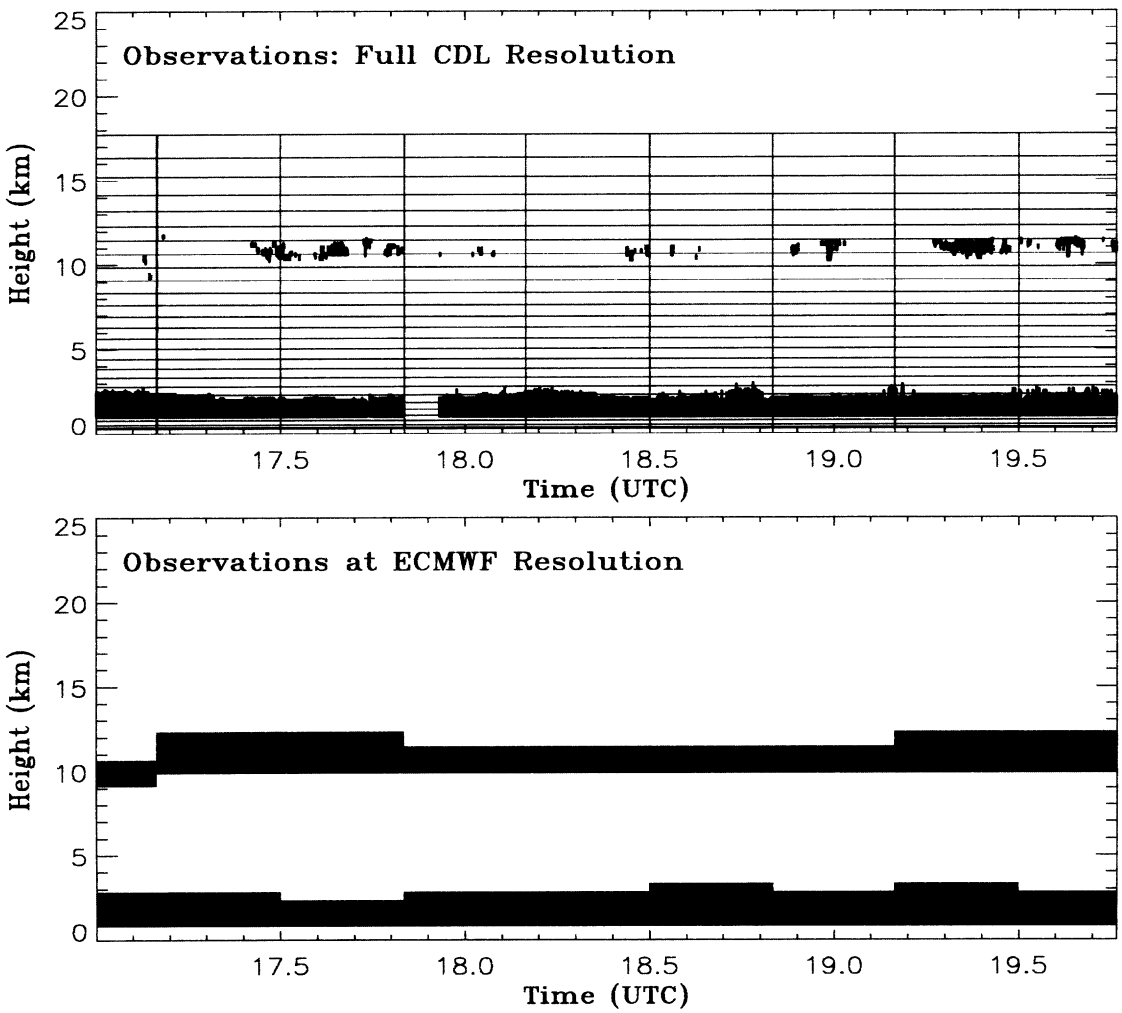

Figure 2. CDL retrieved cloud profile (top panel) rebinned to ECMWF spatial and temporal resolution (lower panel).

An unavoidable source of uncertainty in the cloud-cover comparison stems from the differences in cloud sampling between the model cloud fields and the observations. While the model cloud data are volumetric (spanning an entire grid box), the CDL data are a two-dimensional cross section (along the Egrett flight track) within this volume. The idea of an observational cloud fraction is unattainable from these data, as the extent of cloud within the model grid box is unknown. For this reason, no observed cloud fractions are included in these comparisons. Fortunately, the ARESE October 30, 1995, case featured a simple two-layer cloud profile with largely uniform coverage (especially in the low-level cloud field). Intercomparison of model and observed cloudiness (Figure 3) reveals that the forecast predicts accurately both cloud layers in both height and thickness over the 3-hour observation period. The significance of this high spatial coherence, which has been demonstrated in independent studies (Miller et al. 1998; Mace et al. 1998) as well, should not go unappreciated.

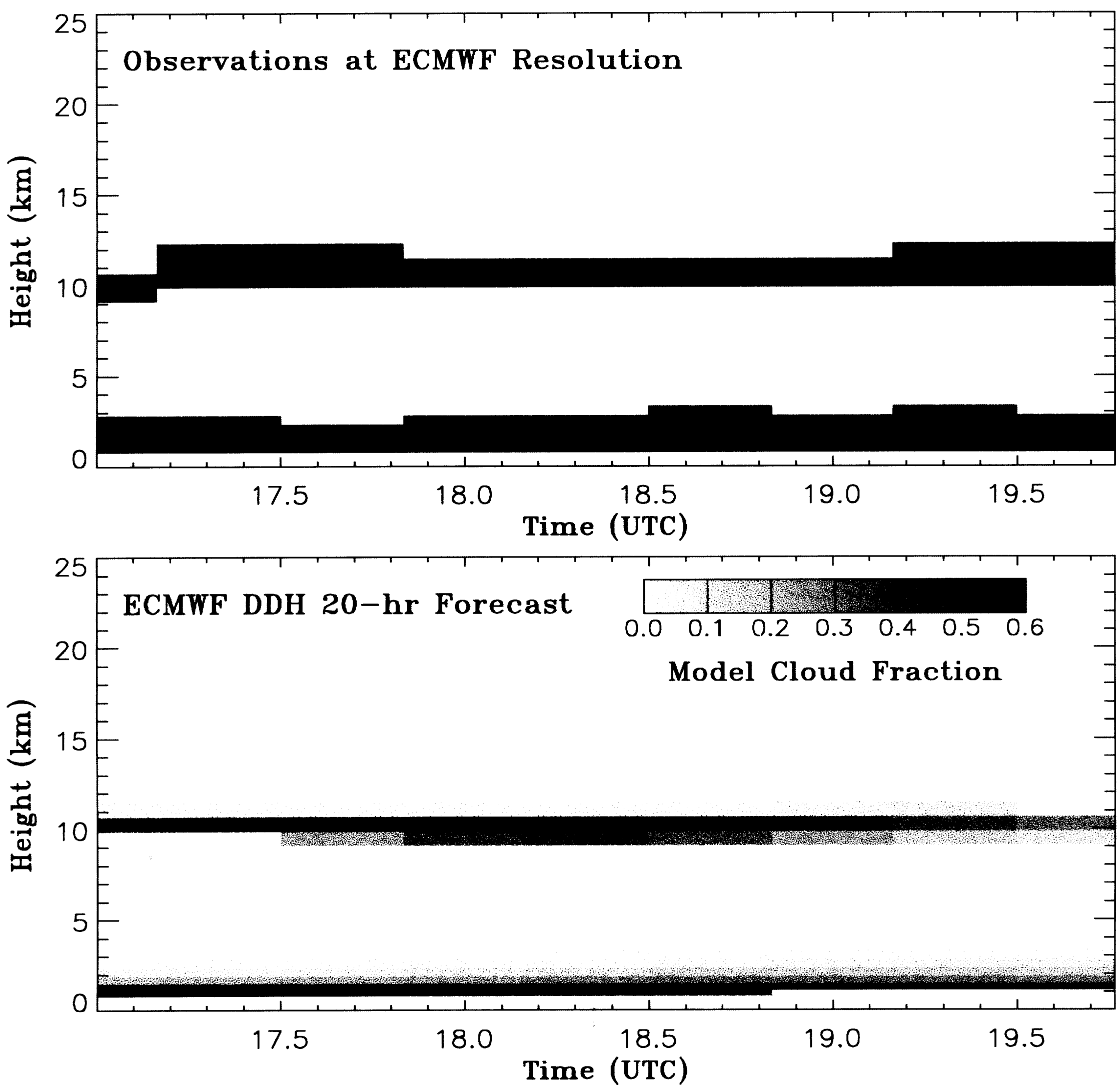

Figure 3. Comparison of model 17-20 hour forecast of cloud cover with rebinned CDL observation data.

Retrieval Theory and Products

The inversion algorithm applied to the SSP radiance data was based on the optimal estimation approach of Rodgers (1976). In brief, we express the SSP radiance measurement vector (y) as follows

$$y = F(x, b) + \varepsilon(y, F, b)$$

where the forward model estimate (F) is a function of the retrieved (x) and unretrieved (b) parameters and an error term (ε) associated with the forward model, the a priori assumptions (e.g. the temperature, humidity, and ozone profiles), and the SSP measurements themselves. The retrieval vector for this study is comprised of cloud optical depth, τ, and the effective particle radius, r_{eff}, of the cloud droplet size distribution (a modified-γ distribution and Mie theory for spheres are assumed). The forward model is a plane parallel doubling and adding code described in Miller et al. (1999).

The retrieved optical depth and effective particle radius can then be transformed into an equivalent liquid/ice water content (LWC) following Stephens (1978):

$$LWC = 2\tau\rho r_{eff} / 3\Delta z$$

where ρ is the density of water or ice and Δz is the vertical thickness of the cloud as determined from the CDL. Conversely, model optical depths can be obtained from this same relationship. The model liquid/ice water contents are divided by model cloud fraction to obtain the in-cloud liquid/ice water contents. An effective radius of 10 μm for model water clouds and a temperature-dependent relationship for ice clouds is assumed. The model and retrieved cloud optical depths are shown in Figure 4. Ostensibly, the model and retrieved optical depths are of similar magnitude. However the point-by-point discrepancies are by no means negligible. The radiative implications of these differences on the boundary fluxes of the atmospheric column (as measurable from surface and satellite-based radiometer instruments) are the subject of the following section.

Simulation of Boundary Fluxes

A 2-stream radiative transfer model based on the Adjoint Perturbation Method (Gabriel et al. 1999) was employed to calculate the broadband shortwave (0.2-4.0 μm) and longwave (4.5-∞ μm) fluxes at the surface and top-of-atmosphere boundaries. Because only the relative flux differences were of concern, no comparisons to broadband flux measurements are included here. Figures 5 and 6 summarize the shortwave and longwave flux comparisons for the ARESE October 30, 1995, flight leg. The discrepancies in model-observed shortwave transmission and reflection are in significant disagreement (on the order of 30 to 60 W/m^2 broadband) with the retrieval-derived quantities. The optically thick lower-level cloud in both the model and retrieval results in a minimal difference in downwelling longwave flux at the surface, while the enhanced upwelling longwave flux at top-of-atmosphere indicates that the ice-water contents in the overlying model cirrus layer are higher than those observed. As thin cirrus serve to warm the lower atmosphere by absorbing upwelling (warm) emissions and

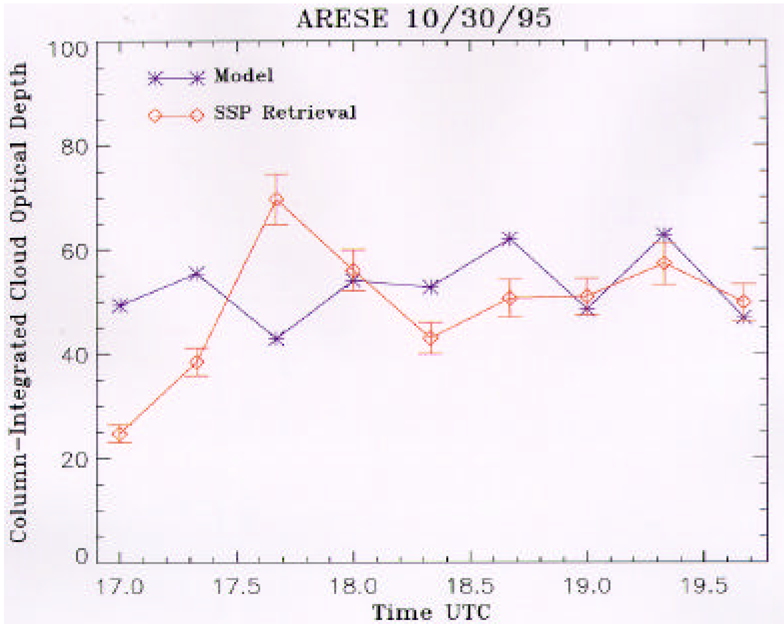

Figure 4. Comparison of mode-derived cloud optical depth with SSP-retrieved quantities.

re-emitting to space at their colder environmental temperature, inaccuracies in these globally-pervasive and radiatively important cloud fields can result in significant and compounding errors in the model radiation budget.

Conclusion

We have investigated the ECMWF prognostic cloud scheme short-range forecast performance for ARESE October 30, 1995. The spatial structure of the forecast agrees well with CDL observations, but model water paths differed from SSP retrieved values to the extent of yielding radiatively significant differences in surface and top-of-atmosphere fluxes. While this study scratches only the surface of the work that needs to be done in the area of model cloud validation, we emphasize here that a great wealth of potential validation data has been compiled already within the ARM archives—waiting to be applied. With the inclusion of active instruments on the space platform now and into the next millenium, new opportunities will emerge to better quantify forecast cloud errors in a more comprehensive way. The needs of the modeling community should serve as an outline to remote sensing orchestrations (such as ARM), and the modeling community must in turn make a concerted effort to utilize of these products to their fullest capacity.

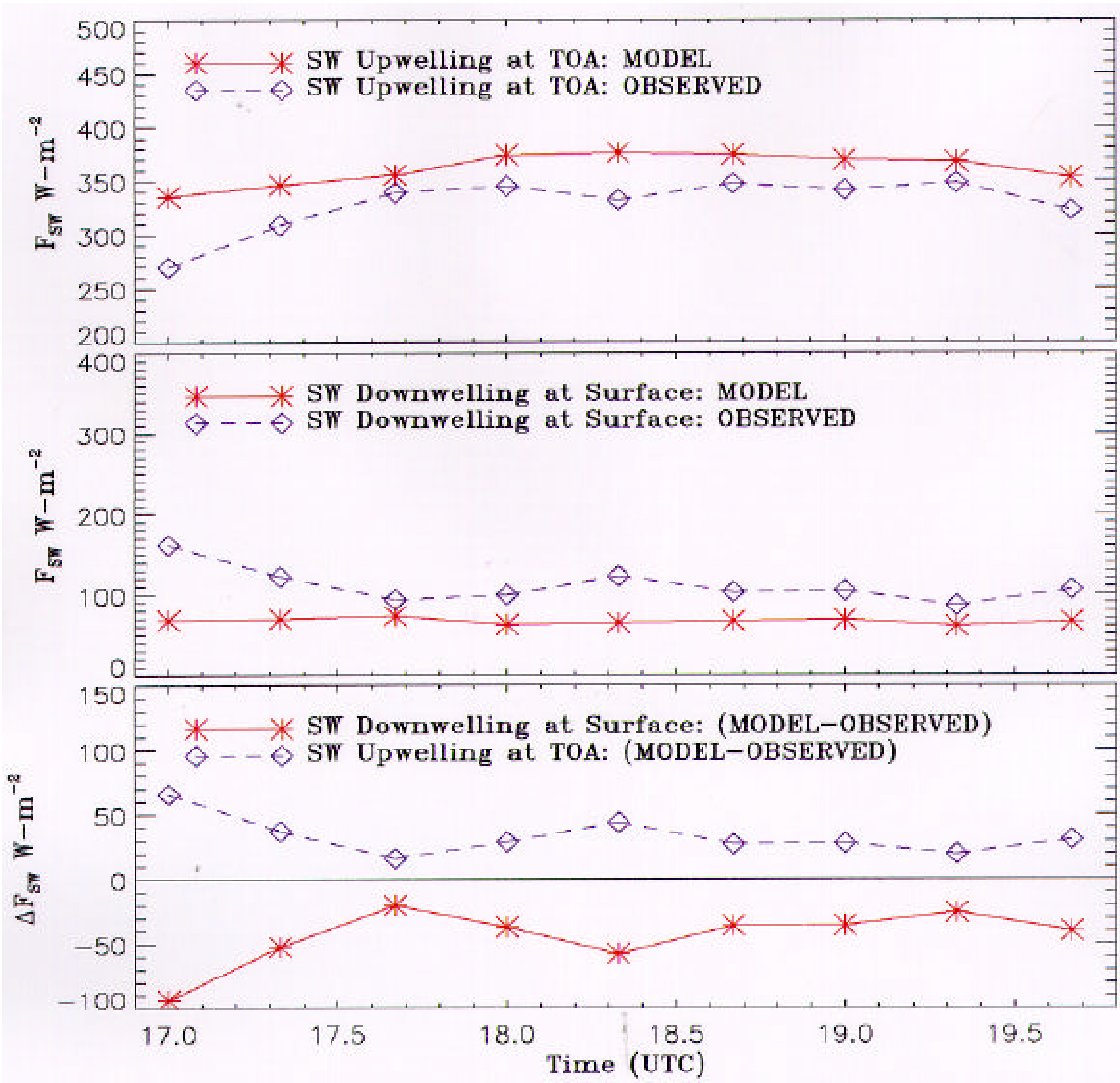

Figure 5. Broadband shortwave fluxes as derived from 2-stream radiative transfer and mode/retrieval-derived liquid/ice water contents.

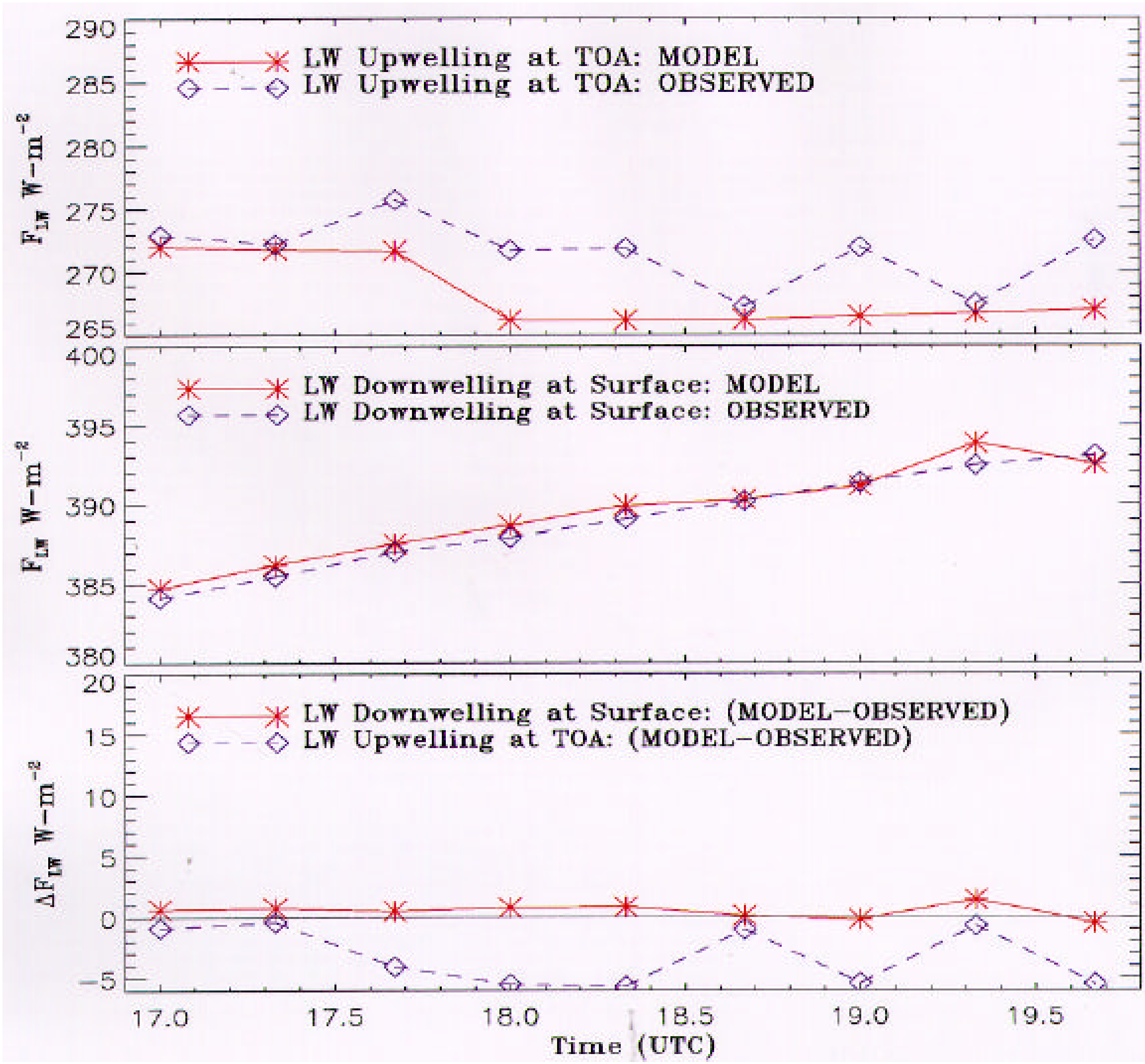

Figure 6. Broadband longwave fluxes as derived from 2-stream radiative transfer and model/retrieval-derived liquid/ice water contents.

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