Assessing the Impact of the Plane-Parallel Cloud Assumption used in Computing Shortwave Heating Rate Profiles for the Broadband Heating Rate Profile Project

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Introduction

The Atmospheric Radiation Measurement (ARM) Program Broadband Heating Rate Profile (BBHRP) project represents a core programmatic effort to produce heating rate profiles that promote the development and testing of cloud parameterization methodologies used in climate models. The profiles are computed using the Rapid Radiative Transfer Models (RRTMs) that employ as input best estimates of cloud characteristics, gaseous profiles, aerosols and surface properties obtained from the suite of ARM sensors and retrieval algorithms. For the shortwave, the model (RRTM_SW) assumes plane-parallel clouds using discrete ordinate radiative transfer to perform the scattering calculations. While for many cases the simulations will be accurate, there will be instances of disagreement in measurement-model comparisons because of either a misrepresentation of the atmospheric state, errors in radiative-flux measurements or the assumption of 1D clouds. Here, we develop a method to flag cloud fields that are likely impacted by 3D radiative effects that cannot be properly accounted for in 1D radiative transfer models. This "3D indicator" is initially applied to BBHRP P_i product for the Southern Great Plains (SGP) 2000 cloud intensive operational period (IOP).

Index Computation

The P_i BBHRP product represents model derived heating rates and radiative fluxes averaged over 20 min. time periods. Observations are made and simulations are performed at the time segments nearest radiosonde launches. Model atmospheric inputs are derived from the radiosondes and cloud fields are generated using the Mbase cloud retrieval algorithm that is primarily based upon Millimeter Cloud Radar (MMCR) imagery. Mbase produces retrievals every 10 s and these are averaged to produce 20 minute cloud field model inputs for the RRTM. To test if the observed fluxes averaged over these periods are impacted by 3D radiative effects the shortwave radiative environment is simulated using a 3D radiative transfer model. Both 3D and 1D computations are performed using the 10 s resolved cloud fields as input. Differences indicate the presence of 3D radiative effects in the observations. The 3D model is based on the Monte Carlo method and uses for its optical properties the RRTM model as shown in Figure 1. To reduce the impact of the periodic boundary conditions used in the Monte Carlo model, the computations are performed on a field consisting of three 20 min. segments with the period of interest placed in the center as shown below in Figure 2.

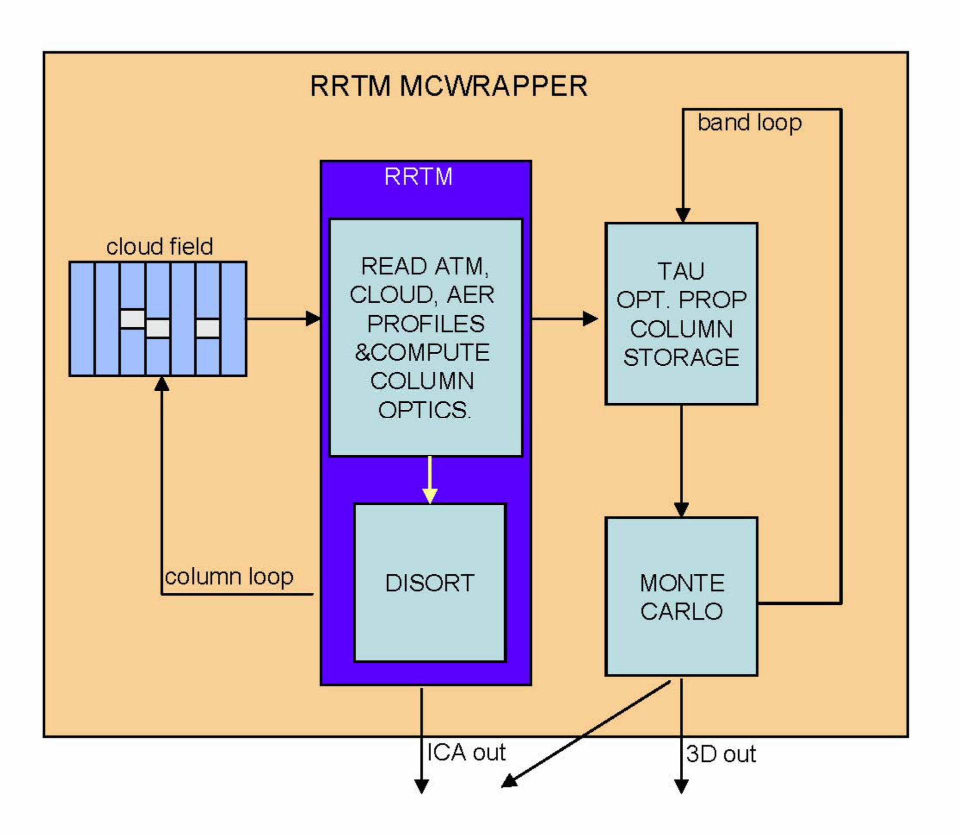

Figure 1. Schematic of the 3D RRTM model.

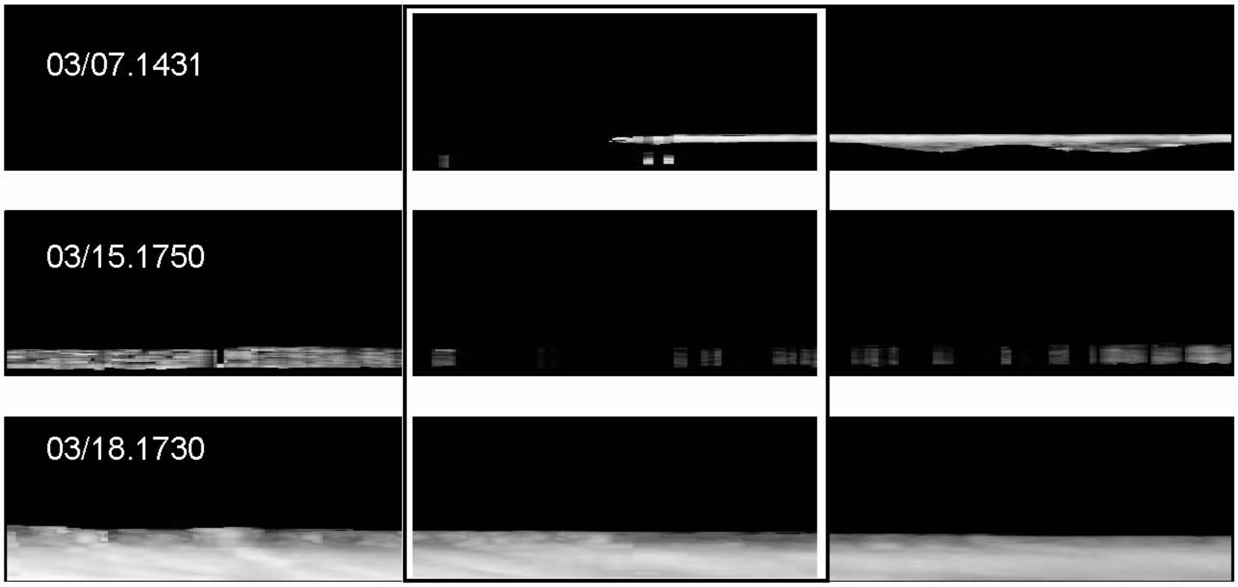

Figure 2. Cloud field model inputs for dates examined in detail. Box represents spatial averaging for equivalent 20 min. P_i BBHRP product.

Since the cloud retrieval algorithm can only produce 2D cloud fields, the 3D model cannot reliably simulate the actual observed radiative field because of the lack of information about the azimuthal orientation of the sun relative to the cloud field. Still, 3D computations can be used to determine the accuracy of using a 1D radiative transfer model by creating an index that examines the directional component of the radiation for a given field. The 3DINDEX is computed as

$$3DINDEX = ((3D_L - ICA)^2 + (3D_R - ICA)^2)^{1/2} / (ICA \sqrt{2})$$

where ICA represents 1D radiative transfer computations using the independent column approach and 3DL and 3DR are 3D radiative transfer computations with the sun oriented towards the left and right, respectively. Both the ICA and 3D results are computed using the same Monte Carlo model. A 3DINDEX value of 0 indicates a plane parallel cloud while higher values suggest greater heterogeneity. For cloud fields that may seem homogeneous from radar imagery, high index values may still be obtained because of steep solar zenith angles.

The red bars presented in Figure 3 show the 3DINDEX for the SGP 2000 cloud IOP. Blue bars represent the different between the P_i product computed using RRTM and the observed irradiance normalized by the observed value. The downwelling irradiances are from Solar Infrared Radiation Station (SIRS) and the top of the atmosphere (TOA) fluxes are based upon a geostationary operational environmental satellite retrieval algorithm. Results are partitioned between cloud fields estimated to be composed primarily of water droplets, ice and mixed phase. The circled dates are analyzed in detail.

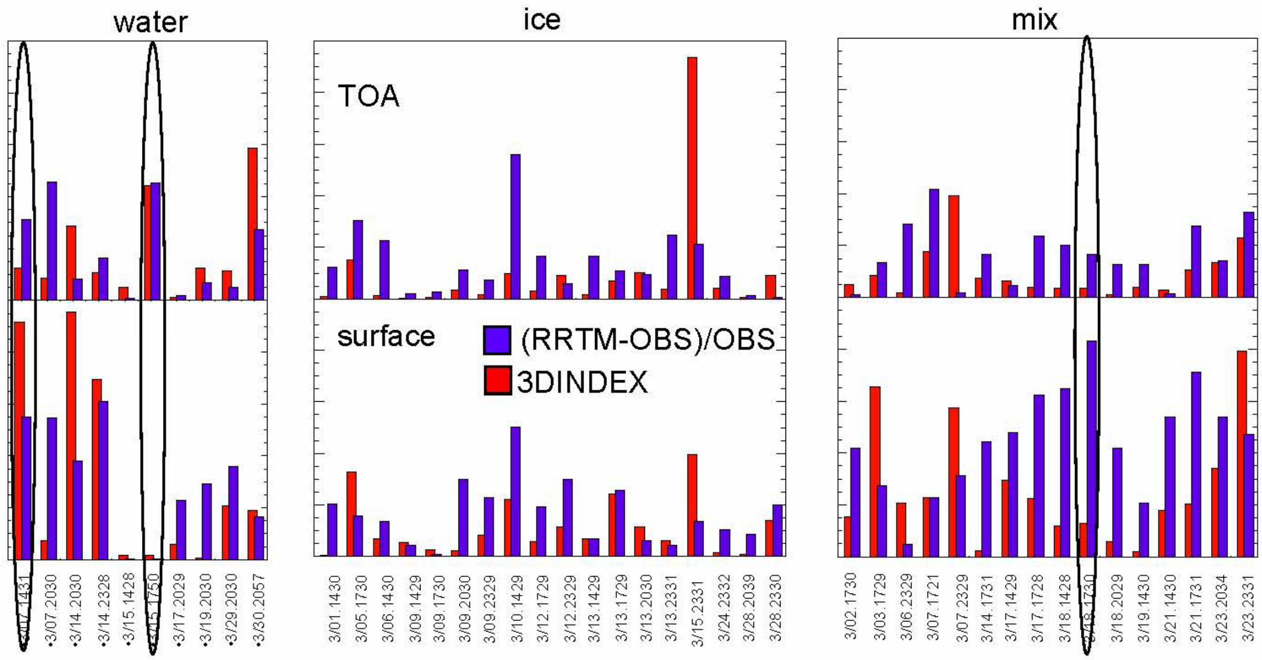

Figure 3 . 3DINDEX (red) and normalized difference between P_i product and observations (blue) for TOA and surface during March 2000 partitioned among water, ice and mixed phased cloud fields.

Results

For the water cloud of 03/07, the 3DINDEX predicts very large 3D effects for the surface fluxes and this is confirmed by the differences between P_i product and observations from SIRS (Figure 4). As shown, the 3D surface values are extremely sensitive to the location of the sun. For the TOA fluxes the index predicts only small 3D effects, but the difference between the P_i product and observed values are substantially larger. Evaluating these differences for the TOA is difficult since the irradiance is not directly measured but estimated using a radiance to irradiance algorithm. In this case the index may not be at fault since the observations are in a sense 1D and will tend to more closely match the 1D computations used in the P_i product. For the 03/15 cloud field where the center 20 minute segment of interest is dominated by clear sky, the surface index and observations both show no 3D effects. However, for the TOA the index predicts large 3D effects because the 3D and 1D model results differ greatly because of the inability for the 1D model to account for the adjacent cloud. Again, there is the radiance to irradiance conversion issue for the TOA observation, but for this case secondary scattering likely makes the scene viewed by the satellite brighter than what would be seen if there was no cloud within the vicinity of the central patch. While the index can predict potential errors associated with the 1D cloud assumption, there are occurrences when large discrepancies are found between the observations and P_1 product that are not related to 3D radiative effects. For example, the mixed phase cloud field of 03/18 is thick and homogeneous and it is expected that 3D effects should be minimal (Figure 6). However, the P_i product shows the largest error for the surface flux of all days examined. In this case, it is believed that this large discrepancy is associated with the difficulties in retrieving cloud microphysics for the mixed phased cloud that are used within RRTM_SW.

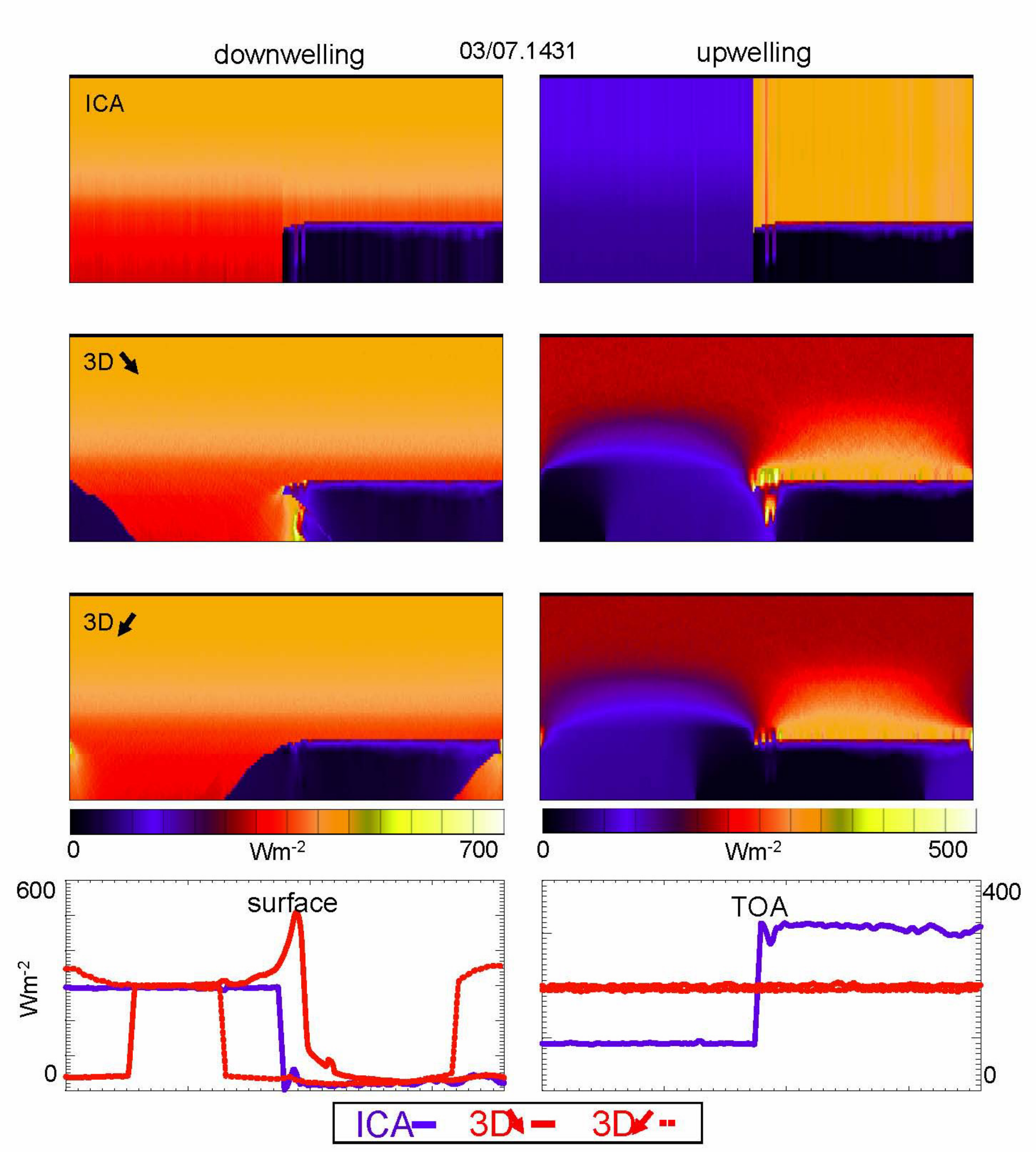

Figure 4. Downwelling and upwelling shortwave fluxes for ICA and 3D model computations for 03/07.1431 cloud field. Arrows indicate direction of the solar beam. Lower panel shows surface and TOA irradiances.

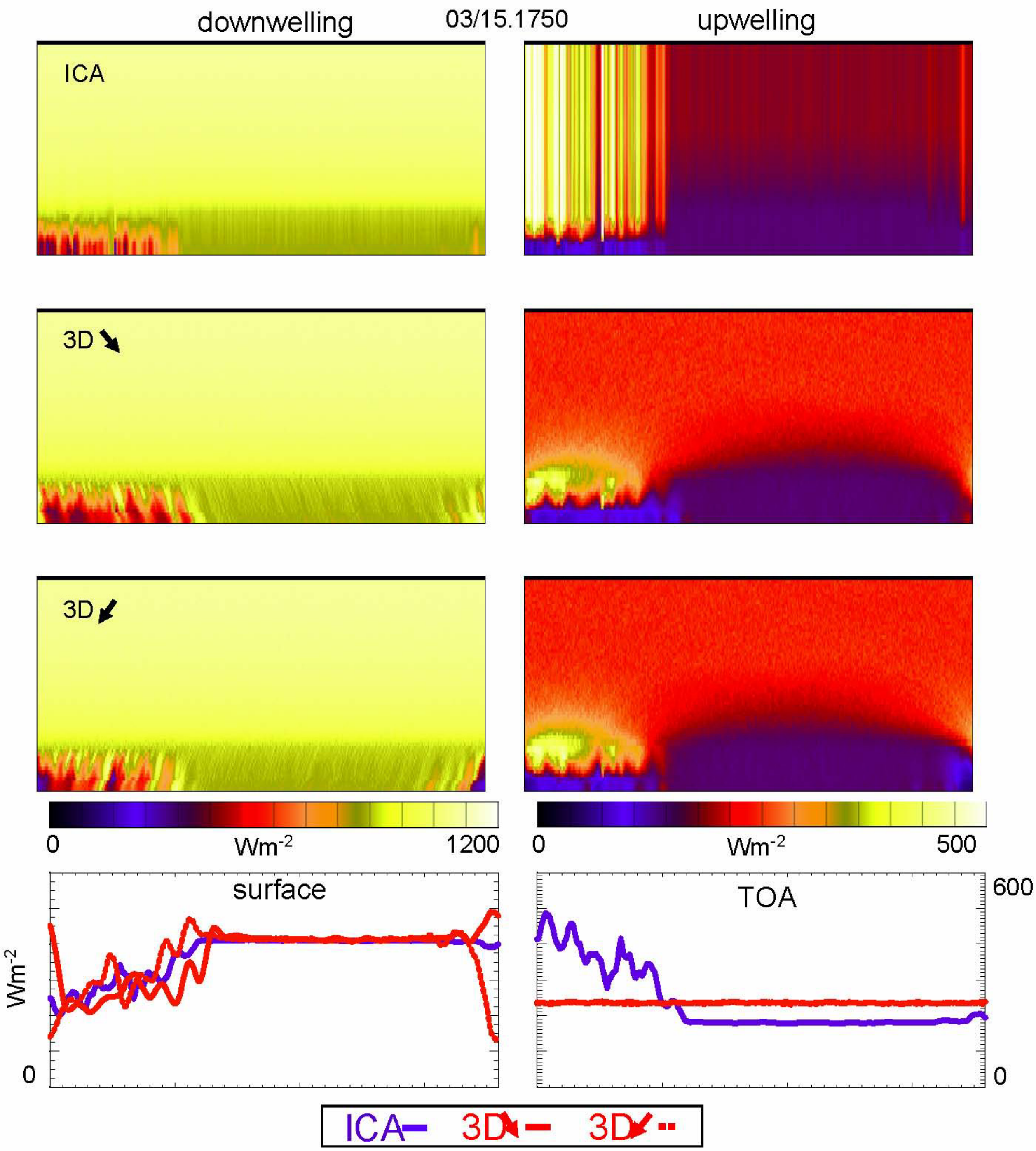

Figure 5. Downwelling and upwelling shortwave fluxes for ICA and 3D model computations for 03/15.1750 cloud field. Arrows indicate direction of the solar beam. Lower panel shows surface and TOA irradiances.

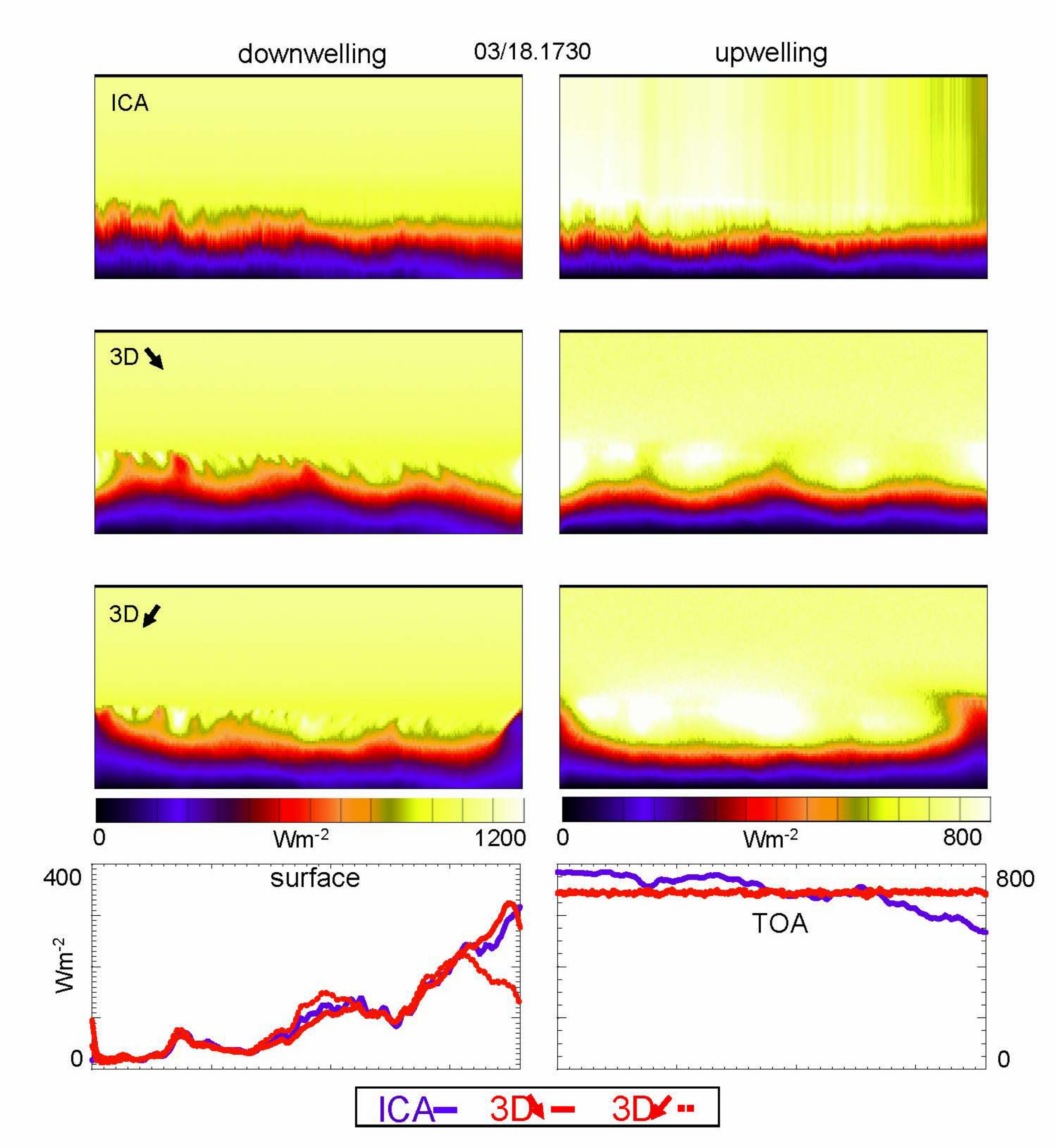

Figure 6. Downwelling and upwelling shortwave fluxes for ICA and 3D model computations for 03/18.1730 cloud field. Arrows indicate direction of the solar beam. Lower panel shows surface and TOA irradiances.

Conclusion

The 3DINDEX is diagnostic tool to be used for determining if measurement-model discrepancies can be attributed to 3D radiative effects that are not accounted for in 1D radiative transfer codes. The next step in the development of this tool is to perform some modifications for the flux evaluation, and also to apply it to shortwave heating rate profiles. Eventually, the 3DINDEX will be computed for an entire year at SGP, North Slope of Alaska and Tropical Western Pacific.