Implied Dynamic Feedback of 3D IR Radiative Transfer on Simulated Cloud Fields

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Introduction

Current radiation parameterizations in numerical models nearly universally use a one-dimensional (1D) treatment of radiative transfer (RT). While computationally attractive, 1DRT neglects horizontal photon transport, which may be important in cases of complicated cloud geometry and internal cloud liquid water content (LWC) structure. Results from the Intercomparison of three-dimensional (3D) Radiation Codes project demonstrate that 1DRT is often unwarranted and can lead to significant errors in domain-mean shortwave heating rates. Guan et al. (1995) show that stratocumulus cloud top structure can lead to a distribution of multi-dimensional longwave (LW) cooling that differs from that of a horizontally homogeneous cloud. They show that multi-dimensional radiative transfer (MDRT) acts on cloud top undulations to reduce the mean forcing relative to a horizontally uniform cloud.

Broadband LW 3DRT calculations are performed on boundary layer cloud fields from a large-eddy simulation (LES) model using the MDRT radiative transfer scheme of Evans (1998; Spherical Harmonics Discrete Ordinate Method—SHDOM). 3DRT flux and heating rate fields are analyzed to infer feedbacks onto the cloud-topped boundary layer dynamics and macroscale cloud field structure relative to independent pixel approximation (IPA) RT.

Methodology

The Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) LES model provides LWC fields for solid and broken cloud fields. From these LWC fields, SHDOM calculates cloud optical properties and then uses a correlated k-distribution to compute LW RT in 12 bands from 4μm to 100 μm. Emission, absorption, and scattering effects are included. Initial conditions for the LES are derived from the ASTEX A209 case simulated by Khairoutdinov and Kogan (1999). For the solid cloud case, the simple saturation adjustment scheme used produces no drizzle. The broken case uses an explicit (bin) microphysical scheme, with initial cloud condensation nuclei (CCN) distributed lognormally and having a total concentration of 41 cm^{-3}. This low value of CCN leads to a prodigious amount of drizzle and eventual cloud breakup. The LWC grid is 40 x 40 x 51 for the solid case, and 50 x 50 x 51 for the broken. Grid spacing is 100 m in the horizontal and 25 m in the vertical. For all cases, the droplet radius is calculated based on a droplet concentration of 50 cm^{-3}. For each cloud, SHDOM calculates 3DRT and IPA RT fluxes and heating rates.

The LES domain is 1250 m deep, but the RT calculation is performed on a grid that extends up to 30 km. The downwelling flux at the LES top may be thought of as a boundary condition and should be the same for all cases. IPA and 3D calculations were performed using SHDOM on a horizontally homogeneous LWC field. Figure 1a shows that a net LW 3D-IPA offset of 2 W m^{-2} is present at an altitude of 1 km, just above the cloud top. This offset arises from differences in downwelling IR in the 3D and IPA calculations. The magnitude of the offset may not seem like much, given ~100 W m^{-2} of radiative forcing at cloud top, but it is of concern since it may bias the 3D-IPA comparison and mask subtle 3D RT effects. This offset problem can be ameliorated by forcing SHDOM to use more grid points in its calculation or by decreasing the “splitacc” parameter, which determines the criterion for dynamic grid splitting in SHDOM. Decreasing splitacc from 5.0 to 0.1 reduces the offset from 2 W m^{-2} to 0.1 W m^{-2} (Figure 1b), at the expense of a great increase in computational expense, however.

Unbroken Cloud

Figure 2a shows a vertical cross section of cloud top and the difference between 3D and IPA heating rates. The differences are most prominent near cloud top undulations. Regions of high cloud tops are generally associated with updrafts and anomalous 3DRT cooling, the valleys with downdrafts and 3DRT warming. Figure 2b shows that, despite the complicated spatial structure of the heating rate, the domain-mean profiles for 3D and IPA cases (overlaid) are nearly equal. The 3D-IPA differences in local forcing might lead to differences in cloud system evolution, however. The covariance of the forcing difference with the model vertical velocity field is negative (Figure 2c), implying that the 3D effect would tend to damp the turbulent eddies.

Broken (Heavy Drizzle) Cloud

Liquid water path and horizontal radiative flux vectors at a height of 512 m are shown for two different model times (3 h and 5 h) in Figures 3a and 3b. For this case, we look at the relative contributions of horizontal and vertical flux divergences rather than differences between 3D and IPA RT calculations. Cloud boundaries are generally areas of radiative flux divergence (cooling), while the broken regions between are zones of flux convergence (warming). Cross sections of LWC and heating rates from the vertical LW flux show the typical cooling and heating patterns at cloud top and base, respectively. Heating rates from horizontal fluxes become more pronounced as the cloud field begins to break apart, and cloud elements are less in radiative equilibrium with adjacent elements. Cooling from horizontal flux is then concentrated in regions of the cloud that have a large solid angle to space. Regions between

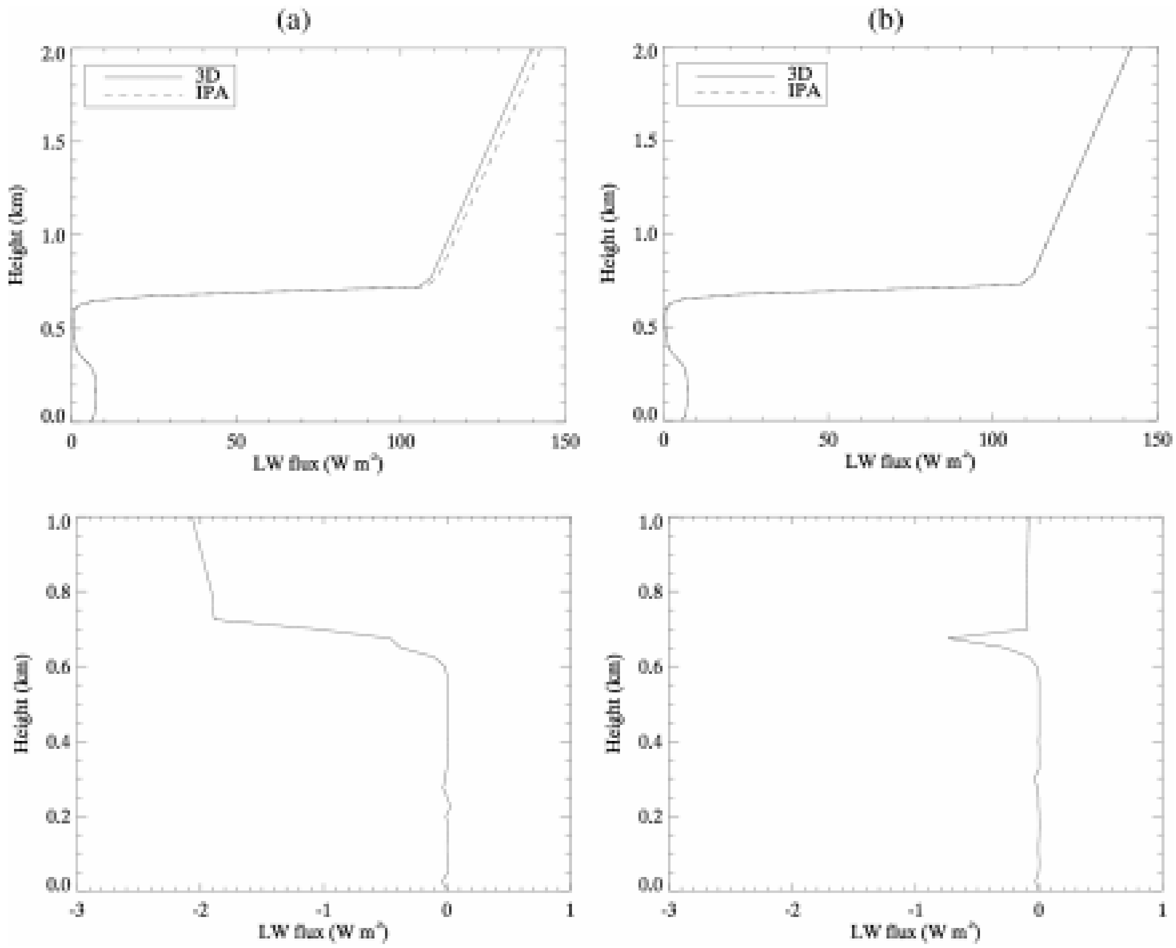

Figure 1. Net LW flux for the horizontally homogeneous cloud case for two different values of "splitace," which is the criterion that determines dynamic grid splitting in SHDOM. A smaller value of splitace means a greater number of spatial grid points. (a) splitace = 5.0. (b) splitace = 0.1. 3D and IPA downwelling fluxes are overlaid on the top row, while the bottom row shows profiles of the 3D-IPA differences.

clouds show a slight warming due to horizontal fluxes. Even where the horizontal flux divergence is appreciable, however, it is typically an order of magnitude smaller than the heating rates from vertical fluxes.

Discussion

The influence on the stratocumulus dynamics of using 3DRT can be inferred from the character of the horizontal fluxes and resulting weak heating rates.

For the solid case:

- 3D-IPA heating rate differences are associated with cloud top undulations and horizontal LWC variability.

- Updraft regions (billows) are generally associated with anomalous cooling (3D relative to IPA), while downdrafts (valleys) are associated with anomalous warming.

- This negative correlation implies that 3DRT might tend to damp the PBL energetics.

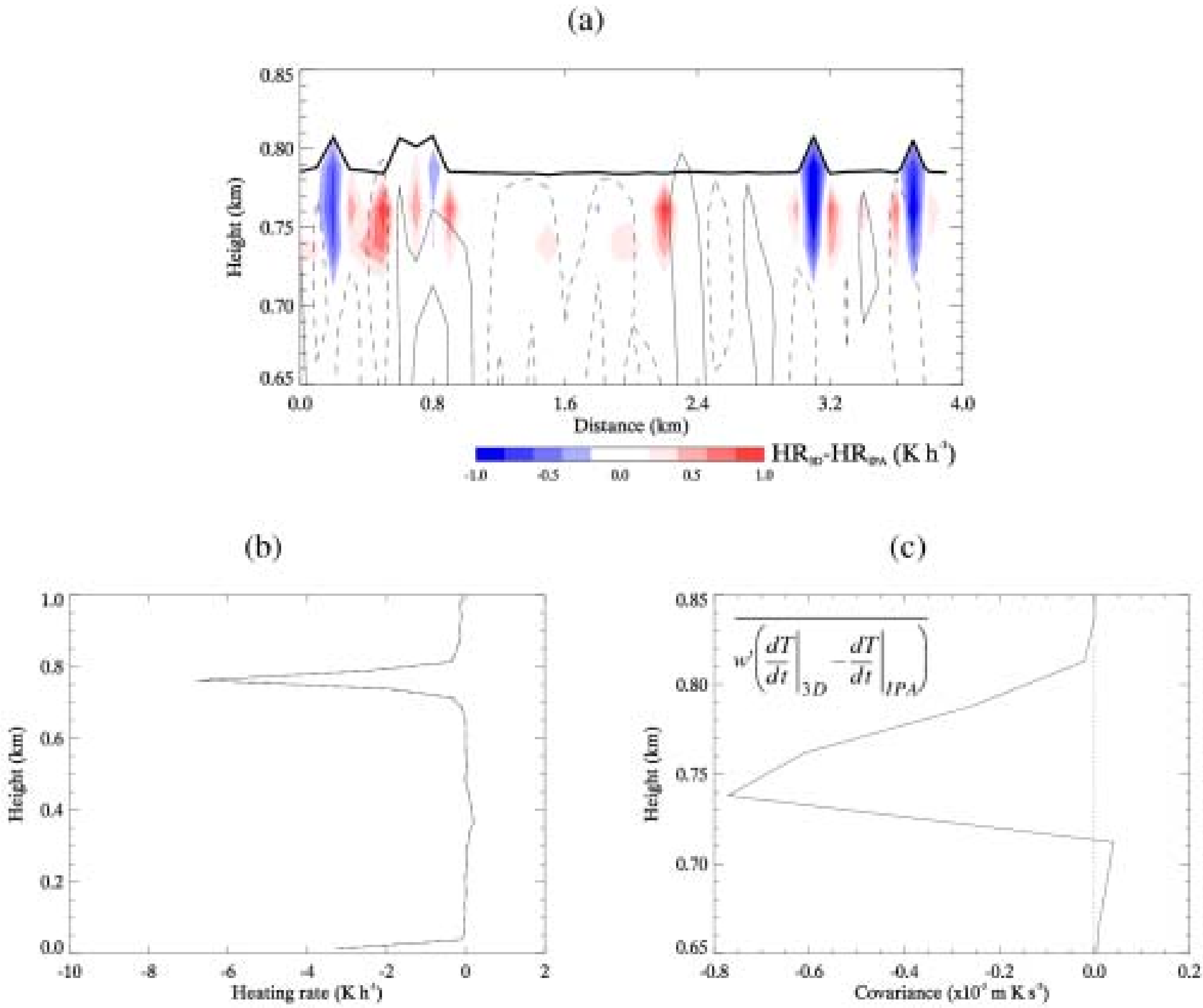

Figure 2. Cloud field and radiative flux at (a) 3 h and (b) 5 h. Vertical cross section and profiles for the unbroken cloud case. (a) Cross section at cloud top of vertical velocity (contours of ±0.25, ±0.75, and ±1.25 ms^{-1}) and 3D-IPA heating rates. Dark line indicates cloud top. (b) Domain-mean heating rates for 3D (solid) and IPA (dashed) cases, virtually on top of each other. (c) Domain-mean of covariance of vertical velocity and 3D-IPA heating rates.

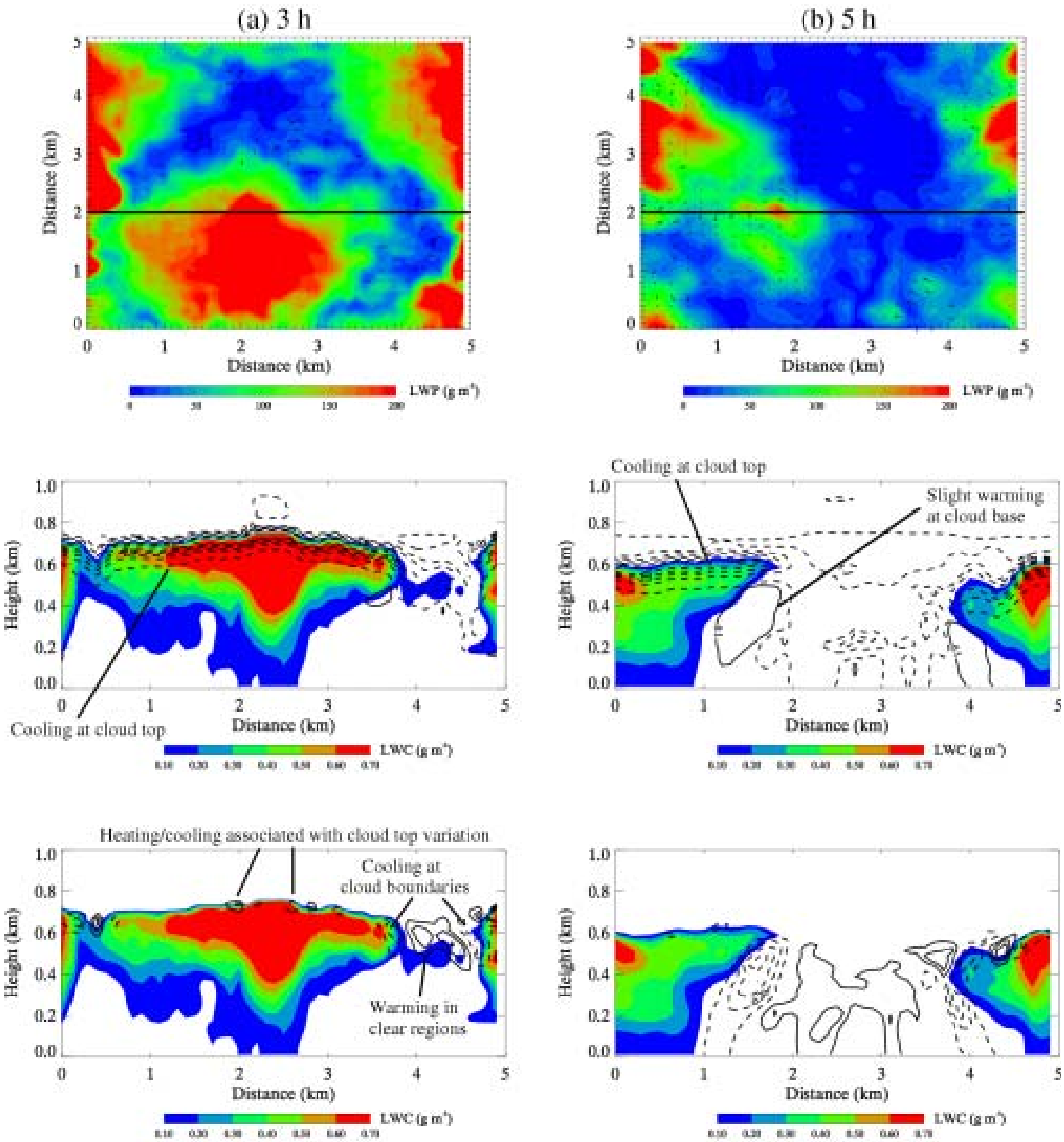

Figure 3. (Top row) LWP (g m^{-2}) and horizontal radiative flux vectors at a height of 512 m. (Middle row) LWC (g m^{-3}) and heating rates from vertical LW flux (interval of 0.1 K h^{-1}), taken along line in the LWP plot. (Bottom row) LWC (g m^{-3}) and heating rates from horizontal LW flux (interval of 0.1 K h^{-1}).

For the broken case:

- Cooling in the vicinity of lateral cloud boundaries, particularly near the detrained cloud-top may enhance the negative thermal buoyancy and enhance the cloud-cell circulation, while aiding breakup of the cloud.

- Warming in the clear regions may further stabilize the PBL to deep circulations, enhancing decoupling.

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