7.5 SOLAR ABSORPTION FEEDBACKS IN SIMULATED STRATOCUMULUS

Jerry Y. Harrington*
Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania

1. INTRODUCTION

The absorption of solar radiation within the cloud-topped boundary layer (CTBL), and its influence on the dynamics and microphysics of stratiform clouds, is a vexing issue. Vexing because, unlike the case of infrared radiation, solar absorption is dependent on cloud microstructure (e.g. Stephens, 1978) and the three-dimensional nature of the cloudy field (e.g. Titov, 1998; Loeb et al., 1998). This makes the inclusion of solar radiative processes in detailed models of the CTBL, such as large eddy simulation (LES), much more problematic than is the case for the infrared.

The issue of modeling stratiform clouds including the effects of solar absorption is not new. Many previous studies have been conducted and, as valuable as those studies have been, most have used simple CTBL models (1-D and 2-D LES, or eddy resolving models) and/or simplified microphysical schemes. However, few studies to date have included the concomitant effects of both relatively detailed microphysics and radiation in less parametrically-constrained models such as LES (except for the recent study of Ackerman et al., 2000).

This issue, however, is important since the presence of a strong diurnal cycle in low, or boundary layer, clouds is prevalent in many observational studies. For instance Rozendall et al. (1999) use weather-ship data to show that the observed frequency of low clouds has a distinct diurnal cycle, with maximum cloud fractions peaking around dawn, and minimum cloud fractions near 15:00 local time. This diurnal cycle is also evident in satellite climatologies and appears most prevalent at Weather Station November, where the mean June-July-August frequency of stratus, stratocumulus or fog is greater than 60% (Klein et al., 1995).

The principal result of previous observational studies has been that stratiform cloud layers thin, often to the point of ‘‘breaking up’’ and dispersing, during the day. Pronounced diurnal cycles have been observed in other large-scale fields (e.g., vertical velocity), nonetheless the diurnal cycle in low cloudiness is normally attributed to the effects of solar radiation; as it is generally believed that the absorption of solar radiation tends to offset cooling by long-wave radiation, and that less radiative driving of the flow leads to more anemic circulations that are unable to maintain a well mixed layer in the face of stabilizing processes such as cloud base warming or entrainment.

From a climate change perspective, understanding the dynamics of the interaction of solar radiation and turbulent boundary layer circulations is also important. For instance, using a very simple model of the planetary boundary layer Boers and Mitchell (1994) showed that the magnitude of the Twomey (1974) effect may be sensitive to radiative-dynamical interactions. Their results showed that changes in drop concentration lead to alterations in solar absorption which then should feedback to cloud thickness and, hence, the reflectivity of the cloud layer. In particular, Boers and Mitchell made use of the fact as drop concentrations are increased from some small initial value (say N = 50 cm^{-3}), solar absorption initially increases, reaches a maximum, and then decreases.Because of this, they were able to show that perturbations of drop concentrations from low to higher CCN concentrations could lead to reductions in cloud thickness and, hence, reductions in the standard Twomey effect.

In this study, a first attempt is made at examining how increases in drop concentration may alter cloud absorption and, therefore, feedback to cloud thickness and the Twomey effect.

2. METHOD

The model used for these studies is the LES version of the Regional Atmospheric Modeling System (RAMS). Longwave and shortwave heating/cooling are computed with a two-stream radiative transfer model using 6 solar and 12 infrared bands (Harrington and Olsson, 2001). To examine first-order effects, we use only a simple condensation-condensed scheme and, therefore, no drizzle. Drop concentrations (N) are fixed and considered constant with height. This allows us to easily examine how perturbations in drop concentration may alter solar absorption/dynamic feedbacks in a simplified framework. Of course, drizzle would be expected to significantly influence our simulations and we plan to treat this effect in future simulations. In order for the radiation model to interact with the cloud, not only is the liquid water content (LWC) and N required, but a spectral width of the size distribution is also required (Harrington and Olsson, 2001). Here, we use a modified gamma distribution as is standard in RAMS (e.g. Walko et al., 1995) with a shape parameter that varies between $\nu = 6$ and 15 (broader to narrower drop size distributions.)

**Corresponding author address:* J. Harrington, Dept. of Meteorology, Penn State University, University Park, PA, 16802.
email: harring@mail.meteo.psu.edu

The stratocumulus case simulated is a variant of that described in Moeng et al. (1996). Our modifications include using a simple constant-θ with height in the boundary layer (BL) initialization and alterations in BL top humidity inversion. These were primarily done to produce a slightly thicker cloud. Simulations were conducted with clouds containing various drop concentrations and using overhead sun only ($\theta_0 = 0^0$) for maximum solar absorptive effects. For brevity, we present results only from the N = 50 cm^{-3} and 500 cm^{-3}, for reasons that will become obvious.

3. Results

3.1 *Some Preliminaries*

To set the stage for our later discussions of cloud evolution for different drop concentrations, and hence solar absorption, some illustrations of these radiative effects are in order.

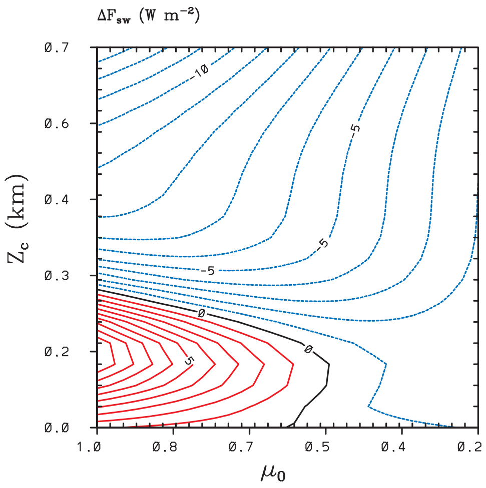

Figure 1. Contour plots of the relative difference (in percent) of the cloud-integrated absorbed solar flux (ΔF_{sw}) for various cloud depths (Z_c) and solar zenith angles ($\mu_0 = \cos\theta_0$). Differences are computed between clouds with drop concentrations of 500 cm^{-3} and 50 cm^{-3}

To give some idea of how important changes in solar absorption might be, given a certain perturbation in drop concentration, calculations of the cloud-integrated solar absorption and long wave emission were done for adiabatic clouds. The radiative model described above was used in for these cases. The results of these computations are shown in Fig. 1.

This figure illustrates the potential magnitude of solar absorption perturbations. Clouds thinner than 300 m tend to show enhanced solar absorption throughout the cloud layer when drop concentrations are perturbed from 50 to 500 cm^{-3}. Thicker clouds, on the other hand, show a reduction in solar absorption. Boers and Mitchell (1984) showed a similar plot in their work. Since BL dynamics seems to scale with integrated forcings (e.g. Lock and MacVean, 1998), the above figure would seem to indicate that BL dynamics, and perhaps cloud thickness, could be reduced under an increase in solar absorption.

Since cloud top longwave (IR) cooling is the main driving force in this case, an even better parameter to examine is the sum of the integrated solar absorption and IR emission.

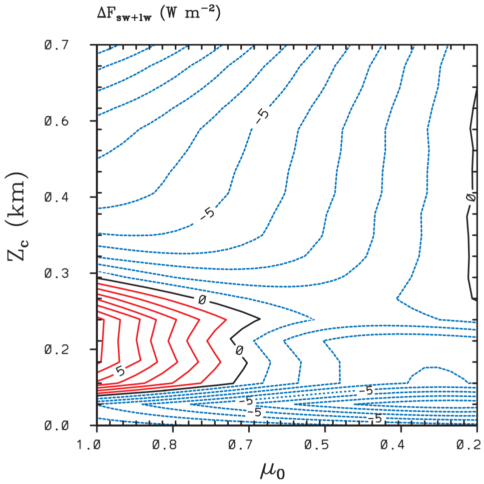

Figure 2. Same as Figure 1 except for integrated solar plus IR (ΔF_{sw+lw}).

This is shown in Fig. 2. The region of strong solar heating is now confined to a smaller set of solar zenith angles and for a smaller cloud depth range. Thick clouds, under a perturbation in drop concentration to 500 cm^{-3}, should show an increase in overall cloud cooling. Thinner clouds, however, when perturbed by a similar increase in drop concentration, should show an overall decrease in cloud cooling. Each situation will produce some sort of feedback to the cloud system itself.

In the LES studies presented below, we consider only overhead sun and clouds of ~ 250 m thickness. Our case falls within the regime, shown in Fig. 2, that should show an increase in solar heating, and therefore a decrease in overall cloud cooling given the above perturbation in drop concentration. Of course, these results will be sensitive to our choice of initial and final drop concentration. We chose values that should maximize the perturbative effect. Though this is the case, we plan to examine this in greater detail in the future.

3.2 *LES Results*

For brevity, and given the results shown in Figs. 1 and 2, we present results for simulations with N = 50 cm^{-3} (low concentration case) and N= 500 cm^{-3} (high concentration case). Since low drop concentration clouds have larger spectral widths, we use a gamma distribution shape parameter of 6 where as for the high drop concentration case we use a much narrower spectrum (shape of 15). Simulations were conducted over a 4 hr (240 min) time period.

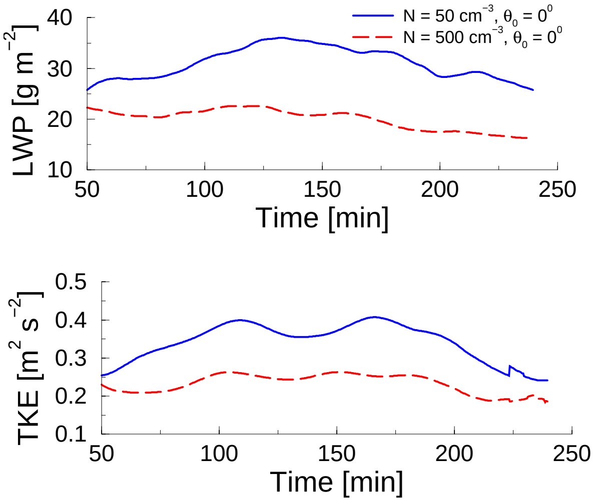

Figure 3. Time-series of LWP and TKE for two non-precipitating stratus simulations with different drop concentrations and overhead sun.

Figure 3 shows the evolution of the domain-averaged liquid water path (LWP) and turbulent kinetic energy (TKE) for the low and high drop concentration cases. Both the LWP and TKE are substantially reduced under the given perturbation in drop concentration. The case with greater drop concentrations shows a much shallower cloud with circulations that are significantly weakened. Figure 4 shows, potentially, why this is the case. After 50 min of simulation time, solar absorption is almost 7 W m^{-2} greater in the high drop concentration case. Apparently, this increase in heating is enough to decrease LWP and TKE. Reductions in LWP is due to the combined effects of increases in temperature and through reduced circulation strength.

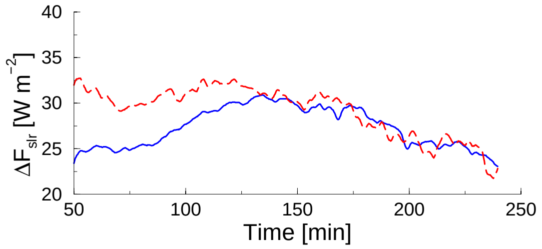

Figure 4. Time-series of the domain-averaged, vertically integrated solar heating. Line types and colors have the same meaning as in Fig. 3.

Note that after about 150 min of simulation time, the total absorbed solar radiation approaches that of the low drop concentration case. After this time period, the two curves tend to track one another quite well. We speculate that the reason for this may that above some certain amount of solar heating, the cloud layer is largely out of equilibrium. If this were the case, then the cloud layer depth and LWP would have to be reduced until the equilibrium is re-established.

Not only is the cloud LWP changing with time, which is altering solar absorption, but the cloud fraction is also changing throughout the domain. Figure 5 shows that the enhanced solar heating experienced by the higher drop concentration case causes a significant increase in the amount of broken cloudiness. As one might imagine, this also affects the reflectivity and transmissivity of the modeled clouds.

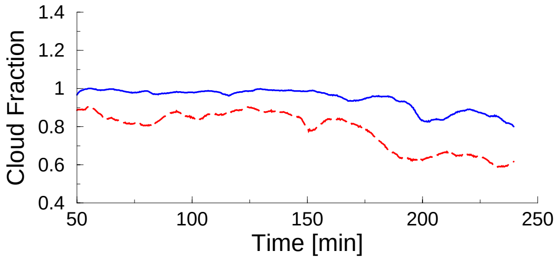

Figure 5. Time-series of the cloud fraction. Line types and colors have the same meaning as in Fig. 3.

Analysis of the various terms in the TKE budget illustrate that the above effects are primarily due to changes in the buoyancy profiles, as one might expect in this case. Figure 6 shows that the vertical component of TKE is strongly affected by greater solar absorption in the high drop concentration case. Not only is the maximum significantly reduced, but it is also displaced higher in the BL. The buoyancy flux profiles for this time, Fig. 7, show that buoyancy production of TKE in the low drop concentration is much larger than that of the high concentration case. Note also that the subcloud layer is stabilized in

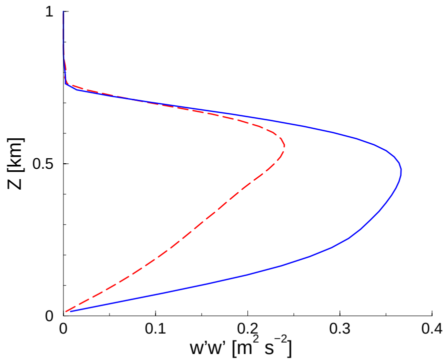

Figure 6. Vertical profile of w'w' at 3 hours. Line types and colors have the same meaning as in Fig. 3.

the high drop concentration case. Although only a snap-shot in time, it turns out that the sub-cloud layer is much more strongly stabilized throughout the simulation in the high concentration case (not shown).

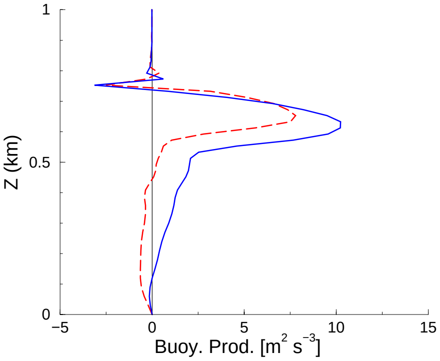

Figure 7. Vertical profile of buoyancy production at 3 hours. Line types and colors have the same meaning as in Fig. 3.

As would be expected, this reduction in cloud depth should have a strong effect on cloud albedo. We expect that the standard Twomey effect would be substantially reduced in this situation. We plan to do further simulations to illustrate just how great the reduction in the Twomey effect may be in this case.

ACKNOWLEDGEMENTS

Discussions concerning this research with Bjorn Stevens and Graham Feingold were very helpful.

REFERENCES

Ackerman, A.S., O.B. Toon, D.E. Stevens, A.J. Heymsfield, V. Ramanathan, and E.J. Welton, 2000: Reduction of tropical cloudiness by soot. *Science*, **288**, 1042-1047.

Boers, R. and R. M. Mitchell, 1994: Absorption feedback in stratocumulus clouds: Influence on cloud top albedo. *Tellus,* **46A**, 229-241

Harrington, J.Y., and P.Q. Olsson, 2001: A method for the parameterization of optical properties in bulk and bin microphysical models. Implications for Arctic cloudy boundary layers. *Atmos. Res.,* **57**, 51-80.

Klein, S. A., D. L. Hartmann and J. R. Norris, 1995: On the relationships among low-cloud structure, sea surface temperature, and atmospheric circulation in the summertime northeast Pacific. J. *Climate,* **8**, 1140-1155.

Lock, A. P. and M. K. MacVean, 1998: A parametrization of entrainment driven by surface heating and cloud-top cooling. *Quart.* J. *Roy. Meteor. Soc.,* **125**, 271-299.

Loeb, N. G., T. Varnai and D. M. Winker, 1998: Influence of subpixel-scale cloud-top structure on reflectances from overcast stratiform cloud layers. J. *Atmos. Sci.,* **55**, 2960-2973.

Moeng, C.-H. and co authors, 1996: Simulation of a stratocumulus-topped PBL: Intercomparison among different numerical codes. *Bull. Amer. Meteor. Soc.,* **77**, 261-278.

Rozendall, Margaret, A., C. B. Leovy and S. A. Klein, 1995: An observational study of diurnal variations of marine stratiform cloud. J. *Climate,* **8**, 1795-1809.

Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization schemes. J. *Atmos. Sci.,* **35**, 2123-2132.

Titov, G., 1998: Radiative horizontal transport and absorption in stratocumulus clouds. J. *Atmos. Sci.,* **55**, 2549-2560.

Twomey, S. A., 1974: Pollution and the planetary albedo. *Atmos. Environ.,* **8**, 1251-1256.

Walko, R. L., W. R. Cotton, M. P. Meyers and J. Y. Harrington, 1995: New RAMS cloud microphysics parameterization. Part I: the single moment scheme. *Atmospheric Research,* **38**, 29-62.

7.5 SOLAR ABSORPTION FEEDBACKS IN SIMULATED STRATOCUMULUS

Jerry Y. Harrington*
Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania

1. INTRODUCTION

The absorption of solar radiation within the cloud-topped boundary layer (CTBL), and its influence on the dynamics and microphysics of stratiform clouds, is a vexing issue. Vexing because, unlike the case of infrared radiation, solar absorption is dependent on cloud microstructure (e.g. Stephens, 1978) and the three-dimensional nature of the cloudy field (e.g. Titov, 1998; Loeb et al., 1998). This makes the inclusion of solar radiative processes in detailed models of the CTBL, such as large eddy simulation (LES), much more problematic than is the case for the infrared.

The issue of modeling stratiform clouds including the effects of solar absorption is not new. Many previous studies have been conducted and, as valuable as those studies have been, most have used simple CTBL models (1-D and 2-D LES, or eddy resolving models) and/or simplified microphysical schemes. However, few studies to date have included the concomitant effects of both relatively detailed microphysics and radiation in less parametrically-constrained models such as LES (except for the recent study of Ackerman et al., 2000).

This issue, however, is important since the presence of a strong diurnal cycle in low, or boundary layer, clouds is prevalent in many observational studies. For instance Rozendall et al. (1999) use weather-ship data to show that the observed frequency of low clouds has a distinct diurnal cycle, with maximum cloud fractions peaking around dawn, and minimum cloud fractions near 15:00 local time. This diurnal cycle is also evident in satellite climatologies and appears most prevalent at Weather Station November, where the mean June-July-August frequency of stratus, stratocumulus or fog is greater than 60% (Klein et al., 1995).

The principal result of previous observational studies has been that stratiform cloud layers thin, often to the point of ‘‘breaking up’’ and dispersing, during the day. Pronounced diurnal cycles have been observed in other large-scale fields (e.g., vertical velocity), nonetheless the diurnal cycle in low cloudiness is normally attributed to the effects of solar radiation; as it is generally believed that the absorption of solar radiation tends to offset cooling by long-wave radiation, and that less radiative driving of the flow leads to more anemic circulations that are unable to maintain a well mixed layer in the face of stabilizing processes such as cloud base warming or entrainment.

From a climate change perspective, understanding the dynamics of the interaction of solar radiation and turbulent boundary layer circulations is also important. For instance, using a very simple model of the planetary boundary layer Boers and Mitchell (1994) showed that the magnitude of the Twomey (1974) effect may be sensitive to radiative-dynamical interactions. Their results showed that changes in drop concentration lead to alterations in solar absorption which then should feedback to cloud thickness and, hence, the reflectivity of the cloud layer. In particular, Boers and Mitchell made use of the fact as drop concentrations are increased from some small initial value (say N = 50 cm^{-3}), solar absorption initially increases, reaches a maximum, and then decreases.Because of this, they were able to show that perturbations of drop concentrations from low to higher CCN concentrations could lead to reductions in cloud thickness and, hence, reductions in the standard Twomey effect.

In this study, a first attempt is made at examining how increases in drop concentration may alter cloud absorption and, therefore, feedback to cloud thickness and the Twomey effect.

2. METHOD

The model used for these studies is the LES version of the Regional Atmospheric Modeling System (RAMS). Longwave and shortwave heating/cooling are computed with a two-stream radiative transfer model using 6 solar and 12 infrared bands (Harrington and Olsson, 2001). To examine first-order effects, we use only a simple condensation-condensed scheme and, therefore, no drizzle. Drop concentrations (N) are fixed and considered constant with height. This allows us to easily examine how perturbations in drop concentration may alter solar absorption/dynamic feedbacks in a simplified framework. Of course, drizzle would be expected to significantly influence our simulations and we plan to treat this effect in future simulations. In order for the radiation model to interact with the cloud, not only is the liquid water content (LWC) and N required, but a spectral width of the size distribution is also required (Harrington and Olsson, 2001). Here, we use a modified gamma distribution as is standard in RAMS (e.g. Walko et al., 1995) with a shape parameter that varies between $\nu = 6$ and 15 (broader to narrower drop size distributions.)

Corresponding author address: J. Harrington, Dept. of Meteorology, Penn State University, University Park, PA, 16802. email: harring@mail.meteo.psu.edu

The stratocumulus case simulated is a variant of that described in Moeng et al. (1996). Our modifications include using a simple constant-θ with height in the boundary layer (BL) initialization and alterations in BL top humidity inversion. These were primarily done to produce a slightly thicker cloud. Simulations were conducted with clouds containing various drop concentrations and using overhead sun only ($\theta_0 = 0^0$) for maximum solar absorptive effects. For brevity, we present results only from the N = 50 cm^{-3} and 500 cm^{-3}, for reasons that will become obvious.

3. Results

3.1 *Some Preliminaries*

To set the stage for our later discussions of cloud evolution for different drop concentrations, and hence solar absorption, some illustrations of these radiative effects are in order. To give some idea of how important changes in solar absorption might be, given a certain perturbation in drop concentration, calculations of the cloud-integrated solar absorption and long wave emission were done for adiabatic clouds. The radiative model described above was used in for these cases. The results of these computations are shown in Fig. 1.

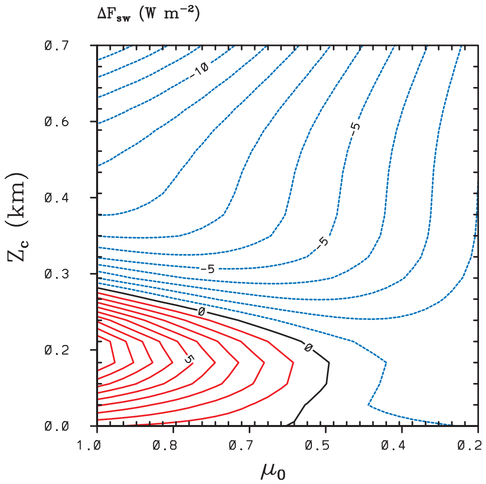

Figure 1. Contour plots of the relative difference (in percent) of the cloud-integrated absorbed solar flux (ΔF_{sw}) for various cloud depths (Z_c) and solar zenith angles ($\mu_0 = cos\theta_0$). Differences are computed between clouds with drop concentrations of 500 cm^{-3} and 50 cm^{-3}

This figure illustrates the potential magnitude of solar absorption perturbations. Clouds thinner than 300 m tend to show enhanced solar absorption throughout the cloud layer when drop concentrations are perturbed from 50 to 500 cm^{-3}. Thicker clouds, on the other hand, show a reduction in solar absorption. Boers and Mitchell (1984) showed a similar plot in their work. Since BL dynamics seems to scale with integrated forcings (e.g. Lock and MacVean, 1998), the above figure would seem to indicate that BL dynamics, and perhaps cloud thickness, could be reduced under an increase in solar absorption.

Since cloud top longwave (IR) cooling is the main driving force in this case, an even better parameter to examine is the sum of the integrated solar absorption and IR emission. This is shown in Fig. 2. The region of strong solar heating is now confined to a smaller set of solar zenith angles and for a smaller cloud depth range. Thick clouds, under a perturbation in drop concentration to 500 cm^{-3}, should show an increase in overall cloud cooling. Thinner clouds, however, when perturbed by a similar increase in drop concentration, should show an overall decrease in cloud cooling. Each situation will produce some sort of feedback to the cloud system itself.

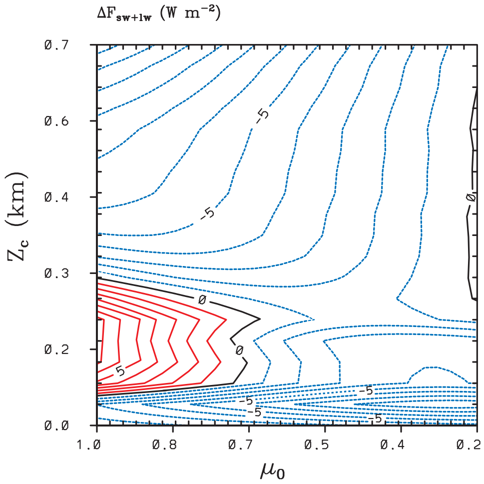

Figure 2. Same as Figure 1 except for integrated solar plus IR (ΔF_{sw+lw}).

In the LES studies presented below, we consider only overhead sun and clouds of ~ 250 m thickness. Our case falls within the regime, shown in Fig. 2, that should show an increase in solar heating, and therefore a decrease in overall cloud cooling given the above perturbation in drop concentration. Of course, these results will be sensitive to our choice of initial and final drop concentration. We chose values that should maximize the perturbative effect. Though this is the case, we plan to examine this in greater detail in the future.

3.2 *LES Results*

For brevity, and given the results shown in Figs. 1 and 2, we present results for simulations with N = 50 cm^{-3} (low concentration case) and N= 500 cm^{-3} (high concentration case). Since low drop concentration clouds have larger spectral widths, we use a gamma distribution shape parameter of 6 where as for the high drop concentration case we use a much narrower spectrum (shape of 15). Simulations were conducted over a 4 hr (240 min) time period.

Figure 3 shows the evolution of the domain-averaged liquid water path (LWP) and turbulent kinetic energy (TKE) for the low and high drop concentration cases. Both the LWP and TKE are substantially reduced under the given perturbation in drop concentration. The case with greater drop concentrations shows a much shallower cloud with circulations that are significantly weakened. Figure 4 shows, potentially, why this is the case. After 50 min of simulation time, solar absorption is almost 7 W m^{-2} greater in the high drop concentration case. Apparently, this increase in heating is enough to decrease LWP and TKE. Reductions in LWP is due to the combined effects of increases in temperature and through reduced circulation strength.

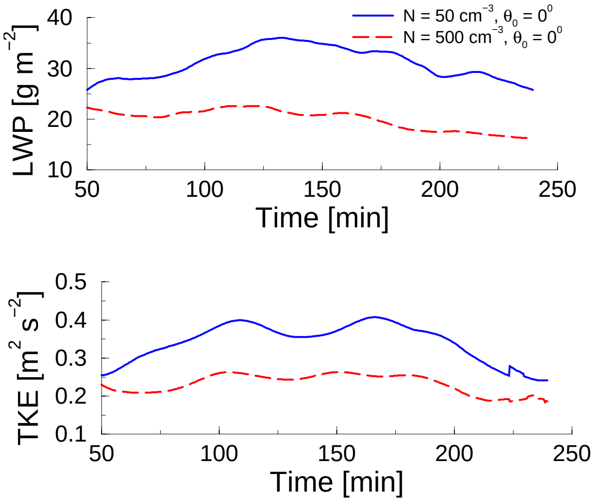

Figure 3. Time-series of LWP and TKE for two non-precipitating stratus simulations with different drop concentrations and overhead sun.

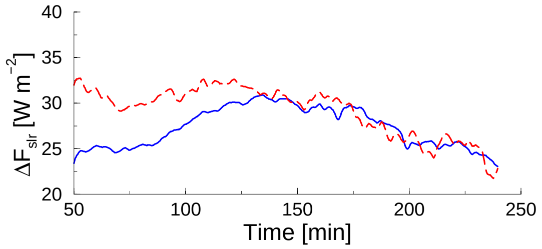

Figure 4. Time-series of the domain-averaged, vertically integrated solar heating. Line types and colors have the same meaning as in Fig. 3.

Note that after about 150 min of simulation time, the total absorbed solar radiation approaches that of the low drop concentration case. After this time period, the two curves tend to track one another quite well. We speculate that the reason for this may that above some certain amount of solar heating, the cloud layer is largely out of equilibrium. If this were the case, then the cloud layer depth and LWP would have to be reduced until the equilibrium is re-established.

Not only is the cloud LWP changing with time, which is altering solar absorption, but the cloud fraction is also changing throughout the domain. Figure 5 shows that the enhanced solar heating experienced by the higher drop concentration case causes a significant increase in the amount of broken cloudiness. As one might imagine, this also affects the reflectivity and transmissivity of the modeled clouds.

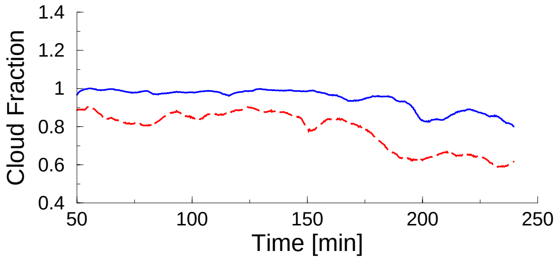

Figure 5. Time-series of the cloud fraction. Line types and colors have the same meaning as in Fig. 3.

Analysis of the various terms in the TKE budget illustrate that the above effects are primarily due to changes in the buoyancy profiles, as one might expect in this case. Figure 6 shows that the vertical component of TKE is strongly affected by greater solar absorption in the high drop concentration case. Not only is the maximum significantly reduced, but it is also displaced higher in the BL. The buoyancy flux profiles for this time, Fig. 7, show that buoyancy production of TKE in the low drop concentration is much larger than that of the high concentration case. Note also that the subcloud layer is stabilized in

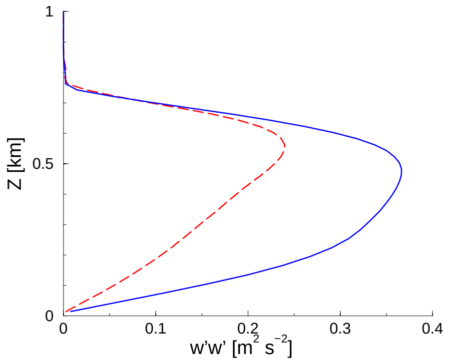

Figure 6. Vertical profile of w’w’ at 3 hours. Line types and colors have the same meaning as in Fig. 3.

the high drop concentration case. Although only a snap-shot in time, it turns out that the sub-cloud layer is much more strongly stabilized throughout the simulation in the high concentration case (not shown).

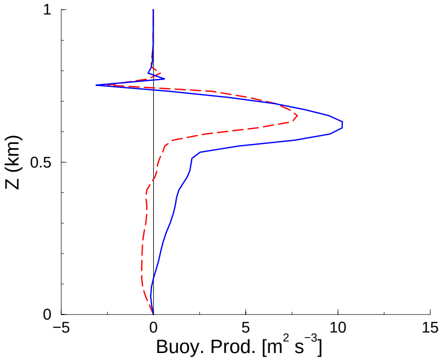

Figure 7. Vertical profile of buoyancy production at 3 hours. Line types and colors have the same meaning as in Fig. 3.

As would be expected, this reduction in cloud depth should have a strong effect on cloud albedo. We expect that the standard Twomey effect would be substantially reduced in this situation. We plan to do further simulations to illustrate just how great the reduction in the Twomey effect may be in this case.

ACKNOWLEDGEMENTS

Discussions concerning this research with Bjorn Stevens and Graham Feingold were very helpful.

REFERENCES

Ackerman, A.S., O.B. Toon, D.E. Stevens, A.J. Heymsfield, V. Ramanathan, and E.J. Welton, 2000: Reduction of tropical cloudiness by soot. *Science*, **288**, 1042-1047.

Boers, R. and R. M. Mitchell, 1994: Absorption feedback in stratocumulus clouds: Influence on cloud top albedo. *Tellus,* **46A**, 229-241

Harrington, J.Y., and P.Q. Olsson, 2001: A method for the parameterization of optical properties in bulk and bin microphysical models. Implications for Arctic cloudy boundary layers. *Atmos. Res.,* **57**, 51-80.

Klein, S. A., D. L. Hartmann and J. R. Norris, 1995: On the relationships among low-cloud structure, sea surface temperature, and atmospheric circulation in the summertime northeast Pacific. J. *Climate,* **8**, 1140-1155.

Lock, A. P. and M. K. MacVean, 1998: A parametrization of entrainment driven by surface heating and cloud-top cooling. *Quart.* J. *Roy. Meteor. Soc.,* **125**, 271-299.

Loeb, N. G., T. Varnai and D. M. Winker, 1998: Influence of subpixel-scale cloud-top structure on reflectances from overcast stratiform cloud layers. J. *Atmos. Sci.,* **55**, 2960-2973.

Moeng, C.-H. and co authors, 1996: Simulation of a stratocumulus-topped PBL: Intercomparison among different numerical codes. *Bull. Amer. Meteor. Soc.,* **77**, 261-278.

Rozendall, Margaret, A., C. B. Leovy and S. A. Klein, 1995: An observational study of diurnal variations of marine stratiform cloud. J. *Climate,* **8**, 1795-1809.

Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization schemes. J. *Atmos. Sci.,* **35**, 2123-2132.

Titov, G., 1998: Radiative horizontal transport and absorption in stratocumulus clouds. J. *Atmos. Sci.,* **55**, 2549-2560.

Twomey, S. A., 1974: Pollution and the planetary albedo. *Atmos. Environ.,* **8**, 1251-1256.

Walko, R. L., W. R. Cotton, M. P. Meyers and J. Y. Harrington, 1995: New RAMS cloud microphysics parameterization. Part I: the single moment scheme. *Atmospheric Research,* **38**, 29-62.