AEROSOLS AND CLOUDS IMPACT ON THE DIURNAL TEMPERATURE RANGE IN THE ATMOSPHERIC BOUNDARY LAYER

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摘要

利用中央氣象局長期的氣象觀測資料之分析與應用一個一維模式來探究台灣地區每日高低溫差（Diurnal Temperature Range, DTR）減小的因果關係。資料分析之氣象參數包括溫度、相對濕度及比濕等；一維模式是利用Fu-Liou輻射傳遞模式與一個大氣-植被-土壤邊界層模式（Couple Atmosphere-Plant-Soil model）做結合，同時也包括氣膠模式及雲微物理模式來模擬眾多可能因素對輻射收支及近地表溫度之影響。氣象資料分析顯示造成DTR減小最可能的因素是區域性雲量增加所致，然影響DTR的因素甚爲複雜，除雲量外，其他如氣膠、地表特性（植被或土壤濕潤度）、大尺度大氣環流的變化等亦會對DTR之逐年變化有貢獻。

本研究採用前述一維模式來測試氣膠與雲造成DTR變化的機制。初步模擬結果顯示，氣膠之垂直分佈、氣膠組成份之不同與其混合狀態的不同，均可能對近地表之DTR造成顯著影響。雲的測試顯示，不同高度的雲對DTR有不同程度的影響，除高度因素外，雲厚度與雲滴有效粒徑亦是關鍵因素。模擬顯示氣膠及雲的角色對輻射收支乃至於氣候變遷等問題存在高度之不確定性，未來需將模式做更完整之偶合，以期能對氣膠-雲-氣候間的回饋機制有更實際的模擬。

關鍵字：每日高低溫差、氣膠、雲、輻射傳遞

ABSTRACT

An analysis of long-term measurements of meteorological parameters and a one-dimensional (1D) model are applied to unravel the complex causes and effects of the observed trend of decrease in diurnal temperature range (DTR) over Taiwan. We apply the Fu-Liou radiation scheme to provide profiles of radiation fluxes and heating rates in the coupled atmosphere-plant-soil model (the CAPS model). In the initial stage of this study, aerosols and clouds are prescribed to evaluate the radiative forcing in the 1D model. Aerosol optical properties are derived primarily based on the Mie theory. The issues of aerosol mixing state and hydroscopic growth on radiative forcing are addressed as well. In addition, the impacts of clouds on the observed DTR are evaluated by means of prescribed clouds at different heights.

The preliminary result shows that low and middle clouds can significantly decrease daytime temperature while increase nighttime temperature, resulting in a decrease of DTR. Aerosols of different compositions and mixing states may also induce significant temperature perturbation. In the near future, when our atmospheric boundary layer model is fully coupled with a photochemical-aerosol-cloud model, the complex feedback processes of aerosol, cloud and climate can be better addressed.

Keywords: diurnal temperature range, aerosols, clouds, and radiative transfer

1. INTRODUCTION

Aerosols can perturb the atmospheric environment and climate through a direct effect of scattering and absorption of atmospheric radiation and an indirect effect via interacting with clouds. Besides the perturbations induced by the purely scattering aerosol such as sulfate aerosols, those induced by strongly absorbing aerosols e.g. soot particles are also of considerable interests (Hansen et al., 1997). Although the importance of radiative effects of aerosol on climate change has been widely recognized, relatively little efforts have been dedicated to the investigation of aerosol impacts on the evolution of atmospheric boundary layer. Due to the computational expenses, the aerosol and cloud processes in models like GCMs tend to be oversimplified or somewhat unrealistic in certain aspects. Therefore, in this study we attempt to develop a one-dimensional (1-D) model by combining a modified atmosphere-plant-soil coupling model (MCAPS model, Chang et al., 1999; Yu, 2000) with a multi-bin and multi-component aerosol and cloud model (Chen, 1992). For the evaluation of radiative effects, we apply the Fu and Liou radiation module (Fu and Liou, 1992, 1993; Fu et al., 1997), with consideration of aerosol optical characteristics based on the Mie theory (Toon and Ackerman, 1981). In addition, a 1-D photochemical model is applied to calculate the sources of precursors for aerosol nucleation (Trainer et al, 1987). This self-consistent 1-D composite model is useful in the investigation of several interesting issues. Our focus is primarily on the role of aerosols and clouds in the evolution of atmospheric boundary layer, such as the observed decrease of diurnal temperature range (DTR). In the initial stage of this study we perform a preliminary test by using prescribed aerosol and cloud properties to emphasize several important issues regarding to boundary processes. More realistic aerosol and cloud will be included shortly.

2. MODEL SETUP

2.1 Initial and boundary conditions

The control run is under clear sky conditions with the solar orientation given as July 15, 25°N. Radiative forcing of aerosols as well as cloud formation are turned off. The vertical wind profile is fixed, and there exists a large-scale subsidence of 0.7 cm/s above 2 km. A bare soil surface (sandy loam, saturated at 0.435) is applied without any canopy (vegetation coverage), and the surface albedo is set at 0.2. The field capacity and air-dry values are assumed to be 0.195 and 0.114, respectively. Soil moisture below surface was held constant and soil water contents were 0.20 and 0.22 in two layers.

2.2 Inclusions of aerosols and clouds

The aerosol effect is estimated by assuming a dry aerosol optical depth (AOD) of 0.5 in the visible wavelength. The extinction coefficients and asymmetric factors are set as those for sulfate aerosols (d'Almeida et al., 1991). Single scattering albedo (SSA) of the purely scattering and strongly absorbing aerosols is taken as 1.0 and 0.8, respectively, for the solar flux; SSA of 0.2 is taken for the thermal flux. In addition, the swelling of aerosol according to ambient humidity is also considered. The mixing state of aerosols can be of importance as well for the evaluation of radiative forcing. Here, we tested the three types of mixture state for soot and $(NH_4)_2SO_4$ as described in Jacobson (2000): 1) internal mixing, 2) core with shell, and 3) external mixing. The optical properties of the mixing aerosols are calculated using the algorithm of Toon and Ackerman (1981).

The impacts of clouds on the diurnal temperature are evaluated by means of prescribed clouds at different heights. Three levels (i.e. low, middle, and high) of clouds are tested with assumed effective radius (r_e) and liquid water content (LWC). For low clouds: height = 2~2.5 km, r_e = 5.89 μm, LWC = 0.22 g/m^3; Middle clouds: height = 4~4.5 km, r_e = 10 μm, LWC = 0.3 g/m^3; High clouds: height = 6~7 km, r_e = 41.54 μm, IWC = 4.7e-3 g/m^3. Other values of r_e and LWC are also applied for sensitivity test on surface radiation budget.

3. RESULT AND DISCUSSION

3.1 Cloud forcing

Figure 1 shows that low and middle clouds tend to decrease the daytime temperature while increase the nighttime temperature. The magnitude of the temperature change caused by clouds can be more than 3°C. Such significant asymmetric change of diurnal temperature can be one of the possible causes associated with the decrease of DTR observed in most of the stations over Taiwan.

The high clouds increase the near surface temperature by about 0.5°C during both daytime and nighttime, suggesting that the longwave effect dominates. When we increase the thickness of high clouds by 2 km, the increase of nighttime temperature may exceed 1°C while the daytime temperature increase is still less than 0.5°C (not shown). The effects of middle and low clouds are much more significant than the high clouds during nighttime, where up to 2.5 and 3°C warming may be expected. But during daytime, the cloud forcing becomes a cooling effect, with a magnitude of about 1°C for middle clouds and 3°C for low clouds. Apparently, all three types of clouds have the potential of reducing DTR. However, actual clouds can be far more complicated than the assumed ones, especially when the clouds contain ice particles. In the near future, our self-consistent model should be able to provide insight into the complicated feedback mechanisms associated with the DTR changes.

3.2 Aerosol forcing

The direct radiative effect of aerosol is first evaluated under clear-sky conditions. We tested three different optical properties (SSA = 1.0, 0.9, and 0.8) with prescribed aerosols as described in Section 2.2. Figure 2 shows the aerosol-induced changes in the air temperature at 2m above the surface. Purely scattering aerosol (SSA = 1.0) tends to induce cooling and decrease daytime air temperature by about 0.5°C, except for the large decrease in the early morning. Strongly absorbing aerosols (SSA = 0.8) appear to warm up the air by as much as 0.5°C during daytime. It is interesting to note that a significant decrease of air temperature in the early morning can be found in the three prescribed aerosols. The stronger the absorbing effects, the larger the decrease in air temperature is. Although the reduction in the radiative heat flux is relatively small in the early morning, the largest temperature decrease occurs during this time because the atmospheric boundary layer is shallow and the temperature is sensitive to the change in the sensible heat flux. In the early morning, the soil temperature is sensitive to the radiative flux because the sensible and latent heat fluxes are very small and a large fraction of radiative flux is used to warm the surface skin. The larger the absorption of aerosols, the smaller the available radiative flux received. That is the reason why different SSA gives different results. A reduction in the sensible heat flux would also result from the stabilization of boundary layer air due to air heating by the strongly absorbing aerosols. In addition, a net warming or net cooling depends not only on the SSA, but also on aerosol vertical profile, surface properties (e.g., surface albedo, Bowen ratio), and meteorological conditions. In spite of the remaining uncertainty, it can be deduce that aerosols should have significant impacts on DTR. Clearly, the direct radiative effect of aerosols could also be one of major contributors to the observed DTR.

The effects of aerosol on surface radiation budgets are further tested for different cloud covers. As shown in Figure 3, under the coverage of low clouds, the aerosol radiative effects on nighttime temperature are much smaller than that on daytime temperature by a factor of 3 to 4. It is interesting to note that the cooling of daytime temperature by low clouds with aerosols is smaller (by 2°C) than that without aerosols. Also, the temperature difference between purely scattering and strongly absorbing aerosols is not very significant. This result implies that the multiple scattering of aerosols under cloudy sky can be an important process and should be carefully considered in relevant calculations.

The radiative effects of aerosols are more prominent under high clouds as shown in figure 4. With strongly absorbing aerosols, the atmosphere tends to heat up more during daytime and the effect even extends through most of the night except during the early morning hours. On the other hand, the purely scattering aerosols tend to reduce that with aerosols. Due to the stabilization of the boundary layer by aerosols, significant cooling in the morning hours can be found for both absorbing and non-absorbing aerosols. Evidently, the chemical compositions are very crucial in the determination of aerosol forcing. Although the impacts of middle clouds with aerosols are not shown here, it is logical to imagine that the patterns of temperature perturbation of middle clouds should be somewhat between low and high clouds (more similar with patterns of low clouds).

Based on the above simulations, the radiative perturbation of aerosols on DTR is evident. The results shown here are more or less similar to the findings of Hansen et al., (1995) who concluded that the observed DTR over continental areas are more likely caused by a combination of radiative forcing from tropospheric aerosols and cloud cover. According to our 1-D simulation, it is worthy of further emphasizing the role of absorbing aerosols in the climate change issues.

3.3 Mixing state of aerosols

The mixing state of aerosols appears to be an influencing factor too as shown in Figure 5. The size distribution and chemical compositions of aerosols can be very complicated and variable in the ambient air, thus, in order to simply the conditions, only mono-dispersion soot (0.2 μm in radius, 500 cm^{-3} of number concentration) and $(NH_4)_2SO_4$ (0.5 μm in radius. 500 cm^{-3} of number concentration) are mixed together to demonstrate the impacts on temperature. Although the patterns of temperature variation are similar for different mixture states, the magnitude can be rather different. A difference of up to 1°C in daytime temperature and about 0.5°C in nighttime temperature may be produced. The highest difference comes from an external mixture, and the weakest from core with shell. This result might be associated with the procedures that are applied to include in the radiative forcing of aerosols in 1-D model and the methods that are used to evaluate the composite refractive index of the mixing aerosols. Therefore, more realistic ways are needed to evaluate the optical properties of aerosols that are size and composition dependent.

Actually, the vertical profile of aerosols is also important as revealed by such 1D model simulation (not shown here). In situ measurements of aerosol compositions and optical properties accompanying with lidar observation of vertical profile can be very helpful in the verification of the simulations conducted by this composite 1-D model.

4. CONCLUSIONS

From the sensitivity tests of aerosol and cloud impacts on the diurnal temperature change, it is obvious that low and middle clouds can significantly decrease daytime temperature while increase nighttime temperature, resulting in a decrease of DTR. Aerosols of different compositions and mixing states may also induce significant temperature perturbation. In the near future, when our atmospheric boundary layer model is fully coupled with a photochemical-aerosol-cloud model, the complex feedback processes of aerosol, cloud and climate can be better addressed. Although so far the impacts of aerosols and clouds on the observed DTR change over Taiwan and other areas remain unresolved, we believe that by combining more observations with detailed simulation with such a 1-D model can be very helpful toward understanding the physical and chemical processes that govern the energy budget in the atmospheric boundary layer.

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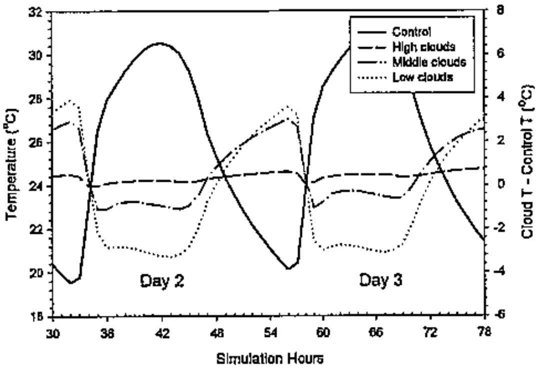

Figure 1. Impacts of clouds at different heights on the diurnal temperature at 2 m above the surface.

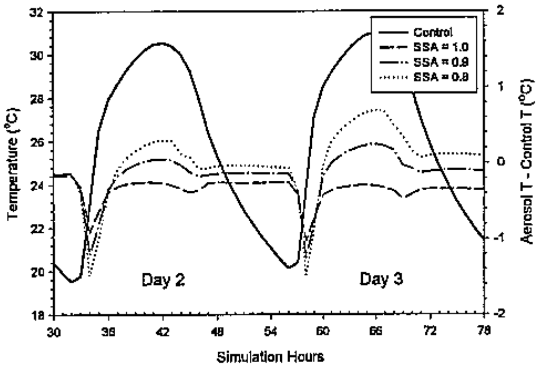

Figure 2. Impacts of aerosols on air temperature at 2 m above the surface.

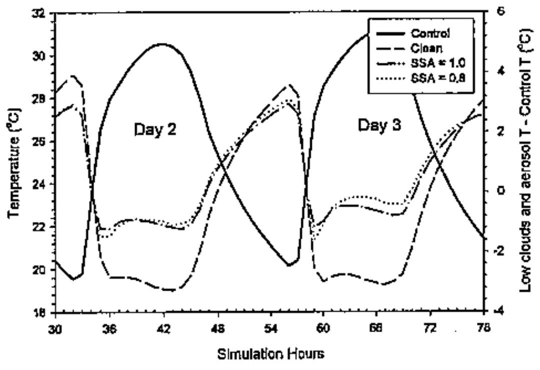

Figure 3. Impacts of aerosols with low clouds on air temperature at 2 m above the surface.

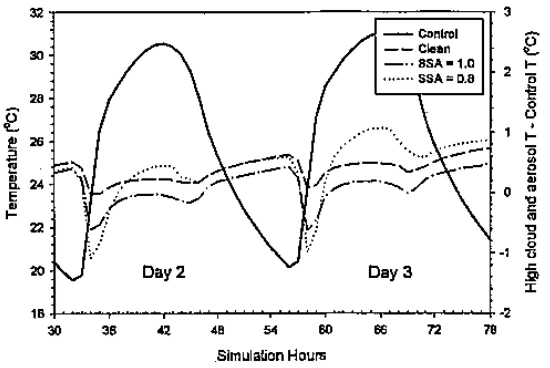

Figure 4. Same as figure 3 except for high clouds

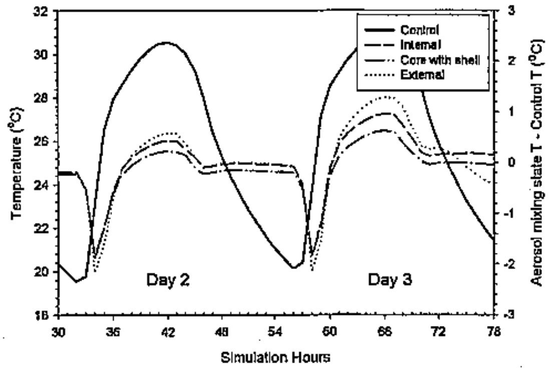

Figure 5. Impacts of mixing state of aerosols on the diurnal temperature at 2 m above the surface.