A Simple Parameterization Scheme for Subtropical Marine Stratocumulus

Hideaki Kawai and Toshiro Inoue
1Japan Meteorological Agency, Tokyo, Japan
2Meteorological Research Institute, Tsukuba, Japan

Abstract

A simple scheme to represent the marine stratocumulus clouds off the west coast of continents is implemented in the Global Spectral Model (GSM) at Japan Meteorological Agency (JMA). The parameterization is based on diagnostic cloud schemes where cloud fraction is diagnosed as a function of inversion strength considering other parameters. The global distribution of marine stratocumulus clouds off the west coast of continents is improved remarkably with this new scheme. Low-level cloud amount shows reasonable agreement with the International Satellite Cloud Climatology (ISCCP). With the improved cloud amount, the radiation fields are also improved in comparison with the Earth Radiation Budget Experiment (ERBE). Seasonal and diurnal variations of marine stratocumulus cloud amount off the west coast of continents also show reasonable agreement with surface-based cloud amount data from Klein and Hartmann (1993) and other observations.

1. Introduction

Marine stratocumulus clouds are characterized by high albedo and strong cloud top cooling effect. Therefore, the radiative effect is very large in comparison with other cloud types. For example, Inoue and Ackerman (2002) studied the radiative effect of cloud type classified by the split window data of Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA-9 polar orbiting satellite, using the collocated ERBE data (e.g., Harrison et al. 1990). They showed that the low-level stratocumulus clouds had a large shortwave cloud radiative forcing comparable with cumulonimbus type clouds.

The ISCCP (e.g., Rossow and Schiffer 1999) analysis shows that cloud amount of the low-level clouds is very large especially off the west coast of continents. These low-level clouds, that have large radiative effect, cover a large area off the west coast of continents. This suggests that the low-level marine stratocumulus clouds affect the climate system significantly.

A comparison of climate sensitivity among climate model predictions for CO2 doubling shows large variability. For instance, two models, AM2.6 from GFDL and the NCA CAM2.0, have cloud sensitivities of 4.5K and 2K (Bretherton et al. 2004a). These are opposite ends of the spectrum of predictions from climate models. The difference of low-level cloud amount data from Klein and Hartmann (1993) and other observations is very large in comparison with other cloud types.

Many efforts to develop prognostic cloud schemes (e.g., Sundquist 1988; Tiedtke 1993; Del Genio et al. 1996), where the liquid water and cloud fraction can be determined prognostically, have been made. Recently, large eddy simulation (LES) models have been used to evaluate and develop the parameterization for marine stratocumulus in GCMs. However, our knowledge is not yet sufficient to model the life cycle of marine stratocumulus clouds. Here, we introduce a simple and practical diagnostic scheme, and the representation of the marine stratocumulus clouds off the west coast of continents in current GSM at JMA is improved significantly with this new scheme.

2. Parameterization for subtropical marine stratocumulus clouds

In the GSM at JMA (detailed description of GSM is available in JMA 2002), the probability density function (PDF) cloud scheme by Sommeria and Deardoff (1977) is adopted. The so-called top hat type PDF, where the PDF is equal around the mean value of the grid with some fluctuations, is used in the GSM at JMA instead of Gaussian distribution for simplicity. The fluctuation is determined from the critical relative humidity set in advance at each level in the model. However, marine stratocumulus clouds could not be well represented in the GSM at JMA. Even if the width of the fluctuation is set unrealistically broad, little stratocumulus can be formed.

Our understanding of this deficiency in the representation of marine stratocumulus, is that the model layer does not become moist enough to form clouds with the current PDF scheme in the GSM at JMA. Presumably, too dry boundary layer in the regions in GSM implies some problems in the physical parameterization and the model layer is often thicker than the geometric thickness of marine stratocumulus, which is sometimes only 50m. The GSM at JMA has only 7 layers below 750 hPa. Therefore, it is very rarely moist enough in this PDF scheme to form the clouds at the model layer of about 300m geometric thickness.

The relationship between lower atmospheric stability and persistent stratocumulus was first discussed by Slingo (1980). Klein and Hartmann (1993) studied it in detail and showed the strong relation clearly. Other observational studies also showed that the stability was essential in forming marine stratocumulus clouds (e.g., Bretherton et al. 2004b).

Relative humidity (RH) has been used to form cloud in many GCMs. Inoue and Kamahori (2001) studied correspondence between ISCCP cloud types and vertical RH profiles from coincident radiosonde observations. They showed that the vertical profile of RH indicates salient features depending on cloud type. The RH is larger at the level where cloud exists. This study suggests that RH is a good indicator for cloud existence in general. However, their study does not include the marine stratocumulus. Further, Slingo (1980) showed that there was no relationship between vertically averaged RH and cloud amount of marine stratocumulus. The marine stratocumulus is very thin, so it is inherently difficult to use RH to represent the cloud as a thicker layer in the model.

Teixeira and Hogan (2002) developed a scheme to form marine stratocumulus with a combination of inversion...
strength and RH. They succeeded in increasing the cloud amount. However, the large cloud amount area was slightly away from the west coast of continents. There also have been many studies to simulate the marine stratocumulus using LES which can resolve large eddies explicitly and has a more sophisticated physical process (e.g., Stevens et al. 2005). However, the life cycle of this cloud type cannot be simulated well at present, even by these models. Therefore, in this study, we tried to find a practical way to simulate marine stratocumulus instead of a detailed consideration of physics in and around stratocumulus.

In this study, the simple and classical parameterization by Slingo (1980, 1987) was re-considered with some minor modifications from the inspection of GSM performance and observational studies. We select the following three conditions to form marine stratocumulus clouds in the GSM at JMA.

\[ \frac{\partial \theta}{\partial p} > 0.07 \text{[K/hPa]} \quad \text{(just above the layer),} \]
\[ \frac{\partial \theta}{\partial p} < 0.01 \text{[K/hPa]} \quad \text{(near the surface),} \]
\[ h = 940 \text{[hPa]} \quad \text{(the height of the layer is below 940[hPa])} \]

where \( \theta \) is potential temperature and \( p \) is pressure.

The first condition relates to the strength of inversion. The strong inversion at the top of the mixed layer is essential in the existence of marine stratocumulus. The vertical gradient of potential temperature that is greater than 0.07 [K/hPa] is selected for a threshold of marine stratocumulus existence.

A strong and thick stable layer near the surface often appears over land or sea ice area during the night. Over the area, the first condition is often satisfied. However, for stratocumulus formation, a supply of moisture from the surface is essential. Therefore, the stability in the very near surface layer should not be large. The second condition is set as a favorable condition for stratocumulus formation, and is set to prevent the pseudo formation of stratocumulus under a strong thick stable layer.

The third condition is to prevent the false development of stratocumulus over a shallow convection area, where the inversion is strong, although the inversion height is higher than off the west coast of continents. When we form the stratocumulus as a function of stability only, then stratocumulus is formed all over the subtropical high area where a strong inversion layer exists. The main objective of this study is to represent more realistic marine stratocumulus clouds just off the west coast of continents. Observational studies indicated that the height of marine stratocumulus clouds over the ocean off the California coast was very shallow. Therefore we set the last condition, though this one is arbitrary (see section 3 last paragraph).

The stratocumulus is formed in areas and layers where all three conditions above are met. Then cloud amount \( C_c \) and cloud water content in cloud \( q_c \), are determined as below.

\[ C_c = 12.0 \left( -\frac{\partial \theta}{\partial p} - 0.07 \right) \]
\[ q_c = 0.03q_{sw} \]

where \( q_{sw} \) represents saturation specific humidity.

Cloud water is determined with a similar equation to that used by Teixeira and Hogan (2002). Further, we assume that the cloud thickness is half of the model layer and set the clouds at the upper half of the layer. The cloud thickness of marine stratocumulus is often significantly thin, for example, an observational study by Duynkerke and Teixeira (2001) showed that the cloud thickness off the coast of California was 50–200m, while the thickness of the fourth layer (940 hPa) in the model is about 215m. Therefore, we consider that this assumption is reasonable. This assumption does not change the cloud amount but changes the cloud water content in the grid \( q_c \), i.e., \( q_c \) is obtained by \( q_c = \frac{1}{2}C_c q_{sw} \). Note that water vapor is reduced by cloud water content to conserve total water.

An important process concerning stratocumulus is the cloud top entrainment (CTE) process. The GSM uses a local turbulence closure model by Mellor and Yamada (1982). However, a local turbulence scheme causes a concentration of moisture leading to the excessive production of cloud at the top of the boundary layer, because there is a large difference of vertical diffusivity above and below the top of the boundary layer over almost all oceans. In addition, the fact that neither a shallow convection scheme nor a cloud top entrainment scheme is implemented in the GSM enhances this shortage. To overcome this problem, vertical diffusivity is vertically smoothed to keep some exchange between boundary layer and free atmosphere in the GSM at JMA. However, this treatment also works over the ocean off the west coast of continents. This causes a large reduction of cloud amount over the region. Therefore, we made an exceptional usage of this treatment. We do not apply it over regions where the above three conditions are valid. As a consequence, this treatment on vertical diffusivity works as a simple CTE-like parameterization because the diffusion through the top of the boundary layer is enhanced only in the case of weak inversion.

Our parameterization scheme determines cloud amount and cloud water content diagnostically by the respective equations (4) and (5) when the above three conditions are met. This parameterization is included in the GSM as an exceptional treatment in the PDF cloud scheme, where cloud amount and cloud water content should be deduced from the PDF automatically and simultaneously.

### 3. Results

We conducted a one month integration of the GSM for July 2001 with T106 resolution. Figure 1 shows the global distribution of low-level cloud amounts for July 2001 without (top panel) and with (bottom panel) the stratocumulus parameterization scheme described in section 2. Low-level cloud amount has remarkably and selectively increased off the west coast of California, Peru, Mauritania, and Namibia. Figure 2 shows the ISCCP low-level cloud amount from day time observation as a comparative reference, though the definitions and altitude ranges are not completely the same. The retrieved low-level cloud in ISCCP is limited to the areas where low-level...
cloud exists in a single layer. The low-level cloud amount in the GSM includes the low-level cloud where upper level cloud coexists. The global distribution of low-level cloud amount, especially off the west coast of continents where low-level cloud is the dominant cloud type, shows reasonable agreement with ISCCP using this parameterization scheme. Figure 3 shows the difference of upward shortwave radiation at the top of the atmosphere between the ERBE observation data and the GSM without (top panel) and with (bottom panel) the parameterization. Serious negative biases caused by a lack of reflection due to stratocumulus in these regions are reduced by the new parameterization, as seen in Fig. 3 (bottom panel). The positive bias in downward shortwave radiation on the surface is also improved (not shown).

In addition, the negative bias of downward longwave radiation on the surface is improved (not shown). The liquid water path increased significantly off the west coast of continents with the parameterization (not shown). This used to be almost zero liquid water path before this new parameterization, though cloud water content was automatically deduced from the PDF. With the new scheme, the liquid water paths in these stratocumulus regions become 50–100 [g/m²], which is consistent with observations. For example, the liquid water path observed in July off the west coast of California is about 70 [g/m²] (Blaskovic et al. 1991;Duynkerke and Teixeira 2001).

Figure 4 shows the comparisons of the seasonal variation of stratocumulus for 1992 off the coasts of California, Peru, Mauritania, and Namibia. These results are from the one month integration of the GSM for January, June, and October in 1992 with T63 resolution. The seasonal variation of stratocumulus represented by the parameterization shows reasonable agreement with the observed seasonal climatology of stratocumulus studied by Klein and Hartmann (1993). They indicated that the seasonal variation of stratocumulus corresponded to the seasonal variation of stability. The parameterization is based on the inversion strength. This causes good representation of the seasonal variation of stratocumulus off the west coast of continents.

Figure 5 shows the diurnal variation of cloud amount off the west coast of California (a), Peru (b), Mauritania (c), and Namibia (d) for January (red), June (green), and October (blue). The cloud amount indicates maximum before sunrise and minimum around noon for all regions. Similar diurnal variation of stratocumulus is reported from observations and satellite data (e.g.,Blaskovic et al. 1991). The mechanisms of the diurnal variation of marine stratocumulus are complex. However, one probable explanation is that solar irradiance heats the cloud layer during daytime, leading to the reduction of cloud amount. During the night, the cloud amount increases, associated with an increase of instability due to the strong radiation cooling at the top of the cloud.

Observations show that the amplitude of diurnal variation off California in July is about 25% (Duynkerke and Teixeira 2001) and off Mauritania in June is 50% (Albrecht et al. 1995). Although these values cannot be compared with model grid values or area averaged values directly because these were obtained by point observation, our results on the amplitude of diurnal variation during the summer season are consistent with these observations. In the Southern Hemisphere, the absolute value of cloud amount is larger during austral winter.
than during summer, while the amplitude of diurnal variation is larger during summer than during winter due to the stronger solar irradiance. These results are consistent with Teixeira and Hogan (2002).

Finally, to check the vertical structure of the stratocumulus by the new parameterization, a vertical cross section from the coast of California to the equator is shown in Fig. 6, as done in Siebesma et al. (2004). Without the parameterization (left panel) there is little low cloud cover near the coast of California, but a large amount of cloud cover is produced by the parameterization (right panel). However, the problem is that the height of the cloud layer cannot be lifted southwestward gradually, and it keeps almost the same altitude due to the height of the cloud layer cannot be lifted southwestward. Therefore, the altitude limitation was set to 940 hPa, considering the observational study off California (e.g., Blaskovic et al. 1991). This treatment is successful in terms of cloud cover near the coast, but has problems in representing a realistic vertical structure of stratocumulus. This indicates the need for a more sophisticated cloud parameterization, including a boundary layer turbulence scheme and a shallow convection scheme.

4. Concluding remarks

We implemented a simple stratocumulus parameterization scheme in the GSM at JMA following Slingo (1980, 1987) with some minor modifications (see Supplement 1). The scheme is based on a diagnostic method using the inversion strength in considering the meteorological conditions over the persistent stratocumulus area off the west coast of continents. The performance of the scheme is reasonably good, especially off the west coast of continents. Diurnal and seasonal variations are consistent with the observations, and the radiation budget is also improved over this region.

However, our scheme forms stratocumulus only at the levels lower than 940 hPa. In the real world, this constraint is not reasonable. Therefore, we are now developing a scheme to improve this cloud level issue.

The marine stratocumulus is a difficult cloud to simulate in large-scale models. Here, we introduced a basic practical scheme to simulate it. In future, we are planning to develop a scheme to represent the marine stratocumulus, by considering more sophisticated physical processes with a higher vertical resolution GSM.

Acknowledgments

This study was partly supported by ‘Kyosei Project 4: Development of super high resolution global and regional climate models’ funded by MEXT, and by ‘Global Environment Research Coordination System: Improvement of low-level cloud parameterization in climate model’ funded by ME of Japan.

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Manuscript received 24 October 2005, accepted 27 December 2005