Evaluation of Relationships between Subtropical Marine Low Stratiform Cloudiness and Estimated Inversion Strength in CMIP5 Models
Using the Satellite Simulator Package COSP

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Abstract

Using the Cloud Feedback Model Intercomparison Project Observation Simulator Package (COSP) outputs, subtropical marine low stratiform cloud (LSC) amounts simulated in 12 Coupled Model Intercomparison Project phase 5 (CMIP5) models are robustly evaluated in terms of the relationship with the estimated inversion strength (EIS). The International Satellite Cloud Climatology Project (ISCCP) low-plus-middle cloud amounts with optical thickness > 3.6, corrected with the random-overlap assumption, are defined as the LSC amount. Although EISs are well-simulated in all the models, more than half of the models show weaker responses of the LSC amount to EIS (2%−3% K⁻¹) than the observations (4.5% K⁻¹), and some models even show negative responses. The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) cloud amounts and layered EISs reveal that most models simulate inversion levels lower than observed, and that the vertical structure of LSCs has a key role for improvement in the modeled relationships.

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1. Introduction

Low stratiform clouds (LSCs) are often spatially extensive over subtropical oceans off the west coasts of continents. They have a strong cooling effect on the Earth’s radiative budget at the top of the atmosphere, owing to their relatively high albedo and cloud-top temperatures (Hartmann et al. 1992; Chen et al. 2000). Absolute increases of just 3.5%−5% in their global coverage would be sufficient to offset the warming induced by a doubling of the atmospheric CO₂ concentration (Randall et al. 1984; Slingo 1990; Wood 2012). It has been recognized for more than a decade that this makes low cloud feedback a major source of climate change uncertainty (e.g., Bony and Dufresne 2005; Webb et al. 2006; Medeiros et al. 2008). LSCs are particularly difficult to simulate in global climate models (GCMs) because they are typically thinner than a single GCM vertical level and result from complicated marine boundary layer (MBL) processes.

The strength of local temperature inversion is a key factor that controls optical thickness of these clouds. Stronger capping inversions prevent the MBL air from mixing with the warmer and drier air in the free troposphere, leading to the enhancement and persistence of LSCs. The tight linear relationship between the LSC amount and the inferred inversion strength measured by the lower tropospheric stability (LTS) and subsequently estimated inversion strength (EIS), approximately 4%−6% K⁻¹, has been robustly observed from numerous empirical studies for their geographical and seasonal climatologies (e.g., Klein and Hartmann 1993; Wood and Bretherton 2006; Myers and Norris 2013; Koshiro and Shiotani 2014, hereafter KS14). However, Caldwell et al. (2013) found that most GCMs participating in the Coupled Model Intercomparison Project phase 3 (CMIP3; Meehl et al. 2007) failed to simulate the climatological linear relationship between the total cloud amount and EIS for typical LSC regions. Myers and Norris (2015) further indicated the increase in intermodel spread of low-level cloud amount response to EIS change among CMIP5 (Taylor et al. 2012) models compared to CMIP3 for subtropical interannual variability. Meanwhile, recent studies intensively argued that the subtropical cloud response to anthropogenic global warming is likely to be a weak positive feedback, resulting from largely canceling effects of increasing sea surface temperature (SST; a positive feedback) and EIS (a negative feedback) (e.g., Qu et al. 2015; Myers and Norris 2016; Kawai et al. 2017a). Therefore, it is critically important to evaluate how well the state-of-the-art CMIP5 models reproduce the observed linear relationship between the LSC amount and EIS in the current climate, as robustly and quantitatively as possible.

Recently, implementation of the Cloud Feedback Model Intercomparison Project Observation Simulator Package (COSP; Bódas-Salcedo et al. 2011) in GCMs has made it straightforward to compare the simulated clouds with satellite observations in a consistent manner. The main COSP outputs requested by CMIP5 are from the simulators of the International Satellite Cloud Climatology Project (ISCCP; Klein and Jakob 1999; Webb et al. 2001) and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; Chepfer et al. 2008). The ISCCP low cloud amounts are now often used for evaluating basic GCM performance in relation to cloud radiative effects (e.g., Kay et al. 2012; Franklin et al. 2013; von Salzen et al. 2013; Lacagnina and Selten 2014), because their “top-down” view is suitable for examining the radiation budget at the top of the atmosphere. However, this view also makes them ill-equipped for investigating the relationship between the LSC amount and inversion strength; low clouds observed from satellites are often obscured by higher-level clouds. Ship-based observations, such as the Extended Edited Cloud Report Archive (EECRA; Hahn and Warren 2009) data, have been conventionally used for this purpose. There are thus very few studies focusing on this relationship itself with regard to the evaluation of GCMs using COSP.

In this paper, we used the ISCCP observations and simulator outputs to robustly evaluate the relationships between the subtropical marine LSC amount and EIS simulated in the Atmospheric Model Intercomparison Project (AMIP) experiments (i.e., atmosphere-only experiments prescribed by observed SSTs) from 12 CMIP5 models, with a reliable method for defining the LSC amount. Moreover, the CALIPSO observations and simulator outputs were able to resolve more detailed vertical profiles of cloud amount beyond the traditional three-layer (i.e., low, middle, and high levels) perspective (e.g., Cesana and Chepfer 2012; Nam et al. 2012; Su et al. 2013; Cesana and Waliser 2016). We also examined the origin of intermodel differences in the relationships regarding the vertical structures of the LSC amount and inversion strength, using the CALIPSO cloud amounts with the layered EISs proposed by KS14.

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2. Data and methods

Our primary observational satellite dataset was the ISCCP-D1 product (Rossow and Schiffer 1999). We used the $2.5^\circ \times 2.5^\circ$ monthly means of the ISCCP-D1 cloud amounts, segregated by cloud-top pressure and cloud optical thickness (Pincus et al. 2012; Zhang et al. 2012). In this study, the ISCCP low-plus-middle cloud amounts with optical thickness $> 3.6$, corrected with the random-overlap assumption, were defined as “the LSC amount”. We constructed the seasonal climatologies of the LSC amounts from July 1998 to June 2008 for ocean areas between 40°N and 40°S where climatological high cloud amounts through the period were less than 20%. On the other hand, as defined in Wood and Bretherton (2006), EIS was calculated from sea-level pressure (SLP), 2-m temperature ($T_{2m}$), and 700-hPa temperature ($T_{700}$) data; six reanalysis datasets were used to capture the range of observational uncertainty as accurately as possible (Table 1). Details of the procedures to derive both variables are described in Text S1.

We confirmed that the annual climatological distribution of the obtained ISCCP-D1 LSC amounts and their seasonal climatological relationship with EISs were almost the same as those obtained from the long-term ship-based cloud observation, EECRA, although insignificant disagreements were observed due to their differences in periodicity and spatial resolutions (Fig. 1). This indicates that the ISCCP LSC amounts derived in this study are at least as reliable as those from the ship-based observations.

Table 1. Summary of data used in this study.

| Cloud dataset            | Time period used                         | Variables used                                      | References                      |
|--------------------------|------------------------------------------|----------------------------------------------------|---------------------------------|
| ISCCP-D1                 | July 1998–June 2008                      | Cloud amount ($c_{isccp}$; joint histogram of optical thickness and cloud-top pressure) | Rossow and Schiffer (1999); Pincus et al. (2012); Zhang et al. (2012) |
| CALIPSO-GOCCP            | July 2006–June 2015                      | Cloud amount ($c_{calipso}$; 40 vertical levels equidistant of 480 m) | Chepfer et al. (2010); Cesana et al. (2016) |
| Reanalyses               |                                          |                                                    |                                 |
| ERA-Interim              | Coincident with paired cloud data        | $T_{700}, T_{850}, T_{925}, T_{2m}$, SLP            | Dee et al. (2011)               |
| ERA-40                   | July 1992–June 2002                      | Same as ERA-Interim                               | Uppala et al. (2005)            |
| CFSR/CFSv2               | Same as ERA-Interim from 2011, CFSv2     | $T_{700}, T_{850}, T_{925}$, $T_{1000}$*           | Saha et al. (2010, 2014)        |
| NCEP/NCAR RA             | Same as ERA-Interim                      | Same as ERA-Interim                               | Kalnay et al. (1996)            |
| MERRA-2                  | Same as ERA-Interim                      | Same as ERA-Interim                               | Gelaro et al. (2017)            |
| JRA-55                   | Same as ERA-Interim                      | Same as ERA-Interim                               | Kobayashi et al. (2015)         |
| Model data               |                                          |                                                    |                                 |
| AMIP runs from 12 CMIP5 models (Table 2) | July 1998–June 2008 except CESM1-CAM5 used through June 2005 | $c_{isccp}, c_{calipso}, T_{700}, T_{850}, T_{925}, T_{2m}$, SLP | Listed in Table 2 |

* The 1000-hPa temperature ($T_{1000}$) was used instead of $T_{2m}$ and SLP.

Fig. 1. (a) Geographical distribution of $2.5^\circ \times 2.5^\circ$ annual climatologies for ISCCP-D1 LSC amount (July 1998–June 2008) over the 40°N–40°S ocean areas where climatological high cloud amounts were less than 20% (i.e., subtropical marine LSC regions). (b) Frequency distributions obtained by classifying each $2.5^\circ \times 2.5^\circ$ climatological seasonal value into 2.5% intervals of the ISCCP-D1 LSC amount and 0.5-K intervals of EIS derived from ERA-Interim for the same period and areas as (a). The correlation coefficient (black) and the linear regression equation (red) are shown in the upper-left corner. The linear regression line is indicated by a red solid line. (c) As in (a), but for $5^\circ \times 5^\circ$ EECRA LSC (i.e., Sc + St + FOG; low cloud condition code $C_L = 4, 5, 6, 8, \text{ and } 11$) amount (September 1957–August 2002) over all ocean areas between 40°N–40°S. (d) As in (b), but for $5^\circ \times 5^\circ$ EECRA LSC amount and EIS derived from ERA-40 for the same period and areas as (c). The data used for (c) and (d) were based on those in KS14.
that have been used in numerous previous studies. Since the geographical distributions of EISs and their relationships with the LSC amount obtained from the different reanalyses are quite similar to one another, only results using the Interim European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim; Dee et al. 2011) are highlighted in this paper. Results for each reanalysis dataset are shown in Fig. S3.

To further examine the vertical structure of LSCs, we used the GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP) version 2.9 (Chepfer et al. 2010; Cesana et al. 2016). In addition, to consider the vertical levels in which temperature inversion contributed to EIS, layered EISs were calculated as defined in KS14:

$$EIS = EIS_{700}^{850} + EIS_{850}^{925} + EIS_{925}^{sfc},$$

where $EIS_{700}^{850}$, $EIS_{850}^{925}$, and $EIS_{925}^{sfc}$ are the EISs for the layers between 700 and 850 hPa, 850 and 925 hPa, and 925 hPa and the surface, respectively. These values were calculated by simply adding the temperatures at 850 hPa ($T_{850}$) and 925 hPa ($T_{925}$) to the EIS calculation (see Text S1 for more details).

Using the ISCCP and CALIPSO simulator outputs from COSP, the “apples-to-apples” analyses were performed on 12 CMIP5 models that submitted the ISCCP and CALIPSO cloud amounts to the AMIP experiment. The data used in this study are summarized in Tables 1 and 2. All analyses were performed based on the $2.5° \times 2.5°$ seasonal climatologies for both observational data and model outputs.

3. Results

Figure 2 displays the relationships between the ISCCP LSC amount and EIS over the subtropical marine LSC regions for 12 CMIP5 models and the relationship determined from the observational data. While HadGEM2-A best reproduces the observed linear relationship ($\sim$4.5% K$^{-1}$), more than half of the models (CESM1-CAM5, MRI-CGCM3, MPI-ESM-LR, bcc-csm1-1-m, CanAM4, GFDL-CM3, and CCSM4) show relationships similar to each other: the positive regression slopes are more gradual (2%–3% K$^{-1}$) than the observations. Some models (MIROC5, GISS-E2-R, and CNRM-CM5) yield negative regression slopes, whereas one model, IPSL-CM5B-LR, has a steeper positive regression slope than the observations (> 6% K$^{-1}$). The more gradual, or negative, regression slopes tend to correspond to the smaller correlation coefficients.

To examine the individual representations of the LSC amount and EIS in each model, Fig. 3 shows the zonal variations in the ISCCP LSC amount and EIS for two typical LSC regions, off the coasts of California and Peru. The zonal distributions of EISs are well-simulated by all the models. The intermodel spread is quite small and almost equivalent to that of the six reanalysis datasets. By contrast, the intermodel spread of the simulated LSC amounts is large. The majority of the models significantly underestimate the LSC amount around the maximum region (near the continental coasts). This is why most models have more gradual regression
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slopes than the observations (Fig. 2). IPSL-CM5B-LR is the only model which greatly overestimates the LSC amount in this region, whereas HadGEM2-A is the most similar to the observations. In regions where the observational LSC amounts are smaller (far off the continental coasts), most models slightly overestimate the LSC amounts. In particular, the LSC amounts are larger than those near the continental coasts for MIROC5, GISS-E2-R, and CNRM-CM5. This leads to the negative correlations for these models in Fig. 2. These results are commonly observed in other subtropical LSC regions of each model (see Fig. S4). Moreover, the vertical resolutions of the models do not seem to be responsible for the differences: most models have around 10 layers in the lower troposphere, although bcc-csm-1-1-m and CCM3 have fewer (Table 2).

Why do the simulated LSC amounts vary so widely, despite the well-simulated EISs for all the models? Given the same EIS, the inferred inversion that contributes to EIS can exist at a different level between the 700-hPa level and the surface. KS14 have climatologically indicated that the inferred inversions at different levels are associated with different LSC types from ship-based observations, using the layered EISs they newly proposed. The usefulness of the layered EISs was also clearly demonstrated in Koshiro et al. (2017) for interannual variability in the LSC amount. This inspired us to investigate the layered EISs and their relationships with the LSC amounts simulated in the models, and to further compare them with the vertical structure of low-level

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**Table 2.** The AMIP experiment data of CMIP5 models used in this study.

| Model name         | Resolution* | Modeling group                                                                 | References |
|--------------------|-------------|--------------------------------------------------------------------------------|------------|
| bcc-csm-1-1-m      | 1.125° × 1.12°, L26(5) | Beijing Climate Center (BCC) of the China Meteorological Administration, China | Wu et al. (2013) |
| CanAM4             | 2.8125° × 2.79°, L35(14) | Canadian Centre for Climate Modeling and Analysis (CCCma), Canada | von Salzen et al. (2013) |
| CCM4               | 1.25° × 0.94°, L26 (5)  | National Center for Atmospheric Research (NCAR), USA                      | Gent et al. (2011) |
| CESM1-CAM5         | 1.25° × 0.94°, L30(9)   | National Science Foundation (NSF)/Department of Energy (DOE)/NCAR, USA    | Hurrell et al. (2013) |
| CNRM-CM5           | 1.4° × 1.4°, L31(9)     | Centre National de Recherches Météorologiques (CNRM)/Centre Européen de Recherches et de Formation Avancée en Calcul Scientifique (CERFACS), France | Voldoire et al. (2013) |
| GFDL-CM3           | 2.5° × 2.0°, L48(12)    | NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA                     | Donner et al. (2011) |
| GISS-E2-R          | 2.5° × 2.0°, L48(9)     | NASA Goddard Institute for Space Studies (GISS), USA                      | Schmidt et al. (2014) |
| HadGEM2-A          | 1.875° × 1.25°, L38(12) | Met Office Hadley Centre (MOHC), UK                                       | Martin et al. (2011) |
| IPSL-CM5B-LR†      | 3.75° × 1.895°, L39(9)  | Institut Pierre-Simon Laplace (IPSL), France                             | Hourdin et al. (2013b) |
| MIROC5             | 1.4° × 1.4°, L40(13)    | Atmospheric and Ocean Research Institute (AORI) of the University of Tokyo, National Institute for Environmental Studies (NIES)/Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan | Watanabe et al. (2010) |
| MPI-ESM-LR         | 1.875° × 1.865°, L47(9) | Max Planck Institute for Meteorology (MPI-M), Germany                     | Stevens et al. (2013) |
| MRI-CGCM3          | 1.125° × 1.12°, L48(10) | Meteorological Research Institute (MRI), Japan                            | Yukimoto et al. (2012) |

*The number of model layers below 3 km (the hybrid height coordinate for HadGEM2-A) or 700 hPa (the hybrid sigma-pressure coordinate for the other models; assuming the surface pressure is 1000 hPa) is presented in the parentheses.

†IPSL-CM5A-LR (Hourdin et al. 2013a) was excluded from our study, because low-level cloud amounts are very small (less than 20%) over the whole ocean between 40°N and 40°S. The improved version of this model is IPSL-CM5B-LR (Hourdin et al. 2013b).
cloud amount obtained from CALIPSO.

Figure 4 displays the average variations in the LSC amount and layered EISs with increasing EIS obtained from the observations and four typical CMIP5 models (results for the other eight models are shown in Fig. S5). As seen in the observations, while the layered EISs increase with EIS in the order of EIS_700–850, EIS_850–925, and EIS_925–sfc, the LSC amounts are significantly correlated with EIS_850–925. The LSCs are composed of three types: stratocumulus (Sc), stratus (St), and sky-obscuring fog (FOG). Since most of the LSCs are Sc over the target ocean areas (e.g., Norris 1998), this result reasonably matches what KS14 found. The result is also consistent with the vertical maxima in the CALIPSO cloud amount, which gradually fall as EIS increases. The lowest maximum occurs at around 1 km when the EIS range reaches its maximum.

It should be noted that the CALIPSO cloud amount corresponds to not only the ISCCP LSC amount, but also to the ISCCP low cloud amount with optical thickness < 3.6, i.e., the ISCCP cumulus (Cu) amount (see Text S1). While the Cu amounts are generally much smaller than the LSC amounts, they are comparable in the range where EISs are around 0 K. The variation in the Cu amount coincides with that of EIS_700–850. This reflects a transition from a relatively shallow, well-mixed MBL topped by Sc to a deeper decoupled MBL with shallow Cu along the trade winds.

The results of HadGEM2-A, which performs best in Fig. 2, concur with those of the observations as described above. There is, however, one exception: the Cu amounts much less occur across the whole EIS range. This is a common weakness of all the models and further discussed in Text S2. The LSC amounts in CCSM4 also increase with EIS_850–925 consistently with the observations. Simultaneously, relatively large EIS_850–925 values occur, which are comparable to the EIS_850–925 values. This indicates the inversion levels are lower than the observations. However, the LSC amounts are smaller than the observations in the range where EISs are higher. The vertical distributions of CALIPSO cloud amount are also consistent with these features; the maxima in the cloud amount are of lower magnitude and at lower altitudes.

For GISS-E2-R, which is a model with a negative regression slope in Fig. 2, the LSC amount decreases despite the increasing EIS_850–925 and EIS_925–sfc values. The vertical distribution of CALIPSO cloud amounts is clearly consistent. These results suggest some problems in the scheme to govern low-level cloud formation. As a result, the LSC amounts in this model are apparently linked to EIS_700–850. This can be said that the simulated LSCs tend to be Cu-like clouds. On the other hand, IPSL-CM5B-LR shows that the increasing EISs are clearly dominated only by EIS_925–sfc. The LSC amount increases with EIS_925–sfc and is overestimated than the observations. This is consistent with the shallower enhanced CALIPSO cloud amounts over the whole EIS range. The results suggest inadequate vertical mixing, possibly due to some problems with the vertical diffusion scheme or the treatment of shallow convection. The high value of EIS_925–sfc suggests a very shallow mixed layer. This usually occurs with St in the coastal areas near the subtropical LSC regions in nature (Norris 1998). Thus, the LSCs in this model tend to be St-like clouds.

Figure 5 summarizes the results of this study. Most models overestimate and underestimate the LSC amounts where EISs are small and large, respectively (Figs. 5a and 5b). The latter is generally dominant, while both of them are responsible for the more gradual regression slopes than the observations, or the negative slopes, for the relationships between the LSC amount and EIS. From the analysis using layered EISs, most models show lower inversion levels than the observations in the range where EISs are
LSC amounts are dominated by those in the upper (i.e., around 1 structures; instead of the cloud amounts in the lowest layer, the relationship (HadGEM2-A) also captures well both their vertical Indeed, the model that simulates well the LSC amount–EIS representation of the LSC amount–EIS relationship results in their tight CALIPSO cloud amounts for the lowest layer are larger than the large. Correspondingly, the majority of the models show that the CALIPSO cloud amounts for the lowest layer are larger than the observations (Fig. 5c). Nevertheless, the LSC amounts derived from ISCCP are underestimated. This implies that the poor presentation of the LSC amount–EIS relationship results in their tight relationship at the different vertical level from the observations. Indeed, the model that simulates well the LSC amount–EIS relationship (HadGEM2-A) also captures well both their vertical structures; instead of the cloud amounts in the lowest layer, the LSC amounts are dominated by those in the upper (i.e., around 1 km, as seen in Fig. 4) layers.

In the models that significantly underestimate the LSC amounts (GISS-E2-R and CNRM-CM5), few clouds occur at any level in the lower troposphere despite of the large EIS. The model that overestimates the LSC amounts (IPSL-CM5B-LR) significantly overestimates the cloud amounts in the lowest layer. These models probably have some problems in the schemes related to the MBL processes. LSCs are maintained by a subtle balance between production processes such as cloud-top longwave radiative cooling and water vapor transport by turbulence, and break-up processes such as cloud-top entrainment, drizzle formation, and ventilation effect of shallow convection (e.g., Duykerke and Teixeira 2001; Wood 2012). Siebesma et al. (2004) indicated that underestimation of LSCs in GCMs can be due to too intense drizzle and too much entrainment. From a single-column model intercomparison, Dal Gesso et al. (2015) also suggested that cloud-top entrainment is a key process for the reproducibility of LSCs. It would be required to improve the representations of these processes, as well as a simple approach such as increasing the GCM vertical resolution.

4. Summary and discussion

For 12 CMIP5 models providing ISCCP simulator outputs, the relationships between the subtropical marine LSC amount and EIS simulated in AMIP experiments are quantitatively evaluated with satellite observations. Seven models underestimate the positive regression slope between them. Three have negative slopes, whereas one has a steeper slope; only one model is in good agreement with the observations. However, all the models accurately simulate EISs. Further analysis using the CALIPSO simulator outputs and layered EISs suggests that the inaccurate representation of closely tied vertical structures of LSCs and inversion strength leads to the poor reproducibility in the LSC amount–EIS relationship. This quantitative evaluation may constrain intermodel spread in low cloud feedbacks. According to Table 1 of Forster et al. (2013), for instance, two models (HadGEM2-A and IPSL-CM5B-LR) having the relatively close regression slopes to the observations show smaller cloud feedback parameters (−0.37 and −0.28 W m⁻² K⁻¹, respectively), compared to “worse” models including MIROC5, GISS-E2-R, and CNRM-CM5 (0.51, 0.48, and 0.20 W m⁻² K⁻¹, respectively). The systematic relationship between the representation skill of the LSC amount–EIS regression in the current climate and strength of low cloud feedback in a warming climate may have important implications for the uncertainty in future climate change. This would deserve further investigation in future studies. Moreover, new GCMs have been developed by many modeling groups for participating in the next phase of CMIP; CMIP6 (e.g., Kawai et al. 2017b). Evaluation of the LSC amount–EIS relationships in the upcoming CMIP6 models, and its comparison with the CMIP5 results, would be required in the near future.

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Supplement

The supplement contains two text sections and three additional figures.

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