Climatic Change (2011) 109:569–582
DOI 10.1007/s10584-011-0047-3

The role of low clouds in determining climate sensitivity in response to a doubling of CO_2 as obtained from 16 mixed-layer models

Richard T. Wetherald

Received: 9 September 2009 / Accepted: 3 December 2010 / Published online: 5 March 2011
© U.S. Government 2011

Abstract The effects that low clouds in sub-tropical to tropical latitudes have in determining a given model's climate sensitivity is investigated by analyzing the cloud data produced by 16 "slab" or mixed-layer models submitted to the PCMDI and CFMIP archives and their respective response to a doubling of CO_2. It is found that, within the context of the 16 models analyzed, changes of these low clouds appear to play a major role in determining model sensitivity but with changes of middle cloud also contributing especially from middle to higher latitudes. It is noted that the models with the smallest overall cloud change produce the smallest climate sensitivities and vice versa although the overall signs of the respective cloud feedbacks are positive. It is also found that the amounts of low cloud as simulated by the respective control runs have very little correlation with their respective climate sensitivities. In general, the overall latitude-height patterns of cloud change as derived from these more recent experiments agree quite well with those obtained from much earlier studies which include increases of the highest cloud, decreases of cloud lower down in the middle and lower tropospheric and small increases of low clouds. Finally, other mitigating factors are mentioned which could also affect the spread of the resulting climate sensitivities.

1 Introduction

Although this paper focuses mainly on cloud changes as obtained from general circulation model (GCM) output it is felt that the analysis and techniques used here can be applied to a wide range of interdisciplinary topics involving climate change. In particular, this study presents a method of analysis which could provide a different perspective on the interpretation of the range of climate sensitivities in other models

R. T. Wetherald (✉)
Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ 08542, USA
e-mail: dick.wetherald@noaa.gov

especially those which are substantially different from those considered in this study or perhaps using the cloud changes in another application.

It has been long recognized that cloud and cloud feedback has been the greatest source of uncertainty in creating the relatively wide spectrum of model sensitivities in response to planetary warming (Cess et al. 1990, 1996). A major reason for this is that different models incorporate varying schemes for cloud prediction which include a wide range of cloud process parameterizations. Past studies dealing with this topic in response to planetary warming include Roads (1978), Schneider et al. (1978), Manabe and Wetherald (1980), Hansen et al. (1984), Wetherald and Manabe (1986), Wilson and Mitchell (1987), Wetherald and Manabe (1988), Mitchell and Ingram (1992), Senior and Mitchell (1993, 2000); Colman (2003), Soden and Held (2006). By and large, fairly consistent patterns of zonal mean cloud cover change have emerged from these investigations which are (1) a general increase of the highest cloud for all latitudes, (2) a general decrease of cloud lower down in the upper and middle troposphere from the tropics to middle latitudes with smaller increases or decreases poleward of 60° latitude for both hemispheres. As stated in these previous studies, these two patterns of cloud change have the combined effect of producing positive cloud feedback; decreasing outgoing long wave radiation at the top of the model atmosphere and increasing the absorption of short wave radiation at the surface. However changes of low cloud cover were found to be generally increasing both in the subtropics and in higher latitudes which produces a negative cloud feedback.

The results of these earlier investigations were verified by the latest IPCC Report (Meehl et al. 2007) where the cloud distributions of 13 different models were compared and averaged. In particular, the same general patterns of zonal mean high and tropospheric cloud change were found (see Figure 10.10a, Chapter 10 of that report) which indicates that the latest generation of climate models with considerably more realistic cloud prediction schemes involving cloud physics, in one form or another, are consistent with the general patterns of cloud amount changes obtained by the earlier studies with much simpler cloud prediction methods.

The observation of subtropical low cloud increases in response to planetary warming is not new; in fact it was discussed as early as 1980 (Manabe and Wetherald 1980; Wetherald and Manabe 1980) but has re-emerged as an issue given the extensive climate data sets now available through PCMDI (Program for Coupled Model Diagnostics and Intercomparison), CMIP3 (Coupled Model Intercomparison Project) and CFMIP (Cloud Feedback Model Intercomparison Project). In both the 1980 studies, it was found that increases of subtropical marine low cloud cover resulted in a negative feedback component due to the relatively high albedo assigned to low clouds in general.

More recently, new studies were conducted concerning the effect of these low level clouds upon climate sensitivity (e.g. Medeiros et al. 2008; Zhang and Bretherton 2008). In the Medeiros et al. study, the National Center for Atmospheric Research Community Atmospheric Model (NCAR CAM) and the Geophysical Fluid Dynamics Atmospheric Model (GFDL AM) were integrated on simulated water covered or "aquaplanets" in response to a uniform +2°C change in sea surface temperature. The difference in sensitivity between the two models was attributed largely to the formation and response of these subtropical low-level clouds. In the Zhang and Bretherton study, the negative feedback effect of these stratus and stratocumulus clouds was analyzed and found to be caused by (a) more liquid water content due to

increased low-level convection and (b) less subsidence and therefore a longer lifetime of these clouds. These two investigations further highlight the potential importance of subtropical low-level clouds in future climate sensitivity studies.

Here 16 different "slab" or mixed-layer model experiments, submitted to the CMIP3 and CFMIP archives, are analyzed and details of their cloud cover changes evaluated as a function of their respective changes of surface air temperature (SAT) in response to a doubling of CO_2. In particular, the study explores the hypothesis that climate sensitivity can be largely regulated by the prediction and response of subtropical low-level clouds or more specifically, the SAT sensitivity is reduced in those models which produce relatively large increases of these clouds.

It should be mentioned that there are two basic issues that are not considered in this investigation. One is illustrated by the study of Gregory and Webb (2008) which demonstrated that many of the cloud changes affecting both short and long wave radiation could be responses to the radiative forcing itself rather than through actual model feedbacks. Another is the fact that the 16 models analyzed here have different methods of formulating cloud optical properties and cloud overlap. Since this study is devoted mainly to changes in cloud amount alone, these issues are beyond the scope of this investigation although it must be recognized that they presumably could affect their respective climate sensitivities.

2 Cloud cover analysis

2.1 Overall cloud cover

As stated in the Introduction, 16 mixed-layer models from both the CMIP3 and CFMIP archives were analyzed. Table 1 lists these models and their respective affiliations. For detailed descriptions of these models, the reader is referred to Table 8.1 of Randall et al. (2007) and the references cited for each model. Each of these models was integrated out to an equilibrium climate in response to a doubling of CO_2 for 40 model years with a corresponding control integration of the same length. For all integrations, the last 20 years were selected for analysis.

Since this study attempts to separate the predicted clouds into high, middle and low categories, these boundaries are defined here. To this end, the following IPCC definitions of high, middle and low cloud types were used: low cloud from the surface to 680 hPa, middle cloud from 680 hPa to 440 hPa and high cloud from 440 hPa to the top of the model atmosphere. To compute the total cloud within a given category, the random overlap formula is used: namely

$$1. - Ct = (1. - C1)^{*}(1. - C2)^{*}(1. - C3)^{*}(1. - C4) \ldots\ldots\ldots\ldots(1. - Cn) \qquad (1)$$

Where C_n are cloud amounts at whatever levels are within a given cloud category and C_t is the total cloud amount within that category.

In this section, six of the models are chosen for illustrating cloud cover changes; three with the lowest SAT sensitivity and three with the highest sensitivity. The first of these illustrations is shown in Fig. 1 which displays the zonal mean cloud change normalized by the corresponding change in SAT for the six models. To facilitate the analysis, the cloud layer boundaries for each of the assumed cloud types are placed in each panel as black horizontal lines. Panels (a), (b) and (c) depict the models

Table 1 A list of slab ocean model simulations used in the analysis of cloud feedback in response to a doubling of CO_2

cccma_agcm4_0	Canadian Center for Climate, Canada
cccma_cgcm3_1	Canadian Center for Climate, Canada
cccma_cgcm3_1_t63	Canadian Center for Climate, Canada
csiro_mk3_0	Commonwealth Scientific and Industrial Research Organization (CSIRO) Atmospheric Research, Australia
gfdl_cm2_0	Geophysical Fluid Dynamics Laboratory/NOAA, USA
giss_model_e_r	Goddard Institute for Space Sciences, USA
inmcm3_0	Institute for Numerical Mathematics, Russia
ipsl_cm4	Institute Pierre Simon LaPlace, France
miroc3_2_hires	Center for Climate System Research, Japan
miroc3_2_medres	Center for Climate System Research, Japan
miroc_losens	Center for Climate System Research, Japan
mpi_echam5	Max Planck Institute for Meteorology, Germany
ncar_ccsm3_0	National Center for Atmospheric Research, USA
ukmo_hadgem1	Hadley Centre for Climate prediction and Research/Met Office, United Kingdom
ukmo_hadsm3	Hadley Centre for Climate prediction and Research/Met Office, United Kingdom
ukmo_hadsm4	Hadley Centre for Climate prediction and Research/Met Office, United Kingdom

This and subsequent tables include both CMIP3 and CFMIP models

with the lowest SAT sensitivity whereas panels (d), (e) and (f) indicate the models with the largest SAT sensitivity, in ascending order, as indicated at the top of each panel. Here, all six models display the general features of zonal mean cloud change in response to the doubling of CO_2 described in the earlier studies, namely an increase of the highest cloud at all latitudes and a general decrease of cloud cover lower down for most latitudes. It should be noted here that, in the tropics and subtropics, the reduction of upper tropospheric cloud is considerably greater than the corresponding increase of cloud higher up which indicates that this feature is not simply an overall readjustment or raising of high cloud to a higher level. The main observation here is that (a), (b) and (c) generally show the smallest overall cloud changes, both positive and negative whereas (d), (e) and (f) indicate larger changes. An exception to this is the increases of low cloud in (a), (b) and (c) which are considerably greater than those of (d), (e) and (f) which is consistent with a reduction of SAT sensitivity for those cases. It appears from Fig. 1, therefore, that the largest SAT sensitivities are associated with the smallest increases in low cloud but this, in itself, does not uniquely determine which cloud types; high, middle or low are mainly responsible for this feature.

2.2 Low cloud cover

Figure 2 shows the control simulations of low cloud by the same six models given in Fig. 1. In general, there is no consistency of low cloud distributions produced by these models and their respective SAT sensitivities (e.g. greater low cloud amounts associated with smaller SAT sensitivities and vice versa). This is further emphasized by Table 2 which indicates the integrals of low cloud amount in percent taken globally

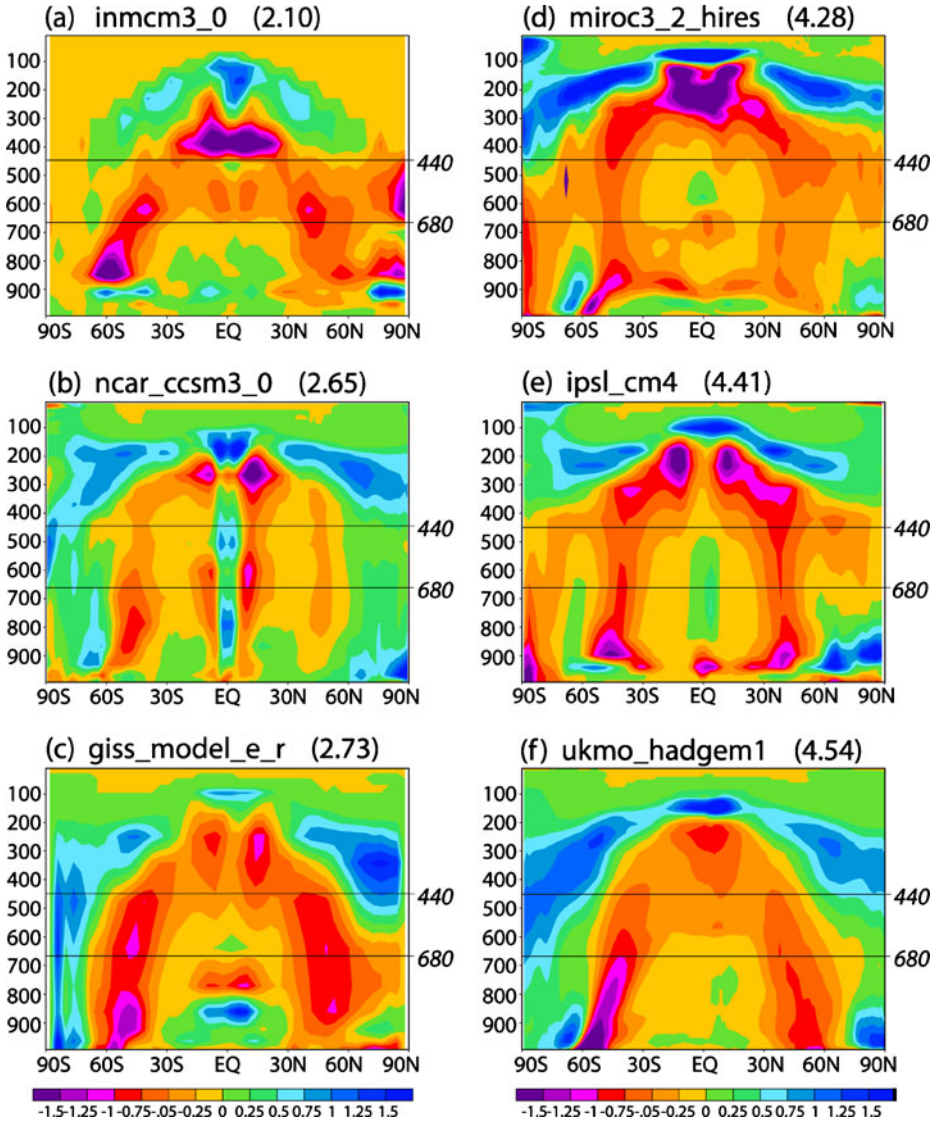

Fig. 1 Latitude-height distribution of zonal mean cloud amount difference normalized by the corresponding change of SAT due to a doubling of CO_2 for six of the models analyzed in this study. **a**, **b**, and **c** indicate the three models with the lowest SAT sensitivity in ascending order; **d**, **e** and **f** represent the corresponding models with the greatest SAT sensitivity again in ascending order. SAT sensitivity for each model is given at the top of each panel in units of °C. To illustrate the IPCC cloud categories used, *horizontal black lines* are placed in each panel denoting the high, middle and low clouds (top to 440 hPa, 440 tp 680 hPa and 680 to surface, respectively). Units of normalized cloud differences are in %./°C

and from 30°S to 30°N for all 16 models as simulated by each model's control run. Again, there appears to be no apparent relationship between low cloud amount and SAT sensitivity. For example according to Table 2, both the ncar_ccsm3_0

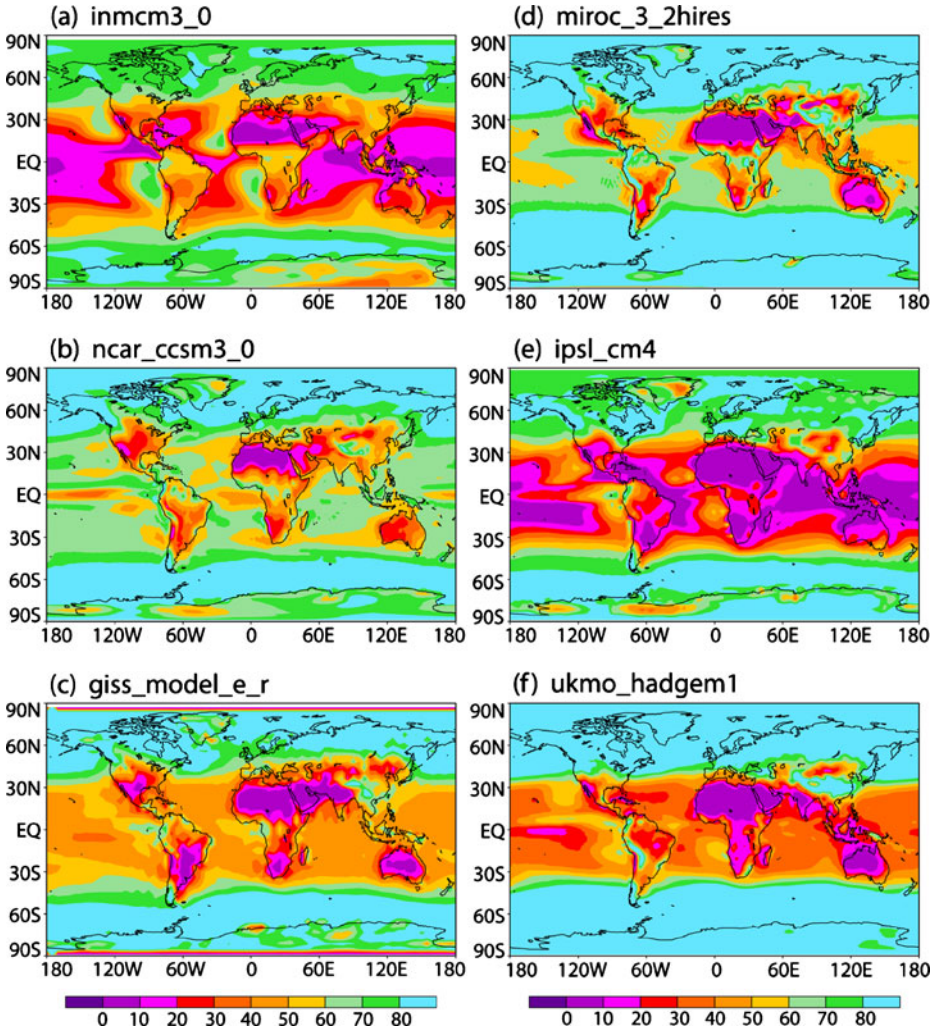

Fig. 2 Geographical distribution of simulated control low cloud amount for the same six models shown in Fig. 1 and in the same order. Units are in %

and miroc_3_2_hires models have a relatively high amount of low cloud in their respective control runs yet have quite different SAT sensitivities.

Figure 3 shows the difference of low cloud amount for the same six models. Here, there is more consistency where the three models with a low SAT sensitivity produce a relatively large amount of positive low cloud increases in the tropics and subtropics whereas the three models with much higher SAT sensitivity, although there is some increase in low clouds near the model surfaces over the Pacific Ocean, produce mainly decreases in low cloud amount. This would tend to support the conclusion that models with a relatively low SAT sensitivity have a much stronger negative cloud feedback due to low cloud increases than the models in which the opposite low cloud changes occur. However, one must consider the changes of all three cloud types before drawing this conclusion completely.

Table 2 Area integrals of simulated low cloud amount for the 16 models considered in this study from their respective control integrations; globally and from 30°S to 30°N in percent along with their respective SAT sensitivities in degrees C

Model	Global	30°S–30°N	Change of SAT
inmcm3_0	42.42	24.82	2.10
ncar_ccsm3_0	62.14	54.54	2.65
giss_model_e_r	53.08	38.22	2.73
gfdl_cm2_0	52.67	26.20	2.91
csiro_mk3_0	45.97	34.03	3.06
mpi_echam5	51.22	16.43	3.32
cccma_cgcm3_1_t63	54.34	44.36	3.38
cccma_cgcm3_1	59.87	45.56	3.50
ukmo_hadsm3	47.24	34.95	3.51
ukmo_hadsm4	61.61	42.33	3.62
cccma_agcm4_0	71.77	55.07	3.75
miroc_losens	45.57	29.2	3.94
miroc3_2_medres	48.17	32.44	4.00
miroc3_2_hires	63.54	47.66	4.28
ipsl_cm4	47.11	14.55	4.41
ukmo_hadgem1	54.08	28.94	4.54

In order to further analyze the low cloud changes in Fig. 3, it is informative to examine also the changes in downward solar radiation (not the net) at the model surface of the same six models as is done in Fig. 4. This is done to remove the effects of surface albedo changes. Since the changes of middle cloud are quite small in low latitudes (see Fig. 1) and the highest cloud increases, this should provide an objective means of analyzing the radiative effect of the low cloud changes shown in Fig. 3. For example if low cloud changes were the dominating factor, one would expect that increases of low cloud amount would lead to decreases of downward solar radiation and vice versa. A comparison of both sets of figures reveals that for most regions from tropical to middle latitudes, the patterns of low cloud change are indeed consistent with the corresponding changes of surface downward solar radiation. Exceptions to this appear over Australia for half of the models, however, where both low cloud and downward solar radiation decrease. In higher latitudes, this relationship is less obvious which may indicate that changes of both middle and high cloud have a greater role in determining the changes of downward solar radiation there as evident in Figs. 1 and 3, respectively. However, there is an additional complication in higher latitudes since the downward component of solar radiation can include multiple reflections from sea ice to the lowest cloud base and back, thus making this analysis more difficult to interpret in these regions.

To further explore this topic, Table 3 contains the linear pattern correlation coefficients between low, middle and high cloud amounts and surface downward solar radiation for each of the 16 models. From Table 3, most of the models show correlation coefficients greater than 0.51 for low cloud with many of them greater than 0.60. The two exceptions to this are the inmcm3_0 and giss_model_e_r models. Further examination of these two models reveals that their relatively low correlation coefficients are mainly caused by the reduction of both low cloud amounts and insolation southward of 30°S. For example, the correlation coefficient for the inmcm3_0 model increases to −0.596 if the region from 30°S to 90°S is excluded. The giss_model_e_r, on the other hand, is almost completely uncorrelated except in

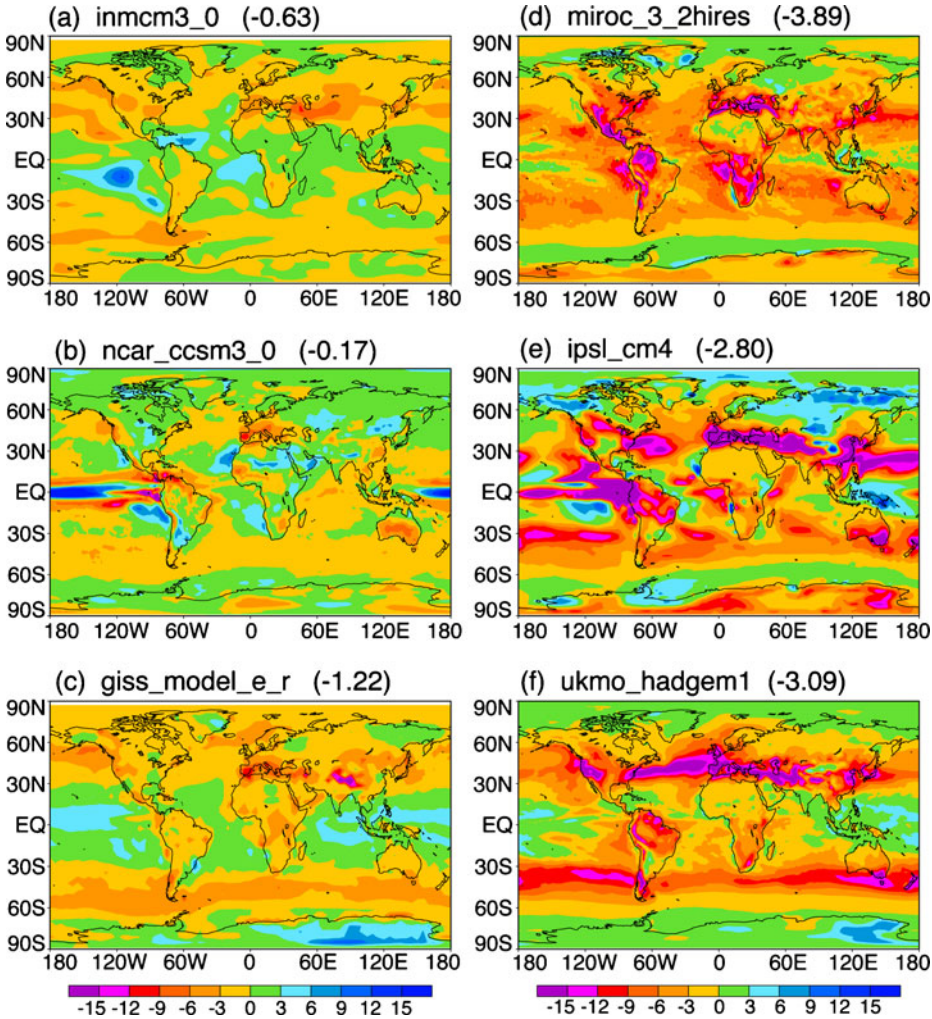

Fig. 3 Geographical distribution of low cloud amount difference in response to a doubling of CO_2 for the same six models shown in Fig. 1 and in the same order. Global cloud differences are placed at the top of each image. Units are in %

the 30°S to 30°N latitude region. Aside from these two cases, this analysis supports the contention that both the low cloud and insolation distributions are reasonably well correlated as stated above.

However, there are other interesting features in Table 3 as well. For example, the correlation coefficients with regard to both middle and low cloud for the gldl_cm2_0 and mpi_echam5 models are, essentially the same, which suggests that changes of middle cloud are as important as those of low cloud for these two models. The same is true for the ukmo_hadgem1 model where the correlation coefficients for all three cloud categories are practically identical which indicates that all three cloud types play an equal role in determining the SAT of that model. While this analysis indicates

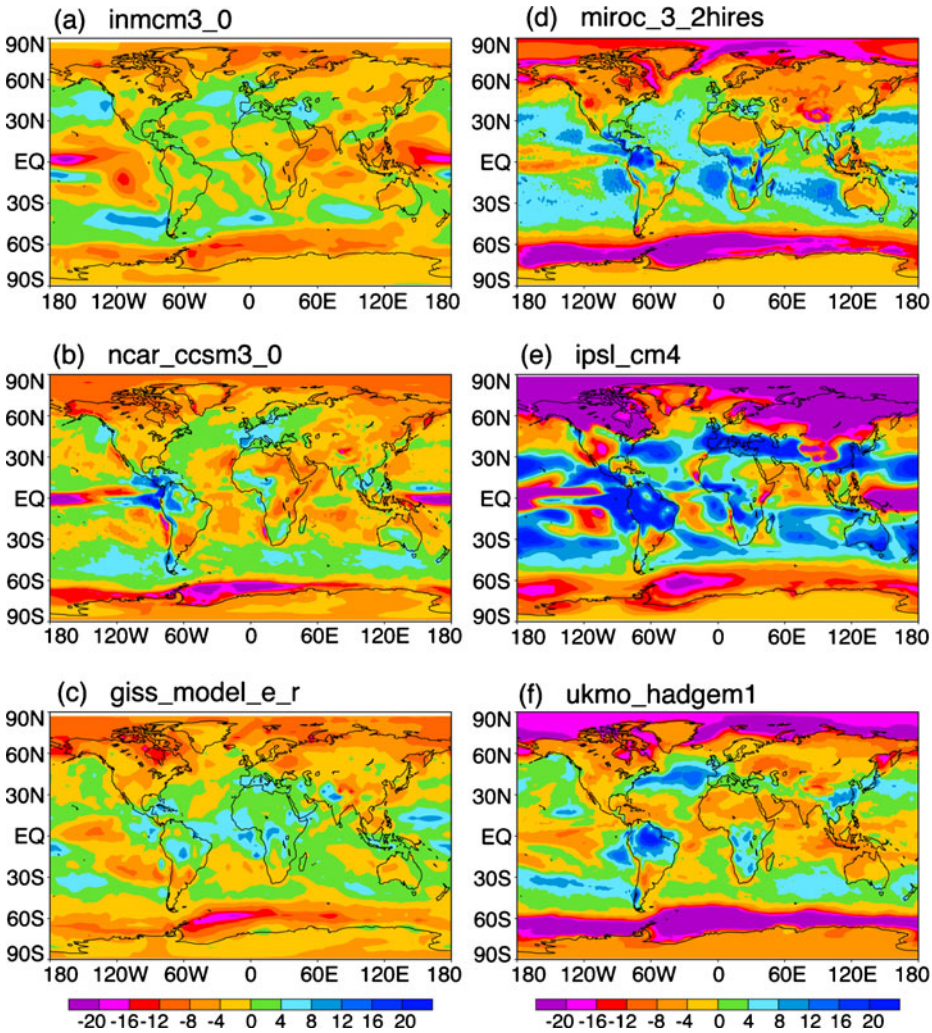

Fig. 4 Geographical distribution of the difference in the downward component of solar radiation at the surface in response to a doubling of CO_2 for the same six models given in Figs. 1 and 2 in the same order. Units are in W/m^2

that low cloud changes appear to play the most important role in determining the SAT sensitivities of most of the models analyzed in this study, the effects of middle and high cloud are certainly important as well.

However before drawing any definitive conclusions concerning low clouds alone, it is necessary to analyze all three cloud types; high, middle and low, separately, to determine their respective variations as functions of model SAT sensitivity. In this analysis, two models were deleted (cccma_cgcm3_1_t63 and ukmo_hadsm4) because they had very similar responses to another member of their respective research groups. This is done in Fig. 5a, b where integrals of cloud change, both global (Fig. 5a) and the latitude belt of 30°S–30°N (Fig. 5b), are plotted. An examination

Table 3 Linear pattern correlation coefficient for all 16 models between low, middle and high cloud amount and downward solar radiation at each models surface

Model	Low	Middle	High
inmcm3_0	−0.332	−0.402	−0.181
ncar_ccsm3_0	−0.671	−0.457	−0.358
giss_model_e_r	−0.039	−0.331	−0.599
gfdl_cm2_0	−0.513	−0.552	−0.363
csiro_mk3_0	−0.806	−0.544	−0.608
mpi_echam5	−0.560	−0.552	−0.374
cccma_cgcm3_1_t63	−0.622	−0.386	−0.448
cccma_cgcm3_1	−0.664	−0.422	−0.483
ukmo_hadsm3	−0.862	−0.566	−0.538
ukmo_hadsm4	−0.649	−0.529	−0.562
cccma_agcm4_0	−0.553	−0.228	−0.342
miroc_losens	−0.765	−0.092	−0.359
miroc3_2_medres	−0.792	−0.159	−0.358
miroc3_2_hires	−0.680	−0.201	−0.163
ipsl_cm4	−0.649	−0.351	−0.373
ukmo_hadgem1	−0.548	−0.548	−0.540

Note, the entire globe has been used in computing these values

of Fig. 5a reveals that as SAT sensitivity increases; middle, low and total cloud cover generally decrease whereas high cloud has no definite trend but is mostly positive in sign. However, there is considerable variation from one model to another in the curves for the changes of all three cloud types as well as the total cloud cover.

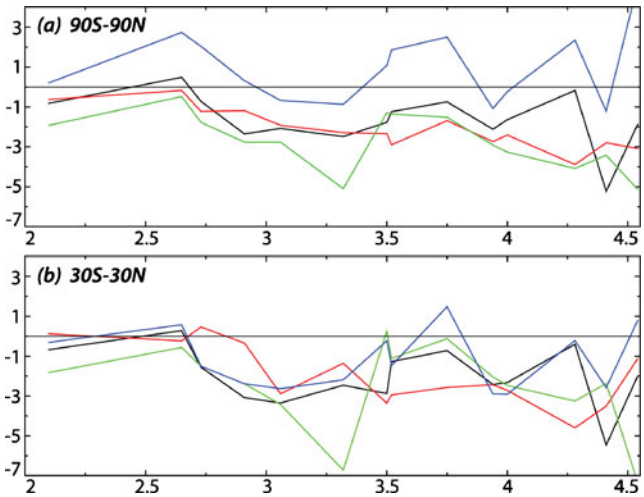

Fig. 5 **a** and **b** are area weighted integrals of various cloud type differences (%): **a** global values, **b** the region between 30°S and 30°N latitude as functions of their respective SAT sensitivities for 14 of the models. Legend for **a** and **b** is high cloud (*blue line*), middle cloud (*green line*), low cloud (*red line*) and total cloud amount (*black line*). Note, both the cccma _cgcm3_1_t63 and ukmo_hadsm4 models have been deleted from this analysis due to a possible lack of independence

Table 4 Slope, statistical t-test and linear correlation coefficient values for cloud cover change for 14 of the 16 models based upon 13 degrees of freedom

	90°S–90°N			30°S–30°N		
	Slope	t-value	r	Slope	t-value	r
High cloud	0.37	0.51	0.14	−0.05	−0.09	−0.03
Middle cloud	−1.10	−2.36	−0.56	−1.01	−1.22	−0.33
Low cloud	−1.22	−5.98	−0.87	−1.49	−3.41	−0.70
Total cloud	−0.76	−1.56	−0.41	−0.69	−1.26	−0.34

Here, the absolute value of "t" must exceed 1.77 for statistical significance greater than zero at the 10% significance level. "r" denotes the corresponding linear correlation coefficient for each case. Here, both the cccma_cgcm3_1_t63 and ukmo_hadsm4 models have been deleted from this analysis due to a possible lack of independence

Similar observations are noted for the cloud changes in the latitude belt of 30°S–30°N (Fig. 5b).

A more detailed analysis can be made on these plots which consist of computing regression lines for each of the cloud categories and then evaluating the statistical significance of their respective slopes by the standard t-test. The results of this analysis are given in Table 4 which lists the slopes of the linear regression lines fitted for each cloud category along with their associated t-test values based upon 13 (the number of models minus one) degrees of freedom. According to Table 4 for the global region, the low cloud category has the largest negative slope of the three cloud categories shown. The same is true for the latitude belt of 30°S–30°N. In other words of the three cloud categories, low cloud reduces the most as SAT sensitivity increases with that reduction being greater for the 30°S–30°N latitude zone than globally. With regard to the t-test values, the slopes of both the global and 30°S–30°N low cloud categories have the greatest significance at the 10% significance level. Table 4 appears to also indicate that while low cloud cover changes are the largest, middle clouds are also important as well for the global region. For the 30°S–30°N latitude zone, changes of low cloud appear to have a more dominant role as compared with the middle cloud changes especially with regard to statistical significance. This observation is also evident with regard to the corresponding linear correlation coefficients with low cloud changes having the highest value of this quantity or explained variance.

3 Summary and conclusions

To summarize the above analysis, the following are noted:

1. According to Fig. 1, the smallest SAT change occurs in conjunction with the smallest overall cloud change and the largest SAT change is associated with the largest overall cloud change with the other sensitivities falling in between. However, in the subtropics and tropics for the same model simulations, the smallest SAT sensitivities occur with the greatest increase of low level cloud whereas the largest SAT sensitivities occur with overall decreases of low cloud.
2. There appears to be no direct correlation between low cloud amount as simulated by the control integrations and their respective SAT sensitivities. Apparently, the simulation of low cloud in each control run has little to do with

the resulting SAT sensitivity for a given model at least for the 16 models being analyzed here presumably as long as there is enough low cloud to respond to the planetary warming.

3. General trends of SAT sensitivities vs cloud type change are: (a) high cloud has very little trend, (b) middle and low cloud generally decrease with increasing SAT sensitivity; both globally and in the 30°S–30°N region, with the greatest reduction of low cloud occurring in the subtropical and tropical region, (c) there is considerable variation from one model to another as evidenced in Fig. 5, (d) low cloud trends are statistically significant for both global and low latitude regions. However, the middle cloud trend is significant only globally. This latter observation suggests that global SAT sensitivity may be governed by changes in both middle and low cloud globally, but with low cloud in sub-tropical to tropical latitudes playing a major role. This is consistent with the overall cloud changes shown in Fig. 1.

Another interesting observation can be made here. In the study by Medeiros et al. (2008), the NCAR model was found to be less sensitive than the GFDL model due mainly to increased negative feedback by low-level clouds. This feature is consistent with the results of the current investigation (see Table 2 and Fig. 5a, b).

In general, it appears that climate SAT sensitivity may be largely governed by changes in low cloud in low latitudes but is also strongly influenced by changes of middle and low cloud in middle to higher latitudes as well. That having been said, there are several caveats that should be noted here. For example, the studies by Bony and Dufresne (2005) and Karlsson et al. (2007) stress that major uncertainties exist among climate models due primarily to the simulation and prediction of low level marine tropical clouds. According to these studies, most climate models tend to under predict this type of cloud cover yet still produce excessive radiative cooling caused primarily by too much shortwave reflection by these clouds. Since this paper does not deal with the issue of the simulation of low marine cloud amount as compared with observation, the model SAT sensitivities and cloud amount data are simply taken at face value and evaluated accordingly with the understanding that these major uncertainties exist. However the control run simulations of low cloud from the 16 models, as shown in this study, suggest that this may not be an important issue with regard to climate sensitivity at least for the climate models being analyzed here.

Another possible uncertainty is given in the study by Gregory and Webb (2008) which noted that tropospheric adjustment and its effect upon the three-dimensional cloud distribution and its radiative forcing may also be responsible for the considerable spread of climate sensitivities due to increases of CO_2. According to their results, climate sensitivities of GCMs can also be driven by direct responses to the radiative forcings themselves as well as indirect responses to the subsequent thermal processes. This is a feature which will probably not alter the conclusions of this current study as far as clouds and climate sensitivity are concerned.

Finally, the study by Williams and Tselioudis (2007) also noted the relative inability of most climate models to simulate trade wind cumulus correctly but further indicates that global mean responses of many climate models to increases of CO_2 results from changes in cloud radiative properties rather than changes in the relative frequency of occurrences of various cloud regimes or types.

Since the IPCC definitions of cloud type were used, account is not taken of the overall reduction of high cloud height with increasing latitude due to the lowering of the tropopause with increasing latitude. Therefore, the high cloud category includes both increases and decreases in low latitudes whereas it mostly increases in middle to high latitudes.

In any event, this current study also notes a considerable spread of climate sensitivities due primarily to different cloud responses but could also be affected, to some degree, by the additional processes cited above. For example, the bias in shortwave reflection, mentioned above, could exaggerate the cooling (or heating) effects of low clouds and their response to planetary warming depending upon the sign of the low cloud changes. Since this investigation concerns an ensemble of models from different modeling groups all employing different methods of cloud prediction and specifications of cloud properties, investigation of these other issues is clearly beyond the scope of this short study. What has been attempted here is an evaluation of cloud changes, using a different method from those used in previous studies, to determine whether or not there is a pattern of low cloud changes that are primarily responsible for the spread of climate sensitivities. Obviously, this issue will require more extensive research in the future to definitively resolve; in particular, investigations which attempt to include and isolate the effects of cloud optical properties.

Acknowledgements The author would like to thank Ronald Stouffer for suggesting this study and assisting in the initial stages of the analysis. Thanks are also due to members of the staff of PCMDI, CMIP3 and CFMIP which include Mark Webb of the Hadley Centre for Climate Prediction and Research, UK, Robert Drach and Karl Taylor of the Lawrence Livermore National Laboratory for making available the mixed-layer model data and assisting with its retrieval.

References

Bony S, Dufresne J-L (2005) Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. Geophys Res Lett 32:L20806. doi:10.1029/2005GL023851

Cess RD, Potter GL, Blanchet JP, Boer GJ, Del Genio AD, Déqué M, Dymnikov, Galin V, Gates WL, Ghan SJ, Kiehl JT, Lacis AA, Le Treut H, McAvaney BJ, Meleshko VP, Mitchell JFB, Morcrette J-J, Randall DA, Rikus L, Roeckner E, Royer JF, Schlese U, Sheinin DA, Slingo A, Sokolov AP, Taylor KE, Washington WM, Wetherald RT, Yagai I (1990) Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. J Geophys Res 95:16601–16615

Cess RD, Zhang MH, Ingram WJ, Potter GL, Alekseev V, Barker HW, Cohen-Solal E, Colman RA, Dazlich DA, Del Genio AD, Dix MR, Esch M, Fowler LD, Fraser JR, Galin V, Gates WL, Hack JJ, Kiehl JT, Le Treut H, Lo KK-W, McAvaney BJ, Meleshko VP, Morcrette J-J, Randall DA, Roeckner E, Royer JF, Schlesinger ME, Sporyshev PV, Timbal B, Volodin EM, Taylor KE, Wang W, Wetherald RT (1996) Cloud feedback in atmospheric general circulation models: an update. J Geophys Res 101:12791–12794

Colman R (2003) A comparison of climate feedbacks in general circulation models. Clim Dyn 20: 865–873

Gregory J, Webb M (2008) Tropospheric adjustment induces a cloud component in CO_2 forcing. J Clim 21:58–71

Hansen J, et al (1984) Climate sensitivity: analysis of feedback mechanisms, Climate Process and Climate Sensitivity, Geophysical Monograph, 29, Maurice Ewing 5: Amer Geophys Union 130–163

Karlsson J, Svensson G, Rodhe H (2007) Cloud radiative forcing of subtropical low level clouds in global models. Clim Dyn 30:779–788

Manabe S, Wetherald R (1980) On the distribution of climate change resulting from an increase of CO_2 content of the atmosphere. J Atmos Sci 37:99–118

Medeiros B, Stevens B, Held I, Zhao M, Williams D, Olsen J, Bretherton C (2008) Aquaplanets, climate sensitivity, and low clouds. J Clim 21:4974–4991

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Kunitti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007) Global Climate Projections, Chapter 10 in Climate Change 2007. The Physical Science Basis, Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Mitchell J, Ingram W (1992) Carbon dioxide and climate: mechanisms of changes in cloud. J Clim 5:5–21

Randall DA, Wood RA, Bony S, Colman R, Fichefet T, Fyfe J, Kattsov V, Pitman A, Shukla J, Srinivasan J, Stouffer RJ, Sumi A, Taylor KE (2007) Climate models and their evaluation. In: Climate change 2007: the physical science basis, Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Roads J (1978) Numerical experiments on the sensitivity of an atmospheric hydrologic cycle to the equilibrium temperature. J Atmos Sci 35:753–773

Schneider S, Washington W, Chervin R (1978) Cloudiness as a climate feedback mechanism: effects on cloud amounts of prescribed global and regional surface temperature changes in the NCAR GCM. J Atmos Sci 35:2207–2221

Senior C, Mitchell J (1993) Carbon dioxide and climate: the impact of cloud parameterization. J Clim 6:393–418

Senior C, Mitchell J (2000) The time-dependence of climate sensitivity. Geophys Res Lett 27:2685–2688

Soden B, Held I (2006) An assessment of climate feedbacks in coupled ocean-atmosphere models. J Clim 18:237–273

Wetherald R, Manabe S (1980) Cloud cover and climate sensitivity. J Atmos Sci 37:1485–1510

Wetherald R, Manabe S (1986) An investigation of cloud cover change in response to thermal forcing. Clim Change 8:5–23

Wetherald R, Manabe S (1988) Cloud feedback processes in a general circulation model. J Atmos Sci 45:1397–1415

Williams K, Tselioudis G (2007) GCM intercomparison of global cloud regimes: present-day evaluation and climate change response. Clim Dyn 29:231–250

Wilson C, Mitchell M (1987) A doubled CO_2 sensitivity experiment with a global model including a simple ocean. J Geophys Res 92:13315–13343

Zhang M, Bretherton C (2008) Mechanisms of low cloud-climate feedback in idealized single-column simulations with the community atmospheric model, Version 3 (CAM3). J Clim 21:4859–4878