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Radiative damping of annual variation in global mean surface temperature: comparison between observed and simulated feedback

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Abstract The sensitivity of the global climate is essentially determined by the radiative damping of the global mean surface temperature anomaly through the outgoing radiation from the top of the atmosphere (TOA). Using the TOA fluxes of terrestrial and reflected solar radiation obtained from the Earth radiation budget experiment (ERBE), this study estimates the magnitude of the overall feedback, which modifies the radiative damping of the annual variation of the global mean surface temperature, and compare it with model simulations. Although the pattern of the annually varying anomaly is quite different from that of the global warming, the analysis conducted here may be used for assessing the systematic bias of the feedback that operates on the CO_2-induced warming of the surface temperature. In the absence of feedback effect, the outgoing terrestrial radiation at the TOA is approximately follows the Stefan-Boltzmann's fourth power of the planetary emission temperature. However, it deviates significantly from the blackbody radiation due to various feedbacks involving water vapor and cloud cover. In addition, the reflected solar radiation is altered by the feedbacks involving sea ice, snow and cloud, thereby affecting the radiative damping of surface temperature. The analysis of ERBE reveals that the radiative damping is weakened by as much as 70% due to the overall effect of feedbacks, and is only 30% of what is expected for the blackbody with the planetary emission temperature. Similar feedback analysis is conducted for three general circulation models of the atmosphere, which was used for the study of cloud feedback in the preceding study. The sign and magnitude of the overall feedback in the three models are similar to those of the observed. However, when it is subdivided into solar and terrestrial components, they are quite different from the observation mainly due to the failure of the models to simulate individually the solar and terrestrial components of the cloud feedback. It is therefore desirable to make the similar comparison not only for the overall feedback but also for its individual components such as albedo- and cloud-feedbacks. Although the pattern of the annually-varying anomaly is quite different from that of global warming, the methodology of the comparative analysis presented here may be used for the identification of the systematic bias of the overall feedback in a model. A proposal is made for the estimation of the best guess value of climate sensitivity using the outputs from many climate models submitted to the Intergovernmental Panel on Climate Change.

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1 Introduction

The sensitivity of the climate is essentially controlled by the so-called feedback parameter, which is the rate of radiative damping of the unit anomaly of the global mean surface temperature due to the outgoing radiation from the top of the atmosphere (TOA). By dividing the radiative forcing of climate by the feedback parameter, one gets the radiatively forced, equilibrium response of global surface temperature. This implies that the stronger is the rate of the radiative damping, the smaller is its equilibrium response to a given radiative forcing.

In the absence of feedback effect, the outgoing radiation at the top of the atmosphere is approximately equal to the fourth power of the effective planetary emission temperature, following the Stefan-Boltzmann's law of blackbody radiation. In the actual atmosphere, however, it deviates significantly from the blackbody radiation. When the temperature of the atmosphere increases, for example, its absolute humidity is likely to increases. Thus, the infrared opacity of the atmosphere increases, thereby lowering the temperature of the effective source of outgoing radiation and weakening the radiative damping of the surface temperature anomaly. This explains why the water vapor feedback weakens the radiative damping of surface temperature anomaly, thereby enhancing the sensitivity of climate.

The changes in the temperatures of the atmosphere and the earth's surface affect not only the outgoing longwave radiation but also the reflected solar radiation at the TOA. For example, an increase in surface temperature is likely to reduce the area covered by snow and sea ice, thereby reducing the heat loss due to the reflection of incoming solar radiation. Thus, the effective radiative damping of surface temperature anomaly is reduced, thereby enhancing the sensitivity of climate.

According to the third IPCC (2001) report, the previously estimated range of the equilibrium response of the global mean surface temperature to the doubling of atmospheric CO_2 has not reduced substantially over the last decade and remains between 1.5°C and 4.5°C. Clearly, the large range in the estimated sensitivity of surface temperature is attributable in no small part to our inability to reliably determine the influence of feedback upon the radiative damping of surface temperature anomaly.

Using the TOA fluxes of radiation obtained from the Earth radiation budget experiment (ERBE), the present study evaluates how the overall feedback of the atmosphere alters the radiative damping of the annual variation in surface temperature. Specifically, we compute the gain factor, which indicates the relative contribution of the overall feedback for reducing the radiative damping of the annual variation in global surface temperature. To identify the systematic bias of the overall feedback simulated by a model, the gain factor thus estimated is then compared with the gain factor of the feedback simulated by the model.

It is well-known that the annual variation of surface temperature is highly transient response to annually varying insolation that is out of phase between the two hemispheres. Thus, it is not our intension to determine the magnitude of feedback, incorrectly assuming that surface temperature were continuously in equilibrium with the annually varying, incoming solar radiation. Instead, we estimate here the magnitude of the overall feedback that operates upon the annual temperature variation, using the outgoing fluxes of terrestrial and reflected solar radiation from the TOA.

The annual variation of the global mean surface temperature is attributable mainly to the difference in effective thermal inertia between the two hemisphere than to the small annual variation of globally averaged, incoming solar radiation. Because the seasonal variation of surface temperature is much larger over continents than over oceans, the annual variation of the global mean surface temperature is dominated by the contribution from the continents in Northern Hemisphere. Its annual range is about 3.3°C with highest temperature in July and the lowest in January. The range is comparable in magnitude to a current estimate of the equilibrium response of global mean surface temperature to the doubling of CO_2 concentration in the atmosphere.

Since the pattern of the annual variation of surface temperature (see, for example, Fig. 1b of Tsushima and Manabe 2001) differs greatly from that of the global warming simulated by a model, it is quite likely that the rate of the radiative damping of the global mean surface temperature anomaly is significantly different between the two. As noted by Raval and Ramanathan (1989) and Inamdar and Ramanathan (1998), the rate of radiative damping of local surface temperature anomaly is similar to the damping of the annual variation in global surface temperature under clear sky. Therefore, it is likely that the rate of the radiative damping of global surface temperature variation under clear sky is similar between the annual variation and global warming despite the difference in pattern. On the other hand, a similar statement may not be made for the albedo-, and cloud feedback. Nevertheless, we are going to estimate the gain factor of the overall feedback for global warming using the gain factor for the annual variation, which is the largest climate change one can observe. The availability of data from the ERBE is another decisive factor for conducting the analysis presented here.

The gain factor of the overall feedback thus obtained is then compared with the gain factor of feedback simulated by a climate model. Similar comparison may be made for other feedback processes such as albedo- water vapor-, and cloud-feedbacks (e.g., Tsushima and Manabe 2001). We hope that such comparison should be useful for identifying the systematic bias of a model, thereby serving as a guide for improving the parameterization of the feedbacks that control the sensitivity of climate.

2 Formulation of feedback parameter

As noted in the Introduction, the sensitivity of climate may be determined by the feedback parameter (Dickinson 1981), which is defined as the rate of radiative damping of global surface temperature anomaly at the TOA (e.g., Wetherald and Manabe 1988). From the given feedback parameter, one can compute the equilibrium response of global mean surface temperature, dividing the radiative forcing of climate by the feedback parameter.

In the present study, the feedback parameter (λ) for the annual variation of global mean surface temperature is defined by the following equation:

$$\lambda = \frac{\mathrm{d}\left(\bar{L} + \overline{[S_\mathrm{r}]^\mathrm{A}}\right)}{\mathrm{d}\bar{T}_\mathrm{S}}, \tag{1}$$

where L and $[S_\mathrm{r}]^\mathrm{A}$ denote the outgoing flux of longwave radiation and annually normalized flux of reflected solar radiation at the TOA (S_r), respectively. T_S denotes surface temperature. $\overline{(\ )}$ indicates the global average operator. Following Cess et al. (1997), the annual normalization is defined as follows:

$$[S_\mathrm{r}]^\mathrm{A} = \frac{(S_\mathrm{i})^\mathrm{A}}{S_\mathrm{i}} \times S_\mathrm{r}, \tag{2}$$

where S_i is the TOA flux of incoming solar radiation, and $[\ ]^\mathrm{A}$ and $(\ )^\mathrm{A}$ indicate the annual normalization and annual averaging, respectively.

The annual variation of the TOA flux of reflected solar radiation (S_r) is attributable not only to the annual variation in the state of the atmosphere-surface system but also to that of the incoming solar radiation (S_i). To extract the contribution to the annual variation from the former without the latter, it is necessary to annually normalize the reflected flux of solar radiation as indicated by Eq. 2, removing the direct contribution from the annual variation of the incoming solar radiation. (One should note here that the seasonal variation of the sun's zenith angle affects not only the incoming flux of solar radiation at the top of the atmosphere but also the albedos of the earth's surface and cloud cover. In addition to removing the former effect as we did, it is desirable to remove the latter effect. We did not do so because of the difficulty involved.)

The TOA flux of outgoing longwave radiation $\bar{L}$ may be subdivided into two components as follows:

$$\bar{L} = \varepsilon\sigma\bar{T}_\mathrm{S}^4 + L^\mathrm{FB}, \tag{3}$$

where the first term represents the black body emission of the planet, and the second term (L^FB) denotes the contribution from feedback. ε is the coefficient of planetary emission and is chosen such that the first term on the right hand side of the Eq. 3 is equal to the TOA flux of outgoing longwave radiation, given the realistic distribution of temperature in the atmosphere.

The feedback parameter (λ) may be subdivided as follows (see Eqs. 1 and 3)

$$\lambda = \lambda_\mathrm{L} + \lambda_\mathrm{S}. \tag{4}$$

where,

$$\lambda_\mathrm{L} = 4\varepsilon\sigma\bar{T}_\mathrm{S}^3 + \frac{\mathrm{d}L^\mathrm{FB}}{\mathrm{d}\bar{T}_\mathrm{S}} \tag{5}$$

$$\lambda_\mathrm{S} = \frac{\mathrm{d}\overline{[S_\mathrm{r}]^\mathrm{A}}}{\mathrm{d}\overline{T_\mathrm{S}}} \tag{6}$$

Following Hansen et al. (1984), the feedback parameter may be related to the gain factor (*f*) that represents the influence of feedback upon the radiative damping of global mean surface temperature anomaly.

$$\lambda = \lambda_0(1 - f), \tag{7}$$

where

$$\lambda_0 = 4\varepsilon\sigma\overline{T}_\mathrm{S}^3 \tag{8}$$

As noted above, the feedback parameter (λ) is inversely proportional to the equilibrium response of the global mean surface temperature to a radiative forcing (i.e., the sensitivity of climate). Based upon Eq. 7, feedback is positive and enhances the sensitivity of climate, if gain factor (*f*) is positive. On the other hand, it is negative, if gain factor is negative.

Referring to Eqs. 4, 5, 6 and 7, the gain factor may be subdivided into longwave and solar gain factors (i.e., f_L and f_S) as follows

$$f = f_\mathrm{L} + f_\mathrm{S}, \tag{9}$$

where

$$f_\mathrm{L} = -\frac{1}{\lambda_0}\frac{\mathrm{d}L^\mathrm{FB}}{\mathrm{d}\overline{T_\mathrm{S}},} \tag{10}$$

$$f_\mathrm{S} = -\frac{1}{\lambda_0}\frac{\mathrm{d}[S_\mathrm{r}]^\mathrm{A}}{\mathrm{d}\overline{T_\mathrm{S}},} \tag{11}$$

To represent the contribution from individual feedback, the gain factor (*f*) may be subdivided further as follows.

$$f = f_\mathrm{LR} + f_\mathrm{WV} + f_\mathrm{a} + f_\mathrm{C}, \tag{12}$$

where f_LR, f_WV, f_a, and f_C represents the contribution from the lapse rate-, water vapor-, albedo-, and cloud-feedback, respectively. The longwave and solar components of cloud gain factors may be represented by the derivatives of longwave and solar cloud forcings (Charlock and Ramanathan 1985) with respect to the global mean surface temperature, respectively (Tsushima and Manabe 2001).

3 Data and analysis

The monthly mean, TOA fluxes of solar and longwave radiation are computed for each month of the year at each grid point, using the data obtained from the ERBE (Barkstrom 1984) mounted on ERB and NOAA satellite over the period from February 1985 to February 1990. The monthly mean global mean surface temperature is computed for each month of the year based upon the reanalysis of past daily weather data (Kalnay 1996) over the period from January 1982 to December 1994. The reanalysis was recently conducted jointly by the National Center for Environmental Prediction and National Center for Atmospheric Research.

Using the Eqs. 6 and 11, λ_S and f_S are computed from the slope of the regression between annually normalized, global mean reflected solar radiation and the global mean surface temperature. Using the Eqs. 5 and 10, λ_L

and f_L are computed from the slope of the regression between the globally averaged, outgoing flux of terrestrial radiation and the global mean surface temperature.

To compute the annually normalized, reflected solar radiation from Eq. 2, it is necessary to know the planetary albedo (reflectivity of solar radiation at the TOA) throughout the year. Obviously, it is impossible to determine the planetary albedo during a polar night in high latitudes. In the present study, we assumed that planetary albedo remains unchanged during a polar night after it reaches the peak value in the fall.

4 Observed feedback

Using the data from the ERBE, the globally averaged monthly mean flux of outgoing terrestrial radiation is computed for all 12 months of the year, and is plotted against the global mean surface temperature in Fig. 1a. This figure shows that, over the global scale, the outgoing radiation at the TOA increases with increase in surface temperature. The slope (with its standard error) of the regression line through the plots is 2.1 ± 0.17 W m^{-2} K^{-1}, and this is substantially less than the slope for the blackbody radiation, which is 3.3 W m^{-2} K^{-1}. Given this slope, one can compute the longwave gain factor (f_L) (with its standard error) as 0.38 ± 0.05. This result implies that the atmosphere affects outgoing terrestrial radiation in such a way that it enhances the annual variation of global mean surface temperature.

Globally averaged monthly mean fluxes of annually normalized, reflected solar radiation $[S_r]^A$ are computed from the ERBE data for 12 months of the year and are plotted in Fig. 1b against the monthly mean, global mean surface temperature. This figure shows that annually normalized, reflected solar radiation decreases with increasing global mean surface temperature. This result implies that reflection of solar radiation also acts in such a way that it enhances the annual variation of global mean surface temperature. It is likely that this positive feedback effect is attributable to the albedo feedback effect of snow and sea ice, which reflects a large fraction of solar radiation. The slope (with standard error) of the regression line through the plotted points in Fig. 1b is -1.07 ± 0.07 W m^{-2} K^{-1}, implying that the solar gain factor (f_S) is 0.32 ± 0.02 (see Eq. 11).

In Fig. 1c, the monthly mean value of total outgoing radiation $\bar{L} + \overline{[S_r]^A}$ is globally averaged, and is plotted against global mean surface temperature. The slope of a regression line through the plotted points is 0.98 ± 0.20 W m^{-2} K^{-1}, yielding the total gain factor (f) of 0.7 ± 0.06. Summing up the solar and longwave gain factors obtained, one also gets a total gain factor of 0.7.

The result presented here indicates that both solar and longwave feedbacks act in such a way as to enhance the annual variation of the global mean surface temperature. Thus, the combined solar and longwave damping of the annual variation of the global mean surface temperature anomaly is only 30% of the damping by blackbody radiation.

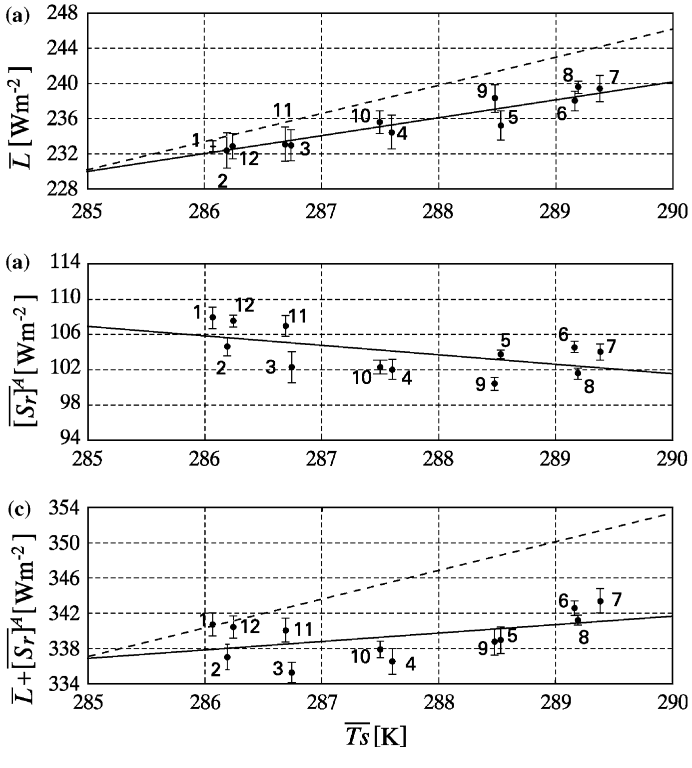

Fig. 1 For each month, the globally averaged monthly mean values of **a** outgoing flux of longwave radiation ($\bar{L}$), **b** annually normalized, outgoing flux of reflected solar radiation $\left(\bar{L} + \overline{[S_r]^A}\right)$ are plotted against the global mean surface temperature $\bar{T}_S$. *A number near each dot* is the month for which the plotting is made. The slopes of the regression lines in **a**, **b** and **c** are 2.05, −1.07 and 0.98, respectively. *Error bar* indicates the standard error of the interannual variation of the radiative flux. *Dashed line* in **a** and **c** indicates the slope of the blackbody radiation

5 Simulated feedback

In the preceding study on the cloud feedback (Tsushima and Manabe 2001), we used the data from the three models among many general circulation models of the atmosphere submitted to the Atmospheric Model Intercomparison Project (AMIP)-I (Gates 1992). They are CCSR 5.4.02 of the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES), MPI-ECHAM 3 of the Max Planck Institute for Meteorology (MPI), and HAD-AM 1 of the United Kingdom Meteorological Office (UKMO). These models are chosen for the cloud feedback study because they explicitly predict the microphysical properties of cloud. The outputs from the time integration of these three models (with prescribed, seasonally varying sea surface temperature) are used again in the present study. It is not our intension to conduct here the comprehensive analysis of the overall feedback obtained from many models submitted to AMIP. Instead, we want to investigate the contribution of the cloud feedback (the subject of the preceding study) to the overall feedback, which is the subject of the present study. For further details of these models, see http://www.pcmdi.llnl.gov/AMIP1/amip1.html.

Using a bar diagram, Fig. 2a illustrates the gain factors, which are obtained from both GCMs and ERBE observation. It shows that the gain factors of overall feedback effect (*f*) from the three GCMs are approximately similar to the value from ERBE observation. However, when the gain factor is subdivided into solar and terrestrial components (i.e., f_S and f_L), the results are quite different from the observation. While solar and terrestrial gain factors obtained from the ERBE observations are similar to each other, the solar gain factors of all three models are smaller than the terrestrial gain factors. In the MPI model, for example, the solar gain factor is −0.08, quite different from the terrestrial gain factor, which is 0.66.

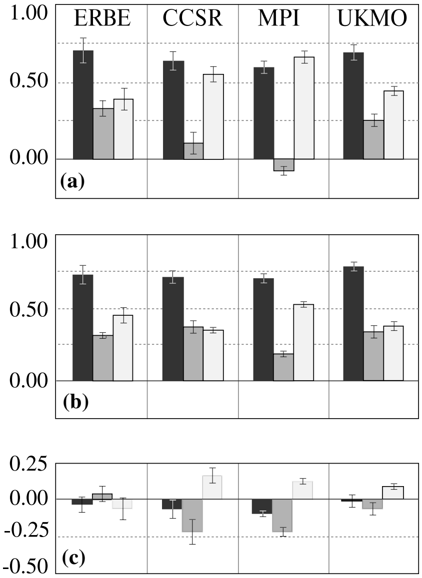

Fig. 2 Gain factors from the ERBE observation and the three models. **a** The gain factor of the overall feedback, and its solar and longwave components. **b** The gain factor of the overall feedback minus the cloud feedback, and its solar and terrestrial components. **c** Gain factor of the cloud feedback. *Black*, *dark grey*, and *light grey bars* indicate gain factors for total radiation, solar radiation, and terrestrial radiation, respectively. The line segments attached to these bars indicate the standard error of gain factors. They are converted from the standard errors of the slope of regression between radiative flux (at the top of the atmosphere) and the global mean surface temperature, referring to Eqs. 9, 10, and 11

Tsushima and Manabe (2001) computed the cloud gain factors from the regression slopes between cloud radiative forcing and surface temperature over the domain between 60°N and 60°S . In the present study, we have repeated this computation, extending the domain to the entire globe. The result from the new analysis is illustrated in Fig. 2c. Despite the expansion of the analysis domain, the cloud gain factors computed from the ERBE data remain small, and are hardly different in the two studies. On the other hand, the solar and longwave gain factors of cloud feedback obtained from the models are not necessarily small and they are significantly different between the two studies. Although the magnitudes of the cloud gain factors are different between the different models, solar and longwave gain factors tend to compensate each other in all three models (Fig. 2c). The large inter-model difference in the seasonal variation of solar and longwave components of cloud radiative forcing was noted earlier in the analysis conduced by Cess et al. (1997).

Subtracting the gain factors of the cloud feedback from the gain factor of the overall feedback effect, we computed, for the three models and the ERBE observations, the gain factors of the feedback without the cloud feedback effect, and illustrated them in Fig. 2b. This figure indicates that the differences in solar and terrestrial gain factors among the three models are reduced substantially in agreement with the ERBE observations, when the contribution of the cloud feedback effect is excluded. In other words, the cloud feedback appears to be mainly responsible for the unrealistically large differences between the solar and terrestrial gain factors obtained from the three models. In short, solar and terrestrial gain factors obtained from the models are similar and realistic without the cloud feedback. Obviously, this does not necessarily imply that the solar and terrestrial gain factors of an individual feedback other than the cloud feedback are realistic. To confirm that they are, it is necessary to confirm that the solar and terrestrial gain factors of each simulated feedback are realistic, when they are compared with observation.

In all atmospheric models submitted to AMIP-I, an identical distribution of sea ice was prescribed, although the assigned value of albedo may differ from one model to another. Obviously, the solar gain factor obtained here is essentially determined by the prescription of sea ice. Our analysis of the simulated solar feedback would have been more meaningful if it is applied to a coupled ocean–atmosphere model, in which sea ice as well as snow cover are predicted rather than prescribed.

6 Summary and concluding remarks

Using the TOA radiative fluxes obtained from ERBE, we have estimated the gain factor of the overall feedback as it affects the radiative damping of the seasonally varying anomaly of the global mean surface temperature. We have found that the feedback as a whole is positive, and weakens the radiative damping of the annually varying anomaly of the global mean surface temperature. Our feedback analysis indicates that the gain factor for the annual variation is 0.7. This implies that the overall feedback is positive, weakening the radiative damping of the annual variation of global surface temperature by as much as 70%.

The gain factor ($f = 0.7$) may be subdivided into longwave and solar components, i.e., f_L and f_S, which are 0.38 and 0.32, respectively. This result implies that both components have positive feedback effect, acting to reduce markedly the radiative damping of the annually varying anomaly of the global mean surface temperature.

Inamdar and Ramanathan (1998) analyzed the annual variation of the TOA flux of clear sky longwave radiation obtained from ERBE. They computed, for the clear sky, the slope of the regression line between the global mean flux of outgoing longwave radiation and global surface temperature. If one computes the gain factor of the water vapor feedback from the result they obtained, one can get the value that is close to 0.4. Reviewing the results from the global warming experiments conducted by various modeling groups, Held and Soden (2000) found that the gain factor of simulated water vapor feedback is about 0.4, and is similar to the gain factor, which is obtained by Inamdar and Ramanathan for the annual variation. One could note here that the terrestrial component of gain factor obtained here is 0.38 and is not very different from 0.4 for the clear sky. This suggests that a major fraction of longwave component of feedback is attributable to the water vapor feedback.

Our analysis indicates that the solar gain factor (f_S) is 0.32, which is smaller but is comparable in magnitude to the longwave gain factor (f_L). Preliminary analysis reveals that this positive feedback effect is attributable in no small part to the albedo feedback effect involving snow and sea ice, which reflects a large fraction of incoming solar radiation. In addition to the albedo feedback, a component of the water vapor feedback involving solar radiation may have a small but significant positive feedback effect (Wetherald and Manabe 1988), slightly enlarging the solar gain factor. Further study is required to confirm the statements made above.

It is likely that the solar gain factor of the feedback for the annual variation differs substantially from the gain factor for the global warming. This is because the annual variation of surface temperature is practically zero in low latitudes, and is much smaller than the annual variation in high latitudes, where the albedo feedback involving snow and sea ice operates. On the other hand, the increase in surface temperature obtained from a global warming experiment has a significant magnitude in low latitudes, though it is smaller than the increase in high northern latitudes. We therefore believe that the change in reflected solar radiation per unit change of the global mean surface temperature is larger by a factor of 2 for the annual variation than for global warming. This implies that the gain factor of the annual variation may be twice as large as that of global warming.

Given that the radiative forcing of the CO_2-doubling is 4 W m^{-2} (e.g., Hansen et al. 1997) the equilibrium response of the global mean surface temperature to the doubling would be about 1.2°C in the absence of feedback. If one assumes that the gain factor of the annual variation obtained here (i.e., $f = 0.7$) were applicable to global warming, the equilibrium response to CO_2-doubling in the presence of feedback would be 4.0°C, which is about 3.3 ($= 1/(1-f) = 1/(1-0.7)$) times as large as 1.2°C, (i.e., the equilibrium response in the absence of feedback). Since the gain factor of the albedo feedback for the annual variation is lager than that of global warming as we discussed above, the equilibrium response of the global mean surface temperature to CO_2-doubling may be less than 4.0°C ($= 1.2°C/(1-0.7)$). Assuming that the gain factor of albedo feedback for global warming is about 0.1, and is half of the gain factor of the annual variation, the gain factor of overall feedback would be reduced by ~0.1, and would be 0.6 for global warming. Using this value, our best guess value of the equilibrium response (to CO_2-doubling) turns out to be ~3°C ($= 1.2°C/(1-0.6)$), and is near the middle of the climate sensitivity range of 1.5°C~4.5°C as estimated by IPCC.

We have applied the same feedback analysis to the annual variation obtained from the three general circulation models (submitted to AMIP-I), in which the microphysical properties of cloud is computed explicitly. Although the gain factors of overall feedback in these models happen to be approximately similar to the gain factor, which is determined using ERBE, the longwave and solar gain factors obtained from these models are quite different from the observed. Since the difference almost disappears if the contribution from the cloud feedback is removed, we believe that a major fraction of the discrepancy is attributable to the failure of the models to satisfactorily simulate the individual contributions from the longwave and solar components of the cloud feedback (Tsushima and Manabe 2001). The result presented here is consistent with the previous works of Raval and Ramanathan (1989) and Cess et al. (1990). They noticed that models simulate reasonably well the radiative damping of surface temperature anomalies over clear sky, while they do not over whole sky. Therefore, it is not certain that the gain factor of cloud feedback is small in other GCMs due to the cancellation between its solar and terrestrial components. Even though the overall feedback is realistic, the individual components of relevant feedbacks are not necessarily realistic as we have shown already. To evaluate satisfactorily the feedback of a model, it is therefore desirable to compute not only the gain factor of the overall feedback but also those of individual components of relevant feedbacks that operate on the annual variation, and compare them with observation.

Although the gain factors of the overall feedback may be significantly different between the annual variation and global warming, it is likely that they are positively correlated to each other, because the physical mechanisms that controls the relevant feedback processes are similar. One can therefore compute the gain factors of the overall feedback for the annual variation, compare it with the simulated gain factor, and estimate the bias of the overall feedback in climate models used for the projection of global warming.

For example, one can conduct regression analysis between the gain factor of global warming and that of the annual variation obtained from many climate models submitted to Intergovernmental panel on climate change. On the regression line through the scatter plots, each of which represents a set of the two gain factors, one can seek the most likely value of gain factor for global warming, which corresponds to the gain factor of the annual variation obtained from ERBE.

The gain factor of the overall feedback may be subdivided into individual components as indicated by the Eq. 12 in Sect. 2. It is very desirable to conduct similar regression analysis for water vapor feedback, albedo feedback, and the cloud feedback using the TOA fluxes of clear and whole skies obtained from ERBE.

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