POTENTIAL LOW-CLOUD OPTICAL THICKNESS FEEDBACKS ON CLIMATE WARMING

George Tselioudis

Columbia University and NASA Goddard Institute for Space Studies, New York, N. Y.

Andrew A. Lacis, David Rind and William B. Rossow

NASA Goddard Institute for Space Studies, New York, N. Y.

Changes in the optical properties of low clouds can produce strong feedbacks in the event of a warming of the climate[1,2]. However, the sign and magnitude of those feedbacks are uncertain, as the observational evidence for large scale cloud optical property variations has been very limited. A recent analysis of satellite data[3] found a relationship between low-cloud optical thickness and cloud temperature that suggests a positive cloud feedback in climate. In this study, we assess the significance of such a feedback in a 2xCO_2 experiment using a simplified version of this relationship in a two-dimensional radiative-convective model. The inferred feedback depends on season, latitude and on cloud location over land and ocean. Zonally averaged, the feedback is positive in the Northern Hemisphere, and is stronger in lower than in higher latitudes. The positive feedback amplifies the overall global climate sensitivity, while the latitudinal gradient in the strength of the feedback acts to eliminate the model's high-latitude amplification of the greenhouse warming.

Cloud radiative impacts on climate are determined by the relative strengths of opposing effects; the solar albedo (cooling effect) and the thermal greenhouse (warming effect). Averaged over an annual cycle and the whole globe, clouds produce a net cooling effect due to the predominance of their solar albedo effect over their thermal greenhouse contributions[4-6]. However, the key question of how clouds will actually change as the climate warms due to trace gas emissions is complex and remains largely unanswered.

Whether cloud changes will produce a positive or negative feedback depends on the detailed changes of cloud radiative properties, mainly cloud cover, cloud height and cloud optical thickness. In a doubled CO_2 experiment with the GISS GCM[7], clouds were found to produce a positive feedback due primarily to a decrease in cloud cover (mostly low clouds) and an increase in cloud height (low clouds replaced by cirrus). Cloud optical thickness was prescribed in the experiment to depend on cloud height and vertical extent. Therefore, no direct cloud optical thickness feedback was allowed to operate.

Cloud optical property feedbacks are difficult to determine, partly because the influences of dynamic and microphysical processes on cloud water content are not fully understood, and also because large scale measurements of cloud optical thickness have not been available. A cloud water content-temperature relationship derived from limited midlatitude continental observations and applied to a one-dimensional model[8], has suggested a negative cloud optical thickness feedback on climate warming. On the other hand, GCM studies with schemes to predict cloud optical properties[9-11], obtained strong cloud optical thickness feedbacks that changed in both magnitude and sign when different parameterizations of cloud processes were employed.

Global observations of cloud optical thickness have recently become available in the International Satellite Cloud Climatology Project (ISCCP) dataset[12], which contains detailed information on the global distribution of cloud radiative properties and their diurnal and seasonal variations, as well as correlative information on the vertical distribution of temperature and humidity in the troposphere. An analysis of one year of ISCCP data[3] shows that changes in the optical thickness of Northern Hemisphere low clouds are correlated with changes in the mean cloud temperature on different time and space scales. A parameter f, defined as the normalized change of cloud optical thickness with cloud temperature,

$$f = \frac{1}{\tau}\frac{d\tau}{dT} \qquad [1],$$

was used to describe this optical thickness-temperature relation.

The latitudinal and seasonal variations of this relation are shown in Figure 1, where the f-parameter for low clouds between 15 and 55N is plotted for the four seasons separately over land (Fig 1a) and ocean (Fig. 1b). (Tropical clouds are excluded from the analysis because the yearly temperature variation in the tropics is too small to obtain meaningful statistics; polar clouds are excluded because of the large uncertainties in the retrieval of cloud optical thickness over ice/snow covered areas.) It can be seen that, for winter continental clouds , optical thickness increases with temperature, as the f-parameter is positive with an average value of about 0.045. This value is consistent with the temperature variation of the adiabatic cloud water content[13] and with the observations discussed by (8). For warmer continental and almost all maritime clouds, however, cloud optical thickness decreases with temperature with an average value for f between -0.04 and -0.05. The only notable exception is subtropical maritime clouds in the fall season.

The latitudinal and seasonal variations of the f-parameter (Fig. 1) show an overall pattern of increasing optical thickness with temperature in colder cloud ensembles and decreasing optical thickness with temperature in warmer cloud ensembles. Additional analysis of the ISCCP data[3] showed that this characteristic pattern remains consistent when clouds at the same latitude and season, sorted into cold and warm ensembles by the day-to-day variations of the temperature field, are examined. Furthermore, the optical thickness-temperature relation is not significantly different in large scale dynamical regimes defined by different large scale vertical velocities[14], although the mean optical thickness does appear to be systematically different. This basic consistency in the shape of the f-parameter vs. temperature curves points towards changes in temperature-dependent cloud process(es) as the primary explanation for the relation. Tselioudis et al.[3] suggest, but do not establish, that the main reason for the transition to negative f-parameter values at warm temperatures is an increase with temperature of the efficiency of precipitation relative to condensation. However, the exception of the subtropical fall maritime clouds implies that dynamical processes may also play an important role.

Figure 2a shows the annual mean f-parameter in the 15N to 55N latitude range for low clouds over land, ocean, and for the zonal mean cloud field. (Annual mean f-parameter values represent averages over the seasons weighted by the cloud amount and the solar insolation in each season.) The zonal/annual mean f-parameter is negative everywhere, with high latitude values around -0.02 and low latitude values around -0.045. The curves for continental and maritime clouds are quite similar at the lower (warmer) latitudes of the range but differ at the higher (colder) latitudes, where the maritime f-parameter values are significantly more positive than the continental ones. This difference is due to the low f-parameter values observed in summer clouds over land (Fig. 1a). The averaging over all seasons smoothes the 'anomalous' behavior of fall subtropical clouds over ocean and, more importantly, hides the seasonal differences observed in midlatitude clouds over land. It is important to keep in mind, then, that the latitudinal gradient in the annual mean f-parameter curve over land is mostly due to the high f-parameter values of wintertime clouds.

The annual mean curves shown in Figure 2a suggest a possible cloud optical thickness feedback that varies with latitude and that, at the higher latitudes of the range, can also vary with location of the clouds over land or ocean. The analysis that follows is meant to illustrate the significance of the latitudinal and longitudinal variations of the potential feedback by assessing the annual mean surface temperature response to changes in the annual mean low cloud optical thickness.

We use a two dimensional radiative/convective dynamic equilibrium model, with nine levels in the vertical and 24 latitude intervals from pole to pole. The meridional transports of sensible heat, latent heat, and geopotential energy are specified from the control run of the 8°x10° version of the GISS GCM[15]. Latitude dependent annual average profiles of atmospheric gases and aerosols and the model's surface properties are also taken from the GISS GCM control run, but the annual mean cloud cover, optical thickness, and vertical distribution at each latitude are taken directly from the ISCCP dataset[12].

The method used to perform the feedback analysis is adapted from Hansen et al.[7]. The 2-D model is first run to equilibrium to establish the reference surface temperatures. The optical thicknesses of all low clouds are then reduced by 50%, and the model is again run to equilibrium with no other structural or feedback changes allowed to operate. The resulting change in equilibrium surface temperature (ΔT_f) can then be calibrated for specified changes in low cloud optical thickness. For this 50% reduction in low cloud optical thickness, the equilibrium surface temperature increases by amounts that vary from 1.5K in the tropics to 2K in the midlatitudes.

The f-parameter values at each latitude, derived from the observed cloud changes (Fig. 2a), are then used to calculate the temperature change that would be needed to produce a 50% decrease in low-cloud optical thickness (ΔT_t). For a 50% decrease in τ, [1] gives

$$\Delta T_t = -\frac{\ln 2}{f} \qquad [2],$$

The ratio of the temperature change ΔT_f resulting from the cloud optical thickness decrease to the temperature change ΔT_t needed to produce that same decrease determines the feedback efficiency G:

$$G = \frac{\Delta T_f}{\Delta T_t} \qquad [3].$$

Knowing the feedback efficiency for low-cloud optical thickness changes at each latitude, we evaluate the net effect of this feedback in a climate change scenario. If ΔT_0 is the surface temperature change needed to restore radiative equilibrium in a $2xCO_2$ simulation when no feedbacks occur, then the equilibrium temperature change if all feedbacks are included would be:

$$\Delta T_{eq} = \frac{\Delta T_o}{1-(G+g)} \qquad [4],$$

where G is the feedback efficiency for low-cloud optical thickness changes and g is the sum of the feedback efficiencies for all other feedback processes operating in the GISS GCM $2xCO_2$ experiment[7] (The sum of the feedback efficiencies includes contributions from changes in water vapor amount and distribution, the atmospheric lapse rate, the ground albedo, and the cloud height and cloud cover). Knowing g and ΔT_o from the GISS GCM $2xCO_2$ experiment, we then calculate an estimate for the new equilibrium temperature ΔT_{eq} that would be obtained with the low-cloud optical thickness feedback also included.

The feedback analysis is done separately for continental and maritime clouds, as well as for the zonal mean cloud field. In other words, the equilibrium temperature change is calculated for an ocean-covered planet, a land-covered planet, and a planet with the actual continental/maritime low cloud ratio of the earth. Figure 2b shows the change in surface temperature from the $2xCO_2$ simulation of the GISS GCM with no direct cloud optical property feedbacks included and the estimated change in surface temperature with the low-cloud optical thickness feedback included for the three cases mentioned above. For the zonal mean cloud field, the additional cloud feedback is positive, increasing the greenhouse warming at all latitudes by amounts that vary from 1.5C in the tropics to 0.5C in the midlatitudes. This latitudinal variation in the values of the optical thickness feedback efficiency reduces the high-latitude amplification of the predicted warming. The 'continental' and 'maritime' temperature changes are relatively similar at lower latitudes, with continental clouds producing larger increases than maritime ones. At higher latitudes, however, a significant difference occurs. Maritime clouds produce smaller temperature increases and even a small decrease at 52°N, resulting in a reduction of the greenhouse warming at that latitude. Continental clouds, on the other hand, produce a significant temperature increase that reaches 1.8K at the highest latitude of the range.

The results presented in this study provide a new and complex perspective on the question of cloud optical property feedbacks in climate. The large difference in the high latitude warming between the continental and maritime cloud cases (Fig. 2b) suggests that the proposed cloud feedback may introduce longitudinal temperature contrasts. Furthermore, the large high latitude warming in the continental cloud case (Fig. 2b), which is due to the very low summertime f-parameter values (Fig. 1a), implies that the latitudinal structure of the greenhouse warming can vary significantly with season. Both issues must be examined further through the use of fully interactive 3-dimensional GCMs. When the annual mean optical thickness-temperature relation (weighted by seasonal cloud amount and solar insolation) is used in a 2-D model, it produces a positive climate feedback everywhere, but one that is stronger at low rather than at high latitudes. This acts to reduce, or even to eliminate, the high-latitude amplification characteristic of model simulations of the greenhouse warming. Such a reduction, since it affects the equator to pole temperature gradient, could also affect changes in the strength of the atmospheric circulation in a $2xCO_2$ scenario, which would feed back on water vapor, oceanic changes and the cloud field itself. The differences between 'continental' and 'maritime' cloud regimes imply the potential for longitudinal gradients in the magnitude of the greenhouse warming which could alter the strength of the eddy component of the circulation.

This study illustrates the potential for an important feedback whose character may be much different from what has been previously believed. One clear implication is that a detailed knowledge of the latitudinal, seasonal, and regional variations of cloud feedback is necessary in order to determine the actual role of clouds in global climate change. Cloud feedback is manifested by a number of components, of which the change in optical thickness with temperature is one. This study shows that the cloud optical thickness feedback has a notable latitude dependence that tends to counteract the high latitude-amplification of the warming predicted by most climate models for doubled CO_2. Understanding the full impact of cloud changes on climate requires determination of the other feedback components as well.

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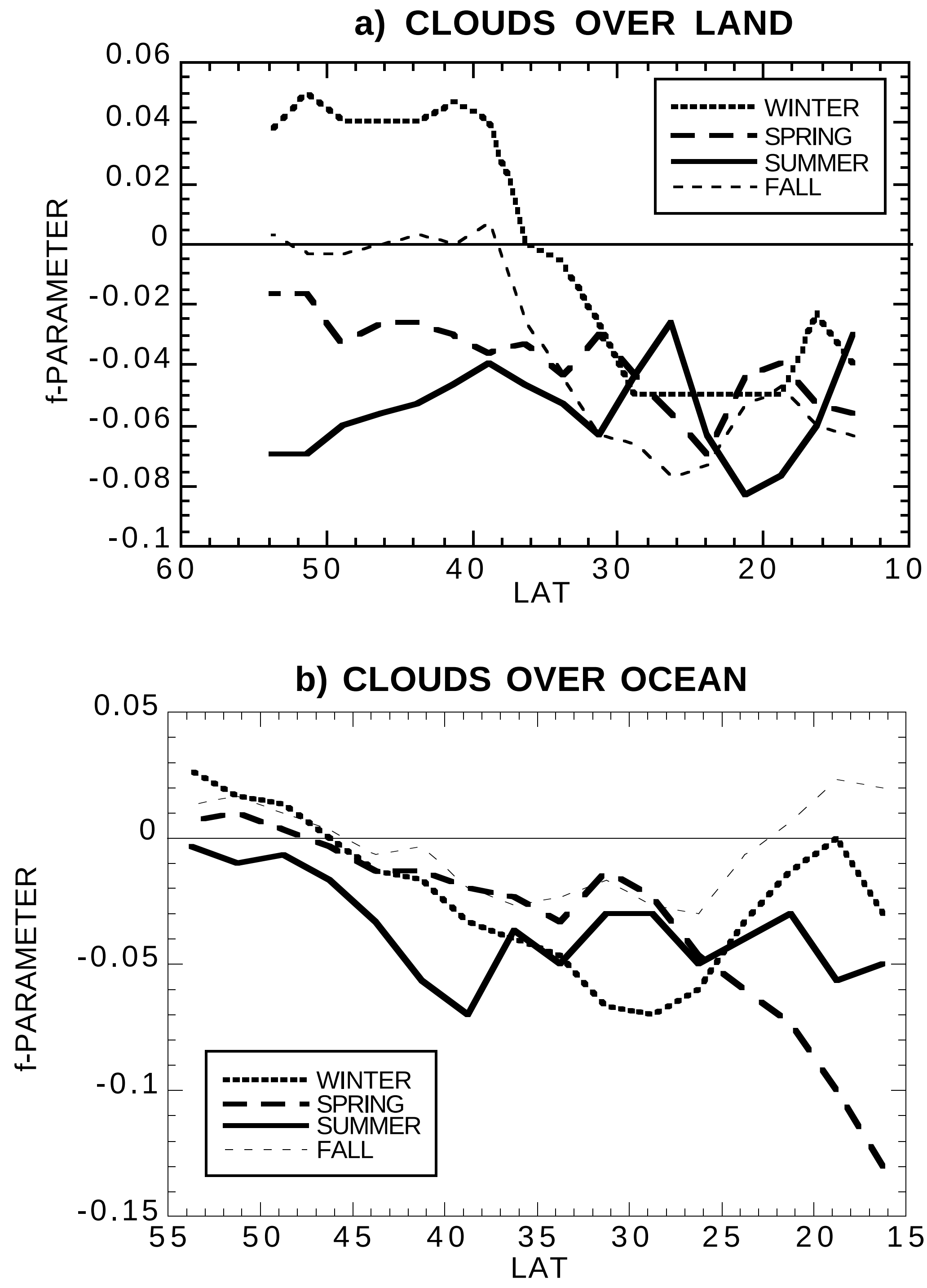
FIGURE CAPTIONS

Figure 1. Latitudinal variation of the f-parameter in the 15-55N latitude range for a) low clouds over land and b) low clouds over ocean in Northern Hemisphere winter, spring, summer and fall. The points are plotted at the ISCCP resolution of 2.5 degrees.

Figure 2. a) Latitudinal variation of the annual mean f-parameter for low clouds over land (dashed line), low clouds over ocean (dotted line) and the zonal mean low clouds (solid line) in the 15-55N latitude range. The points are plotted at the model resolution of 8 degrees.
b) Change in surface temperature from the 2xCO_2 run of the GISS GCM (thin solid line) and estimated change of the same quantity with the low cloud optical thickness feedback included, for a land-covered planet (dashed line), an ocean covered planet (dotted line) and the earth (thick solid line).


a) CLOUDS OVER LAND
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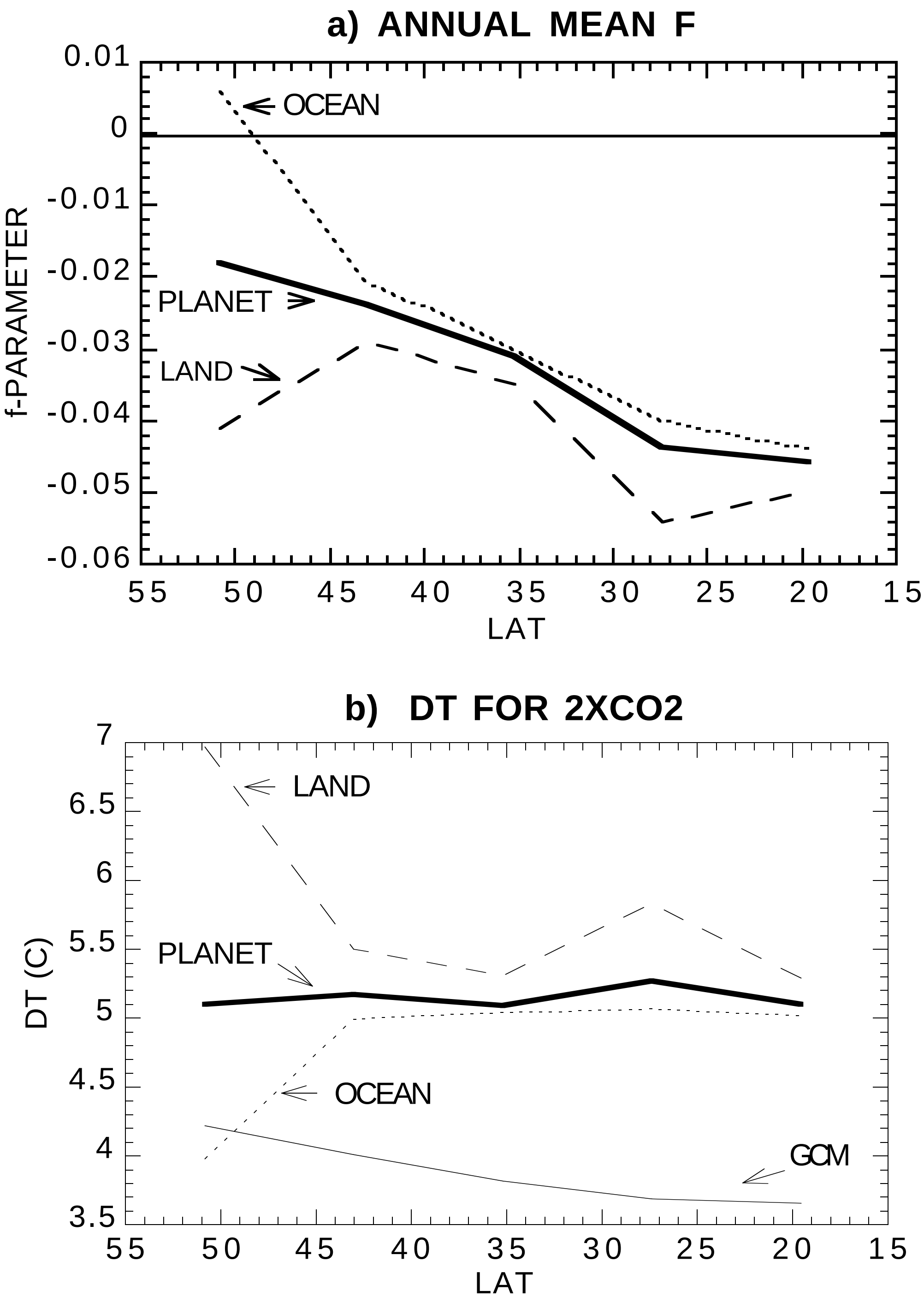
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
60
50
40
30
20
10
LAT
f-PARAMETER
WINTER
SPRING
SUMMER
FALL
b) CLOUDS OVER OCEAN
0.05
0
-0.05
-0.1
-0.15
55
50
45
40
35
30
25
20
15
LAT
f-PARAMETER
WINTER
SPRING
SUMMER
FALL

FIGURE 1


a) ANNUAL MEAN F
f-PARAMETER
0.01
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-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
OCEAN
PLANET
LAND
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50
45
40
35
30
25
20
15
LAT
b) DT FOR 2XCO2
DT (C)
7
6.5
6
5.5
5
4.5
4
3.5
LAND
PLANET
OCEAN
GCM
55
50
45
40
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LAT

FIGURE 2

Corresponding address:

Dr. George Tselioudis

NASA / GISS

2880 Broadway

New York, N.Y 10025

U.S.A

tel: (212) 678-5578

FAX: (212) 678-5552