GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 9, PAGES 1295-1298, MAY 1, 1999

Cirrus Detrainment-Temperature Feedback

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Abstract. In considering the role of cirriform clouds in climate change, it is important to distinguish among the relationships of different high cloud types to large-scale atmospheric dynamics. While cirrostratus and cirrocumulus (CsCc) have a clear relation to deep convective sources, the ensemble behavior of cirrus is more subtle. An empirical relation is found between cirrus fraction and deep cloud top temperature that points to detrainment temperature as a dominant factor governing tropical and subtropical cirrus. This cirrus-detrainment-temperature (CDT) relation provides a target for modelers, and suggests an additional cloud-climate feedback. As surface temperatures warm, detrainment temperatures cool as deep cloud top height increases. The CDT relation implies that cirrus fraction increases. Because cirrus are optically thinner than CsCc, the competition between longwave feedbacks and cloud albedo feedbacks leads to a hypothesized positive climate feedback by cirrus fraction.

1. Introduction

Interaction among clouds, radiation and atmospheric dynamics continues to be one of the most challenging aspects of climate change [*Cess et al.*, 1989]. Cirriform clouds (ice clouds) cover over 20% of the globe and have a major effect on the earth's radiation balance and climate [*Liou*, 1986]. As is well known, complications arise from the opposition of cloud albedo effects, tending to cool, and cloud-longwave radiation feedback, tending to warm the climate system [*Ramanathan et al.*, 1989; *Kiehl*, 1994]. The net radiative cloud forcing of the cirriform clouds can be either positive or negative depending on the optical thickness [*Platt*, 1981; *Stephens and Webster*, 1981]. It proves useful to distinguish among categories of cirriform clouds not only for their optical properties but because they are governed by different dynamical processes. In many studies, the term of "cirrus" is used for both thinner and thicker cirriform clouds [*Fu et al.*, 1992; *Liou*, 1986; *Ramanathan and Collins*, 1991]. "Thin cirrus" is commonly used for very thin cirriform cloud [*Woodbury and McCormick*, 1986], which not every satellite can detect. To avoid confusion, we use the term "cirriform" when discussing high layer clouds collectively. When discussing specific types of cirriform cloud, we follow the ISCCP (the International Satellite Cloud Climatology Project) terminology [*Rossow and Schiffer*, 1991]: "cirrus" denotes thinner cirriform cloud (visible optical depth between 0.1 and 3.6); CsCc denotes thicker cirriform cloud (visible optical depth between 3.6 and 23). Note that the ISCCP data does not include the "thin cirrus" since the ISCCP detection limit is equivalent to a visible optical depth of 0.1 [*Liao et al.*, 1995]. A third high cloud type (with cloud top higher than 440 mb) is deep cloud, the optically thickest cloud, which is closely associated with deep convection.

A number of cloud radiative feedbacks involving cirriform cloud have been hypothesized. Many global warming experiments in general circulation models (GCMs) show an increase of high cloud fraction near the tropopause and of the height of deep convection (e.g. Mitchell and Ingram 1992; Wetherald and Manabe 1988). In these GCMs, this is largely a change in the height of the cirrus-like clouds producing the well-known positive feedback of reduced outgoing longwave radiation by lower emission temperature. Additional feedbacks, not yet properly represented in GCMs, involve effects of changes in the ice crystal size distribution, which affects optical depth [e.g. *Stephens et al.*, 1990; *McFarquhar and Heymsfield*, 1997]. Since optical thickness is affected by both water/ice mass and crystal size, this may imply additional climate feedbacks [*Jensen et al.*, 1994; *Liou et al.*, 1991]. *Ramanathan and Collins* [1991] noted an increase in cirriform cloud associated with enhancement of deep convection in local regions of warm sea surface temperature (SST). The increases in highly reflective cirriform clouds tend to oppose surface warming by reducing incoming solar radiation. This effect involves three-dimensional large-scale dynamics which may differ from the dynamics of global scale warming [*Fu et al.*, 1992; *Pierrehumbert*, 1995; *Wallace*, 1992].

Cirriform clouds have strong connection with deep cloud, especially in the tropics. Deep cloud detrainment is a main source of moisture for the upper troposphere, and the moisture produces cirriform clouds. The interplay of large-scale atmospheric dynamics and the deep convection source can influence this cirriform clouds. Other effects of large-scale circulation include the role of upper level flow in transporting detained water mass and effects on condensation by adiabatic uplift [*Pierrehumbert and Yang*, 1993; *Pierrehumbert*, 1998].

In this study, we focus on a new aspect of the relation between cirriform clouds and their deep convective source: an empirical relation between cirrus fraction and deep cloud top temperature. This relation is very different than the relation of CsCc to deep cloud. We then examine the possible consequences of this empirical relation as a climate feedback.

Paper number 1999GL900219.
0094-8276/99/1999GL900219$05.00

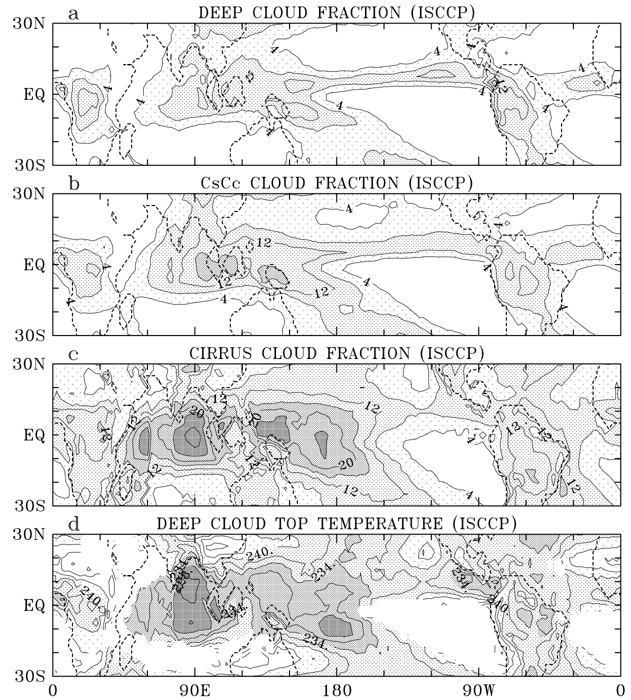

Figure 1. Cloud fraction for various high cloud types from the ISCCP C2 climatology: (a) deep cloud, (b) CsCc, (c) cirrus; and (d) deep cloud top temperature.

2. Relation of Deep Convection with CsCc and Cirrus

Figure 1 shows the climatology of the three high cloud types, along with deep cloud top temperature. In Fig. 1, a close relation may be noted between the horizontal distributions of deep cloud (Fig. 1a) and CsCc (Fig. 1b), as expected, since CsCc tends to occur as anvil cloud corresponding to the tower cloud of deep convection [*Houze*, 1989; *Machado and Rossow*, 1993]. Figure 2a shows that the association of CsCc cloud fraction with deep cloud fraction in the ISCCP C2 data follows a linear relation. *Houze* [1989] and *Slingo* [1987] note similar relations. *Machado and Rossow* [1993] point out that deep cloud top temperature (or deep cloud top height) has a systematic correlation with deep cloud fraction, and both parameters indicate strength of deep convection. However, CsCc has only a poor relation to deep cloud top temperature (Fig. 2b), with large scatter. It may be inferred that CsCc most strongly depends on the frequency of occurrence of the deep cloud detrainment source.

Cirrus has a looser relation with deep convection than CsCc, as may be noted from the differing spatial patterns in Fig. 1a and Fig. 1c. Figure 3a shows that cirrus does not have a good relation with deep cloud in terms of cloud fraction (compare to Fig. 2a). One might think that the lighter ice crystals may simply be carried further from their source. However, our trajectory calculations show that with normal wind variability in the upper troposphere, the detrained cloud ice from deep cloud is carried only a few hundred kilometers from its source within the cloud ice microphysical fallout time scale (less than a half day). Mechanisms such as adiabatic uplift on isentropic surfaces [*Pierrehumbert*, 1998] and diabatic uplift [*Jensen et al.*, 1996] might play a role in maintaining cirrus farther from the source, but these mechanisms would act in addition to a local relation apparent in Fig. 3b.

According to Fig. 3b, cirrus fraction is related to another deep cloud property, cloud top temperature. This is a relatively local relation (i.e., for 280km×280km spatial averages) between cirrus and its source that tends to hold in the tropics and subtropics. Cirrus fraction tends to increase strongly as deep cloud top temperature drops. Because the deep cloud top temperature indicates the temperature at which cirrus cloud ice is detrained, we refer to this relation between deep cloud top temperature and cirrus fraction as the CDT relation. This relationship is consistent with potential microphysical explanations: as detrainment from near cloud top occurs at colder temperatures, ice production is favored. Other possibilities include colder detrainment favoring smaller crystals where longer fallout times might enhance cloud fraction [*Chen and Lamb*, 1994; *Heymsfield and McFarquhar*, 1996; *Meyers et al.*, 1992], or effects of gravity waves associated with stronger convection [*Pfister et al.*, 1993]. Whatever the detailed processes are, the contrast between the CDT relation in Fig. 3b and the higher scatter in Fig. 3a shows that cirrus depends more strongly on how cold the deep convection detrainment source is than on how frequently deep convection happens. Deep cloud top temperature is averaged over times when deep convection is occurring, and can be cold even in regions where average deep cloud fraction (occurrence of deep cloud) is not large. This occurs especially on the margins of the convection zones (Fig. 1d). Deep convection with colder cloud top acts as effective source of cirrus even if deep cloud fraction is not large.

3. Radiative Effect of Cirrus and CsCc

Because of the different optical depth of CsCc and cirrus, their effects on the net radiation budget can be of opposite sign [*Platt*, 1981; *Stephens and Webster*, 1981]. This is mainly due to strong variation of cloud albedo through the range of cirriform cloud optical depth. We have used the Fu and Liou [*Fu and Liou*, 1993] radiation scheme to calculate the net radiative effect of cirrus and CsCc with particle size distribution described by the ISCCP. The results are consistent with the previous studies [*Platt*, 1981; *Stephens and Webster*, 1981]: a net cooling effect for CsCc and a heating effect for cirrus. *Prabhakara et al.* [1993] discuss an optically thin cirriform cloud which has a positive feedback.

Considering the relation to large-scale atmospheric dynamics, the effects of CsCc and cirrus have differing dependence on spatial scale. Deep cloud and CsCc tend to increase in regions of anomalous low-level convergence. There must necessarily be regions of compensating divergence. with reduced cloudiness, and effects of convergent and divergent regions tend to cancel in large-area averages. Cirrus does not have as strong a connection to the large-scale circulation associated with deep convection (Fig. 3a), so cloud fraction perturbations of cirrus tend not to cancel when averaged over a large domain. *Wylie et al.* [1994] indicate that the tropical average of cirrus increases while the tropical average for other high cloud types has little change during the warm phase of ENSO (El Niño/Southern Oscillation). Estimating the longwave effect averaged over the tropics for each high cloud type [*Chou and Neelin*, 1996], even though cirrus has at least the same magnitude of radiative effect as deep cloud and CsCc combined, the effect of CsCc and deep cloud has locally greater contributions than cirrus. For instance, in the central Pacific region examined by *Ramanathan and Collins* [1991], the large local increase in cirriform clouds during El Niño is substantially associated with CsCc, closely related to the change in deep convection. The behavior and possible feedbacks of cirrus clouds discussed here tend to be both radiatively and dynamically different than those of CsCc.

4. Cirrus Detrainment-Temperature Feedback

Th cirrus-detrainment-temperature relation suggests a cirrus detrainment-temperature (CDT) feedback on the global energy budget. Because the CDT relation is effectively a one-dimensional relation, the conjectured CDT feedback is relatively straightforward. For instance, in a global warming experiment, a common climate change is that deep cloud top temperature becomes lower everywhere because of the increase in height of tropopause [e.g. *Mitchell and Ingram*, 1992; *Wetherald and Manabe*, 1988]. According to the CDT relation, the decrease of deep convection detrainment temperature would produce more cirrus cloud fraction. Because of the net radiative effect of cirrus is heating, the CDT feedback is positive. This result is consistent in sign with the increase of high clouds near tropopause found in GCM simulations [*Hansen et al.*, 1984; *Mitchell and Ingram*, 1992; *Wetherald and Manabe*, 1988]. The CDT feedback hypothesized here can act simultaneously with the other cloud feedbacks reviewed in the Introduction, but emphasizes a hitherto overlooked impact of deep cloud temperature: as the height of deep cloud increases, the cirrus *fraction* increases. This feedback is the same in sign as the direct effect of lower emission temperatures with higher cloud top, but physically different since it involves a change in cloud fraction.

We underline some caveats on this conjectured feedback. Because of the scatter in the CDT relation (Fig. 3b), this feedback can only be expected to operate on a statistical average. The feedback as conjectured here makes an assumption in addition to the CDT relation, namely that cloud top temperature decreases with increased surface temperature. Finally, the CDT relation itself is empirically based, and the hypothesized causal relation of cirrus fraction to detrainment temperature is not proven. It is our hope that this empirical relation will prove an attractive target for cloud modelers. However, the increasing tendency of cirrus cloud fraction with lower detrainment source temperature is highly suggestive. It indicates that for global warming studies, it is important to distinguish between different cirriform cloud feedbacks, such as those involving mainly CsCc, and the CDT feedback. It points to the importance of including and verifying a parameterization of cirrus fraction dependence on cloud detrainment temperature in climate models.

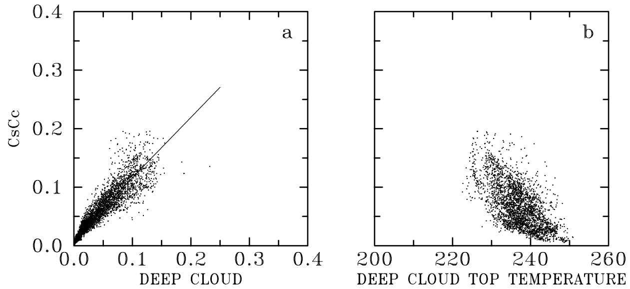

Figure 2. (a) Relation between CsCc fraction and deep cloud fraction. The thick line is the linear regression between these two cloud types. (b) Relation between CsCc cloud fraction and deep cloud top temperature. From the ISCCP climatology (July 1983 to June 1991) in the tropics (30N-30S).

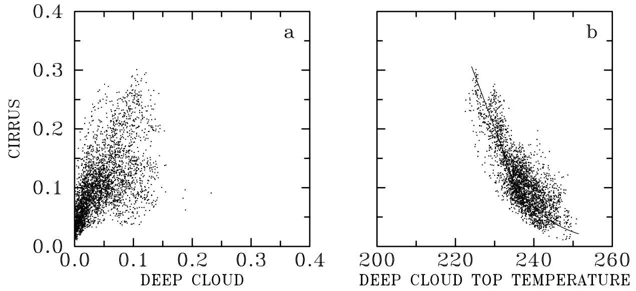

Figure 3. (a) Relation between cirrus fraction and deep cloud fraction. (b) Relation between cirrus fraction and deep cloud top temperature, suggesting the CDT relation. The curve used to fit the relation is $\alpha_{ci} = exp((213-CT_{deep})/10)$, for $CT_{deep} \geq 233^0K$ and $\alpha_{ci} = 1-0.018\times(CT_{deep}-185)$, for $CT_{deep} < 233^0K$, where α_{ci} is cirrus cloud fraction, CT_{deep} is deep cloud top temperature, and 233^0K is the microphysical transition from pure ice to coexisting ice and supercooled water [*Heymsfield,* 1993]. From the ISCCP climatology in the tropics (30N-30S).

Acknowledgments. This work was supported under NSF grant ATM-9521389 and NOAA grant NA46GP0244. Discussions with W. Collins, K. N. Liou and R. Pierrehumbert were helpful.

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(Received November 4, 1998; revised January 29, 1999; accepted March 6, 1999.)