Positive cirrus feedback on climate fluctuations

Chen Zhou, Andrew E. Dessler, Mark D. Zelinka, Ping Yang, Tao Wang

Introduction

Cirrus clouds are not only important in determining the current climate, but also play an important role in climate change and variability. Analysis of satellite observations shows that increases in the amount and altitude of cirrus clouds (optical depth<3.5, cloud top pressure<440 hPa) act as a positive feedback on short-term climate fluctuations, by reducing the planet's ability to radiate longwave radiation to space in response to planetary surface warming. The magnitude of cirrus feedback is $0.20\pm0.21 W/m^2/°C$, and is comparable to the surface albedo feedback. Most of the cirrus feedback comes from increasing cloud amount in the tropical tropopause layer (TTL) and subtropical upper troposphere.

Background

Cirrus clouds, a genus of thin, high and wispy clouds covering about 20% of the earth's surface, are among the principal cloud types controlling the Earth's radiation budget. Most cirrus clouds are thin and hard to observe, but they have a significant warming effect on our planet by absorbing outgoing longwave (LW) radiation more efficiently than they reflect incoming shortwave (SW) solar radiation.

While the warming effect of cirrus clouds in the current climate has been widely realized, the role of changing cirrus in climate change and variability remains uncertain. Cirrus clouds exert a positive feedback in most climate models [Zelinka et al., 2012], but the magnitude has a large spread among models, primarily due to large uncertainties in cirrus cloud parameterizations [Stephens et al., 1990; Liou, 2005]. This is exacerbated by a lack of observations: most satellite retrieval products do not provide reliable properties of thin cirrus clouds [Pincus et al., 2012], especially cirrus clouds that overlap middle and low clouds. As a result, the cirrus feedback remains an important source of uncertainty in our understanding of the climate system.

In this study, we analyze observations from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, which has a unique ability to identify thin cirrus clouds over middle and low clouds.

Data and Method

Dataset: CALIPSO level 2 1-km cloud layer product. We use data 2007/12-2014/02, to avoid horizontally oriented crystals.

We limit our analysis to cirrus clouds with cloud top pressure (CTP) less than 440 hPa and that are not opaque to the laser (i.e., lidar signals can be detected from below the high cloud layer, which typically requires τ<3.5). The classification criteria are consistent with the ISCCP cirrus cloud classification (CTP<440 hPa, τ<3.6).

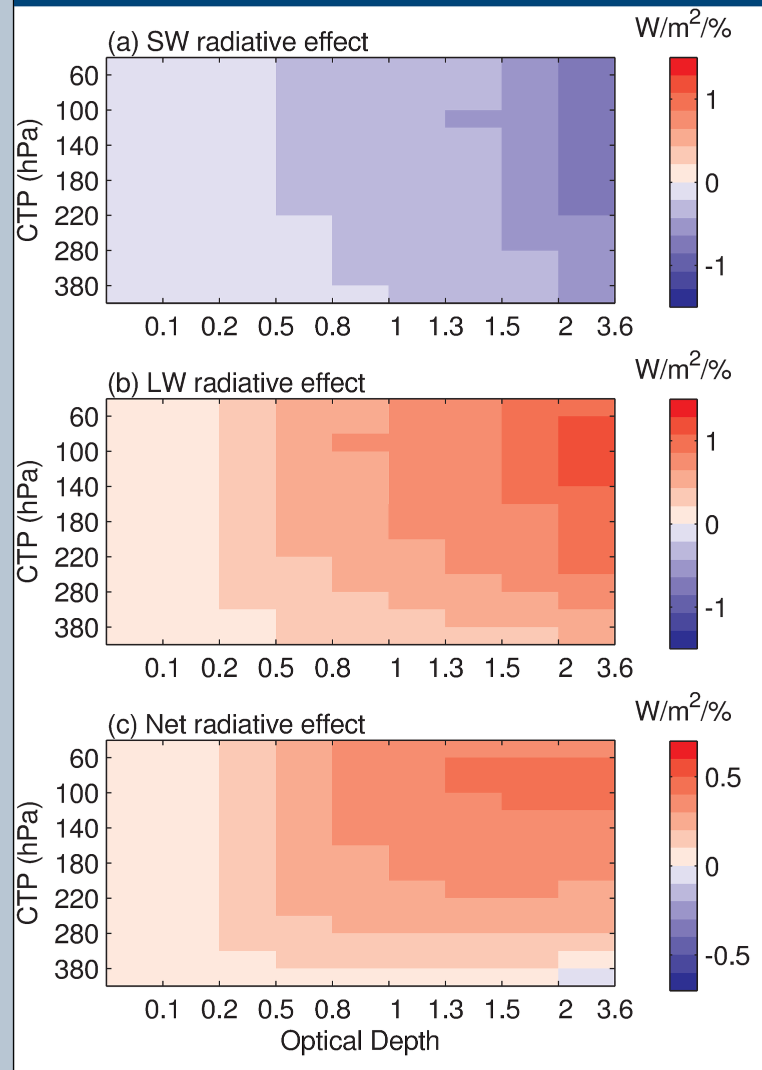
Optical depth is retrieved from: [Reverdy et al., 2012]

$$\tau = -\frac{1}{2\eta}\ln(1-2\eta S\gamma')$$

We use the latest retrieval values [Josset et al. 2012]: Lidar ratio S=33sr, multiple scattering factor η=0.61. Multiple cirrus cloud layers are combined into an effective single cloud layer, to produce CTP-τ joint histograms. Then the radiative effect of the cirrus layer is estimated with cirrus cloud radiative kernels.

The magnitude of cirrus feedback is defined as the change in global average cirrus cloud radiative effect (ΔR_{cirrus}) per unit of change in global surface temperature (ΔTs).

Cirrus cloud radiative kernels



Calculation of cirrus cloud radiative kernels:

$K=(R_c-R_{nc})/100\%$,

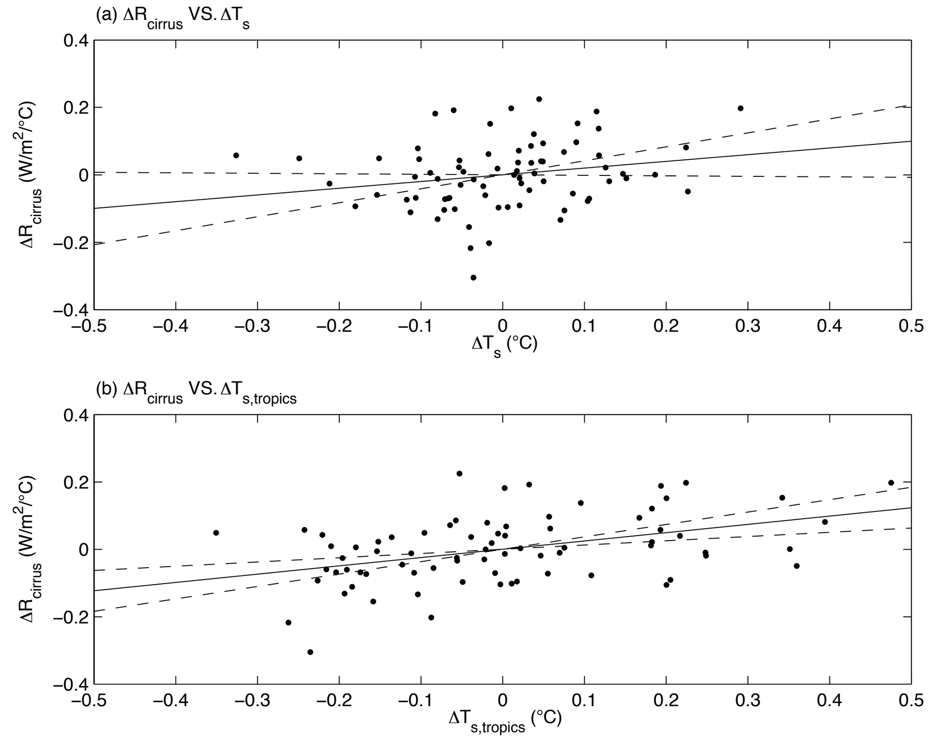
where K is cirrus cloud radiative kernel. R_c and R_{nc} are the TOA flux for scenes with 100% cirrus coverage and without any cirrus, respectively.

Calculated with Fu-Liou radiative transfer model. They are weighted average values of cirrus over clear-skies and cirrus overlapping non-cirrus clouds (i. e., low clouds and middle clouds). Cloud effective particle size is set as a function of cloud top temperature in the calculation.

Then change in global average cirrus cloud radiative effect can be estimated with the CTP-τ joint histograms:

$\Delta R_{cirrus}=\Sigma(K\Delta C)$

Cirrus cloud radiative effect and surface temperature

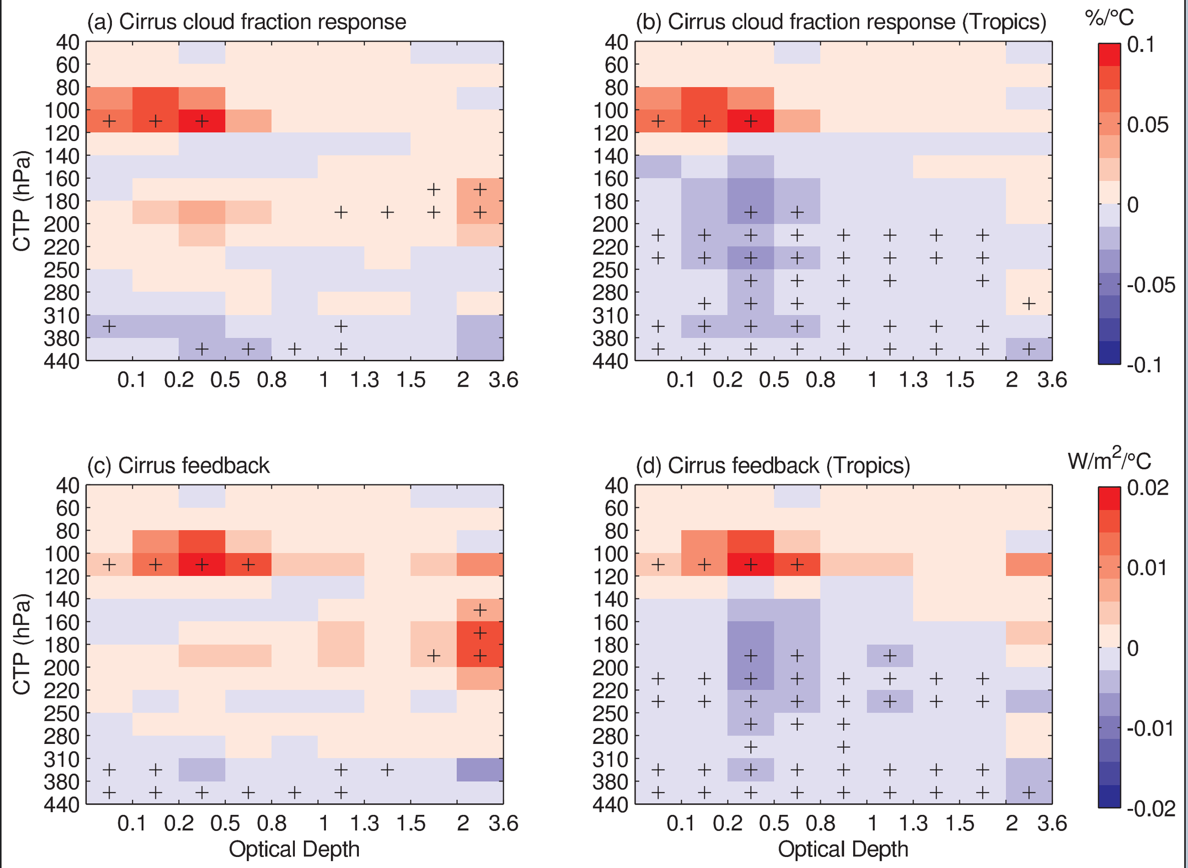


Total cirrus cloud radiative effect increases when surface temperature increases

(a) Scatter plot of monthly global average values of ΔR_{cirrus} versus global average ΔT_s. Solid line is the least squares fit, and dashed lines denote the 2σ uncertainty intervals. The regression slope is cirrus feedback.

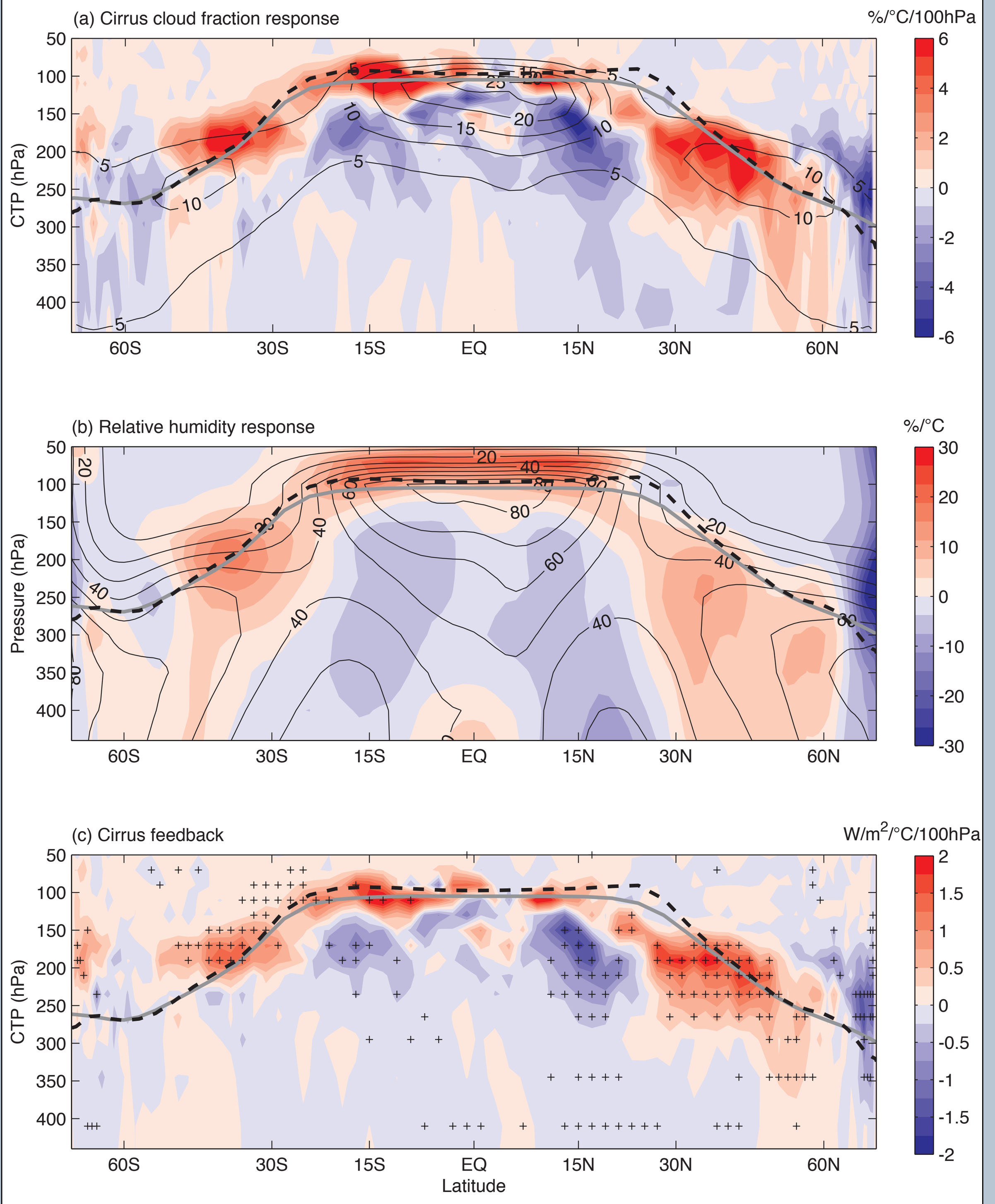
(b) Global ΔR_{cirrus} as a function of tropical (30°S-30°N) temperature anomaly ΔT_s,tropics. Variability of ΔR_{cirrus} appears to be primarily controlled by tropical surface temperature.

CTP-τ histograms of short-term cirrus feedback



Most of the cirrus feedback comes from increasing cloud amount in the tropical tropopause layer (TTL) and subtropical upper troposphere.

Zonal mean cirrus feedback



(a) Response of cirrus clouds fraction to inter-annual surface warming (shading), calculated by regressing monthly mean anomalies of cloud fraction against monthly mean anomalies of global mean surface temperature (from ERA-interim). Contours are the 6-year mean cirrus cloud fraction (in %/100hPa), the gray solid line denotes the ERA-interim climatological tropopause pressure (calculated with the WMO definition), and black dashed line is the climatological value plus the response to 1K surface warming.

(b) Response of relative humidity to inter-annual surface warming (shading), and the 6-year mean relative humidity (in %, contours).

(c) Cirrus feedback as a function of latitude and CTP. Crosses denote pixels where the linear regression slope is statistically distinguishable from zero.

Conclusions and Discussions

Analysis of CALIPSO observations shows that the cirrus cloud amount and altitude increase in response to inter-annual surface warming. Using cirrus cloud radiative kernels, we have quantified the short-term cirrus feedback to be 0.20±0.21W/m2/°C. Increases in cirrus clouds in both the tropical tropopause layer and the subtropical upper troposphere make the primary contributions to the feedback, and appear to be primarily driven by tropical surface temperature anomalies. The positive cirrus feedback represents an important component of the cloud feedback and of the response of the climate to perturbations.

If the cirrus feedback under long-term global warming has a comparable magnitude to that observed during short-term climate variations, then cirrus clouds will enhance global warming significantly. A feedback with a magnitude of $+0.20 W/m^2/K$ will increase the climate sensitivity by ~15% relative to a hypothetical climate state with fixed cirrus clouds. Note that the magnitude of cirrus feedback in response to long-term global warming may be different from the observed short-term cirrus feedback, because short-term surface warming is more concentrated on the tropical area.

Therefore, to better predict the future climate changes, it is necessary to further study the properties of cirrus clouds, and improve the cirrus parameterization in climate models.

References

Liou, K. N. (2005), Cirrus clouds and climate, in McGraw-Hill 2005 Yearbook of Science & Technology, edited by McGraw Hill, pp. 51–53, Columbus, OH.

Josset, D., J. Pelon, A. Garnier, Y.X. Hu, M. Vaughan, P.W. Zhai, R. Kuehn, and P. Lucker (2012), Cirrus optical depth and lidar ratio retrieval from combined CALIPSO-CloudSat observations using ocean surface echo, J. Geophys. Res., 117, D05207.

Pincus, R., S. Platnick, S. A. Ackerman, R. S. Hemler, and R. J. P. Hofmann (2012), Reconciling Simulated and Observed Views of Clouds: MODIS, ISCCP, and the Limits of Instrument Simulators, Journal of Climate, 25, 4699-4720.

Reverdy, M., V. Noel, H. Chepfer, and B. Legras (2012), On the origin of subvisible cirrus clouds in the tropical upper troposphere, Atmos. Chem. Phys. 12, 12081-12101.

Stephens G. L., S. Tsay, P. W. Stackhouse, and P. J. Flatau (1990), The Relevance of the Microphysical and Radiative Properties of Cirrus Clouds to Climate and Climatic Feedback, J. Atmos. Sci. 47, 1742–1754,

Zelinka, M.D., S. A. Klein, S. A., and D. L. Hartmann (2012), Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms. Part I: Cloud Radiative Kernels, J. Climate, 25, 3715–3735.

Contact information

Email: chenzhou@tamu.edu