LLNL-JRNL-661816

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Cirrus feedback on climate fluctuations

C. Zhou, A. E. Dessler, M. D. Zelinka, P. Yang, T. Wang

October 1, 2014

Geophysical Research Letters

Cirrus feedback on climate fluctuations

C. Zhou[1,2], A.E. Dessler[2], M.D. Zelinka[1], P. Yang[2], T. Wang[2]

[1] Program for Climate Model Diagnosis and Intercomparison,
Lawrence Livermore National Laboratory, Livermore, California, USA
[2] Dept. of Atmospheric Sciences
Texas A&M University
College Station, TX, USA 77843

Corresponding author: zhou8@llnl.gov

Key Points:

1. Cirrus clouds likely contribute a positive feedback on short-term climate fluctuations.
2. Cirrus cloud amount and altitude increase in response to surface warming.
3. Cirrus clouds represent an important component of the cloud feedback.

Abstract:

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 the amount and altitude of cirrus clouds (optical depth<3.5, cloud top pressure<440 hPa) increase in response to inter-annual surface warming. Thus, cirrus clouds are likely to 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. Using cirrus cloud radiative kernels, the magnitude of cirrus feedback is estimated to be $0.20\pm0.21 W/m^2/°C$, which 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.

Key words: Cirrus, Cloud feedback, Climate change and variability

1. Introduction

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 [Liou, 1986; Lynch, 1996]. 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 [Stephens et al., 1990].

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 passive satellite retrieval products may partially miss thin cirrus clouds [Pincus et al., 2012], especially if they overlap middle and low clouds.

As a result, the cirrus feedback remains an important source of uncertainty in our understanding of the climate system. To address this uncertainty, we analyze observations from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite [Winker et al., 2003], which has a unique ability to identify thin cirrus clouds over middle and low clouds. We quantify the short-term cirrus feedback as the radiative impact of changes in these thin cirrus clouds in response to inter-annual surface temperature fluctuations.

2. Data and methods

CALIPSO level-2 1-km cloud layer products between December 2007 and February 2014 are used to quantify the cirrus feedback. This period is chosen because the off-nadir angle of the lidar is 3° during this period, allowing us to avoid complications from horizontally oriented crystals [Noel and Chepfer, 2010; Zhou et al., 2012].

The cloud optical depth (τ) is not provided in the dataset we used, so we calculate the optical depth of single-layer cirrus clouds using the formulation of [Reverdy et al., 2012]:

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

where γ' is the layer-integrated backscatter of cirrus, S is the cirrus lidar ratio, and η is the multiple scattering factor. Following Josset et al. [2012], we use S=33 sr and η=0.61. This cloud optical depth retrieval process is similar to the cloud extinction retrieval in CALIOP operational product [Young and Vaughan 2009].

We then generate a joint histogram from the optical depth calculated as described above and the cloud top pressure (CTP) provided in the CALIPSO data. We limit our analysis in this paper to cirrus clouds with CTP less than (altitudes above) 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 for cloud layers above the 440-hPa pressure level). These classification criteria are consistent with the International Satellite Cloud Climatology Project (ISCCP) cirrus cloud classification (CTP<440 hPa, τ<3.6) [Rossow and Schiffer, 1999].

There are frequently multiple cirrus cloud layers above 440 hPa [Wang and Dessler, 2006], and we combine multiple cirrus cloud layers in each pixel into a single effective cloud layer with the following properties:

$$\tau = \sum \tau_i \text{, and } CTP = \sum (CTP_i \times \gamma'_i) / \sum \gamma'_i \text{,} \qquad (2)$$

where γ'_i , τ_i and CTP_i are the layer-integrated backscatter, optical depth and cloud top pressure for the i'th cirrus cloud layer, respectively. The optical depth of the effective cloud layer equals the sum of the multiple cirrus cloud layers, while the CTP of the effective cloud layer is a weighted average of the multiple cirrus cloud layers, so the LW radiative effect of the effective cloud layer is also close to that of the multiple cirrus cloud layers.

To quantify the radiative feedback of cirrus, we use the approach of Zelinka et al. [2012; 2013]. This approach requires calculation of cloud radiative kernels, which quantify the change in downwelling top-of-atmosphere (TOA) flux per percent change in cloud fraction with a particular CTP and τ:

$$K = \partial R / \partial C = (R_c - R_{nc}) / 100\%, \qquad (3)$$

where R_c and R_{nc} are the TOA flux for scenes with 100% cirrus coverage and without any cirrus, respectively. Our kernel calculations follow Zelinka et al. [2012], except that the input zonal mean temperature, ozone, and water vapor fields are monthly mean fields from ECMWF Re-Analysis Interim (ERA-interim) [Dee et al., 2011]. Because cloud particle size is smaller in colder clouds, we set the input effective particle diameter to be a function of cloud top temperature using the lookup table of Donovan [2003]. We use the Fu-Liou model [Fu and Liou 1992] to perform the radiative transfer calculations.

One challenge is to correctly handle thin cirrus cloud layer overlapping a non-cirrus cloud layer. To do this, we estimate the average radiative effect of four types of cirrus clouds: cirrus over clear-skies, cirrus over middle clouds, cirrus over low clouds, and cirrus over high-opaque clouds. For cirrus cloud layers over clear-skies, the cirrus radiative effect is calculated with the same method of Zelinka et al. [2012]. To calculate the radiative effect for cirrus layers above low-cloud layers (CTP>680 hPa), a liquid cloud layer (τ=5, CTP=850 hPa) is inserted into the radiative transfer calculations for scenes with and without cirrus. The low-cloud layer also reflects SW solar radiation, so the SW radiative effect of cirrus is less negative than cirrus over clear-skies. On the other hand, the LW component of radiative effect for cirrus over low-cloud layers – which have little TOA LW impact – is similar to that for cirrus over clear-skies, so the net warming effect of cirrus over low clouds is greater than cirrus over clear-skies. For cirrus layers above mid-cloud layers (440hPa<CTP<680hPa), a liquid cloud (τ=5, CTP=550 hPa) is inserted into the kernel calculations. The net warming effect of cirrus over middle clouds is smaller than cirrus over low clouds, but greater than cirrus over clear-skies. For cirrus layers above high-opaque clouds (CTP<440 hPa), a cloud layer (τ=9, $CTP=[440+CTP_{cirrus}]/2$) is inserted into the kernel calculations. The net warming effect of cirrus above high-opaque clouds is smaller than cirrus above clear-skies, because high-opaque clouds have large SW and LW cloud radiative effect. The non-cirrus cloud optical depths used in the kernel calculation are derived from ISCCP observations, and total cirrus feedback values are not sensitive to the choices of CTP and τ for non-cirrus cloud layers. If the optical depth of non-cirrus cloud below cirrus changes by 40% in the kernel calculations, the net cirrus feedback changes only by ~5%. If the average CTP of non-cirrus clouds is changed by 100hPa in the kernel calculations, the net cirrus feedback changes less than 5%.

The cirrus cloud radiative kernels used in our calculation (Fig. 1) are weighted average values of the radiative effect of the four scenarios described above, with each scenario weighted by the fraction of times it is observed in the 6-year CALIPSO data set (the weighting is calculated for each latitude and longitude). The cirrus cloud kernels are functions of latitude, longitude, CTP, τ, and month.

The radiative kernels are then multiplied by the inter-annual anomalies in cirrus cloud fraction to get an estimate of the contribution of each cloud type to the change in TOA radiation, ΔR_{cloud}. 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 (ΔT_s), and is calculated as the linear least-squares regression slope of the ΔR_{cloud} monthly anomalies against the global surface temperature monthly anomalies.

3. Results

Fig. 2a shows a scatter plot of monthly values of ΔR_{cirrus} versus ΔT_s, where ΔT_s is calculated from ERA-interim. The slope of this scatter plot is the strength of the cirrus feedback, and it is estimated by a traditional least squares fit to be 0.20 ± 0.21 W/m^2/°C (2σ interval of liner regression slope). Because the error bars overlap zero, we cannot conclude anything about the sign of the feedback with 95% confidence. However, using a 2-tailed Student's t-test, we estimate that there is a 94% chance that the regression slope (and therefore the feedback) is positive. Thus, it is very likely that cirrus clouds trap additional energy as the surface warms, and thereby contribute a positive feedback to the climate system.

The magnitude of net cirrus feedback is comparable to both short-term and long-term surface albedo feedback, and is about half the size of the short-term total cloud feedback [Dessler, 2010]. Therefore, the cirrus feedback is an important component of the climate system. The feedback is primarily due to increased trapping of LW radiation opposed by a small increase in reflection of SW radiation: The SW and LW component of cirrus feedback is -0.12±0.20 $W/m^2/°C$ and 0.32±0.40 $W/m^2/°C$, respectively.

The positive cirrus feedback primarily results from the positive response of global cirrus cloud radiative effect to tropical surface warming. Fig. 2b shows the scatter plot of ΔR_{cirrus} and tropical surface temperature anomaly $\Delta T_{s,tropics}$; it shows that ΔR_{cirrus} is better correlated to $\Delta T_{s,tropics}$ than to global average surface temperature, and the regression slope is statistically distinguishable from zero. The time series of both tropical and subtropical (45°S-45°N) cirrus cloud amount are better correlated with tropical surface temperature than with extratropical surface temperature. This suggests that the variability of global cirrus radiative effect may be primarily controlled by tropical surface temperature. In this respect, the cirrus feedback is similar to the global water vapor feedback, which is also primarily controlled by tropical surface temperature changes [Dessler and Wong, 2009].

We have carried out sensitive analyses to address uncertainties from the choice of datasets and input parameters. Dessler and Loeb [2013] pointed out that choice of temperature data set has a large impact on the calculation of the total cloud feedback, so we checked the sensitivity of our net cirrus feedback to the choice of surface temperature dataset. The net cirrus feedback is 0.16±0.22 $W/m^2/°C$ using GISTEMP [Hansen et al., 2010], 0.20±0.24 $W/m^2/°C$ using NCDC [Smith et al., 2008], and 0.20±0.25 $W/m^2/°C$ using HadCRUT4 [Morice et al., 2012]. Thus, the uncertainty from the choice of surface temperature dataset is small for calculations of cirrus feedback in this study. Choice of S and η in Eq. (1) also affects the magnitude and uncertainty interval of cirrus. If the average lidar ratio changes from 33 to 28 or 38, the total cirrus feedback changes to

0.17±0.18 or 0.23±0.24. If the average lidar multiple scattering coefficient changes to 0.5, the total cirrus feedback would be 0.19±0.20 $W/m^2/°C$. In addition, if we use fixed particle size following Zelinka et al. 2012, the total feedback value is ~0.23±0.24 $W/m^2/°C$.

Fig. 3a shows the cirrus cloud fraction changes per degree of global average surface warming, calculated from least-squares linear regression. As the surface temperature gets warmer, tropical (30°N-30°S) cirrus cloud fraction increases above and decreases below the altitude at which it peaks on average. This indicates an overall increase in the cirrus altitude in the tropics, consistent with the overall increase in the high-thick cloud altitude [Zelinka and Hartmann, 2011]. An increase in cirrus fraction is also apparent over a broad range of the mid-latitude upper troposphere of both hemispheres, with no apparent compensatory decreases at other altitudes. The cirrus cloud fraction decreases in polar regions of both hemispheres.

Fig. 3b shows the relative humidity (RH) response to surface temperature anomalies, which are calculated from ERA-interim. Regionally, RH changes substantially during interannual climate variations [Dessler et al., 2008]. The RH response has a very similar pattern as the cloud response, suggesting that the change of cirrus cloud fraction may be a result of changing upper tropospheric RH.

Fig. 3c shows the net cirrus feedback contributed from each latitude-CTP bin. Pixels with an increase in cirrus cloud fraction in Fig. 3a contribute a positive feedback to the climate, and pixels with a decrease in cirrus cloud fraction contribute a negative feedback. This is consistent with the fact that cirrus clouds generally have a warming effect to our climate system.

It is worth noting that much of the cirrus feedback comes from clouds in the Tropical Tropopause Layer (TTL, 70-150 hPa and between 30°S and 30°N) [Fueglistaler et al., 2009]. These clouds are frequently thin and difficult to observe, but they have a large greenhouse effect because they are so much colder than the surface. This is shown more clearly in the CTP-τ histogram of cirrus feedback (Fig. 4), which indicates that much of the TTL cirrus feedback comes from optically thin cirrus (τ<1.3). TTL cirrus clouds contribute 0.11±0.13 $W/m^2/°C$ to the total cirrus feedback, accounting for more than half of the total cirrus feedback.

Cirrus feedback is an important component of the cloud feedback, and the positive cirrus feedback may partially explain the discrepancy between the short-term total cloud feedback calculated from MODIS [Zhou et al., 2013] and that calculated from CERES [Dessler, 2010; 2013]. MODIS often fails to retrieve the cloud properties of thin clouds [Pincus et al., 2012; Holz et al., 2008]: The optically thin cirrus (τ<1.3, CTP<440hPa) cloud fraction is less than 1% in MODIS lv3 CTP-τ joint histograms compared to 6% optically thin cirrus clouds over clear-skies in CALIPSO data. Thus, the positive cirrus feedback is at least partially missed by MODIS. CERES, on the other hand, is a broadband flux measurement, so it incorporates the radiative effect of all clouds. Therefore, if all cirrus clouds were retrieved by MODIS, we would expect the total cloud feedback calculated from MODIS to be closer to the value derived from CERES measurements.

Using the CTP-τ histogram generated by the ISCCP simulator [Klein and Jakob, 1999; Webb et al., 2001] and corresponding cloud radiative kernels, Zelinka et al. [2012] calculated the feedback due to individual cloud types in an ensemble of Cloud Feedback

Model Intercomparison Project (CFMIP) simulations and found cirrus feedbacks ranging from -0.05 to +0.06 $W/m^2/°C$ under long-term global warming, with an ensemble average of +0.02 $W/m^2/°C$. Note that the cirrus feedback calculated from the ISCCP simulator is not exactly comparable to the results in this study, because thin cirrus above thick middle and low clouds are typically aliased to mid-level clouds rather than regarded as cirrus clouds in these calculations. Performing the same calculation as Zelinka et al. [2012] but in unforced control runs of CFMIP models (runs without any changes in external forcing), we find that the short-term cirrus feedback ranges from -0.03 to +0.17 $W/m^2/°C$, with an ensemble average of +0.05 $W/m^2/°C$. Therefore, climate models suggest that cirrus feedback is likely to be positive in response to both short-term and long-term surface warming, though the ensemble average of the models yields a smaller short-term cirrus feedback than the most likely value from the CALIPSO observations. The lower model estimate may be due in part to the reliance on the ISCCP simulator.

4. 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±0.21$W/m^2/°C$. 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.

The magnitude of cirrus feedback on long-term global warming may be different from the short-term cirrus feedback on climate fluctuations, because the inter-annual surface warming is more concentrated on the tropical area than long-term surface warming, and cirrus cloud radiative effect are more sensitive to the change of tropical surface temperature. But 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 play an important role in global warming, because 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.

Acknowledgements: CALIPSO level-2 cloud layer data were obtained from the NASA Langley Research Center Atmospheric Science Data Center. ERA-interim data were obtained from http://www.ecmwf.int. This study is supported by NASA grants NNX10AM27G and NNX13AK25G to Texas A&M University. C. Z. was supported by the NASA Earth and Space Science Fellowship grant NNX12AN57H, also to Texas A&M University. M. D. Z. and C. Z.'s contribution was supported by the Regional and Global Climate Modeling Program of the Office of Science at the U. S. Department of Energy (DOE) and was performed under the auspices of the DOE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References:

Dee, D. P., and coauthors (2011), the ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quart. J. Roy. Meteor. Soc., 137, 553-597, doi: 10.1002/qj.828.

Dessler, A.E. and N.G. Loeb (2013), Impact of dataset choice on calculations of the short-term cloud feedback, J. Geophys. Res., 118, 2821-2826, doi:10.1002/jgrd.50199, 2013.

Dessler, A. E., and S. Wong (2009), Estimates of the water vapor climate feedback during the El Niño Southern Oscillation, J. Climate, 22, doi: 10.1175/2009JCLI3052.1, 6404-6412.

Dessler, A.E. (2013), Observations of climate feedbacks over 2000-2010 and comparisons to climate models, J. Climate, 26, 333-342, doi: 10.1175/JCLI-D-11-00640.1.

Dessler, A.E. (2010), A determination of the cloud feedback from climate variations over the past decade, Science, 330, 1523-1527, doi: 10.1126/science.1192546.

Dessler, A. E., P. Yang, and Z. Zhang (2008), Water-vapor climate feedback inferred from climate fluctuations, 2003-2008, Geophys. Res. Lett., 35, L20704, doi: 10.1029/2008GL035333.

Dessler, A.E., M.R. Schoeberl, T. Wang, S.M. Davis, and K.H. Rosenlof (2013), Stratospheric water vapor feedback, Proc. Natl. Acad. Sci. 110, 18087-18091, doi: 10.1073/pnas.1310344110.

Donovan, D. P. (2003), Ice-cloud effective particle size parameterization based on combined lidar, radar reflectivity, and mean Doppler velocity measurements. J. Geophys. Res. 108, D18, 2156-2202, doi: 10.1029/2003JD003469.

Fu, Q. and K. N. Liou (1992), On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres. J. Atmos. Sci. 49, 2139–2156, doi: http://dx.doi.org/10.1175/1520-0469(1992)049<2139:OTCDMF>2.0.CO;2.

Hansen, J., Ruedy, R., Sato, M., and Lo, K. (2010), Global surface temperature change, Rev. Geophys., 48, Rg4004, doi: 10.1029/2010rg000345.

Holz, R. E., S. A. Ackerman, F. W.Nagle, R. A. Frey, S. Dutcher, R. E. Kuehn, M. A. Vaughan, and B. A. Baum (2008), Global Moderate Resolution Imaging Spectroradiometer (MODIS) cloud detection and height evaluation using CALIOP, J. Geophys. Res., 113, D00A19, doi: 10.1029/2008JD009837.

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, doi: 10.1029/2011JD016959.

Klein, S. A., and C. Jakob (1999), Validation and sensitivities of frontal clouds simulated by the ECMWF model, Mon. Weath. Rev. 127, 2514-2531, doi: http://dx.doi.org/10.1175/1520-0493(1999)127<2514:VASOFC>2.0.CO;2.

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.

Liou, K. N. (1986), Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective, Monthly Weather Review, 114 (6), 1167-1199, doi: http://dx.doi.org/10.1175/1520-0493(1986)114<1167:IOCCOW>2.0.CO;2.

Lynch, D. K. (1996), Cirrus clouds: Their role in climate and global change, Acta Astronautica, 38 (11), 859-863, doi: 10.1016/S0094-5765(96)00098-7.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones (2012), Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, J. Geophys. Res., 117, D08101, doi:10.1029/2011jd017187.

Noel V., and H. Chepfer, 2010: A global view of horizontally oriented crystals in clouds from CALIPSO, J. Geophys. Res., 115, D4, doi:10.1029/2009JD012365.

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, doi: 10.1175/JCLI-D-11-00267.1.

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, doi: 10.5194/acp-12-12081-2012.

Rossow, W.B., and R. A. Schiffer (1999), Advances in Understanding Clouds from ISCCP, Bull. Amer. Meteor. Soc., 80, 2261-2288 , doi: http://dx.doi.org/10.1175/1520-0477(1999)080<2261:AIUCFI>2.0.CO;2.

Santer, B. D., and coauthors (2005), Amplification of surface temperature trends and variability in the tropical atmosphere, Science, 309, 1551-1556, doi: 10.1126/science.1114867.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore (2008), Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880-2006), J. Climate, 21, 2283-2296, doi:10.1175/2007jcli2100.1.

Schneider, T., K. L. Smith, P. A. O'Gorman, and C. C. Walker (2006), A Climatology of Tropospheric Zonal-Mean Water Vapor Fields and Fluxes in Isentropic Coordinates, J. Climate, 19, 5918–5933. Doi: http://dx.doi.org/10.1175/JCLI3931.1.

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,

Wang, L. K., and A. E. Dessler (2006), Instantaneous cloud overlap statistics in the tropical area revealed by ICESat/GLAS data, Geophys. Res. Lett., 33, L15804, doi: 10.1029/2005GL024350.

Webb, M., C. Senior, S. Bony, and J. J. Morcrette (2001), Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models, Climate Dyn. 17, 905-922, doi: 10.1007/s003820100157.

Winker, D. M., J. R. Pelon, and M. P. McCormick (2003), The CALIPSO mission: spaceborne lidar for observation of aerosols and clouds, Proc. SPIE 4893, Lidar Remote Sensing for Industry and Environment Monitoring III, 1-11, doi:10.1117/12.466539.

Young, S. A., M. A. Vaughan (2009), The Retrieval of Profiles of Particulate Extinction from Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) Data: Algorithm Description, J. Atmos. Oceanic Technol., 26, 1105–1119, doi: http://dx.doi.org/10.1175/2008JTECHA1221.1.

Zelinka, M.D. and D. L. Hartmann (2011), The Observed Sensitivity of High Clouds to Mean Surface Temperature Anomalies in the Tropics. J. Geophys. Res., 116, D23103, doi:10.1029/2011JD016459.

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, doi:10.1175/JCLI-D-11-00248.1.1.

Zelinka, M. D., S. A. Klein, K. E. Taylor, T. Andrews, M. J. Webb, J. M. Gregory, and P. M. Forster (2013), Contributions of Different Cloud Types to Feedbacks and Rapid Adjustments in CMIP5, Journal of Climate, 26, 5007-5027, doi: 10.1175/JCLI-D-12-00555.1.

Zhou, C., P. Yang, A. E. Dessler, Y.-X Hu, and B. A. Baum (2012), Study of horizontally oriented ice crystals with CALIPSO observations and comparison with Monte Carlo radiative transfer simulations, J. Appl. Meteor. Climatol., 51, 1426–1439. doi: 10.1175/JAMC-D-11-0265.1.

Zhou, C., M. D. Zelinka, A. E. Dessler, and P. Yang (2013), An analysis of the short-term cloud feedback using MODIS data, J. Climate, 26, 4803-4815, doi:10.1175/JCLI-D-12-00547.1.

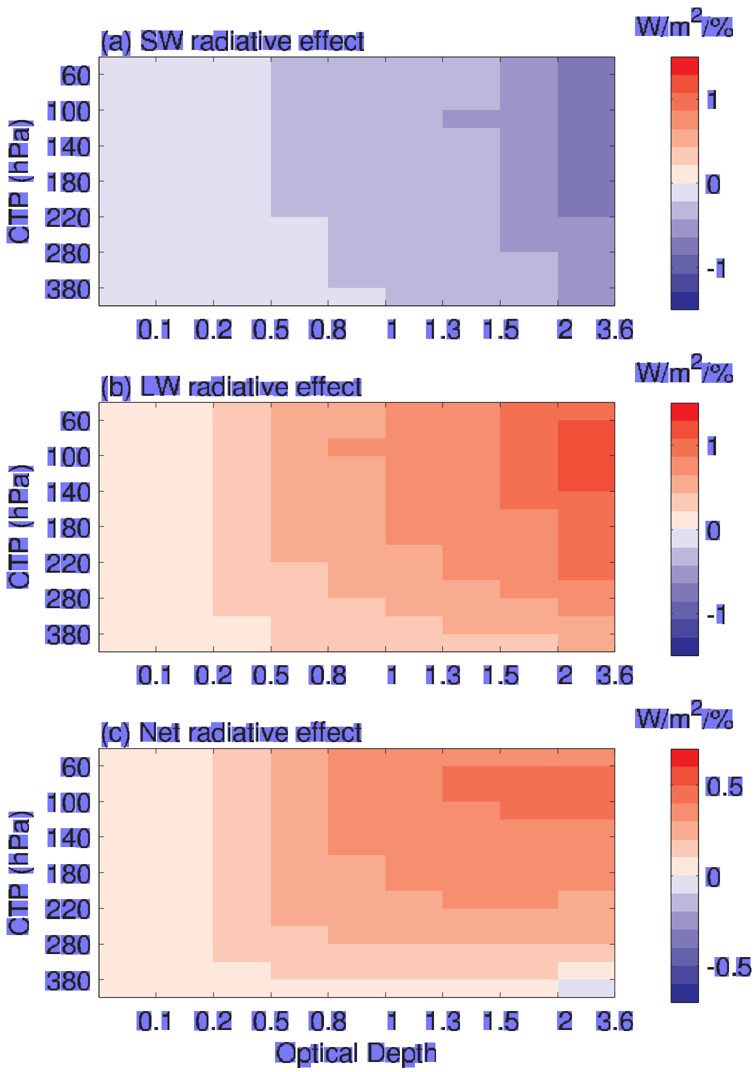

Figure 1. Cloud radiative kernels for cirrus clouds, averaged globally. The upper panel is for the SW component, the middle panel is for LW component, and the bottom panel is the net (SW+LW) cloud radiative kernels. Note that the color bar in (c) spans a range that is half as large as in (a) and (b).

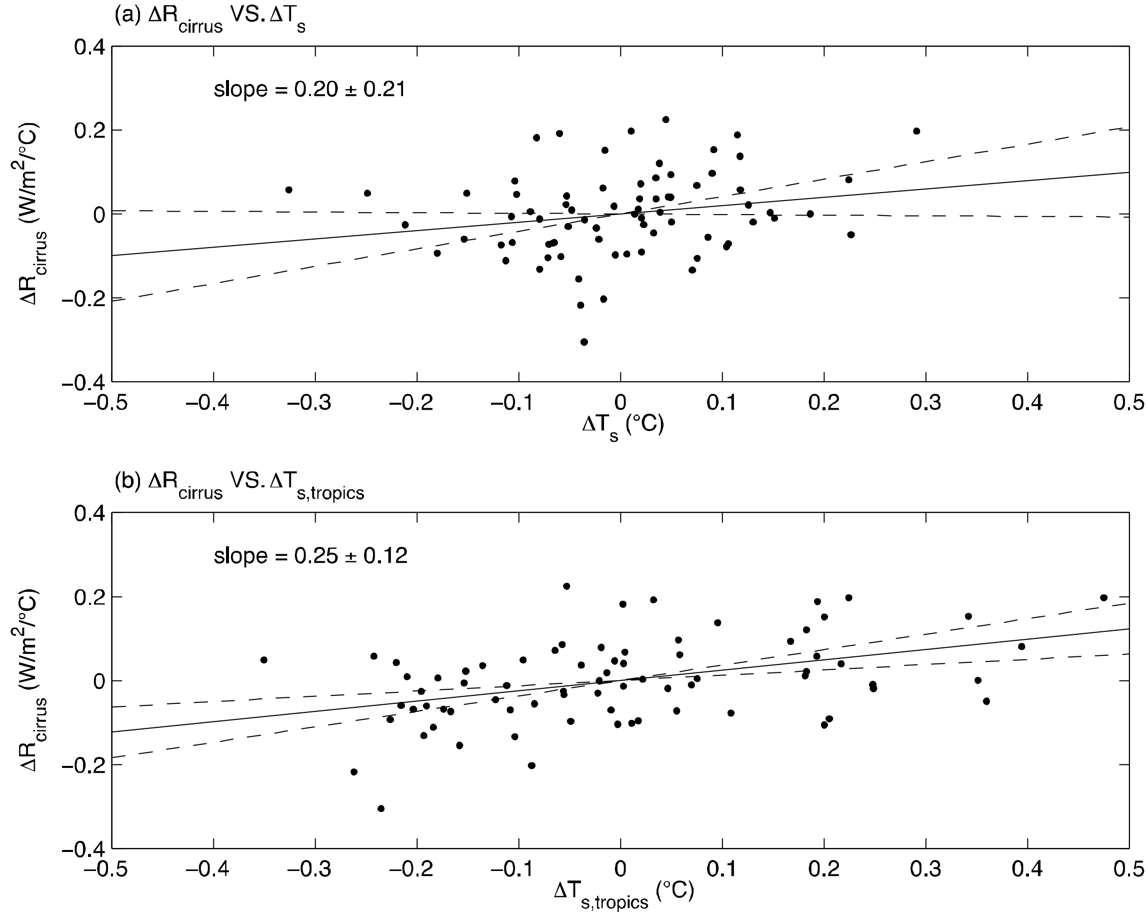

Figure 2. Cirrus feedback in response to inter-annual surface warming. (a) Scatter plot of monthly global average values of ΔR_{cirrus} versus global average ΔT_s. Solid line is the least squares fit, and dashed lines denote the 2σ uncertainty intervals. (b) Global ΔR_{cirrus} as a function of tropical (30°S-30°N) temperature anomaly $\Delta T_{s,tropics}$.

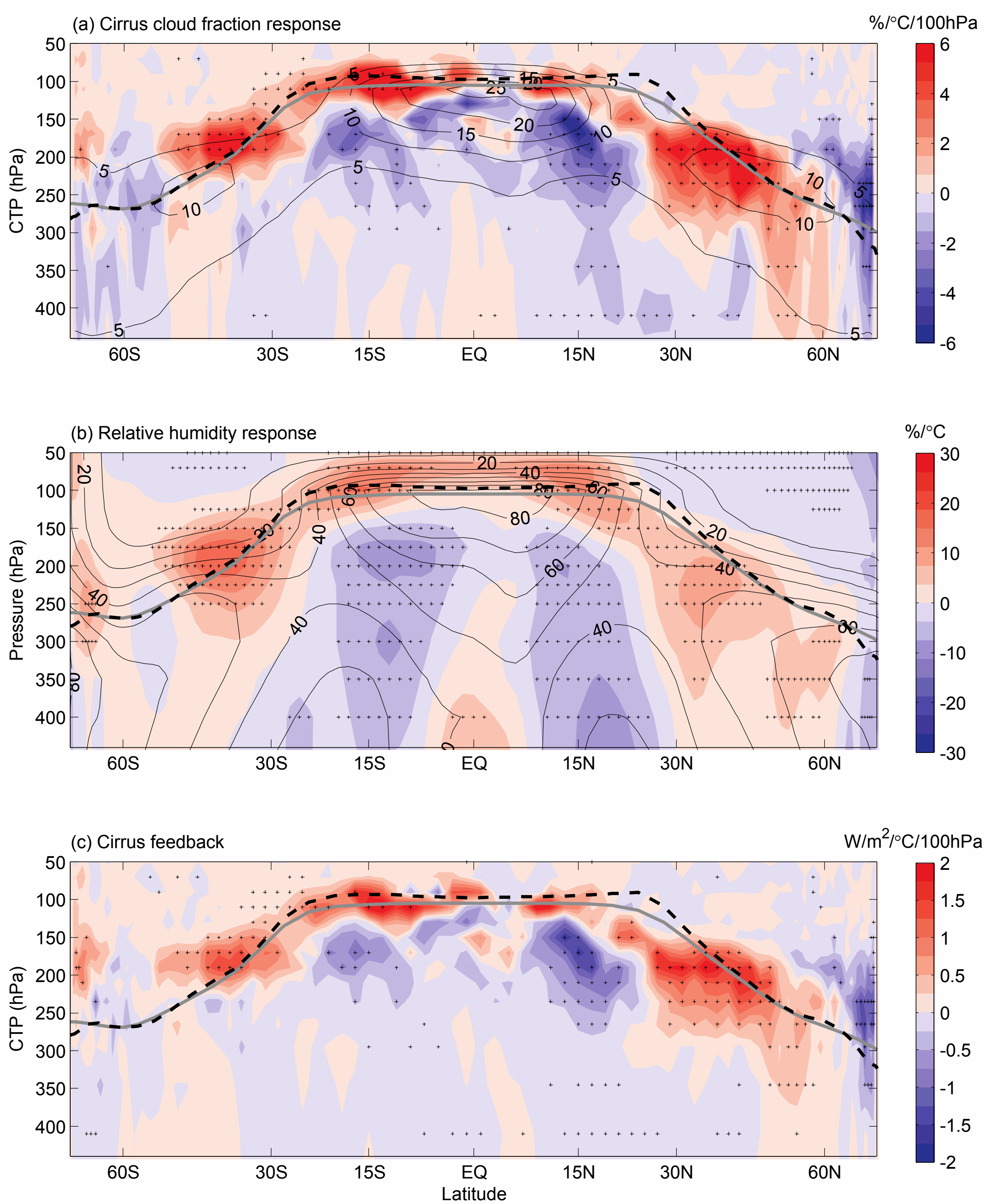

Figure 3. Zonal mean cirrus feedback. (a) Response of cirrus clouds fraction to inter-annual surface warming (shading), calculated by regressing monthly mean anomalies of cloud fraction against monthly mean anomalies of global mean surface temperature (from ERA-interim). Contours are the 6-year mean 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.

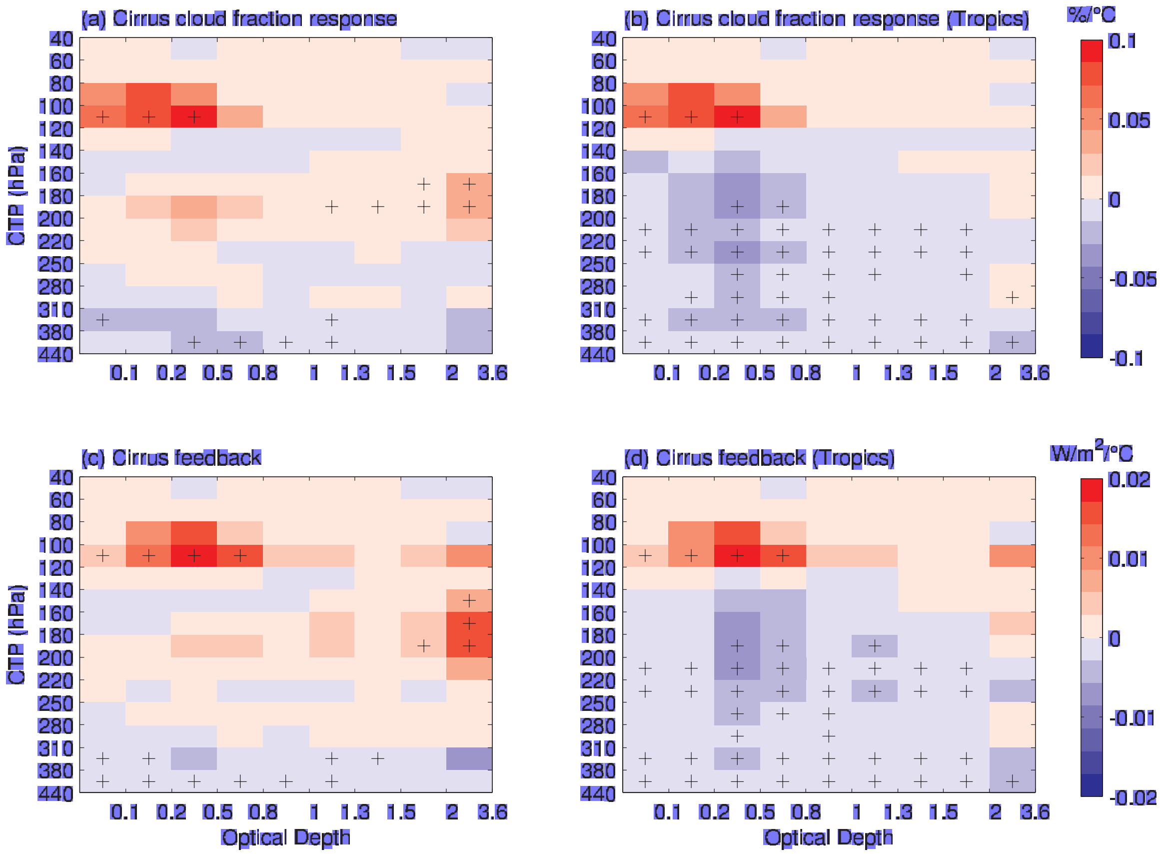

Figure 4. Cirrus feedback contributed from each CTP-τ bin. (a) Response of global mean cirrus cloud fraction to inter-annual surface warming. (b) Cirrus cloud fraction response contributed from the tropical region. (c) Global cirrus feedback. (d) Cirrus feedback contributed from the tropical region. Crosses denote pixels where the linear regression slope is statistically distinguishable from zero.