Interactive comment on "Long-term aerosol-mediated changes in cloud radiative forcing of deep clouds at the top and bottom of the atmosphere over the Southern Great Plains" by Hongru Yan et al.

Anonymous Referee #1

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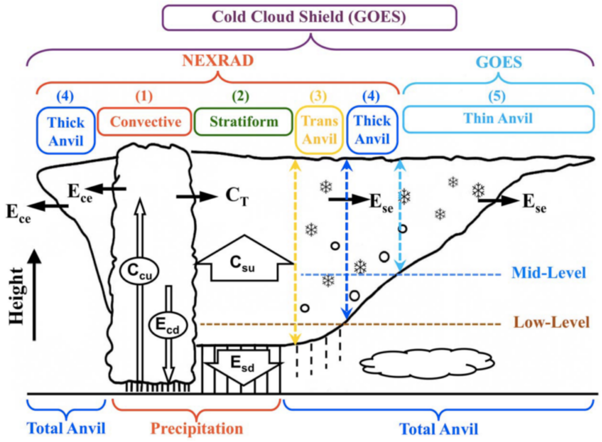
In this work the authors provide more evidence to the cloud invigoration effect. They are presenting a thorough analysis of more than 10 years using a combination of surface and satellite measurements supported by reanalysis data. They also estimate the radiative forcing of the effect. Although the variety of data sets is impressing, essential information on the analysis is missing.

We have added more analyses about the invigoration effect and meteorological influences on the invigoration effect as suggested by the reviewer.

First of all the authors should provide information on the type of clouds and the typical meteorological states over the SGP site. Examples of essential questions waiting to be answered are: Is it only convective clouds, or do stratiform clouds form there? Do they separate frontal from post-frontal systems? Do they combine clouds from many different years and seasons? Do they account for air masses that come from different directions?

This study is a follow-up study of Li et al. (2011, Nature-Geosci) that revealed the phenomenon of the aerosol invigoration effect (AIV). This paper attempts to quantify the radiative effects of the AIV. Both studies deal with deep convective clouds (DCC), while this study further divides DCC systems into deep core, moderate stratiform, and thin anvil parts by virtue of GOES satellite-retrieved COD. As such, the same approach is followed to identify DCCs based on ground-based retrievals of cloud top and bottom height and temperature. Once a DCC (core) is identified, GOES satellite data are used to define the associated stratiform and anvil clouds, which is illustrated in the figure below from Feng et al. (2011).

Given the volume of data collected over a 10-year period, it is not practical to classify weather regimes in terms of frontal activities and relative locations with respect to the location of a front to decide whether a DCC is part of a frontal or post-frontal system. This could be done for a handful of case studies though. As far as the AIV is concerned, a front may not matter as much as known factors such as convection strength, wind shear, and humidity. The influences of these variables were investigated to the extent that could be done *with the observation data available as shown in Figure2, in addition to those described by Li et al. (2011).*



The authors use GOES data in 4 km resolution. It is not clear how many pixels they require to define a cloud. Even if they take one (which is not a good practice in remote sensing data analysis), it means that clouds sized below 4by4 km will not be analyzed. A 4by4 km cloud is not small and in case of convective clouds such one-pixel clouds can be 3-5 km thick. In some conditions such clouds could reach the freezing level. Therefore I would have doubts regarding the quality of such an analysis for warm clouds. The authors should note that satellite analysis is always biased to large clouds.

We have added statements about this limitation in the revised manuscript.
Yes, GOES data has a resolution of 4 km which is too coarse to resolve clouds, especially warm cumulus clouds. However, this study is concerned with large DCC systems like those shown in the schematic plot above. As stated before, DCCs are identified using ground observations, while cloud amount and the TOA radiation budget are obtained from the GOES satellite. GOES cloud products are only used to inspect the structure of clouds (see Fig. 6). Dong et al. (2002) evaluated the GOES cloud products against surface and aircraft data and found that they have sound quality.

It is not clear why the authors have not used MODIS (at least as supporting information), which have more reliable retrievals and higher resolution.

MODIS data was not used because multiple daytime measurements are needed to determine daily mean radiative forcing values. The MODIS is onboard a polar-orbiting satellite that has only one daytime and one nighttime overpass over a particular location, while the GOES provides samples every 30 minutes. The diurnal variation in SW CRF is governed by both varying SZA and diurnal changes in DCCs. This necessitates the use of data from the GOES to estimate the diurnal mean AMCRF, which was done in this study.

The authors should explain more about the paper's statistics. How many shallow clouds?

What are their definitions to the cloud subsets? Having a GOES image every 30 minutes, they probably sampled many of the clouds more than one time during different stages of their development. Will it affect their results?

When both ARSCL and GOES data are available, the total number of cases is 22, 820. After constraining the data to single-layer clouds with base temperatures greater than 15°C, the number of cases dropped sharply to 861. The number of samples further decreased when limiting the CTT to greater than 0°C: 195, 240, and 81 samples corresponding to CN ranges of 0-2000 cm^{-3}, 2000-4000 cm^{-3}, and 4000-6000 cm^{-3}, respectively. This information is added to the revised manuscript, per the reviewer's suggestion.
Because our estimates of AMCRF are for the column surrounding the ARM central facility with a maximal horizontal domain of 20 km x 20 km, samples separated by 30 min should be independent on average, based on the mean speed of cloud movement over the area (Dong et al., 2002).

Acronym usage is very intensive and it makes the paper's points difficult to follow.

The use of acronyms in the revised manuscript has been changed so that the text reads more easily.

They summarize empirical observations without explaining their physics. Why invigoration is mostly shown in moist environment (competition with entrainment)? Why warm base and mix or cold tops?

As the reviewer suggested, we have added explanations in the revised manuscript. Note that the physics behind the empirical observations is not the thrust of this study.
In a moist environment, there is an ample supply of water vapor available for condensation to generate more latent heat to invigorate convection.
Under weak wind shear conditions, the increase in condensational heating can be larger than the increase in evaporative cooling and/or entrainment as the amount of aerosols increases, leading to an increase in net latent heat release and then stronger convection. With strong wind shear, the increase in evaporative cooling is always larger than the increase in condensational heating with increasing aerosol loading, leading to the suppression of convection.
For a warm-based cloud, an increase in aerosol loading reduces the cloud droplet size and suppresses rainfall. More cloud water can then be lifted by updrafts to form more mixed-phase regions which invigorate convection.

Finally, the introduction is not exact. It uses most of the right keywords and many of the important references but not in their precise context. For example, Andrea 2004 did not deal with anvils at all. Anvils were discussed in Koren et al, 2010 (which they cite). They could find few physical insights in the review of Tao et al, 2012 (which they cite) and new ideas in http://onlinelibrary.wiley.com/doi/10.1002/2013JD020272/abstract

We have improved the introduction. Guidance to suggested readings is appreciated.

Interactive comment on “Long-term aerosol-mediated changes in cloud radiative forcing of deep clouds at the top and bottom of the atmosphere over the Southern Great Plains” by Hongru Yan et al.

Anonymous Referee #3
Received and published: 17 March 2014

This observational study quantifies the changes in deep convective clouds radiative effects that are associated with changes in surface measured aerosol concentrations at the SGP. It does so over a climatologically meaningful sample size and finds a rather large net warming effect. This finding is of potential great importance, because presently even the sign of the net effect of aerosols on cloud radiative forcing is unknown. However, the results may change after addressing my comments below. This paper should be published after the authors will address the following comments.

Page 4601 line 5: The AIV was not "discovered" by Andrea et al. (2004), but rather proposed or hypothesized by the second author of Williams et al. (2002). Please see the third line of Section 1.3 of that paper.

The citation, ‘Andrea et al. (2004)’ has been changed to ‘Williams et al. (2002)’ in revised manuscript.

Page 4601 line 13: Please reference the latest IPCC here and elsewhere in the manuscript.

We have referenced the latest version of the IPCC report (IPCC, 2013) in the revised manuscript.

Page 4601 line 18: The AIV was not observed directly in the referenced studies, but rather the microphysical effects leading to the invigoration were observed, i.e., the delay of initiation of rain to above the freezing level.

The word ‘observed' has been replaced by the word ‘demonstrated’ in the revised manuscript.

Page 4603 line 13: It is still not completely clear how the CTT is measured. Lidar cannot see cloud tops except for thin cirrus. Radar may be attenuated through heavily precipitating clouds, and may not have the sensitivity to see the tops of the thin cirrus. Was GOES used for CTT?

The cloud top height is from the ARM value-added product called ARSCL (http://science.arm.gov/vaps/arscl.stm), which combines the data from millimeter cloud radars, laser ceilometers, microwave radiometers, and micropulse lidars to produce a time series of vertical distributions of cloud hydrometeors over ARM main sites. Temperature profiles from the European Centre for Medium-Range Weather Forecasts diagnostic analyses are used to produce CTT. These explanations have been added to section 2.1. The stated limitations are true under those special circumstances, but they are also valid for the majority of DCCs that do not rain, nor are they thin cirrus, which are stated in the revision.

Page 4603 line 16: Please replace the word "ensures" with "maximizes the likelihood".

The word 'ensures' has been replaced by the phrase 'maximizes the likelihood' in the revised manuscript.

Page 4603 line 11: How is cloud optical thickness determined at nighttime to the sufficient accuracy to separate at COT=10?

The VISST and SIST algorithms generate COT for daytime and nighttime, respectively (Minnis et al., 2011a). Minnis et al. (2011b) have evaluated their algorithms using ARM data. Results show that the SIST algorithm tends to misclassify supercooled liquid clouds as ice clouds and is sensitive to cirrus clouds. So the correlation between satellite retrievals and surface retrievals of COT are good for cirrus cloud but bad for stratus clouds (see Table 3). In the study, COT=10 is used to separate the anvil from DCCs. This value is a reasonable one to use because anvils and cirrus clouds have similar properties.

Page 4608 Eq. 2: CRF(SZA,CN = 0) is physically impossible. I suggest changing the definition, say, from 0 to CNo, which would be the unperturbed CN value.

'CRF(SZA, CN=0)' has been replaced by 'CRF(SZA, CN_0)' in the revised manuscript.

Page 4608 Eq. 3: Define T.

'T' has been defined in the revised manuscript.

Page 4609 line 14: The differences in cloud top temperatures are not shown in Figure 4d. Please point to the right figure.

We have changed the y-axes of those figures to make the trends stand out more.

Page 4609 line 20: The differences in the daily mean TOA SW CRF for the different CN values can be affected by the time of the measurement within the diurnal cycle. The same cloud will have different CRF when occurring at different times with different solar zenith angle. This factor must be taken into account when calculating the CRF. This may change the results substantially.

This is exactly the point we try to make. Our estimation of the AMCRF accounts for diurnal variations in cloud, aerosol, and sun angle, as described in equations 3-5.

Page 4610 line 15: How is cirrus classified between SAC and other kinds of cirrus clouds that are not generated by DCC?

In our data processing, we first use the ARSCL data to identify cases where the CBT is greater than 15°C and the CTT is less than -4°C. Then we use the satellite-retrieved pixel-level data to identify SACs ($\tau < 10$). In this way, we conclude that cloud pixels with $\tau < 10$ must be associated with DCCs present nearby. The cirrus is likely generated by DCCs.

Page 4614 line 7: Please specify the country to which this MOST belongs.

It belongs to China.

It would be very helpful to provide the figures in color. Since it is an online publication, there is no reason to eliminate the colors.

Figures 1-2 and 4-6 are now in color.

List of all relevant changes made in the manuscript

1. Page 4600, line9: '(GOES)' has been deleted.
2. Page 4600, line11: '(AME)' has been deleted.
3. Page 4601, line5: 'discovered by Andreae et al. (2004)' → 'first noted by Williams et al. (2002)'
4. Page 4601, line5-7: 'This effect is the so-called aerosol invigoration effect (AIV), which was discovered by Andreae et al. (2004) who found that aerosols can fuel cloud vertical development, lift cloud-top heights and expand cloud anvils under certain circumstances.' → 'This effect is the so-called aerosol invigoration effect (AIV), which was first noted by Williams et al. (2002) who found that aerosols can fuel cloud vertical development and lift cloud-top heights. This was reinforced by an airborne experiment conducted in the Amazon (Andreae et al., 2004). The AIV is also associated with the expansion of cloud anvil extent (Koren et al. 2010).'
5. Page 4601, line 12: '(IPCC, 2007)' → '(IPCC, 2013)'
6. Page 4601, line 18: 'observed' → 'demonstrated'
7. Page 4601, line 23: '; Storer et al., 2014' has been added after 'Koren et al., 2005'
8. Page 4602, line 14: 'at the SGP site' → 'at the U.S. Department of Energy's Atmospheric Radiation Measurement Program's Southern Great Plains (SGP) site'
9. Page 4602, line 25: 'to' has been deleted.
10. Page 4602, line 25: 'yr' → 'years'
11. Page 4603, line 10: 'The cloud top height might be blurred under heavy rain condition as the radar signal would be attenuated, but they are also valid for the majority of DCCs that do not rain.' has been added after '(Clothiaux et al., 2000)'
12. Page 4603, line 16: 'ensures' → 'maximizes the likelihood'
13. Page 4603, line 16: ', Min et al., 2008; Wang and Min, 2008' has been added after 'Min et al., 2004'
14. Page 4604, line 9: ', Huang et al., 2005' has been added after 'Minnis et al., 2011'
15. Page 4605, line 6: 'A variety of cloud types can appear over the SGP site which experiences large seasonal variations in temperature and humidity. Analyses of long-term cloud products from ARM measurements reveal that stratus and cirrus clouds are the major cloud types seen at the SGP site (Lazarus et al., 2000; Kollias et al., 2007). Cumulonimbus clouds are not frequent there.' has been added at the beginning of the paragraph.
16. Page 4605, line 6: 'Theory' → 'Theoretical'
17. Page 4605, line 10: 'τ' → 'cloud optical depth (COD, or τ)'
18. Page 4605, line 12: 'GOES data has a resolution of 4 km which is too coarse to resolve clouds, especially warm cumulus clouds. However, this study is concerned with large DCC systems, which are identified using ground observations.' has been added after '(2010a)'
19. Page 4605, line 14: 'During the decade-long period, the total number of matched cloudy cases identified using ground-based and GOES data is 22, 820. Of the total, 861 are single-layer clouds with CBT greater than 15°C. The number of warm shallow clouds (CTT > 0°C) and mixed-phase clouds (CTT < -4°C) are 516 and 299, respectively.' has been added after 'were used.'

20. Page 4605, line 18: ‘For mixed-phase warm-based clouds, an increase in aerosol loading reduces the size of cloud droplets. These droplets are more likely to be lifted by updrafts to become mixed-phase clouds due to buoyancy from the release of latent heat which invigorates convection.’ has been added after ‘Li et al. (2011).’
21. Page 4606, line 21: ‘increasing the aerosol concentration in mixed-phase warm-based clouds generates more latent heat which, in turn, invigorates convection.’ has been added after ‘Under unstable and/or moist conditions,’.
22. Page 4606, line 13: ‘within 7 km from the ground’ → ‘within the lowest 7 km of the atmosphere’
23. Page 4606, line 21: ‘the magnitude of the slope in the CTT-CN relationship is larger than that under stable and/or dry conditions’ → ‘increasing the aerosol concentration in mixed-phase warm-based clouds generates more latent heat which, in turn, invigorates convection. The magnitude of the slope in the CTT-CN relationship is then larger than that under stable and/or dry conditions’
24. Page 4606, line 24: ‘(solid line)’ has been deleted.
25. Page 4606, line 25: ‘(dotted line)’ has been deleted.
26. Page 4606, line 25: ‘Under weak wind shear conditions, the increase in condensational heating is more than the increase in evaporative cooling and/or entrainment as the aerosol load increases, leading to an increase in net latent heat release and stronger convection. With strong wind shear, the opposite holds, leading to the suppression of convection.’has been added at the end of the paragraph.
27. Page 4606, line 26: ‘an’ has been added before ‘earlier’.
28. Page 4606, line 26: ‘by’ has been added before ‘Li’.
29. Page 4606, line 27: ‘at’ → ‘and in’.
30. Page 4606, line 27: ‘as’ has been deleted.
31. Page 4606, line 28: ‘in’ → ‘by’
32. Page 4606, line 28: ‘The causes’ → ‘Causes’
33. Page 4606, line 29: ‘aerosol’ → ‘aerosols’
34. Page 4607, line 1: ‘aerosol’s’ → ‘the aerosol’
35. Page 4607, line 3: ‘anvil fraction’ → ‘the anvil fraction’
36. Page 4608, line 18: ‘In principle, ’ has been deleted.
37. Page 4608, line 19: “CN=0” →“CN_0”.
38. Page 4608, line 20: ‘In principal, CN_0 should be equal to zero, which is physically impossible. So an unperturbed CN value representative of relatively clean conditions is used instead.’ has been added prior to ‘Diurnal mean AMCRF is defined as’.
39. Page 4609, line 1: ‘T is the half-day length which varies according to latitude and season, and ’ has been added after ‘where’
40. Page 4609, line 1: ‘denote’ → ‘are’
41. Page 4609, line 2: ‘does’ has been deleted.
42. Page 4609, line 3: ‘include’ → ‘includes’
43. Page 4609, line 3: ‘variation of’ → ‘changes in’
44. Page 4609, line 25: ‘τ’ → ‘cloud optical depth (COD)’
45. Page 4610, line 9: ‘So changes’ → ‘Changes’

46. Page 4610, line 10: ‘accounted for’ → ‘taken into account’
47. Page 4610, line 18-19: ‘CCC (convective and core clouds) and SAC (stratiform anvil clouds)’ → ‘convective and core clouds (CCC) and stratiform anvil clouds (SAC)’
48. Page 4611, line 14: “20 km^2” → “400 km^2”
49. Page 4612, line 5: “the frequency” → “frequencies”
50. Page 4612, line 6: “larger” → “greater”
51. Page 4612, line 6: “darker” → “reddish”
52. Page 4612, line 6: “occurs” → “occur”
53. Page 4612, line 26: “for” → “of”
54. Page 4613, line 8: “2007” → “2013”.
55. Page 4613, line 24: “10 yr” → “10-years”
56. Page 4615, line 13-16: “IPCC: Climate Change 2007…..” has been deleted.
57. Page 4615, line 13: ‘Huang, J., Minnis, P., Lin, B., Yi, Y., Khaiyer, M. M., Arduini, R. F., and Mace, G. G. : Advanced retrievals of multilayered cloud properties using multispectral measurements, J. Geophys. Res., 110, D15S18, doi:10.1029/2004JD005101, 2005.’ has been added.
58. Page 4615, line 13: ‘IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.’ has been added.
59. Page 4615, line 30: ‘Kollias, P., Tselioudis, G., and Albrecht, B. A.: Cloud climatology at the Southern Great Plains and the layer structure, drizzle, and atmospheric modes of continental stratus. J. Geophys. Res., 112, D09116, doi:10.1029/2006JD007307, 2007.’ has been added.
60. Page 4616, line 7: ‘Lazarus, S. M., Krueger, S. K., and Mace, G. G.: A Cloud Climatology of the Southern Great Plains ARM CART. Journal of Climate., 13, 1762-1775, doi:10.1175/1520-0442(2000)013<1762:ACCOTS>2.0.CO;2, 2000.’ has been added.
61. Page 4616, line 28: ‘Min, Q., Wang, T., Long, C. N., and Duan, M.: Estimating fractional sky cover from spectral measurements, J. Geophys. Res., 113, D20208, doi:10.1029/2008JD010278, 2008.’ has been added.
62. Page 4617, line 27: ‘Storer, R. L., van den Heever, S. C., and Ecuyer, T. S. L.: Observations of aerosol-induced convective invigoration in the tropical east Atlantic, J. Geophys. Res. Atmos., 119, 1–13, doi:10.1002/2013JD020272, 2014.’ has been added.
63. Page 4618, line 7: ‘Williams, E., et al., Contrasting convective regimes over the Amazon: Implications for cloud electrification, J. Geophys. Res., 107(D20), 8082, doi:10.1029/2001JD000380, 2002.’ has been added.
64. Page 4618, line 7: ‘Wang, T. and Min, Q.: Retrieving optical depths of optically thin and mixed-phase clouds from MFRSR measurements, J. Geophys. Res., 113, D19203, doi:10.1029/2008JD009958, 2008.’ has been added.
65. Except for Figure 3, all other figures have been changed to colored ones.