Response to Reviewer #1's Comments:

Jiming Li et al. (Author)

We are very grateful for the Review #1's detailed comments and suggestions, which help us improve this paper significantly. Based on the two Reviewers' comments and suggestions, we reorganized the introduction and added some interpretations in each section in order to make the manuscript more clear. In addition, some superfluous information in each section was deleted.

Important revision includes:

(1) The structure of the manuscript, especially for the Abstract and Introduction sections, was reorganized in order to make the manuscript more clear.

(2) The physically means of technical terms were added in the Abstract section.

(3) The Introduction section also interpreted the main aims of this study.

(4) In each section, we also added some interpretations about the comments from reviewers.

Please see our point-by-point reply to comments. In addition, all revisions were highlighted in revised manuscript by using yellow color.

Specific responses:

(1) As early as the abstract, quantities used to characterize the degree of overlap of cloud layers are introduced but never explained. These are the parameter α and the decorrelation length L. The authors need to explain what these parameters physically mean. This is to say that the cloud overlap characterization and parameterizations need to be explained at the beginning of the paper. The sooner the jargon is introduced and explained the easier it is to follow the paper. The authors have to realize that not a lot of people are familiar with this formalism, and a reminder is necessary. So, the third paragraph of the introduction should be rewritten and include: 1) what is meant by

overlap and the three different types, with reference to papers that actually describe parameterizations; 2) explain the formalism introduced by Hogan and Illingworth (2000)and the two quantities that are used to characterize the overlap and 3) the efforts that have been made to characterize the overlap using observations (e.g. Mace and Benson-Troth 2002) and to improve model representation (e.g. the Di Giuseppe and Tompkins2015 paper, Shonk et al 2010,etc). Then explain the distinction between continuous and discontinuous cloud layers (I thought that the exact term was contiguous, and noncontiguous) and that there is a consensus on the fact that discontinuous cloud layers are always randomly overlapping. This way you can focus on only contiguous cloud layers later on.

Response: We very thank reviewer for providing detailed comments and suggestions. Based on these suggestions, we reorganized the structure of the Introduction section in order to make the manuscript more clear.

The second and third paragraphs in the revised manuscript are:

"However, our incomplete understanding of the cloud physical processes and the limited cloud observations over the TP make the simulation of total cloud cover in the climate models still unreliable. One of the remaining challenges involves how to reasonably represent the characteristics of the vertical overlapping of cloud layers in these models. Cloud overlap means that two or more cloud layers are simultaneously present over the same location but at different levels in the atmosphere. To derive the reasonable total cloud cover between cloud layers, models have to make some assumption about the cloud layers how to overlap in the vertical direction, such as, maximum, random and minimum assumptions. If the cloud covers of two model layers are given by C_i and C_j, respectively, total cloud cover between these two layers from maximum assumption is $C_{i,j}^{\max} = \max\{C_i, C_j\}$, while the random and minimum assumptions define the total cloud cover as $C_{i,j}^{ran} = C_i + C_j - C_i \times C_j$ and $C_{i,j}^{\min} = \min\{C_i + C_j, 1\}$, respectively. Thus, the maximum assumption minimizes the total cloud cover, while minimum assumption produces minimally overlap between cloud layers and results in maximum total cloud cover (Weger et al., 1992). The total cloud cover predicted by the random assumption will fall somewhere between maximum and minimum assumption (Geleyn and Hollingsworth, 1979). Studies have shown that these different overlap assumptions result in obvious different total cloud covers and will significantly affect the calculated radiative budgets and heating/cooling rate profiles (Morcrette and Fouquart, 1986; Barker et al., 1999; Barker and Fu, 2000; Chen et al., 2000; Pincus et al., 2005; Zhang and Jing, 2010; 2016; Zhang et al., 2013; Jing et al., 2016).

To improve the simulation of total cloud cover, Hogan and Illingworth (2000) revisited the cloud overlap assumptions and proposed a simpler and more useful expression for the degree of cloud layer overlap (exponential random overlap assumption) by using the ground-based radar measurement. In the expression, the observed cloud cover between two cloud layers can be expressed as the linear combination of the maximum and random overlap by using a weighting factor, termed as cloud overlap parameter α:

$$\alpha = \frac{C_{i,j}^{obs} - C_{i,j}^{ran}}{C_{i,j}^{\max} - C_{i,j}^{ran}} \tag{1}$$

The overlap parameter α ranges from 0 (random) to 1 (maximum) when the observed total cloud cover falls between the values using the maximum and random overlap assumptions. The α will be negative if the degree of cloud overlap is lower than that predicted by the random overlap assumption. Finally, Hogan and Illingworth (2000) fitted the reduction in α with layer separation D as an inverse exponential function of the decorrelation length scale L: $\alpha = e^{-D/L}$. Thus, α and L are both used to characterize the transition from the maximum to random overlap assumption with increasing layer separations. Until now, many efforts have been made to derive the values of α and L using ground-based radar observations (e.g. Mace and Benson-Troth, 2002; Willén et al., 2005; Naud et al., 2008; Oreopoulos and Norris, 2011) and improve the representation of L in the models (Shonk et al 2010; 2014; Di Giuseppe and Tompkins, 2015). For example, Oreopoulos and Norris (2011) derived L based on radar measurement taken over the US Southern Great Plains (SGP). Their results indicated that L ranges from 2 to 4.5 km across different seasons and smaller spatial scales correspond with smaller L values. Based on two months of cloud mask profile information from the Space-based radar and lidar, Barker (2008) quantified the properties of cloud overlap on a global scale and found a wide range of L values, with a median value of 2 km. In other studies, decorrelation length scale L is also parameterized as a function of latitude (Shonk et al., 2010; 2014), total cloud cover (Yoo et al., 2014) or wind shear (Di Giuseppe and Tompkins, 2015). These findings suggest that meteorological factors could be connected to the overlap way between cloud layers."

In the abstract part, we also added the physically means of the parameter α and the decorrelation length L. "To do this, the cloud overlap parameter α, which is an inverse exponential function of the cloud layer separation D and decorrelation length scale L, is calculated and discussed. The parameter α and L are both widely used to characterize the transition from the maximum to random overlap assumption with increasing layer separations".

(2) The focus of the paper is not very clear: it starts off as an observational study of overlap over the Tibetan Plateau, but navigates through the best way to analyze the data and then moves on to proposing a new parameterization. I think that the interesting point of the study is to test whether existing overlap parameterizations (e.g. the Di Giuseppe and Tompkins 2015 parameterization) are valid over the Tibetan Plateau, demonstrate that it is having difficulty because the relation between cloud overlap and wind shear is not the same as that used in the DGT15 study, and moreover that by also taking into account instability you actually improve the overlap parameterization there. Actually, I think that it is an interesting result that the Shonk et al 2010 scheme is giving fairly decent results too, when it is only latitude dependent. It would have been interesting though if you could demonstrate that your scheme also works in other parts of the world, in particular over the tropical oceans. In any case these conclusions should be made more prominent, in both the abstract and the conclusions section.

Response: We very thank reviewer for providing detailed comments and suggestions. Studies have showed that the changes of cloud cover are responsible for the rapid climate warming over the Tibetan Plateau (TP) in the past three decades. It means that the reliable simulation of cloud cover in the climate models will favor the prediction of climate change over TP. However, our incomplete understanding of the cloud physical processes and the limited cloud observations over the TP make the simulation of total cloud cover in the climate models still unreliable. One of the remaining challenges involves how to reasonably represent the characteristics of the vertical overlapping of cloud layers in these models. Thus, **the main aim of this study is to examine the cloud overlaps over the TP region, and further build an empirical relationship between cloud overlap properties and large-scale atmospheric dynamics** by using 4 years (2007–2010) of data from the CloudSat cloud product and collocated ERA-Interim reanalysis product. Recent study has discussed the impact of wind shear on the cloud overlap parameter (Di Giuseppe and Tompkins, 2015). As we know, the TP during summer is usually considered to be an atmospheric heat source or "air pump" due to its higher surface temperature compared with surrounding regions at the same altitude. Additionally, a humid and warm air intrudes from the South Asia monsoon area into the lower atmosphere over the TP to intensify the atmospheric instability of moist convection when combined with the enhanced surface heating. This feature favors the development of convective clouds. It means that the impact of atmospheric instability on the cloud overlap properties should be considered in parameterization. Although previous studies have verified the importance of instability on the cloud overlap properties, its impact wasn't included in the parameterizations of decorrelation length scale *L*. Therefore, the **key focus of this paper** is to develop a new scheme, which considered decorrelation length scale *L* as a function of the wind shear and atmospheric stability. Our results indicated that new scheme may improve the prediction of cloud cover over TP compared with wind shear-dependent scheme or other schemes. The suggestions from reviewer are very important to us. However, as stated in our paper, current results can't suggest our parameterization was superior in other regions. At present, we are performing another cloud overlap analysis by combining the effects of wind shear, atmospheric stability and vertical velocity in the parameterization. Meantime, the effects of precipitation and cloud system scale also will be considered. Thus, we hope that we may answer the question of reviewer in the further work.

(3) It seems to me that the overall method is very much identical to the method used by Di Giuseppe and Tompkins (2015), in particular the choice of horizontal scale, the choice

of threshold for the lidar information and the use of the reanalysis to obtain the large scale atmospheric conditions. Therefore most of section 2 could be significantly simplified by summarizing the Di Giuseppe and Tompkins method and choices.

Response: We agreed with reviewer. In the revised manuscript, we simplified the section 2.3 and 2.4 based on the suggestion of reviewer (please see the section 2.3 and 2.4), but some important information was still kept for the readability of manuscript, especially the retrieval method of overlap parameter.

(4) It would be great to see the results of the impact of vertical velocities in the paper rather than in supplementary materials. First there are only 7 figures for now, so more could be added, second Figures 3 and 4 could be put together. Mace et al. (2009) found some connection between the occurrence of maximum overlap and strong ascent over the Tropics. Also, according to Naud et al 2008 there is an impact at a continental site in the US, so I am intrigued as to why this is no longer true over the TP. I also wonder what would happen to the total cloud cover if the overlap was parameterized with instability, wind shear and vertical motion: would this make the difference between parameterized and real cloud cover closer to zero? This would be a more convincing test to decide whether vertical velocity has any impact on cloud overlap, other the Tibetan Plateau and elsewhere.

Response: We very thank reviewer for providing detailed comments and suggestions.

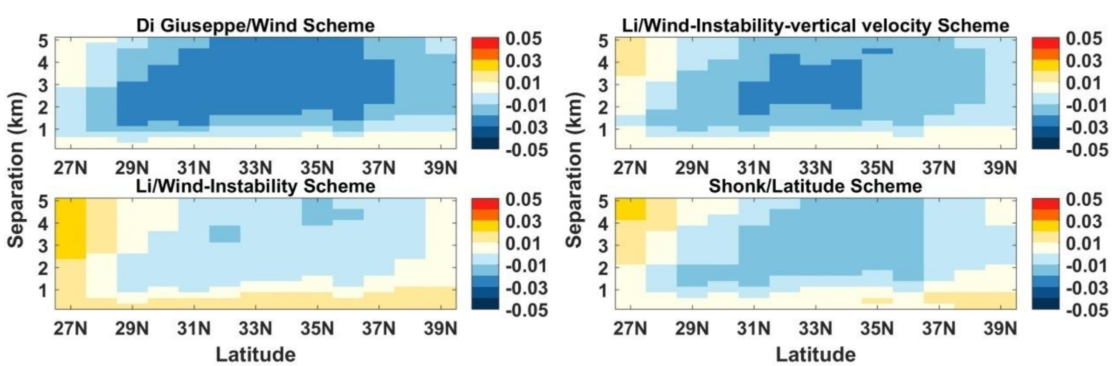

Fig.s1.The zonal difference of cloud cover between calculated and observed for different schemes and its variation with layer separations. The Li/Wind-Instability-vertical velocity and Li/Wind-Instability Schemes are from our study.

Indeed, several previous studies have found the impact of vertical velocity on the cloud overlap parameter over Tropics and mid-latitude site. In the revised manuscript, we added the effect of vertical velocity in the Fig 3, Fig4 and Fig5. Based on the suggestion from reviewer, we also parameterized the overlap parameter as a function of instability, wind shear and vertical velocity (see the Figure s1). We agreed with the comments of reviewer. From the Fig.1, we can see that if we combined the impacts of wind shear, instability and vertical velocity on the overlap parameter in the parameterization of decorrelation length scale *L*, the Li/Wind-Instability-vertical velocity produces better cloud cover prediction than Li/Wind-Instability Scheme when cloud layer separations are smaller than 1 km. As the cloud layer separation exceeds 1 km, the biases obviously increase. Compared with Li/Wind-Instability scheme, Li/Wind-Instability-vertical velocity scheme has a relatively lower R-squared values (R^2=0.89). Although our results indicated that the vertical velocity at 500hPa has an effect on the cloud overlap parameter, especially for small cloud layer separation, the Li/Wind-Instability-vertical velocity scheme doesn't show better superiority than Li/Wind-Instability Scheme, at least over the TP region. The current study only considered the 500hPa vertical velocity, we are performing another cloud overlap analysis by using the vertical velocity at different levels to determine whether includes the vertical velocity at different levels into the scheme may improve the cloud cover predictions over mid-latitude. **In addition, as stated by reviewer, Naud et al (2008) indicated that vertical velocities are not well captured in the reanalysis when convection occurs, while the convective clouds are very frequent during summer over the Tibetan Plateau. As a result, we only parameterized decorrelation length scale *L* as a function of the wind shear and atmospheric stability in current study.**

Point-by-point response:

(5) Line 35: you mention an "overlap parameter" but you have not explain what this is. You might want to add a sentence prior to this one explaining that there is such a parameter to characterize the transition from maximum to random overlap with increasing layer separation. "sensitivity" should be "sensitive".

Response: In the abstract part of the revised manuscript, we added one sentence to interpret the physical meanings of overlap parameter and decorrelation length, respectively. That is, "To do this, the cloud overlap parameter α, which is an inverse exponential function of the cloud layer separation *D* and decorrelation length scale *L*, is calculated and discussed. The parameter α and *L* are both widely used to characterize the transition from the maximum to random overlap assumption with increasing layer separations".

(6) Line 42: "above 1 km" is confusing: since these are layer separations, use "greater than1 km" instead.

Response: We corrected the ambiguous words in the revised manuscript.

(7) Line 85-90: the phrase in brackets (L85) is incorrect, please explain here what these three assumptions are and how they relate to the "cloud overlap parameterizations" more explicitly. You have two sentences after that explaining what they do, but only explain what maximum overlap is, not the other two.

Response: In the revised manuscript, we reorganized the introduction section and added some explanations about different cloud overlap assumptions. That is:

"To derive the reasonable total cloud cover between cloud layers, models have to make some assumption about the cloud layers how to overlap in the vertical direction, such as, maximum, random and minimum assumptions. If the cloud covers of two model layers are given by C_i and C_j, respectively, total cloud cover between these two layers from maximum assumption is $C_{i,j}^{\max} = \max\{C_i, C_j\}$, while the random and minimum assumptions define the total cloud cover as $C_{i,j}^{ran} = C_i + C_j - C_i \times C_j$ and $C_{i,j}^{\min} = \min\{C_i + C_j, 1\}$, respectively. Thus, the maximum assumption minimizes the total cloud cover, while minimum assumption produces minimally overlap between cloud layers and results in maximum total cloud cover (Weger et al., 1992). The total cloud cover predicted by the random assumption will fall somewhere between maximum and minimum assumption (Geleyn and Hollingsworth, 1979)".

(8) Line 93: isn't the whole point of the overlap parameterization to help make the radiative budget calculation. Here you write "will also", maybe remove "also"?

Response: It was removed in the revised manuscript.

(9) Line 104: remove "other" before "passive measurements", otherwise it sounds as if radar observations are passive and not active measurements.

Response: Related information was removed in the revised manuscript.

(10) Line 107-108: add "Mace et al. 2009" in your list of references as they also explore overlap using CloudSat-CALIPSO.

Response: We added the reference in the revised manuscript.

(11) Line 130: add "Mace and Zhang 2014" for reference to the GEOPROF-LIDAR product.

Response: We added the reference in the revised manuscript.

(12) Section 2.3: The first sentence of the section is mentioning an overlap parameter that has still not been defined. So you need to reorder the section such that the equations come first, then the overlap parameter and decorrelation length are introduced and then you can discuss the importance of horizontal scale. In fact this is discussed in section 2.4, so why not wait until then. My preference would be to have most of this material on the formalism of cloud overlap as early as the introduction (see above).

Response: We reorganized the sections 2.3 and 2.4, and moved some important information to the second and third paragraphs of the introduction part.

(15) Section 2.4: this is a rather long and confusing section, is this necessary when it seems you are in the end using a similar horizontal scale as in Di Giuseppe and Tompkins 2015? Part of the confusion comes from a lack of distinction between the horizontal scale, that is the length of the segment of CloudSat orbit you choose to calculate the cloud cover, and your vertical scale as you mention the larger distance here for Figure 2d. As

mentioned above, do you need to discuss “discontinuous” layers when you are only interested in continuous layers?

Response: Following the comments from two reviewers, we deleted some superfluous information and meanwhile kept some details. In addition, we also added a few explanations about distinction between the horizontal scale of cloud system and spatial scale in order to make this version more readable. The cloud overlap properties over the TP have received little attention. Thus, we still kept a little bit discussion about noncontiguous layers in the revised paper.

(16) Line 293: what does “is resolvable to approximately 2%” mean?

Response: Because the along-track resolution of the CPR measurements is about 1.1 km, we used 50 CloudSat profiles as a surrogate of the spatial scale of 50 km. It means that the each cloudy CloudSat profile has a cloud cover about 2% for given spatial scale of 50 km. That is, cloud cover is resolvable to approximately 2%. We added a little bit explanation in the revised manuscript.

(17) Line 333-335: I do not understand this sentence, in particular the phrase “cloud-pair related pentad-averaged the degree of conditional instability…”

Response: We replaced this sentence with" Figures 3c and 3e show the monthly variations in pentad-averaged conditional instability of the moisture convection ($\partial\theta_{es}/\partial z$) and the wind shear (dV/dz) for the contiguous cloud-pairs over the TP, respectively".

(18) Line 339: do you really mean "May and September” or instead “May to September”?

Response: We replaced the "May and September" with "May to September" in the revised manuscript.

(19) Line 343: “is” should be “are”. Here it might be the case that vertical velocities might be large because of extratropical cyclones or other baroclinic instability which could explain maximum overlap. “the increasing of layer distance” should be “the layer separation increases” (check entire text as this phrase is used a few time).

Response: We added the suggestion from reviewer and corrected the phrase in the revised manuscript.

(20) Lines 349-352: here it is also quite possible that other large scale forcings might influence the overlap, this should be considered.

Response: Thanks for your comments. We added the suggestion of reviewer in the revised manuscript. Indeed, current investigation only considers the impact of wind shear, instability and vertical velocity on cloud overlap. The effects of other large scale forcings will be considered in further study.

(21) Line 360: “cloud layer with large distance” should be “cloud layers with large separations”. How large? Greater than 2 km, more?

Response: It was corrected in the revised manuscript and the separations are greater than 2km.

(22) Line 375: this is not exactly true, Naud et al (2008) say that vertical velocities in the tropics are not well captured in reanalysis when convection occurs, however they use them in the mid-latitudes.

Response: We agreed with reviewer. In the revised manuscript, this sentence was corrected as "For example, Naud et al. (2008) indicated that vertical velocities in the tropics are not captured in the reanalysis dataset when convection occurs, thus they only discussed the impact of vertical velocity on the cloud overlap parameter over the mid-latitude and found that vigorous ascent tends to favor maximum overlap."

(23) Line 375-384: as mentioned previously, the monthly and zonal variation plots are not sufficient proof that vertical velocity is not impacting the overlap. It was found to be the case in the mid-latitude winter over land. At least these figures should be included in the manuscript.

Response: We agreed with reviewer. In the revised manuscript, we included the impact of vertical velocities in the text and added further discussion in the section 3.1. (See the revised manuscript). For the related response, please see the reply of question (4) (Line: 174-204).

(24) Line 381: sensitivity to what? “relative” should be “relatively”

Response: It was corrected in the revised manuscript.

(25) Line 407: the use of “stable” is not clear, do you mean “uniform”? I would write instead that the “relationship display some variability, in particular spatially and seasonally” Or something like that.

Response: Based on the suggestion of reviewer, we added the sentence: "relationship display some variability, in particular spatially and seasonally" in the revised manuscript.

(26) Line 454: what does “small cloud cover bias” mean?

Response: We replaced the sentence with "Compared with random and maximum assumptions, the differences of cloud over caused by other schemes are small and range from -3% to 3%".

(27) Line 468: “are still difficult” should be “still have difficulties”

Response: It was corrected in the revised manuscript.

(28) Line 470: replace “rare” with “scarcity”. I do not understand this statement. Why would overlap representation have anything to do with radio soundings. I think that you refer to the Di Giuseppe and Tompkins (2015) statement about reanalysis being less reliable in places where assimilation of radio soundings is scarce. This is because in this case, within the fine scale information from the radio sounding missing, the reanalysis is driven mostly by its model (IFS in the case of ECMWF) and the model has a resolution that is too coarse for small separations. Please elaborate. What is the minimum separation in your study, 250 m?

Response: In the revised paper, we deleted the inaccurate presentations. In addition, the minimum separation in my study is 250m.

(29) Line 475: the sentence “The biases…distinguishable” does not make sense. Please rewrite.

Response: In the revised manuscript, we replaced the sentence with "The differences of cloud cover caused by different overlap schemes are distinguishable"

(30) Line 476: “close cloud layers”: how close, please specify.

Response: It was specified in the revised manuscript.

(31) Line 477-478: replace “are still cause slightly overestimation” with something like “overestimate total cloud cover slightly”. This sentence is unclear.

Response: We replaced the “are still cause slightly overestimation” with "overestimate total cloud cover slightly" in the revised manuscript.

(32) Lines 475-484: this whole paragraph is very hard to follow, please try and clarify.

Response: We reorganized whole paragraph in the revised manuscript.

(33) Line 500: please specify “over the Tibetan Plateau” after “data”

Response: It was added in the revised manuscript.

(34) Line 506: “greater α values”: please explain what this means physically.

Response: We added the explanation about overlap parameter α in the revised manuscript.

(35) Line 508: again explain what the decorrelation length is physically

Response: We added the explanation about decorrelation length in the revised manuscript.

(36) Line 536: here I am not sure I understand the logic of these last few lines. Surely, cloud trends over the Plateau were obtained with observations and not models? Or do you mean to say that these trends are in fact obtained from GCMs prediction runs? Please specify. Cloud trends from observations have little to do with overlap.

Response: We agreed with reviewer. The last several sentences was corrected as "By using surface observations over 71 stations, some studies verified that annual and seasonal total cloud covers have declined during 1961-2005 (Duan and Wu, 2006; You et al., 2014). However, whether such variations of total cloud covers are linked with the changes of degree of cloud overlap over the TP are still unclear. Thus, more efforts are needed to reasonably evaluate the impact of cloud overlap on the total cloud cover variations over these sensitive areas of climatic change (e.g., Tibetan Plateau and Arctic)"

(37) Acknowledgments: please specify the locations of the datasets so readers can find them.

Response: We added the available links about datasets in the Acknowledgments part.

(38) Line 34: “overlapped” should be “overlap”. Here and every else in the manuscript, the “increasing of layer distance” is incorrect, it should read “increasing layer separation”.

Response: It was corrected in the revised manuscript.

(39) Line 38: “well agreement” is incorrect, replace with “in good agreement”. Add “a” before “multiple linear regression method”.

Response: These errors were corrected in the revised manuscript.

(40) Lines 66-67: this sentence is confusing, “increasing” should be “increase”, “became” should be “has” and the last statement is unclear, has the “variation” also weakened?

Response: These errors were corrected in the revised manuscript.

(41) Line 72: “such as” is not appropriate here, maybe you mean “For example”?

Response: It was corrected in the revised manuscript.

(42) Line 160: replace “other radar information” with “the radar information”

Response: We replaced “other radar information” with “the radar information” in the revised manuscript.

(43) Line 327: replace “occurs” with “during”

Response: We replaced “occurs” with “during” in the revised manuscript.

(44) Line 340: “instability” should be “unstable”

Response: We replaced “instability” should be “unstable” in the revised manuscript.

(45) Line 348: replace “of” with “between”

Response: We replaced “of” with “between” in the revised manuscript.

(46) Line 354: replace “to the south part” with “in the southern part”

Response: We replaced “to the south part” with “in the southern part” in the revised manuscript.

(47) Line 355: replace “instability” with “a relatively more unstable”

Response: We replaced “instability” with “a relatively more unstable” in the revised manuscript.

(48) Line 356: add “that” before “enhances”

Response: It was added in the revised manuscript.

(49) Line 359: add “the” before “southern part”

Response: It was added in the revised manuscript.

(50) Line 364: replace “contributed” with “attributed”

Response: We replaced “contributed” with “attributed” in the revised manuscript.

(51) Line 366: add “the” before “accelerated”

Response: It was added in the revised manuscript.

(52) Line 370-371: replace “are still difficult to capture” with “still have difficulties to represent”

Response: We replaced “are still difficult to capture” with “still have difficulties to represent” in the revised manuscript.

(53) Line 371: “those cloud layer” is plural, i.e. “cloud layers”

Response: It was corrected in the revised manuscript.

(54) Line 400: replace “relative” with “relatively”

Response: We replaced “relative” with “relatively” in the revised manuscript.

(55) Line 408: remove “shortly”

Response: It was removed in the revised manuscript.

(56) Line 497: replace “and related to” with “and it impact on”

Response: We replaced “and related to” with “and it impact on” in the revised manuscript.

(57) Line 503: again rewrite “the increasing of layer distance”, not correct phrase.

Response: It was corrected in the revised manuscript.

(58) Line 506: again, “well agreement” should be “in good agreement”

Response: It was corrected in the revised manuscript.

(59) Line 507: again, add “a” before “multiple”

Response: It was added in the revised manuscript.

(60) Line 511: again, replace “above” with “greater than”

Response: We replaced “above” with “greater than” in the revised manuscript.

Response to Reviewer #2's Comments:

Jiming Li et al. (Author)

We are very grateful for the Review #2's detailed comments and suggestions, which help us improve this paper significantly. Based on the two Reviewers' comments and suggestions, we reorganized the introduction and added some interpretations in each section in order to make the manuscript more clear. In addition, some superfluous information in each section was deleted.

Important revision includes:

(5) The structure of the manuscript, especially for the Abstract and Introduction sections, was reorganized in order to make the manuscript more clear.
(6) The physically means of technical terms were added in the Abstract section.
(7) The Introduction section also interpreted the main aims of this study.
(8) In each section, we also added some interpretations about the comments from reviewers.

Please see our point-by-point reply to comments. In addition, all revisions were highlighted in revised manuscript by using yellow color.

Specific responses:

(1) Distance between layers

It is not entirely clear how cloud populations are separated by distance between layers. If a continuous cloud layer stretches over 6 km in depth, does it contribute to all distances from 0-6km, or only the maximum distance? If all distances, does it therefore contribute to the "1 km distance" multiple times? That is, in a 6-km deep cloud, we can identify 6 pairs of layers that are separated by 1 km. This issue should be addressed when describing the methodology (see also comment about Figure 1, line 213-221).

Response: Yes, for the contiguous cloud layer which stretches over 6 km in depth, it contributes to all distances and multiple times for a given distance (e.g., 1 km distance). In the revised manuscript, we added some explanations in the section 2.3:" Layers are analyzed in pairs and no 'double-counting'. If cloud layer pairs have the same separation distance but different altitudes, they will be categorized into the same statistic group". The methodology is same with those of used in previous studies (e.g., Hogan and Illingworth, 2000; Di Giuseppe and Tompkins, 2015).

(2) The second issue is that multiple cloud types – or clouds at different heights in the atmosphere – may be grouped together. For instance, a contiguous cloud layer that is 1 km deep can occur anywhere, from stratocumulus, to altostratus, to cirrus. I would expect the shear and stability calculated over 1 km to differ a lot for these different cloud types. The authors should address this, perhaps in a brief discussion section.

Response: We very thank for reviewer' comments and suggestions. Indeed, the shear and stability calculated over 1 km should be different for different cloud types. Thus, we added a little bit discussion about uncertainty in the section 4. The added information is **"**In addition, Li et al. (2015) indicated that the overlap properties between different cloud types are obvious different but the most significant components of the global climate system. Although current study doesn't include the information of cloud type, the sensitivity of α on the meteorological parameters in our analysis actually exhibit the effects of cloud types on the α due to different combinations of cloud type with same layer separation possibly take place in distinct wind shear and stability conditions".

(3) **Calculation of cloud cover using parameterization schemes**

Section 3.2 is very interesting, but it is sprung upon the reader. The inverse exponential function is not previously introduced. The authors do not explain how the cloud cover is calculated from the different parameterization schemes. Presumably, the decorrelation length scale L is calculated from the dV/dz and dtheta/dz derived from ERA-Interim data interpolated to the CloudSat track. Subsequently, alpha can be calculated for each separation using equation 6. But how does this lead to a calculation of cloud cover (which is compared in Figure 6, according to line 450)? One additional paragraph in this section (prior to presentation of Figure 6) describing the cloud cover calculation is required.

Response: We agreed with reviewer. Based on the comments and suggestions from two reviewers, we reorganized the third paragraph of the introduction to make the definitions of overlap parameter α and decorrelation length scale *L* more clear.

We added the sentence "Finally, Hogan and Illingworth (2000) fitted the reduction in α with layer separation *D* as an inverse exponential function of the decorrelation length scale *L*: $\alpha = e^{-D/L}$. Thus, α and *L* are both used to characterize the transition from the maximum to random overlap assumption with increasing layer separations." in the third paragraph of introduction part in the revised manuscript.

In addition, we also added one additional paragraph in this section 4 in order to describe the cloud cover calculation. "After deriving the regression formula of decorrelation length scale *L*, we re-apply it to all contiguous cloud samples and retrieve the *L* and corresponding α based on the formula: $\alpha = e^{-D/L}$ and dynamical conditions. Finally, retrieved overlap parameter α is used to calculate the total cloud cover between any two cloud layers by using the Equ. (1) and the definitions of random and maximum overlap assumptions".

Point-by-point response:

(4) Line 27: One sentence in the abstract on the importance of understanding cloud overlap in the Tibetan Plateau would draw in a broader audience.

Response: We reorganized the abstract part in the revised paper. The beginning of the abstract is "Studies have showed that the changes of cloud cover are responsible for the rapid climate warming over the Tibetan Plateau (TP) in the past three decades. To derive reliable simulation of the total cloud cover, atmospheric models have to reasonably represent the way of vertical overlap between cloud layers in them."

(5) Line 32: "Unique" suggests that the authors have compared the TP to all other regions. Perhaps remove this sentence.

Response: It was removed in the revised manuscript.

(6) Line 68: "Kang et al summarized" – based on what? Observations? Models?

Response: It was corrected in the revised manuscript. See the Introduction section.

(7) Line 82 & 85: Please specify what type of models you are mostly concerned with, e.g. "horizontal grid length greater than 10 km". So that it is clear to the reader that only those models rely on some overlap parameterization.

Response: Our study focused on the climate change, thus climate models is the first choice. In the revised manuscript, we specified it.

(8) Line 106: Are there any radar sites in the TP region at all?

Response: There is no long-term Radar observation over the TP region.

(9) Line 113: Remove "fortunately".

Response: It was removed in the revised manuscript.

(10) Line 124: Break paragraph at "However, the related question…" and merge the remainder with the following paragraph. That sentence is a clear purpose of the paper.

Response: We agreed with reviewer. It was corrected in the revised manuscript.

(11) Line 148: Remove "can".

Response: It was removed in the revised manuscript.

(12) Line 160: At this point, it is important to clarify that the radar does not distinguish between cloud and precipitation. Then the text at 320-332 will not be such a surprise.

Response: We agreed with reviewer. We added the explanation: "It is noting that the 2B-GEOPROF-LIDAR dataset does not distinguish cloud and precipitation, therefore any bias in our results caused by precipitation can't be removed in current analysis." in the revised manuscript.

(13) Line 165: Add here the lines 196-199 regarding noise in the observations and surface contamination.

Response: It was added in the revised manuscript. See section 2.1.

(14) Line 213-221 & Figure 1: This is rather difficult to follow. It would be useful to have one or two additional panels that illustrate the cloud cover and overlap parameter for the particular scene, perhaps for the different length scales considered. For instance, it would be great to have an example of a continuous cloud that is more than 4 km deep, so that the reader can see how it may have “less than random” overlap.

Response: We agreed with reviewer. In the revised manuscript, we reorganized the sections 2.3 and 2.4. In addition, we also added two additional subplots in the figure1 to illustrate the cloud cover and overlap parameter for the given cloud scene. Please see the sections 2.3 and 2.4.

(15) Line 217: What does “cloudy” mean in this context?

Response: The "cloudy" means that the atmospheric layers are classified as cloud layers. In the revised manuscript, we replaced "cloudy" with "cloud layers".

(16) Line 233: Please change all references to “discontinuous” to “non-continuous”, or adjust your figures (be consistent).

Response: In the revised manuscript, we replaced "discontinuous" with "noncontiguous ".

(17) Line 248: “correlation” – no correlation has been shown or calculated.

Response: It was corrected in the revised manuscript.

(18) Line 253-254: Remove “provided … error. Simply these authors”

Response: It was removed in the revised manuscript.

(19) Line 260-261: “should account for the typical cloud system scales” add “in their parameterization schemes” (presumably).

Response: It was added in the revised manuscript.

(20) Line 281: “the number of available samples” – What is a sample? Is it a 50-km

stretch in a CloudSat orbit?

Response: In the revised manuscript, we replaced "the number of available samples" with "the number of available cloud pair samples". Thus, the number is just for the cloud layer-pair, not for the 50-km segment in a CloudSat orbit.

(21) Line 281-294: Figure 2d is rather difficult to interpret. It is likely that these values make more sense when they are presented in a table.

Response: In revised manuscript, we added some explanations about sample number in order to make the sentence more clear. That is, "Fig.2d shows the variations of sample number and the cumulative percentage with cloud layer separation for both noncontiguous and contiguous clouds at a given spatial scale of 50 km. It shows that the cumulative proportion of cloud sample significantly increases with increasing layer separation. For the contiguous cloud, the cumulative percentage accounts for 90% of all samples when layer separation is smaller than 4 km".

(22) Line 281-294: The description of cloud cover (versus cloud fraction) would have been helpful sooner, probably around line 213-221 (possibly in combination with an illustration in Figure 1).

Response: We agreed with reviewer. In the revised manuscript, we moved the description of cloud cover and cloud fraction to the beginning of section 2.3.

(23) Line 301: "thicker than other seasons" – is there a simply explanation for this, e.g. a greater tropopause height?

Response: We added a simply explanation about this in the revised manuscript. That is, "frequent strong convective motions during summer season favor deep cloud systems".

(24) Line 321: "small horizontal scale of cumulus" – The authors should also comment on the fact that these are poorly observed by CloudSat alone, so require the lidar to be available (not extinguished by cloud aloft). How does that affect the statistics?

Response: We agreed with reviewer. Indeed, although the 2B-GEOPROF-lidar dataset includes the lidar information, cumulus with small scale and cloud systems closed the surface are still missed in our study. It means that our statistical results will be slightly underestimated, but this bias can be partly offset by precipitation effect, especially during the summer season. Thus, it isn't the main source of uncertainty in our analysis.

(25) Line 395: Regarding Figure 5, please mention which scale is used for the segments, presumably 50 km?

Response: It was added in the revised manuscript.

(26) Line 400: "seems relatively weaker" – this is difficult to quantify when the two parameters have different units.

Response: The sentence was removed in the revised manuscript.

(27) Line 411: "As we know" – actually, this is completely new to the reader! (remove).

Response: It was removed in the revised manuscript.

(28) Line 481: "this new scheme" – please refer to the name of the scheme.

Response: It was corrected in the revised manuscript.

(29) Figure 1: Apart from the comment above (213-221), mention in the caption that observations near the surface have been removed.

Response: We already added the sentence in the caption of Figure 1.

(30) Figure 2: What is the uncertainty on alpha? Although the authors provide the sample number in panel d, there could still be a lot of variation in alpha. The authors should provide some measure of uncertainty, e.g. standard deviation or interquartile range.

Response: We agreed with reviewer. In the revised manuscript, we added the error bars in the Figure 2 and revised the figure caption.

(31) Figure 5: Again, what is the uncertainty in alpha? The sample number will be smaller due to the compositing on dV/dz and dtheta/dz. The reference to "50% continuous" is confusing in the legend and should be placed in the caption.

Response: We agreed with reviewer. In the revised manuscript, we added the error bars in the Figure 5 and reorganized the legends. In addition, we also added the subplots about vertical velocity in the Fig.5. Please see the revised manuscript.

The impact of atmospheric stability and wind shear on vertical cloud overlap over the Tibetan Plateau

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Abstract

Studies have showed that the changes of cloud cover are responsible for the rapid climate warming over the Tibetan Plateau (TP) in the past three decades. To derive reliable simulation of the total cloud cover, atmospheric models have to reasonably represent the way of vertical overlap between cloud layers in them. Until now, however, this subject has received little attention due to the limited observation, especially over the TP. Based on the above information, the main aim of this study is to examine the cloud overlaps over the TP region, and build an empirical relationship between cloud overlap properties and large-scale atmospheric dynamics by using 4 years (2007–2010) of data from the CloudSat cloud product and collocated ERA-Interim reanalysis product. To do this, the cloud overlap parameter α, which is an inverse exponential function of the cloud

layer separation D and decorrelation length scale L, is calculated and discussed. The parameter α and L are both widely used to characterize the transition from the maximum to random overlap assumption with increasing layer separations. For those nonadjacent layers without clear sky between them (that is, contiguous cloud layers), it is found that the overlap parameter α is sensitive to the unique thermo-dynamic and dynamic environment over the TP, i.e., the unstable atmospheric stratification and corresponding weak wind shear, which leads to maximum overlap (that is, greater α values). This finding agrees well with the previous studies. Finally, we parameterize the decorrelation length scale L as a function of the wind shear and atmospheric stability based on a multiple linear regression. Compared with previous parameterizations, this new scheme can improve the simulation of total cloud cover over TP when the separations between cloud layers are greater than 1km. This study thus suggests that effects of both wind shear and atmospheric stability on cloud overlap should be taken into account in the parameterization of decorrelation length scale L in order to further improve the calculation of radiative budget and the prediction of climate change over TP in the atmospheric models.

1. Introduction

The Tibetan Plateau (TP), which is also known as the “roof of the world” or the “world water tower”, plays a significant role in determining global atmospheric circulations, in addition to its strong influence over Asia via its thermal-dynamic and dynamic forcings (Yanai et al., 1992; Ye and Wu, 1998; Duan and Wu, 2005; Xu et al., 2008; Wu et al., 2015). Some studies have showed that the TP has experienced significant climate warming over the past three decades (e.g., Yang et al., 2014; Kang et al., 2010), and it will continue in the future (e.g., Duan and Wu., 2006; Wang et al., 2008). The rapid warming has caused glacier retreat and expansion of glacier-fed lakes (Zhu et al., 2010), permafrost degradation (Cheng and Wu, 2007), and weakening of heating source (Yang et al., 2011). Based on the satellite and surface observations, many studies have linked the rapid warming over TP to the changes of cloud cover over this region (e.g., Chen and Liu, 2005; Duan and Wu, 2006; Li et al., 2006; Yang et al., 2012; You et al., 2014). For example, a recent study has indicated that the increased nocturnal cloud cover over the northern TP could increase the nighttime temperature by enhancing downward surface infrared radiation, while the decreased daytime cloud cover over the southern TP has contributed to the increase of surface air temperature during daytime by enhancing downward surface solar radiation (Duan and Xiao, 2015). It means that the reliable simulation of cloud cover in the climate models will favor the prediction of climate change over TP.

However, our incomplete understanding of the cloud physical processes and the limited cloud observations over the TP make the simulation of total cloud cover in the climate models still unreliable. One of the remaining challenges involves how to reasonably represent the characteristics of the vertical overlapping of cloud layers in these models. Cloud overlap means that two or more cloud layers are simultaneously present over the same location but at different levels in the atmosphere. To derive the reasonable total cloud cover between cloud layers, models have to make some assumption about the cloud layers how to overlap in the vertical direction, such as, maximum, random and minimum assumptions. If the cloud covers of two model layers are given by C_i and C_j, respectively, total cloud cover between these two layers from maximum assumption is $C_{i,j}^{\max} = \max\{C_i, C_j\}$, while the random and minimum assumptions define the total cloud cover as $C_{i,j}^{ran} = C_i + C_j - C_i \times C_j$ and $C_{i,j}^{\min} = \min\{C_i + C_j, 1\}$, respectively. Thus, the maximum assumption minimizes the total cloud cover, while minimum assumption produces minimally overlap between cloud layers and results in maximum total cloud cover (Weger et al., 1992). The total cloud cover predicted by the random assumption will fall somewhere between maximum and minimum assumption (Geleyn and Hollingsworth, 1979). Studies have shown that these different overlap assumptions result in obvious different total cloud covers and will significantly affect the calculated radiative budgets and heating/cooling rate profiles (Morcrette and Fouquart, 1986; Barker et al., 1999; Barker and Fu, 2000; Chen et al., 2000; Pincus et al., 2005; Zhang and Jing, 2010; 2016; Zhang et al., 2013; Jing et al., 2016).

To improve the simulation of total cloud cover, Hogan and Illingworth (2000) revisited the cloud overlap assumptions and proposed a simpler and more useful expression for the degree of cloud layer overlap (exponential random overlap assumption) by using the ground-based radar measurement. In the expression, the observed cloud cover between two cloud layers can be expressed as the linear combination of the maximum and random overlap by using a weighting factor, termed as cloud overlap parameter α:

$$\alpha = \frac{C_{i,j}^{obs} - C_{i,j}^{ran}}{C_{i,j}^{\max} - C_{i,j}^{ran}} \qquad (1)$$

The overlap parameter α ranges from 0 (random) to 1 (maximum) when the observed total cloud cover falls between the values using the maximum and random overlap assumptions. The α will be negative if the degree of cloud overlap is lower than that predicted by the random overlap assumption. Finally, Hogan and Illingworth (2000) fitted the reduction in α with layer separation D as an inverse exponential function of the decorrelation length scale L: $\alpha = e^{-D/L}$. Thus, α and L are both used to characterize the transition from the maximum to random overlap assumption with increasing layer separations. Until now, many efforts have been made to derive the values of α and L using ground-based radar observations (e.g. Mace and Benson-Troth, 2002; Willén et al., 2005; Naud et al., 2008; Oreopoulos and Norris, 2011) and improve the representation of *L* in the models (Shonk et al 2010; 2014; Di Giuseppe and Tompkins, 2015). For example, Oreopoulos and Norris (2011) derived *L* based on radar measurement taken over the US Southern Great Plains (SGP). Their results indicated that *L* ranges from 2 to 4.5 km across different seasons and smaller spatial scales correspond with smaller *L* values. Based on two months of cloud mask profile information from the Space-based radar and lidar, Barker (2008) quantified the properties of cloud overlap on a global scale and found a wide range of *L* values, with a median value of 2 km. In other studies, decorrelation length scale *L* is also parameterized as a function of latitude (Shonk et al., 2010; 2014), total cloud cover (Yoo et al., 2014) or wind shear (Di Giuseppe and Tompkins, 2015). These findings suggest that meteorological factors could be connected to the overlap way between cloud layers.

To date, however, the related question of the cloud overlapping over the TP region has received little attention due to the limited observation. It is still an open question on how the unique thermo-dynamic and dynamic environment over the TP region affects cloud overlap there. The millimeter-wavelength cloud profiling radar (CPR) launched on CloudSat (Stephens et al., 2002) and the cloud-aerosol lidar with orthogonal polarization (CALIOP) (Winker et al., 2007) launched on CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) provide an unprecedented opportunity to investigate vertical cloud overlaps on a global scale (e.g., Barker et al., 2008; Kato et al., 2010; Mace et al., 2009; Li et al., 2011; 2015; Tompkins and Di Giuseppe, 2015). In the following study, we investigate the cloud overlap properties over the TP region and identify an empirical relationship between decorrelation length scale *L* and large-scale atmospheric dynamics by combining the cloud cover profile information from the 2B-GEOPROF-LIDAR dataset (Mace et al., 2009; Mace and Zhang, 2014) and the meteorological fields from the ERA-Interim reanalysis datasets (Dee et al., 2011). The parameterization of decorrelation length scale *L* will favor the simulation of total cloud cover and the calculation of radiative energy budget over TP in the models. This paper is organized as follows. The datasets and methods used in this study are briefly described in Section 2. Section 3 outlines the monthly and zonal variations of the cloud overlap parameters over the TP region. The impacts of the atmospheric state and large-scale atmospheric dynamics on cloud overlap are presented in Sections 4. The conclusions and discussion are given in Section 5.

2. Datasets and methods

4 years (2007–2010) of data from the CloudSat 2B-GEOPROF-LIDAR, ECMWF-AUX and the daily 6-hour ERA-Interim reanalysis are used to analyze the impacts of atmospheric states and dynamics on the cloud overlap over the TP (27 °N-39 °N;78 °E-103 °E) region (Fig. 1a).

2.1 Satellite datasets

Radar signals can penetrate the optically thick cloud layers that attenuate lidar signals, but lidar signals may sense the optically thin hydrometeor layers that are below the detection threshold of radar signals. Thus, with the unique complementary capabilities of the CPR on CloudSat and the CALIOP on the CALIPSO, the 2B-GEOPROF-LIDAR dataset produces the most accurate description of the locations of the hydrometeor layers in the atmosphere on the global scale (Mace and Zhang, 2014). In this dataset, every CloudSat profile includes 125 height layers (e.g., vertical bin), and the "*Cloud Fraction*" parameter reports the fraction of the lidar volume within each radar vertical bin that contains hydrometeors (Mace et al., 2009; Mace and Zhang, 2014). Several previous studies have identified a cloudy atmospheric bin based on different thresholds of the lidar-identified cloud fraction, including a 99% (Barker, 2008; Di Giuseppe and Tompkins, 2015) or a 50% threshold (Haladay and Stephens, 2009; Verlinden et al., 2011). Here, a threshold of 99% is used in our study. Due to the significant attenuation of lidar signals to the optically thick layers, this parameter fails to provide the "*Cloud Fraction*" for optically thick layers. Thus, we also use the radar information (i.e., cloud "*LayerBase*" and "*LayerTop*" fields) from the aforementioned dataset to construct the complete two-dimensional cloud mask (See Fig. 1b). It is noting that the 2B-GEOPROF-LIDAR dataset does not distinguish cloud and precipitation, therefore any bias in our results caused by precipitation can't be removed in current analysis. Besides the 2B-GEOPROF-LIDAR dataset, the ECMWF-AUX dataset (Partain, 2004), which is an intermediate dataset that are the ancillary ECMWF state variables interpolated across each CloudSat CPR bin, is also used to provide the pressure and height information of each vertical bin in the cloud mask profile. The vertical and horizontal resolutions of these products are 240 m and 1.1 km, respectively. To avoid sunlight scattering contamination to lidar observation and minimize surface contamination of the CPR, we only use the nighttime datasets above 1 km over the TP surface in the following analysis.

2.2 Meteorological reanalysis dataset

The 6-hourly ERA-Interim reanalysis with a grid resolution of 0.25 °×0.25 ° (Dee et al., 2011), is used to characterize the atmospheric thermodynamic and dynamic states over the TP. For each cloud mask profile in the 2B-GEOPROF-LIDAR, the vertical profiles of the zonal wind *u*, meridional wind *v*, relative humidity *rh*, specific humidity *sh* and atmospheric temperature *T* closest to the cloud profile in both space and time are extracted and further interpolated vertically to match the vertical bins of the cloud mask profile. Following Di Giuseppe and Tompkins (2015), the *u* and *v* winds at every vertical bin are then projected onto the satellite overpass track, being averaged in the along-track direction for all profiles in the selected CloudSat data segment to derive the scene-average, along-track horizontal wind *V*. Here, we define the wind shear $dV/dz_{i,j}$ between the layers *i* and *j*, as follows:

$$dV/dz_{i,j} = \frac{\max\{V_i;V_j\} - \min\{V_i;V_j\}}{D_{i,j}}, \qquad (2)$$

Where V_i and V_j are the horizontal winds at layers *i* and *j*, respectively, and $D_{i,j}$ is the layer separation distance. The derived wind shear will be used to calculate the cloud overlap parameter. For the CloudSat overpass track (Fig. 1a), Di Giuseppe and Tompkins (2015) indicated that the cross-track shear of the zonal wind *u* has little statistical significance.

Similarly to the wind shear, we calculate the vertical gradient of the saturated equivalent potential temperature ($\partial\theta_{es}/\partial z_{i,j}$) between the same two layers to quantify the dependence of the cloud overlap on the degree of the conditional instability of the moist convection. Here,

$$\theta_{es} = \theta \exp\left(\frac{L_v r_s}{C_p T}\right)$$

$$\theta = T\left(\frac{1000}{p}\right)^{0.286}, L_v = 2.5\times10^6 - 2323\times(T - 273.16) \qquad (3)$$

$$r_s = \frac{sh}{rh\times(1-sh)}$$

where θ is the potential temperature, L_v is the latent heat of vaporization, r_s is the saturation mixing ratio, C_p is the specific heat capacity at a constant pressure, and T is the atmospheric temperature. The smaller the $\partial\theta_{es}/\partial z_{i,j}$, the more unstable the atmosphere. Furthermore, the scene-averaged vertical velocity at 500 hPa is also extracted from the ERA-Interim reanalysis to analyze the impact of vertical motion on cloud overlap. The positive values are for the updraft, and negative values are for the subsidence.

2.3 The overlap parameter and its dependence on the spatial scale

Previous studies have shown that the overlap parameter α and decorrelation length L are sensitive to the spatial scale of the GCM's grid box (Hogan and Illingworth, 2000; Oreopoulos and Khairoutdinov, 2003; Oreopoulos and Norris, 2011; Pincus et al., 2005). For example, Hogan and Illingworth (2000) found that cloud overlap parameter tends to increase with decreasing spatial and temporal resolutions (i.e., increasing vertical and horizontal grid scales) of GCMs.

To examine the dependence of overlap parameter on the spatial scale, each CloudSat orbit over the TP region is divided into segments with different horizontal lengths including 25, 50, 100 and 200 km. Hereafter, this horizontal length is referred to as the spatial scale of the GCM's grid box. Fig.1b shows an example of cloud mask from the 2B-GEOPROF-lidar dataset over the TP region. This cloud mask includes eight, four, two and one segments, which correspond to the horizontal resolution of 25, 50, 100 and 200 km, respectively. Given the threshold of 99% for cloud fraction, the segment-average cloud cover profile of each segment is first derived. Here, it is important to emphasize that cloud fraction and cloud cover are different variables in our study. The "*Cloud fraction*" reports the fraction of lidar volumes in each radar vertical bin that contains hydrometeors and is used to identify a cloudy atmospheric bin based on the chosen threshold, which is 99% in this study. When averaging all cloud fraction profiles in the along-track direction for given CloudSat data segment, we derive the segment-average cloud cover profile, which represents the percentage of clouds in a given spatial scale and certain height. Then, the vertical overlap between any two atmospheric layers in this profile is calculated if the cloud covers (C_i and C_j) of both layers exceed 0. Layers are analyzed in pairs and no 'double-counting'. If cloud layer pairs have the same separation distance but different altitudes, they will be categorized into the same statistic group.

Following Hogan and Illingworth (2000) and Di Giuseppe and Tompkins (2015), we consider the nonadjacent layers to be a contiguous cloud pair when all layers between them are classified as cloud layers. Otherwise, these layers are classified as a noncontiguous cloud pair (Hogan and Illingworth, 2000; Di Giuseppe and Tompkins, 2015).

Based on the definitions of different overlap assumptions and α in the introduction section, Figs.1c and 1d show an example of the observed and calculated segment-average cloud cover profiles based on maximum and random assumptions, and corresponding overlap parameters of contiguous cloud pairs for 25, 50, 100 and 200 km spatial scale in given cloud mask sample (Fig. 1b). It is clear that the observed and calculated cloud covers and corresponding overlap parameters tend to increase as the spatial scale increases. Meantime, the observed cloud covers tend to transform from the maximum to random overlap assumption with increasing layer separations.

By collecting 4 years of cloud sample from the 2B-GEOPROF-LIDAR dataset, Figs.2a and 2b further show the dependence of α on the layer separation and its sensitivity to the spatial scale for both noncontiguous and contiguous cloud layers. Many studies have used ground- and space-based radars to examine the validity of the random overlap assumption for the vertically noncontiguous clouds (Hogan and Illingworth, 2000; Mace at al., 2002; Naud et al., 2008; Di Giuseppe and Tompkins, 2015). Fig.2a shows that the degree of cloud overlap of the noncontiguous clouds over the TP region is lower than the random overlap, especially when the layer separation is smaller than 2km. Given the spatial scale of 50 km, almost all of the α-values are negative and fall between -0.25 and -0.05. Thus, the total cloud cover would still slightly be underestimated for noncontiguous cloud pairs by using the random overlap assumption. Assuming a cloud layer separation of less than 9 km, α for noncontiguous cloud pairs increases as the spatial scale increases (e.g., from 25 km to 200 km). For a contiguous cloud pair (Fig. 2b), α decrease from 0.95 to 0 with an increasing separation. Meantime, a slight dependence of α on the spatial scale is also observed for contiguous cloud pairs when they are separated by a distance of about 1 km to 4 km. This indicates that the maximum overlap is slightly more common for a larger horizontal domain, which is consistent with previous studies (Hogan and Illingworth, 2000; Oreopoulos and Khairoutdinov, 2003;

Oreopoulos and Norris, 2011).

2.4 Selection of thresholds for cloud cover and spatial scale

About the dependence of α on the spatial scale, Tompkins and Di Giuseppe (2015) theorized that some overcast or single cloud layers would be removed from the samples when the spatial scale is smaller than the cloud system scale, thus biasing α and its decorrelation length *L*. Given a spatial scale of 50 km, the ratio of the spatial scale to the cloud system scale decreases strongly from the equator to the poles because many of the frontal cloud systems of the middle and high latitudes are larger than the convective cloud systems over the tropics. Ultimately, the corresponding bias in α would increase with latitude. For the foregoing reasons, regional atmospheric models should account for the typical cloud system scale in their parameterization schemes when using a fixed horizontal resolution.

Fig. 2c depicts the probability distribution functions (PDFs) of the horizontal scales of the along-track cloud systems at different heights over the TP region. Here, the horizontal scale of a cloud system at a given height along the CALIPSO/CloudSat track is determined by calculating the number of continuous cloud profiles (*N*) at a given height. Using a 1.1 km along-track resolution for the CPR measurements, the along-track scale (*S*) of a cloud system is $S=N\times 1.1$ km (Zhang et al., 2014; Li et al., 2015). It is clear that the probability of cloud system with small-scale decreases with increasing height (Fig.2c). The mean horizontal scale of 59.2 km for a cloud system at a height of 15 km is almost twelve times greater than that (i.e., 4.6 km) at a height of 2 km. For TP region, we can see that the horizontal scales of cloud system below 10 km are smaller than the spatial scale of 50 km, thus we apply the spatial scale of 50 km to perform the following analysis although this scale would still result in significant errors in α at higher atmospheric heights (e.g., 15km) where cloud has large horizontal scale.

In addition, to further reduce the sensitivity of α to the spatial scale caused by data truncation, we follow the study from Tompkins and Di Giuseppe (2015) and apply a simple data filter so that only atmospheric layers with segment-average cloud cover below a given threshold of 50% are retained. As stated by Tompkins and Di Giuseppe (2015), data might still be truncated with this filter, but the sensitivity of the results to the spatial scale should largely be reduced. After limiting the spatial scale (50 km) and upper limit of cloud cover (50%), the number of available cloud layer-pair samples is still at least one million, thus ensuring statistical significance. Fig.2d shows the variations of sample number and the cumulative percentage with cloud layer separation for both noncontiguous and contiguous clouds at a given spatial scale of 50 km. It shows that the cumulative proportion of cloud sample significantly increases with increasing layer separation. For the contiguous cloud, the cumulative percentage accounts for 90% of all samples when layer separation is smaller than 4 km. Given the 1.1 km along-track resolution of the CPR measurements and a spatial scale of 50 km (that is, about 50 CloudSat profiles), the each cloudy CloudSat profile has a cloud cover about 2% (Di Giuseppe and Tompkins, 2015).

3. Monthly and zonal variations of overlap parameter for contiguous clouds

Figure 3a shows the monthly variations in α for the contiguous cloud-pairs based on pentad-average over the TP. In Fig.3a, the maximum separation of contiguous cloud layers gradually increases from January (approximately 6 km) to August (beyond 8 km) and then gradually decreases, indicating that the cloud systems over TP during summer are thicker than other seasons due to frequent strong convective motions. When the cloud layer separation is less than 1 km, the overlap parameter α has little monthly variation and is always large (even beyond 0.7). However, the monthly variation of α becomes manifest as the layer separation is larger than 1 km. For a 2-km cloud separation, e.g., α reaches its maximum of 0.45 in August and a minimum of 0.1 in February (see Fig. 3d). For a separation of 3 km, α is generally lower but has the similar monthly variation to those seen for a 2-km separation. By checking the negative value of α in Fig.3a, it is clear that even random overlap assumption could underestimate the total cloud cover between two cloud layers with large separation during all seasons except summer. These cloud overlap features may be associated with the unique topographical forcing and corresponding thermo-dynamic and dynamic environment of the TP. In summer, the TP is usually considered as an atmospheric heat source or “air pump” due to its higher surface temperature compared with surrounding regions at the same altitude (Wu et al., 2015). Additionally, a humid and warm air intrudes from the South Asia monsoon area into the lower atmosphere over the TP would intensify the atmospheric instability of moist convection when combined with the enhanced surface heating (Taniguchi and Koike, 2008). This process further promotes the transportation of water vapor into high altitudes and favors the development of convective clouds. Indeed, satellite observations have indicated that cumulus prevails over the TP during the summer (Wang et al., 2014; Li and Zhang, 2016).

Due to cumulus over the TP has a small horizontal scale, thus a 50 km-spatial scale from CloudSat should not bias α estimate too much in our study. However, previous studies have pointed out that precipitation may bias the cloud overlap statistics toward maximum overlap (Mace et al., 2009; Di Giuseppe and Tompkins, 2015). Present study does not eliminate the influence of precipitation on the overlap parameter. If we exclude the samples with precipitation from the analysis, the overlap parameter α would become smaller. The feature may be even more obvious during summer due to more frequent precipitation over TP during this season (Yan et al., 2016). The seasonal variation of α is also found at different ground sites (Mace and Benson-Troth, 2002; Naud et al., 2008). For example, Oreopoulos and Norris (2011) indicated that clouds tend to be more random in the winter and most maximum during the summer. In fact, these overlap properties are associated with cloud system scale, which is dominated by dynamical situation (Tompkins and Di Giuseppe, 2015).

Figures 3b and 3c show the monthly variations in pentad-averaged conditional instability of the moisture convection ($\partial\theta_{es}/\partial z$) and the wind shear ($dV/dz$) for the contiguous cloud-pairs over the TP, respectively. The $\partial\theta_{es}/\partial z$ and dV/dz both exhibit obvious monthly variations for all cloud-layer separations. The atmospheric stability and wind shear gradually decrease from January to August and then steadily increase (see Figs. 3c, 3d, 3e and 3f). From Fig.3c, we can see that the adjacent atmospheric layers during May to September tend to be more unstable and have weak wind shear. These atmospheric states favor the development of clouds and result in maximum overlap between cloud layers. During other month (e.g., December), clouds also tend to follow the maximum overlap more although adjacent atmospheric layers are stable with large $\partial\theta_{es}/\partial z$ and dV/dz. It might be the case that vertical velocities might be large because of extratropical cyclones or other baroclinic instability. With the layer separation increases, atmospheric layers become more stable and then favor random overlap, especially during summer season. These results verify that a more unstable atmosphere tends to favor a maximum overlap over a random one, as shown in previous studies (Mace and Benson-Troth, 2002; Naud et al., 2008). Note that Figs. 3d and 3f might reveal an inconsistency between the wind shear and atmospheric stability. For example, we can see that the wind shear for a 2-km layer distance is greater than that for a 3-km distance, but the atmosphere is also more unstable. This inconsistency is probably because two cloud layers with the same separation but at different altitudes are sorted into the same statistical group. Or, it is also quite possible that other large scale forcings might influence the overlap. In addition, we find the monthly variations in pentad-averaged vertical velocity (ω) at 500 hPa (see Figs.3g and 3h) are also consistent with the monthly cycle of α. It means that vigorous ascent tends to favor maximum overlap. This result agrees well with the previous studies (Naud et al., 2008).

Figure 4 shows the zonal variations of α, $\partial\theta_{es}/\partial z$, dV/dz and ω over the TP. Figs. 4a and 4b indicate that α is larger in the south part of the TP and smaller in the north. This is mainly because the atmospheric instability in the southern part of the TP enhances the convective activity (Fujinami and Yasunari, 2001). Due to the weakening of the monsoon and the blocking by topography, less water vapor may reach the northern part, and thus fewer clouds from there (You et al., 2014). Compared with the southern TP, the stability and wind shear are both larger over the northern part, especially for those cloud layers with large separation (e.g., >2km). This meteorological condition will result in more frequent negative α, indicating that random overlap assumption used in models would underestimate the total cloud cover and thus bias the surface radiation over these regions (see Fig.4a). The most significant warming occurring over the northern part of TP has been attributed to pronounced stratospheric ozone depletion (e.g., Guo and Wang, 2012). However, a more recent study indicates that the accelerated warming trend over the Tibetan Plateau may be due to the rapid cloud cover increases at nighttime over the northern Tibetan Plateau and the sunshine duration increase in the daytime over the southern Tibetan Plateau (Duan and Xiao, 2015). Therefore, an accurate representation of cloud overlap and its relations to atmospheric thermodynamic and dynamic conditions in models is critically important to the understanding of rapid warming over the TP. Although it is still difficult for models to capture the cloud overlap properties, especially for those cloud layers with large separation over north TP, our results confirm that the α is well related with wind shear and instability. However, the zonal variation of α is inconsistent with the variation of vertical velocity (see Figs. 4g and 4h).

4. Sensitivity of α on the meteorological conditions and its parameterization

To facilitate the parameterization of α for cases of contiguous clouds, we further investigate the sensitivity of α on the different meteorological conditions. Here, each meteorological factor over the TP region is grouped into one of four bins as follows. The four bins for $\partial\theta_{es}/\partial z$ are $\partial\theta_{es}/\partial z > 5$ K/km, $2.5 < \partial\theta_{es}/\partial z < 5$ K/km, $0 < \partial\theta_{es}/\partial z < 2.5$ K/km and $\partial\theta_{es}/\partial z < 0$ K/km. For wind shear, the four bins are $dV/dz < 0.5$ m • s^{-1}/km, $0.5 < dV/dz < 2$ m • s^{-1}/km, $2 < dV/dz < 3.5$ m • s^{-1}/km and $dV/dz > 3.5$ m • s^{-1}/km. For vertical velocity, the four bins are $\omega <$ -40 hPa/day, $-40 < \omega < 0$ hPa/day, $0 < \omega < 40$ hPa/day and $\omega > 40$ hPa/day. These groupings ensure that a statistically significant number of samples fall within each bin (i.e., at least one hundred thousand samples per bin). In addition, Li et al. (2015) indicated that the overlap properties between different cloud types are obvious different but the most significant components of the global climate system. Although current study doesn’t include the information of cloud type, the sensitivity of α on the meteorological parameters in our analysis actually exhibit the effects of cloud types on the α due to different combinations of cloud type with same layer separation possibly take place in distinct wind shear and stability conditions.

Figure5 illustrates the sensitivity of α to wind shear, instability and vertical velocity at given upper limit of cloud cover (50%) and spatial scale (50 km) for the contiguous clouds. Since the cloud samples with layer separation below 3.5 km account for 90% of all samples for contiguous clouds, we only present the results for layer distances smaller than 3.5 km. Naud et al. (2008) tested the sensitivity of α to wind shear at three sites and found that wind shear slightly affects α when the layer distance is larger than 2 km. In a recent study, Di Giuseppe and Tompkins (2015) demonstrated the important effect of wind shear on the global cloud overlap by using a combination of the CloudSat-CALIPSO cloud data and the ECMWF reanalysis dataset. Our results along with previous studies suggest that the cloud overlap strongly depends on atmospheric conditions, but their relationship displays some variability, in particular spatially and seasonally. The effect of the atmospheric stability on cloud overlap may be more important over convective regions (e.g., the intertropical convergence zone and TP during summer season) while the effect of wind shear may be dominant over the mid-latitudes. Besides the wind shear and instability, some studies also tested the sensitivity of the overlap parameter to the large-scale vertical velocity. For example, Naud et al. (2008) indicated that vertical velocities in the tropics are not captured in the reanalysis dataset when convection occurs, thus they only discussed the impact of vertical velocity on the cloud overlap parameter over the mid-latitude and found that vigorous ascent tends to favor maximum overlap. Fig.5c shows that vertical velocity at 500hPa has somewhat effect to cloud overlap parameter. However, by combining the effects of wind shear, instability and vertical velocity into parameterization of decorrelation length scale *L*, we find that this scheme doesn't show better superiority than the scheme which only includes the wind shear and instability.

Here, we derive the decorrelation length scale *L* values (km) from the least squares exponential fit to the original α curve at given wind shear and instability bin. Then, we further parameterize *L* as a function of wind shear or both wind shear and atmospheric instability based on a (multiple) linear regression. The regression formula of *L* can be written as:

$$L = L_{\alpha} - b1\frac{\partial \theta_{es}}{dz} - b2\frac{dV}{dz} \quad \text{or} \quad L = L_{\alpha 1} - c1\frac{dV}{dz} \qquad (4)$$

Here, L_{α} , $L_{\alpha 1}$,*b1* ,*b2*,and *c1* are the fitting parameters. Table 1 lists several parameterization schemes for the decorrelation length scale *L*. The scheme with wind shear from Di Giuseppe and Tompkins (2015) using the global CloudSat-CALIPSO cloud data and ECMWF reanalysis dataset is shown for a comparison. Di Giuseppe and Tompkins (2015) discussed the uncertainties from fitting methods and calculation of wind shear. Related to the observational orbit, the impact of cross-track wind shear is neglected in our study, which would exclude many large wind shears associated with jet structures (Di Giuseppe and Tompkins, 2015).The parameterization scheme of Shonk et al. (2010) is also shown in Table 1, which is an empirical linear relationship between *L* and latitude based on CloudSat and CALIPSO data. Our parameterization schemes in terms of wind shear or both wind shear and instability are given in Table 1. Note that the R-squared values (R^2) for our wind shear and wind shear-instability schemes are 0.88 and 0.96, respectively.

After deriving the regression formula of decorrelation length scale L, we re-apply it to all contiguous cloud samples and retrieve the L and corresponding α based on the formula: $\alpha = e^{-D/L}$ and dynamical conditions. Finally, retrieved overlap parameter α is used to calculate the total cloud cover between any two cloud layers by using the Equ. (1) and definitions of random and maximum overlap assumptions. Figure 6 presents the monthly difference between calculated and observed cloud covers using various overlap parameterization schemes. It is seen that the maximum and random overlap assumptions result in large cloud cover biases, especially for layer separations greater than 1 km for maximum overlap and less than 2 km for random overlap where the bias exceeds 5%. Compared with random and maximum assumptions, the differences of total cloud over caused by other schemes are small and range from -3% to 3%. In addition, the wind shear scheme and the wind shear-instability scheme from the present study overall show less biases than other schemes. However, several points still need to be further noticed. First, the wind shear scheme from Di Giuseppe and Tompkins (2015) significantly underestimates the cloud cover for layer separations above 1 km (e.g., reach 3%). This large bias may be because it is based on the global CloudSat-CALIPSO measurements and ECMWF reanalysis dataset for a short period (January-July 2008); as such, some obvious regional or seasonal cloud overlap properties are easily obscured by global averaging. Furthermore, the role of atmospheric stability is not considered in this scheme. However, the scheme from Di Giuseppe and Tompkins (2015) causes little bias for layer separations below 1 km. This is because this scheme retrieves much larger L and overlap parameter values than other schemes. An interesting finding is that Shonk/latitude scheme leads to comparable bias with new schemes from this study. The bias is even smaller for Shonk/latitude scheme when the layer separation is below 1 km. In fact, Fig.5 has demonstrated that the sensitivity of α to wind shear and instability is rather weak when cloud layers are very close. Compared with our wind shear scheme, our wind shear-instability scheme further combines the impact of atmospheric instability and has a relatively lower bias at large layer separations with higher R-squared values (R^2=0.96).

Fig.7 shows the zonal difference between calculated and observed cloud covers for the aforementioned schemes. The differences of cloud cover caused by different overlap schemes are distinguishable. Similar with Fig.6, the maximum and random overlap assumptions still result in the most prominent cloud cover biases (exceed ±5%) at most of the layer separations. Compared with our wind shear scheme and wind shear-instability schemes, the scheme from Di Giuseppe and Tompkins (2015) and latitude scheme from Shonk et al. (2010) cause relatively obvious underestimation of total cloud cover when cloud layer separations exceed 1 km, especially for scheme from Di Giuseppe and Tompkins (2015) (bias reach -3%). Only if cloud layer separations are smaller than 1 km, these two schemes produce better cloud cover simulation than our schemes. In summary, these results indicate that new parameterization (that is, our wind shear-instability scheme) of decorrelation length scale *L*, which includes the effects of both wind shear and atmospheric stability on cloud overlap, may improve the simulation of total cloud cover over TP.

5. Conclusions and discussion

Clouds strongly modulate the Earth's radiative energy budget via changes in their macro- and micro-physical properties (e.g., Hartmann et al., 1992; Fu and Liou, 1993; Fu et al., 2002; Kawamoto and Suzuki, 2012; Yan et al., 2012; Wang et al., 2010). Many studies have showed that annual and seasonal changes of total cloud cover are responsible for the rapid climate warming over the Tibetan Plateau in the past three decades (e.g., Yang et al., 2012; You et al., 2014; Duan and Xiao, 2015).

To accurately simulate the total cloud cover and its impact on the radiative energy budget, climate models need to reliably represent the cloud vertical overlap, which has received less attention than necessary because of the limited regional cloud observations. In view of the passive sensors only provide limited information about the cloud overlap (Chang and Li, 2005a, b; Huang, 2006; Huang et al., 2005, 2006a) and the vertically resolved advantage of active sensors (Ge et al., 2017; 2018), this study utilizes the 4 years (2007–2010) of data from the space-based radar cloud product and collocated ERA-Interim reanalysis product to analyze the cloud overlaps over the Tibetan Plateau and build an empirical relationship between cloud overlap properties and large-scale atmospheric dynamics. It is confirmed that the contiguous cloud layers tend to have maximum overlap at small separation but gradually become randomly overlapped with an increase of the layer separation. Focusing on the contiguous cloud layers, we evaluate the effects of the meteorological conditions on the cloud overlap. It is found that he unstable atmospheric stratification with a weak wind shear over the TP would tend to favor maximum overlap, agreeing well with previous studies. We parameterize the decorrelation length scale *L*, which is used to characterize the transition from the maximum to random overlap assumption, as a function of the wind shear and atmospheric stability. Compared with other parameterizations, this new scheme improves the prediction of total cloud cover over TP when cloud layers separations are greater than 1km. Although the scheme derived in our study focuses only on the TP, our results suggest that the parameterization of the decorrelation length scale *L* by considering multiple thermodynamic and dynamic factors and microphysical effects (e.g., precipitation) has the potential to improve the model-simulated total cloud covers.

In a recent study, Di Giuseppe and Tompkins (2015) applied the wind shear-dependent decorrelation length scale in the ECMWF Integrated Forecasting System. They found that the impact of wind shear-dependent parameterization on radiative budget calculation is comparable in magnitude to that of latitude-dependent scheme of Shonk et al. (2010). Our results also show that latitude-dependent scheme has similar bias of cloud cover relative to the new scheme developed in this study. Although our results can't suggest which of the scheme is superior, the scheme based on the meteorological factors has some potential advantages. For example, cloud overlap parameter is significantly controlled by atmospheric thermodynamic and dynamical conditions, therefore the long-term variations of meteorological factors are bound to affect the trend of cloud overlap and corresponding calculations of total cloud cover and radiation budget. Indeed, recent study has shown that rapid warming and an increase of atmospheric instability over the TP leads to more frequent deep clouds, which are responsible for the reduction of solar radiation over the TP (Yang et al., 2012). By using surface observations over 71 stations, some studies verified that annual and seasonal total cloud covers have declined during 1961-2005 (Duan and Wu, 2006; You et al., 2014). However, whether such variations of total cloud cover are linked with the changes of degree of cloud overlap over the TP are still unclear. Thus, more efforts are needed to reasonably evaluate the impact of cloud overlap on the total cloud cover variations over these sensitive areas of climatic change (e.g., Tibetan Plateau and Arctic).

Competing interests. The authors declare that they have no conflict of interest.

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Table 1.Parameterizations of decorrelation scale length L from the exponential fit as a function of atmospheric stability $\partial\theta_{es}/\partial z$, wind shear dV/dz or latitude Φ

Scheme	description	decorrelation length scale L
Wind shear (Di Giuseppe and Tompkins, 2015)	Random/Maximum, only wind shear	$L = 4.4 - 0.45 \times \frac{dV}{dz}$
Wind shear (this study)	Random/Maximum, only wind shear	$L = 2.19 - 0.14 \times \frac{dV}{dz}$
Wind shear-instability (this study)	Random/Maximum, wind shear and instability	$L = 2.18 - 0.09 \times \frac{dV}{dz} - 0.15 \times \frac{\partial\theta_{es}}{dz}$
Latitude(Shonk et al., 2010)	Random/Maximum, only latitude	$L = 2.899 - 0.02759 \times \lvert \Phi \rvert$

Figure Captions

Figure 1. (a) CloudSat overpass tracks (blue line: daytime; red line: nighttime) over the Tibetan Plateau (27°N-39°N; 78°E-103°E); (b) A sample of CloudSat 2B-GEOPROF-LIDAR cloud mask product along the ground track of 200km (white color: cloud fraction>99%; light blue: 0<cloud fraction<99%; deep blue: clear sky; orange color: surface).(c) The observed and calculated segment-average cloud cover profiles based on maximum and random assumptions for different spatial scales and given cloud mask sample in Fig. 1b. (d) The corresponding cloud overlap parameters of contiguous cloud layers for 25, 50, 100 and 200 km spatial scales, respectively. Note that the observations below 1 km over the TP surface have been removed.

Figure 2. The dependence of α on the layer separation and its sensitivity to the spatial scale for (a) noncontiguous and (b) contiguous cloud pairs; the error bars correspond to $\pm$3 standard error; (c) The probability distribution functions (PDFs) of the along-track horizontal scales of cloud system at different height over TP region; (d) The variations of cloud sample number and the cumulative percentages with cloud layer separations for both noncontiguous and contiguous clouds at a given spatial scale of 50km. The cumulative percentages represent the proportions of cloud sample below corresponding layer separation to all samples.

Figure 3. The monthly variations of the pentad-averaged (a) cloud overlap parameter, α, (c) conditional instability to moist convection, $\partial\theta_{es}/\partial z$, (e) wind shear, dV/dz, (g) and vertical velocity at 500 hPa, ω for the contiguous cloud layers over the TP ; The monthly variations of the pentad-averaged (b) α, (d) $\partial\theta_{es}/\partial z$, (f) dV/dz and (h) ω for the contiguous clouds for the layer separation of 2 km (red) and 3km (black).

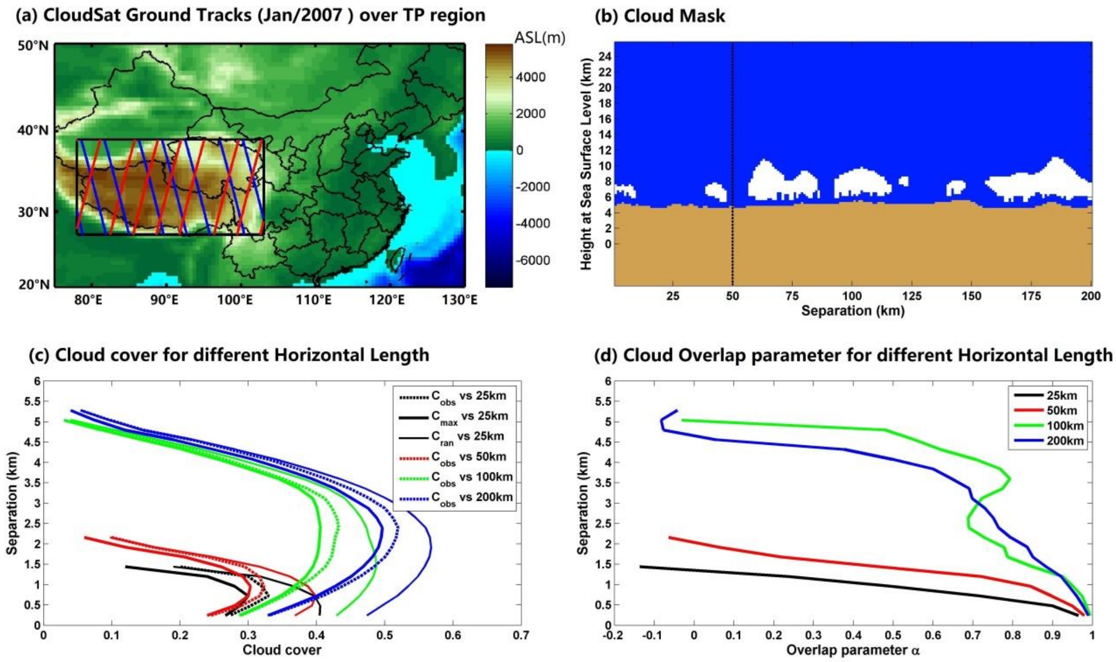
Figure 4. The zonal variations of the (a) α, (c) $\partial\theta_{es}/\partial z$, (e) dV/dz, and (g) ω for the contiguous cloud layers over the TP ; The zonal variations of the (b) α, (d) $\partial\theta_{es}/\partial z$, (f) dV/dz and (h) ω for the contiguous cloud layers for the layer separation of 2 km (red) and 3km (black).

Figure 5. The sensitivities of median overlap parameter α to the (a) wind shear, (b)

instability and (c) vertical velocity at 500 hPa at given upper limit of cloud cover (50%) and spatial scale (50 km) for the contiguous cloud layers. The error bars correspond to $\pm$ 3 standard error.

Figure 6. The monthly differences in total cloud cover between calculation and observation for different schemes (see the Table 1) and its dependence on the layer separation.

Figure 7. The zonal differences in cloud cover between calculation and observation for different schemes (see the Table 1) and its dependence on the layer separation.



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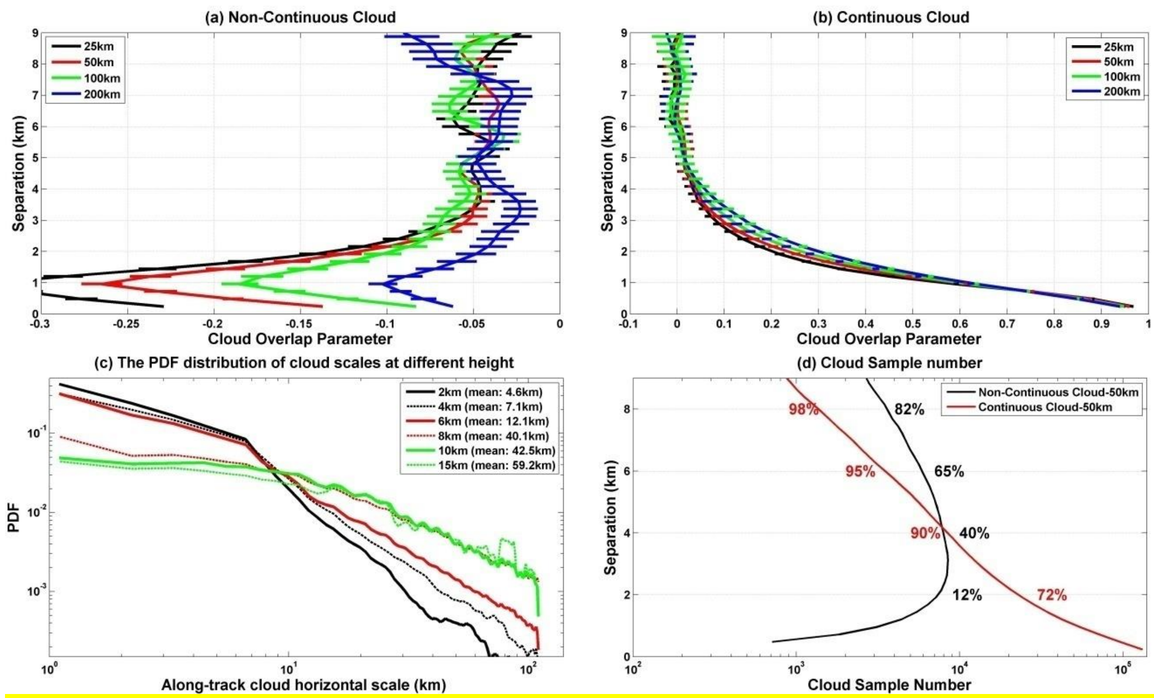

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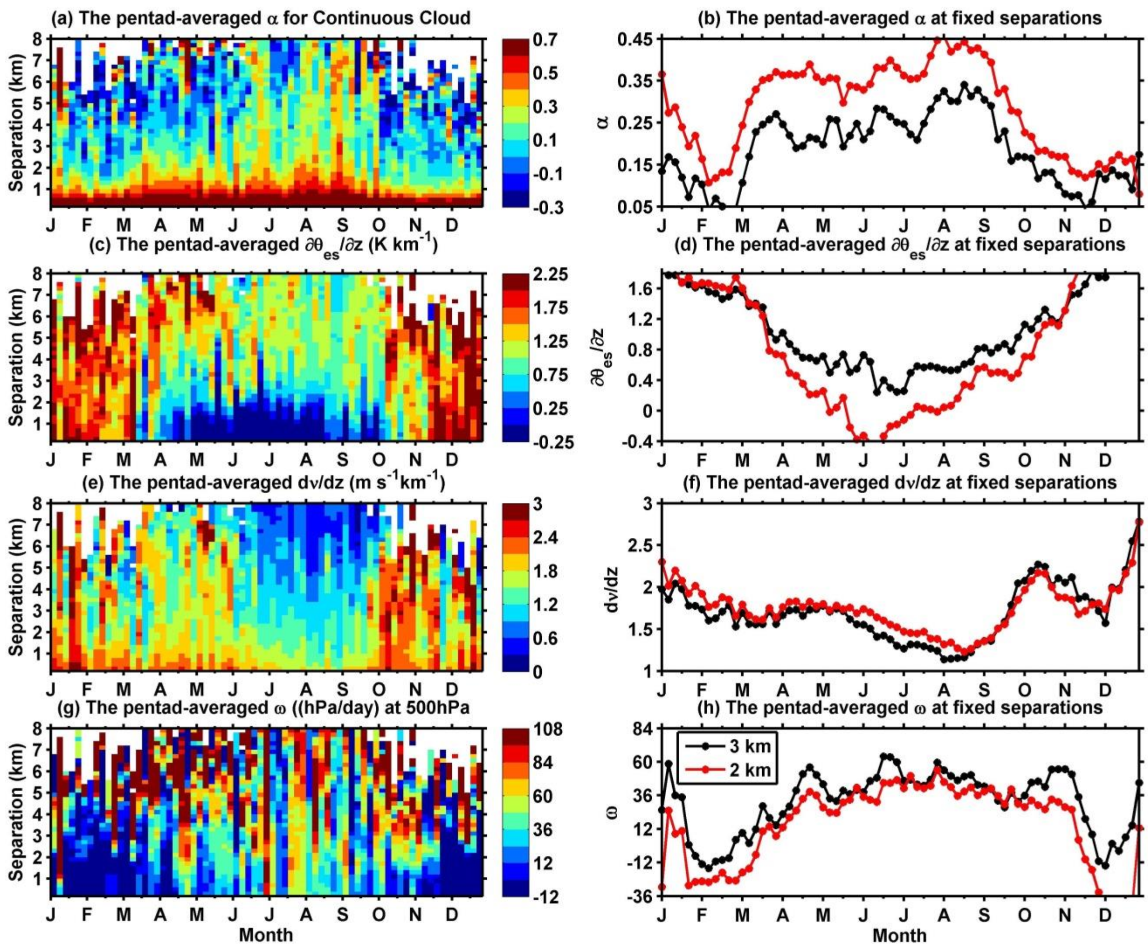

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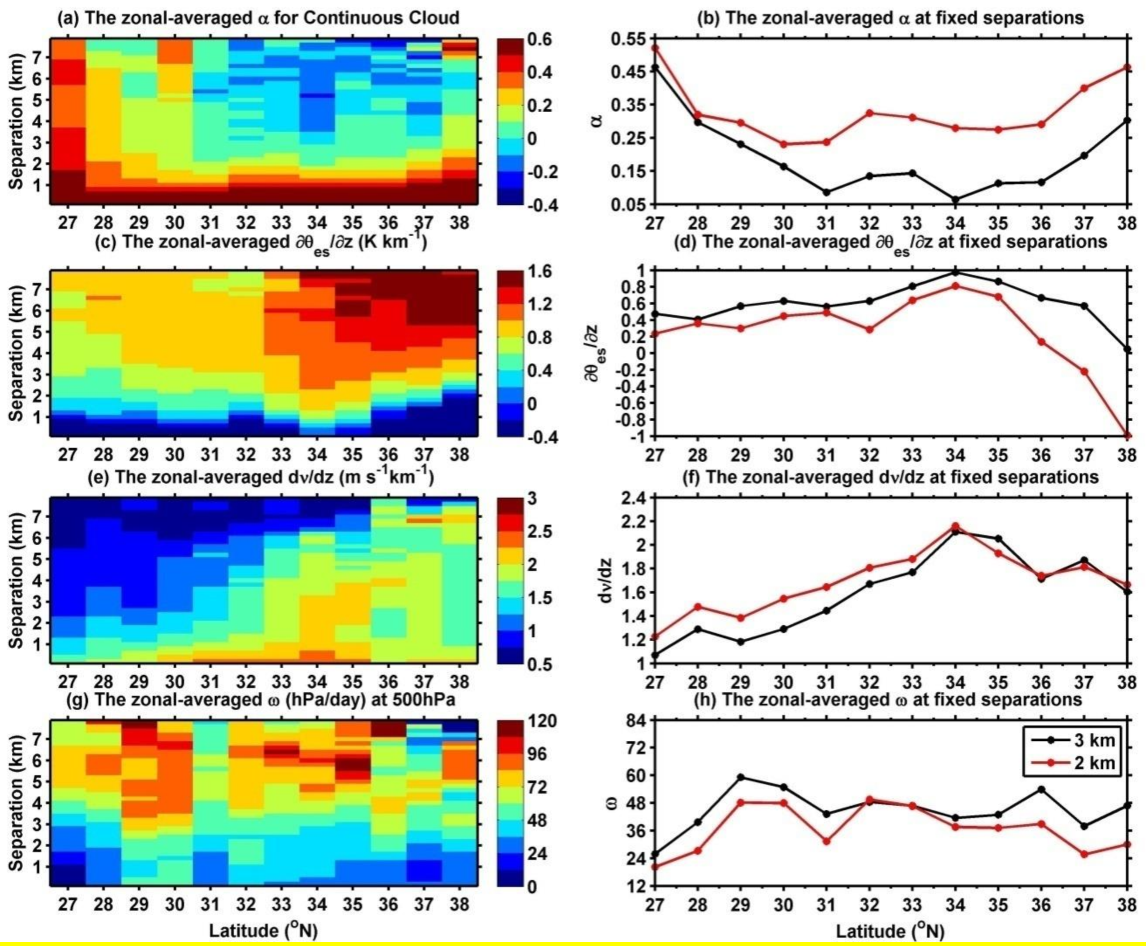

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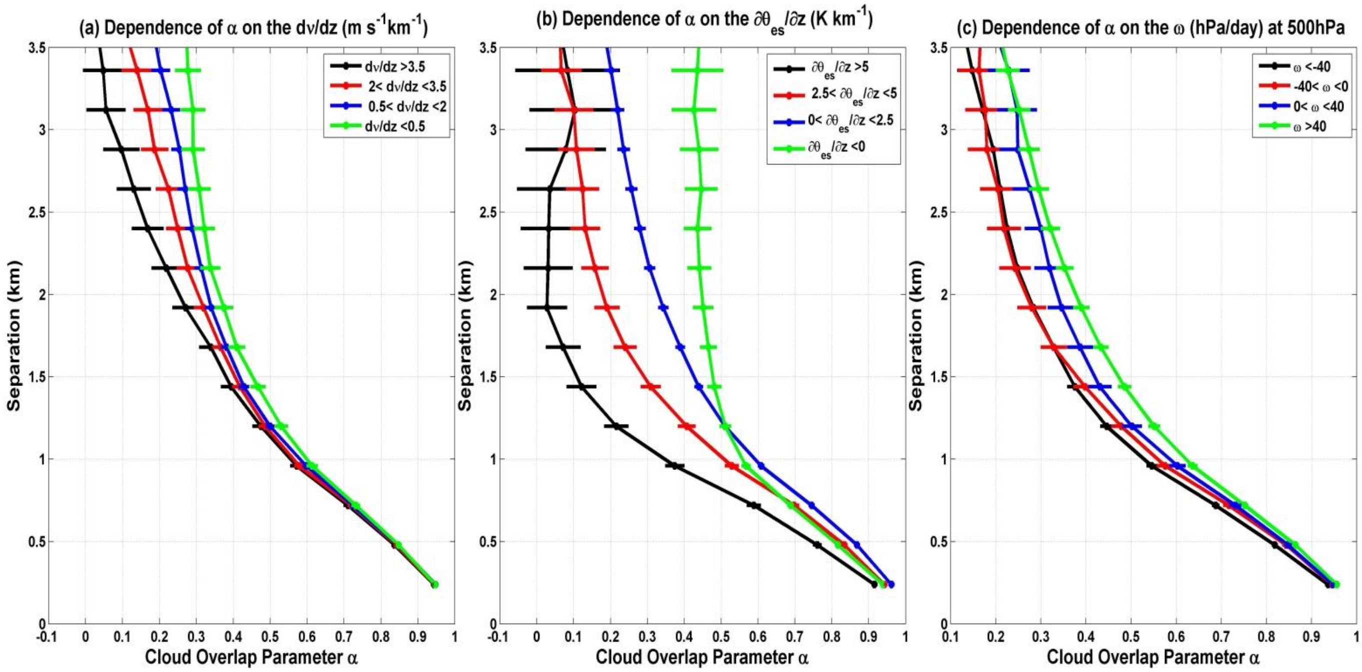

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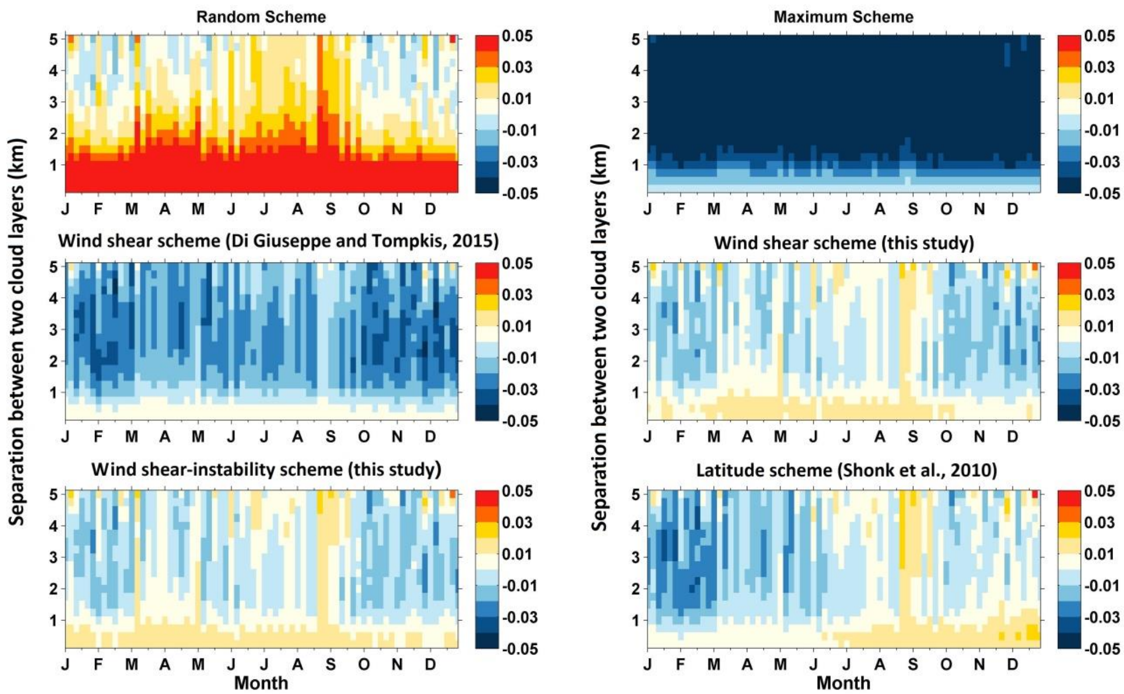

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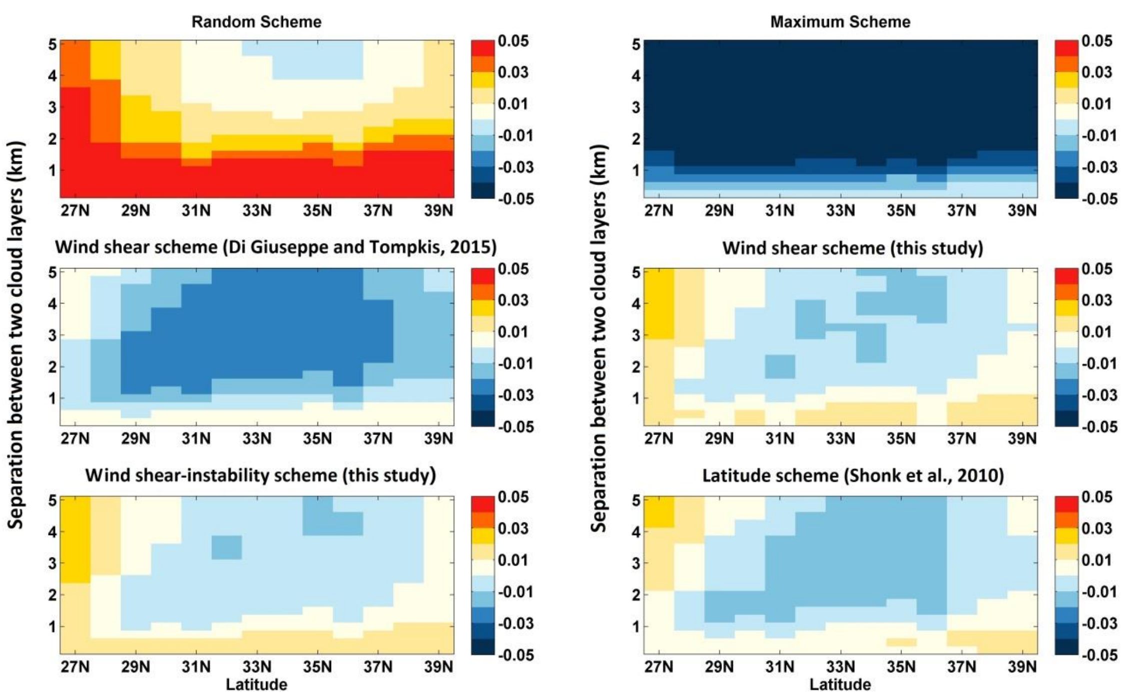

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