Dear Dr. David Covert,

In response to your editing manuscript No. acp-2015-952, which requested revision for our manuscript submitted to the Atmospheric Chemistry and Physics. We have revised the manuscript following both your instructions and reviewers' comments. And the corresponding revisions have been marked in the revised manuscript by blue (reviewers) and yellow (authors) color. All the coauthors concur with the submission of the revised manuscript.

We believe the revised manuscript adequately addresses all the comments/concerns from two anonymous reviewers and our response to the reviewers will be attached with our revised manuscript.

We hope you find the revision and our response to the reviewers' comments are appropriate and that the revised manuscript will be deemed acceptable for publication.

Your consideration of the revised manuscript will be highly appreciated.

Sincerely Yours,

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Reviewer 1:

We are grateful for the reviewers' useful advice and comments. They helped us greatly to improve this paper. Our point-by-point responses to the reviewers' comments are listed as follows.

General comments:

It is known that human activities have impacts on anthropogenic aerosol emissions, but few studies analyze this problem because there are many contributing factors and technical constraints. The authors of this paper employ a state-of-the-art algorithm to distinguish human-induced dust aerosols from CALIPSO satellite observations, and study the relationship between anthropogenic dust burden and population density (growth rate) over various land covers. This paper deserves to be published, but several problems need to be addressed. More discussion, analysis, and references are considered necessary to be added to better support the conclusions.

Part 1:

Major issues:

(1) The title is better changed to "The relationship between anthropogenic dust emission and human activity over global semi-arid regions". The reason for the suggested title change is that the authors barely discussed about the "impacts" but the "relationship". In addition, more in-depth analysis about why such a relationship exists between anthropogenic dust and human activity.

Response: Thank you for your suggestion. The title has been changed to "The relationship between anthropogenic dust emission and human activity over global semi-arid regions." The revised manuscript has also included more description and discussion on the relationship between anthropogenic dust and human activity.

(2) The abstract should be revised in order to better reflect the content of this manuscript. The authors should add the temporal ranges of the data used, otherwise the values (i.e. population growth rate, dust burden, etc.) will be meaningless.

Response: We appreciated this suggestion, the abstract has been revised and the temporal range of data used has also been introduced in the revised manuscript.

(3) The introduction part is also deemed insufficient. First, not enough references are provided to support the acclaims. For example, in page 1, line 24-26: "The economic policy of most developing countries is an extensive economic model. This type of economic policy always results in a lower efficiency of resource use." Three is no explanation of what is "extensive economic model". And there is no support (reference or evidence) of why this model "always" results in a lower efficiency of resource use. Similar problems also exit in the manuscript, such as page 1, line 20-22; Also, Page 7, line 15-17: the authors need to add some supporting references to prove that "semi-arid areas have fragile eco-system to support large population" and that "semi-arid area are sensitive to natural change and human activities".

Second, there is not enough discussion of the previous studies about the human impact on anthropogenic dust emission. That is, how do different human activities (i.e.agriculture practice, water use, and industrial practice) practically impact the generation/distribution of anthropogenic dust? This is a critical point in order to understand the variations of human-dust relationship in various regions.

Response: The introduction has been revised, and the questions have been replied separately as below.

(a) in page 1, line 24-26: “The economic policy of most developing countries is an extensive economic model. This type of economic policy always results in a lower efficiency of resource use.” Three is no explanation of what is “extensive economic model”.

Response: “Extensive economy” is a type of economic growth that depends on high consumption of material resources and energy to a great extent. Its explanation has been added in the revised manuscript.

(b) And there is no support (reference or evidence) of why this model “always” results in a lower efficiency of resource use.

Response: The related references have been added in the revised manuscript. Currently, the high economic growth depends on high consumption of material resources and energy to a great extent, which is a kind of extensive economic growth mode and inevitably encounters the restriction of population, resources, energy, and the pressure of environment, facing a " bottleneck" of the limited resources.

(c) Similar problems also exit in the manuscript, such as page 1, line 20-22;

Response: Similar problems have been fixed in the revised manuscript.

(d) Also, Page 7, line 15-17: the authors need to add some supporting references to prove that “semi-arid areas have fragile eco-system to support large population” and that “semi-arid area are sensitive to natural change and human activities”.

Response: More references related to “the semi-arid areas that have fragile ecosystem to support large population” and “the semi-arid area that are sensitive to natural change and human activities” have been added in the revised manuscript.

(e) Second, there is not enough discussion of the previous studies about the human impact on anthropogenic dust emission. That is, how do different human activities (i.e. agriculture practice, water use, and industrial practice) practically impact the generation/distribution of anthropogenic dust? This is a critical point in order to understand the variations of human-dust relationship in various regions.

Response: Thank you for your suggestion. The discussion about human impact on anthropogenic dust emission has been revised. More references about the influence of different human activities on anthropogenic dust have been added in the revised manuscript.

(4) Since the four semi-arid regions, namely East China, India, North America, and North Africa, are selected for in-depth study, why the relationships between anthropogenic dust and population index in these regions are not investigated/provided? It is also helpful to show the anthropogenic dust column burden changes as a function of population density in the four regions (Figure 12). These regional evidences are crucial to support the authors' arguments and thus should be added.

Response: Thanks for your insightful suggestions. The revised manuscript includes the description and discussion over the four typical semi-arid regions, which cover both the relationship between anthropogenic dust and population density, and the relationship between anthropogenic dust and population change. According to your suggestion, we added Figure1 in the revised manuscript to illustrate the relationship between anthropogenic dust aerosol and population density in the four typical semi-arid regions. Four different semi-arid regions perform different relationships between population density and anthropogenic dust. More description and discussion about the relationship between anthropogenic dust and population density have been stated in the revised manuscript.

(5) A major problem with this manuscript is quite a few arguments/conclusions derived from the analysis are not considered fully supported by the evidences provided. For instance, in Page 6, line 11-16: the authors argue that the difference in anthropogenic dust in different seasons could be due to the difference in human activities (especially agriculture activities). And, agricultural activities are claimed to be most frequent in summer. Then, why and how do agriculture activities impact the most in summer? Similarly, in Page 7, line 27-29: please explain how the difference in population growth rate closely relates with economic status? In page 8, line 31-33: please explain more about why "the land type experiences more human activities, the more anthropogenic dust aerosol will be produced"? How do you figure out the human activity frequencies?

Response: In order to reply the question well, it has been divided into three parts.

(a) For instance, in Page 6, line 11-16: the authors argue that the difference in anthropogenic dust in different seasons could be due to the difference in human activities (especially agriculture activities). And, agricultural activities are claimed to be most frequent in summer. Then, why and how do agriculture activities impact the most in summer?

Response: Spring and summer have the highest anthropogenic dust, which was a conclusion from Huang et al. (2015). They compared the global seasonal distribution of total dust optical depth and found that "the total anthropogenic dust column burden (DCB) is greater in spring and summer than in autumn and winter. This difference is most significant in arid and semi-arid regions. " Summer always has more human activities than the other seasons, both in day and night. It has longer day and indirect induced an increase frequency of human activities.

(b) Similarly, in Page 7, line 27-29: please explain how the difference in population growth rate closely relates with economic status?

Response: Population change reflects the economic status to some extent. For the distribution of economic development in the world, the more developed countries have low population change are, even negative growth; the developing countries usually has positive population growth. It depends on the economic status and style, such as the extensive economic development depends on high consumption of material resources and energy to a great extent; it requires a great number of labor to support development of industries. However, in the developed countries, the high level industrialization needs much less people who has the technology to handle the machines to finish the project that used to need much more people. Therefore, the economic status has the ability to change population growth.

(c) In page 8, line 31-33: please explain more about why "the land type experiences more human activities, the more anthropogenic dust aerosol will be produced"? How do you figure out the human activity frequencies?

Response: Anthropogenic dust aerosol is a type of dust aerosol; it is most originated from exposed land, especially in semi-arid region. Anthropogenic dust aerosol is a result of human activities. According to its sources, anthropogenic dust originates mainly from agricultural practices (harvesting, ploughing, overgrazing), changes in surface water (e.g., shrinking of the Caspian and Aral Sea, Owens Lake), and also from urban practices (e.g., construction), and industrial practices (e.g., cement production, transport) (Prospero et al., 2002). The sentence of "the land type experiences more human activities, the more anthropogenic dust aerosol will be produced" is also been changed to "the land type experiences more human activities, the more anthropogenic dust aerosol may be produced". And Population density and population change have been included in to measure human activities.

(6) Population density and population change are taken as measurement of human activities. They have a positive relationship with anthropogenic dust in the global semi-arid region. It is better if you use one figure to show the relationship of anthropogenic dust with population density and population change. In addition, what's the advantage and disadvantage of taking human population density (and variation) as surrogates of human activities? What is the expected impact on the results?

Response: Thanks for these insightful suggestions. First, the figures that show the relationship of anthropogenic dust with population density and population change have been combined to one figure. Second, the relationships of anthropogenic dust with population density and population change have been re-organized in the revised manuscript. As we stated in answering the previous question, population and population change have been used as an index of human activities. As an index of human activities, it has both merit and shortcoming. Population-related index has a close relationship with economic development; it is also a result of government policy. However, it has a limitation of scale. Its limitation also can be found in the comparison of four typical semi-arid regions. The traditional agriculture is the most suitable for using the population index, as most people has been limited in the agriculture. The population and its change can greatly impact on anthropogenic dust, which is been greatly reflected in semi-arid region of India. In the semi-arid region of India, traditional agriculture dominated the economic body in selected area, the agriculture anthropogenic dust aerosol exhibited close relations with population density and population change.

Part 2:

final problem is with the language. A detail check of the mistakes in grammar and sentence structure is highly recommended.

Minor problems:

(1) Page 1, line 25:"always" is better changed to "frequently"

Response: Done.

(2) Page 1, line 28:"anthrpogenic effect on emission"-emission of what? Aerosols?

Response: It has been revised as "anthropogenic effect on aerosol emission."

(3) Page 2, line 8: "these regions are ..." should be "where they are ..."

Response: Done

(4) Page 2, line 12:" soils distributed by human activities" should be "soil distributed by human activities"

Response: Done.

(5) Page 2, line 14:"global dust cycle, historical and possible future changes" should be "global dust cycle, as well as historical and possible future changes"

Response: Done.

(6) Page 2, line 29:" a study of human activity on anthropogenic dust column burden" should be "a study the impact of human activity on anthropogenic dust column burden"

Response: Done.

(7) Page 2, line 33-34:"and investigated its relationship with human activities" should be "and its relationship with human activities is investigated"

Response: Done.

(8) Page 3, line 20: what is "population layer"?

Response: It has been changed to "population" to avoid misunderstanding.

(9) Page3, line 24: what is the unit of "population density"?

Response: the unit of population density is persons km^{-2}

(10) Page 3, line26: section "2.3 Anthropogenic dust detection data" is better changed to "2.3 Dust detection data"

Response: Done.

(11) Page 4, line 30: what is "|CAD|>70"? what does it mean?

Response: CAD is cloud aerosol discrimination. |CAD|>70 is a threshold for dust extinction coefficient for the highest confidence level.

(12) Page 5, line 5: "the dust density of dust" should be "the density of dust"

Response: Done.

(13) Page 5, line 7: "This method does not only modify" should be "This method not only modifies"

Response: Done.

(14) Page 5, line 10: "detection" should be "detecting"

Response: Done.

(15) Page 5, line 25: "... regional anthropogenic dust ... of globe" should be "... global anthropogenic dust ..." – I think Figure 2 is the global (not regional) average of anthropogenic dust burden, isn't it?

Response: Done. Figure 2 is the global anthropogenic dust burden.

(16) Page 6, line 9: it's better to add a legend for Figure 3.

Response: The legend for Figure 3 has been added in the revised manuscript.

(17) Page 6, line 12: "that may be a result of " should be "which may be because"

Response: Done.

(18) Page 6, line 28: what do you mean by "emission effect"?

Response: "Emission effect" has been changed to "radiative effect."

(19) Page 6, line 34: "differing" should be "different"

Response: Done.

(20) Page 7, line 15: "that are difficult" should be "that is difficult"

Response: Done.

(21) Page 8, line 8;11: please pay attention to the sentence structure. You may consider separate it into several short sentences.

Response: Thanks. This sentence has been separated into several short ones that are easy to understand.

(22) Page 8, line 23: "rear population" should be "rare population"?

Response: Done.

(23) Page 8, line 27: what is “cropland mosaics”?

Response: Cropland mosaic is a mosaic of less than 60 percentages of cropland in the landscape. Its definition has been added in the revised manuscript.

(24) Page 8, line 29: “is remain unchanged” should be “remains unchanged”

Response: Done.

(25) Page 9, line 3: “starts obvious increase” should be “shows obvious increase”

Response: Done.

(26) Page 9, line 4: “make significant effect in production of anthropogenic dust” should be “have significant effect on anthropogenic dust production”

Response: Done.

(27) Page 9, line 9: “the sensitive of” should be “the sensitivity of”

Response: Done.

(28) Page 9, line 10 “appears obvious increasing” should be “shows obvious increase”

Response: Done.

(29) Page 9, line 14: “benefit in production of ...” should be “contribute to production of ...”

Response: Done.

(30)Page 9, line 15: “It found that ...” should be “It is found that ...”

Response: Done.

(31) Page 9, line 21: “correlated to ...” should be “correlated with ...”

Response: Done.

(32) Page 9, line 25: “on study the influence of ...” should be “to study the influence of ...”

Response: Done.

(33) Page 17, figure 2 caption: although “AI” is defined in the text, it is still better to give “aridity index (AI)” here for readers who only view the figures.

Response: The description of AI has been added in the place for readers to follow the manuscript easily.

Reviewer 2:

We are grateful for the reviewers' useful advice and comments. They helped us greatly to improve this paper. Our point-by-point responses to the reviewers' comments are listed as follows.

General comments:

The authors aim to explore the relationship between population and anthropogenic dust in semi-arid regions, which has significant implications for local climate change-an important research topic facing the climate change research community. The study clearly reveals that the global semi-arid regions present in average the highest anthropogenic dust burden, and the dust emissions vary substantially across semi-arid regions with different population density and socioeconomic development levels. His paper has great potential for making an important contribution to scholarly discussions on the interactions between human intervention and climate systems at both global and local levels.

Part 1:

(1) Here are some comments and suggestions for the authors to consider in the revision. My main concern is that the human impacts on dust emission are not only determined by the number and growth rate of the population but also affected by the types in intensities of human activities. To choose the four semi-arid regions of different continents and at various socioeconomic development levels for the study of the relations between population density/change and anthropogenic dust burden is a good research design. However, the decision of excluding almost half of the semiarid

areas with a population density below 10 persons km^{-2} from the analysis unfortunately makes the research less robust.

Response: We appreciated the reviewer's insightful question and agreed that almost half of the semi-arid areas has a population density below 10 persons km^{-2}. The figures 1 and 2 are the revised figures include the population density below 10 persons km^{-2}. They are similar with the primary figures. The new figures in the revised manuscript and related description have been updated in the revised manuscript.

(2) The areas excluded are believably dominantly the less populated regions in North America and North Africa, which represents two regimes of human activities and seems to generate very different impacts on anthropogenic dust emissions. While the inclusion of these areas in the analysis of overall interacting patterns may lead to mixed results, one should consider analyzing the relationships in the four regions separately and exploring whether or not there is a common pattern in the relationship between population density and anthropogenic dust burden among all four regions. Even if the resulted relationship varies across regions, it could lead to further analysis of the reasons: why they differ? Is it due to the different levels of aridity, or different types and intensities of human activities?

Response: We agree and appreciate the reviewer's suggestion and comment. As the reviewer mentioned, the points with population densities less than 10 persons km^{-2} are greatly located in North America and North Africa, since the semi-arid regions in East China and India have higher population densities. The differences of population densities in the four semi-arid regions seem to show very different impacts on anthropogenic dust emission. While the inclusion of these areas in the analysis of overall interacting patterns may lead to mixed results, we have added the description and discussion on the relationships in the four regions separately (Fig. 3) in the revised manuscript. The typical economic mode has great impact on the relationship between anthropogenic dust and population densities over different semi-arid regions. The comparison in East China, India, North America, and North Africa (Fig. 3) demonstrate the Indian semi-arid region with a traditional agriculture has a close relationship between population density and anthropogenic dust. Related with other semi-arid regions, India as a developing country, agriculture is its major industry, the relationship between human activities and population is more direct, and its agriculture is an industry that directly impacts the land that is easily leading to production of anthropogenic dust. It illustrated that anthropogenic dust has a close relationship with development level of agriculture.

(3) Would the pattern be clearer after controlling AI index, or/and economic level/activity?

Response: We think the pattern will be clearer after controlling the economic level. This part of description and discussion has been added in the revised manuscript. As shown in Fig. 3 above, we can find that different semi-arid regions have inconsistent relationships between population density and anthropogenic dust, which illustrates the role of economic level in relationship between anthropogenic dust and population.

Part 2:

Other comments:

(1) In section 4.1, it would be preferable to use “mixed dust” instead of “combined dust” to avoid confusion, particularly when Figure 5 stacks (or combines) anthropogenic and natural dust burden from the “mixed” dust regions.

Response: Thanks for the suggestion. The “combined dust” has been replaced by “mixed dust,” and we have checked the whole manuscript to ensure no similar problem exists in the revised manuscript.

(2) The sentence of Lines 28-29 on Page 6 can be moved to introduction section, and expressed as a key contribution of this research.

Response: Thanks for the suggestion. The sentence in lines 28-29 on Page 6 has been moved to the introduction section, as a key contribution of this research.

(3) While Figure 4 displays anthropogenic vs. combined (mixed) dust burden, the text on Page 6 talks about the natural vs. mixed dust burden. It should make them consistent.

Response: The text on Page 6 has been revised to be consistent with the figure caption.

(4) While Page 7 Line 19 says “both India and East China have higher population density (>= 250 persons km^{-2}) which is also displayed in Figure 6, the other parts of the paper uses 45 persons km^{-2} for East China. Is the number in Figure 8 derived from the data of Figure 6? Please explain why.

Response: It is our poor English expression, and we have revised the text. In Line 19 on Page 7, we want to state that “For the four selected semi-arid regions, only India and East China have grids with population density greater than 250 persons km^{-2}, most of North Africa has the population density between 10 and 40 persons km^{-2}, and the population density in semi-arid region of North America is in the range of less than 10 persons km^{-2}.”

(5) The last paragraph of Page 7 and Figure 7 is not really relevant and could be removed. There are some contradictions in texts of the first two paragraphs on Page 8. For instance, it says 8% population increase in East China in the first paragraph but 6.16% in the second; 30% increase in N. Africa in the first paragraph, and 29.26% in the second. While the paper is generally well written, the second half of the text needs to be improved.

Response: Thanks for the suggestion. We agree with reviewer. This paragraph has been rewritten. The contradiction in text has been revised.

(6) In particular, Section 4.2 and 4.3 are not always easy to follow. For instance, what does it mean “Most semiarid regions locate in the anthropogenic dust areas”(Page 8 Line 18)? What is “rear population” (Page 8 Line 23)?

Response: Sections 4.2 and 4.3 have been revised. (1) According to the distribution of anthropogenic dust (Huang et al., 2015), anthropogenic dust not only appears in the semi-arid regions, but also relatively concentrated in the semi-arid regions. The sentence of “Most semi-arid regions are located in the anthropogenic dust areas” has been removed, in order to avoid misunderstanding. (2) “[R]ear population” should be “rare population”. Similar problems no longer appear in the revised manuscript.

Reference:

(1) Huang, J., Liu, J., Chen, B., and Nasiri, S. L.: Detection of anthropogenic dust using CALIPSO lidar measurements, Atmos. Chem. Phys., 15, 11653–11655, doi:10.5194/acp-15-11653-2015, 2015.

(2) Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, Rev. Geophys., 40, 2-1–2-31, doi:10.1029/2000RG000095, 2002.

The relationship between anthropogenic dust and population over global semi-arid regions

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Abstract. Although anthropogenic dust has received more attention from the climate research community, its dominant role in the production process is still not identified. In this study, we analyzed the relationship between anthropogenic dust and population density/change over global semi-arid regions, and found semi-arid regions are major source regions in producing anthropogenic dust. The results showed that the relationship between anthropogenic dust and population is more obvious in cropland than in other land-cover types (crop mosaics, grassland and urbanized regions), and that the production of anthropogenic dust takes an increasing as the population density becomes more than 90 persons per km^2. Four selected semi-arid regions, namely, East China, India, North America, and North Africa were used to explore the relationship between anthropogenic dust production and regional population. The most significant relationship between anthropogenic dust and population occurred in Indian semi-arid region that had a greater portion of cropland. And the high peak of anthropogenic dust probability appeared with 220 persons per km^2 of population density and 60 persons per km^2 of population change. These results suggest that the influence of population on production of anthropogenic dust in semi-arid regions is obvious in cropland regions. However, the impact does not always have a positive contribution to the production of anthropogenic dust, and overly excessive population will suppress the increase of anthropogenic dust. Moreover, radiative and climate effects of increasing anthropogenic dust need more investigation.

1 Introduction

It is well acknowledged that anthropogenic activities play an important role in drylands' climate change. Salinization, desertification, loss of vegetative cover, loss of biodiversity, and other forms of environmental deterioration are partly caused by anthropogenic activities (Huang et al., 2016a, b). With rapid economic development, more fossil fuels have been consumed, which produced a great deal of greenhouse gases (GHGs) as well as energy (Barnett and O'Neill, 2010). The released GHGs and heat have induced a strong influence on temperature spatial distribution in recent years (Li and Zhao, 2012), especially in developing countries, where the economic policy is belong to extensive economic category that prefers results in a lower efficiency of resource and energy waste.

Jiang and Hardee (2011) noted that main factors influencing anthropogenic effects on aerosol emission are economic growth, technological change and population growth, which cannot be easily simulated using numerical models (Zhou et al., 2010). Recently, better understanding about the effects of human activities on dryland expansion in various scenarios has been achieved (Huang et al., 2016b). It appears that higher densities of younger workers are strongly correlated with increased energy use (Liddle, 2004), carbon dioxide emission (Liddle and Lung, 2010; H. Huang et al., 2014) and energy consumption, and the accomplished production of heat has been released into the atmosphere along with GHGs. Although human activities play an important role in the process of regional climate change, our understanding on their relationship is extremely limited, especially in drylands (Jiang, 2010).

Huang et al. (2012) showed that drylands are most sensitive to global warming; this warming was induced by dynamical and radiative factors. Guan et al. (2015a) found that the enhanced warming in drylands was a result of radiative-forced temperature, which has a close relationship with aerosol column burden. The aerosol in drylands has an obvious warming effect (Huang et al., 2006a, 2008; Chen et al., 2010; Ye et al., 2012; Jin et al., 2015). And the aerosol has a widely distribution and tends to have a relatively large optical depth (H. Huang et al., 2010; Bi et al., 2011; Liu et al., 2011; Xu and Wang, 2015; Xu et al., 2015), leading to a significant radiative effect in the drylands. According to Tegen and Fung' result (1995), the existing atmospheric dust load is hard to explain by natural sources alone. The atmospheric dust load that originates from soil and is disturbed by human activities, such as various land-use practices, can increase the overall dust load and in turn affect radiative forcing. Efforts to quantify the relative importance of different types of dust sources and the factors that affect dust emissions are critical for understanding the global dust cycle, as well as historical and possible future changes in dust emission (Okin et al., 2011; Huang et al., 2015). Therefore, studies on different types of aerosols are necessary in the study of radiative effect (Huang et al., 2009, 2014; Wang et al., 2010; Yi et al., 2014).

Generally, the aerosols in drylands are divided into two categories, natural and anthropogenic dusts. Anthropogenic dust originates predominantly from agricultural practices (e.g., harvesting, ploughing and overgrazing) and changes in surface water (e.g., shrinking of the Caspian Sea, the Aral Sea and Owens Lake), as well as urban (e.g., construction) and industrial practices (e.g., cement production and transport) (Prospero et al., 2002). Over the past few decades, a combination of higher frequency of warmer and dryer winters - springs in semi-arid and semi-wet regions, and changes in vegetated land cover due to human activities have likely increased anthropogenic dust emission over different regions (Mahowald and Luo, 2003). Mulitza et al. (2010) studied the development of agriculture in the Sahel, which was associated with a large increase in dust emission and deposition in the region, and found that dust deposition is related to precipitation in tropical West Africa on the century scale. Due to the importance of anthropogenic dust in climate study, Huang et al. (2015) developed a detection method of anthropogenic dust emission and presented a global distribution of anthropogenic dust aerosol. The current consensus is that up to half of the modern atmospheric dust load originated from anthropogenically disturbed soils (Tegen et al., 2004). Such a great proportion of anthropogenic dust will greatly influence local radiative forcing. Therefore, influence of human activities on production of anthropogenic dust is critical for predicting and estimating the radiative effect of aerosol in regional climate change.

Most of previous results focused on the emission of natural dust aerosol (Z. Huang et al., 2010; Li et al., 2011; Yi et al., 2011, 2012); the study on anthropogenic dust is relatively limited. In this study, the anthropogenic dust over semi-arid regions is identified by CALIPSO data, and its relationship with human activities is investigated. The method used to distinguish anthropogenic dust from the total dust aerosols is based on that of Huang et al. (2015). This paper is organized as follows. Section 2 introduces the datasets used in this study. Section 3 presents the method used to identify the anthropogenic dust aerosols in the semi-arid regions. Section 4 discusses anthropogenic dust emission over global semi-arid regions and its relationship to human activities, including a comparison among four different semi-arid regions. Our major findings, followed by a discussion of the radiative effect of anthropogenic dust on regional climate change in semi-arid regions, are given in Section 5.

2 Data

2.1 The aridity index dataset

In this study, we use the aridity index (AI) to classify different types of regions. The AI is defined as the ratio of annual precipitation to annual potential evapotranspiration, representing the degree of climatic dryness. The AI dataset used in this study (Feng and Fu, 2013; Huang et al., 2016b) based on the Climate Prediction Center (CPC) datasets. Drylands are identified as regions with AI values less than 0.65 and are further classified into hyper-arid ($AI < 0.05$), arid ($0.05 \leq AI < 0.2$), semi-arid ($0.2 \leq AI < 0.5$), and dry sub-humid ($0.5 \leq AI < 0.65$) following Middleton and Thomas (1997). Of the four types, hyper-arid regions are the driest, followed by arid, semi-arid and dry sub-humid regions. The AI dataset is provided by Feng and Fu (2013) and cover the period from 1948 to 2008, with a spatial resolution of 0.5° by 0.5°.

2.2 Population data

The population data are from the Gridded Population of the World dataset, version 3 (GPWv3, http://sedac.ciesin.columbia.edu/data/collection/gpw-v3), which is maintained by the Center for the International Earth Science Information Network (CIESIN) and the Centro Internacional de Agricultura Tropical (CIAT). GPWv3 depicts global population distribution. It is a gridded, or raster, data product that renders global population data at the scale and extent required to illustrate spatial relationship between human population and global environment. It aims to provide a spatially disaggregated population compatible with datasets from social, economic and Earth science disciplines. The spatial resolution is 0.5°×0.5°. The population data estimates are for the years of 1990, 1995, 2000, 2005, and 2010.

2.3 Dust detection data

The instrument used to detect anthropogenic dust is the CALIPSO Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). CALIOP acquires vertical profiles of elastic backscatter at two wavelengths (532 and 1064 nm) and linear depolarization at 532 nm from a near-nadir viewing geometry for both day and night (Hu et al., 2007a, b, 2009; Liu et al., 2008). The datasets detail the information of Level-1 backscatter, depolarization ratio, and color ratio profiles along with the Level-2 Vertical Feature Mask (VFM) product and the 5-km aerosol profile product. The CALIPSO algorithm uses volume depolarization ratio (δ_V) greater than 0.075 to indentify dust (Omar et al., 2009). In the CALIPSO version 3 VFM data, the cloud aerosol discrimination (CAD) algorithm can separate clouds and aerosols based on multi-dimensional histograms of scattering properties (e.g., intensity and spectral dependence), which is used in the identifying process.

2.4 Land cover data

The Collection 5.1 MODIS global land cover type product (MCD12C1) in 2011 is used to identify types of anthropogenic dust sources. It includes 17 different surface vegetation types and was developed based on the data from the International Geosphere-Biosphere Programme (IGBP) (Friedl et al., 2010), with a spatial resolution of $0.05^{o} \times 0.05^{o}$. It provides the dominant land cover type and the sub-grid frequency distribution of land cover classes. In the present analysis, croplands, grasslands, cropland mosaics, and urban are the land cover types that are considered as sources of anthropogenic dust. In addition, urban environments are also identified based on the dataset of Global Rural–Urban Mapping Project (GRUMP) v1 with a spatial resolution of 500 m (Schneider et al., 2010). GRUMP is a valuable resource both for researchers studying human-environment interactions and for users who want to address critical environmental and societal issues. GRUMPv1 consists of eight global datasets, namely, population count grids, population density grids, urban settlement points, urban-extent grids, land/geographic unit area grids, national boundaries, national identifier grids, and coastlines. These components allow the GRUMP v1 to provide a raster representation of urban areas.

3 Method for detecting anthropogenic dust aerosol

Recently, Huang et al. (2015) developed a new method of separating natural dust and anthropogenic dust at the global scale using CALIPSO measurements. They defined a schematic framework of dust sources and used vertical and horizontal transport processes as the foundation for their approach to discriminate anthropogenic dust from natural dust in CALIPSO data, which proceeds in a sequence of four steps. The first step is to detect the total dust load (both natural and anthropogenic). The second step is to determine the source region from which the dust originates. The third step is to determine the height of a planetary boundary layer (PBL), and the final step is to determine what proportion of the dust, i.e., that subset of the total dust within the PBL.

After the anthropogenic dust was identified by the detection method described above, the anthropogenic dust column burden was calculated as follows. First, we determined dust extinction coefficient from the “Atmospheric Volume Description,” which is used to discriminate between aerosols and clouds in the CALIPSO Level-2 aerosol extinction profile products. And then the dust extinction coefficients with the highest confidence levels (|CAD| ≥ 70) (Liu et al., 2008) and quality control flags of QC=0 or QC=1 were selected. The dust optical depth (DOD, τ) was calculated by integrating CAD and QC-filtered extinction coefficient of dust aerosols over the height of the dust layer. After calculating the global total DOD (τ_t) and the anthropogenic DOD (τ_a) from the CALIPSO profile products between January 2007 and December 2010, the dust column burden (M) was converted from DOD (τ), which was performed following Ginoux et al. (2001):

$$M = \frac{4}{3}\frac{\rho r_{eff}}{Q_{ext}}\tau = \frac{1}{\varepsilon}\tau \tag{1}$$

where r_{eff} is dust effective radius, ρ is dust density, Q_{ext} is dust extinction efficiency, and ε is mass extinction efficiency. The formula also referred empirical values from Ginoux et al. (2012) and assume r_{eff}=1.2 µm, ρ=2600 kg m^{-3}, Q_{ext}=2.5, and ε=0.6 m^2 g^{-1}. This method not only modifies the maximum standard technique developed by Jordan et al. (2010), its derived dust column burden also has a correlation coefficient of 0.73 with the ground-based lidar observation at the Semi-Arid Climate and Environment Observatory of Lanzhou University (SACOL) (Huang et al., 2008; Guan et al., 2009; Liu et al., 2014), indicating its effectiveness in detecting anthropogenic dust.

4 Results

4.1 Anthropogenic dust emission over global semi-arid regions

Figure 1 shows the global distribution of semi-arid regions along with the mean anthropogenic dust column burden from 2007 through 2010, demonstrating the wide spread of anthropogenic dust. Most of the areas with high anthropogenic dust loading are located in the mid to high latitudes of the Northern Hemisphere, such as North China, Mongolia, northern India, central western North America, and Sahel. The highest values are generally distributed throughout Eastern China and India. Note that the Northern Hemisphere has much more anthropogenic dust than the Southern Hemisphere. Therefore, we select four geographical regions that encompass semi-arid regions and are influenced by anthropogenic dust in order to quantify the recent changes.

These regions marked in Fig. 1 include East China, India, North America, and North Africa. From a visual inspection of the overlap between the anthropogenic dust distribution and the semi-arid regions, it can be seen that most semi-arid regions coincide with regions of high anthropogenic dust. However, the anthropogenic dust column burdens are different over the selected semi-arid regions: East China and India appear to have greater amounts of anthropogenic dust than North America and North Africa.

Figure 2 displays the total global anthropogenic dust column burden as a function of climatological annual AI during the period of 1948-2008. The mean AI varies from 0.0 to a maximum of 2.0. Note that the intervals in this figure are non-uniform because they are from the classification standard for different types of regions based on the AI, as defined in Section 2. Semi-arid region is the transition zone between arid and semi-wet regions; it is defined as the area where precipitation is less than potential evaporation, and is characterized by high temperatures (30-45^{o}C) during the hottest months. According to Huang et al. (2016a), the annual mean precipitation in semi-arid regions ranges from 250 to 500 mm yr^{-1} and the AI of semi-arid region is between 0.2-0.5. The global semi-arid regions in Fig. 2 exhibit relatively high peaks in the anthropogenic dust column burden, with AI values ranging between 0.2-0.5, where also experienced enhanced warming in recent decades (Huang et al., 2012).

Figure 3 compares the anthropogenic dust column burdens in summer (blue), spring (green), autumn (red), and winter (black) as a function of the climatological mean AI. The curves are similar in all four seasons, and the anthropogenic dust column burden exhibits a dominant peak in semi-arid regions in all four seasons, with values much larger than those in the other regions. For the semi-arid regions, the total anthropogenic dust column burden is the greatest in summer, followed by spring, autumn and winter, which may relate with the different frequency of human activities (Huang et al., 2015), such as the construction activity is likely to be greater in summer.

In order to illustrate the key role of anthropogenic dust in generating dust aerosols in the semi-arid regions, we compared the dust column burdens corresponding to natural with mixed dust (natural and anthropogenic dusts) in the semi-arid regions of the globe, North America, East China, North Africa, and India in Fig. 4. It is evident that mixed dust aerosol column burden is greater than the pure natural dust of the globe. Both mixed and pure natural dust column burdens are the greatest in India, followed by North Africa and East China. The mixed dust burden of North American region mixed dust burden is a little less than that of the natural dust. Among these regions where the mixed dust is greater than natural dust, the difference between mixed dust and natural dust is the largest in North Africa, followed by India and East China. For the mixed dust aerosol, the dust column burdens of natural and anthropogenic dusts are presented separately in Fig. 5. It shows that the anthropogenic dust column burden is greater than that of natural dust. And the highest value of anthropogenic dust column burden is in India, followed by North Africa, East China and North America; among these regions, the natural dust burden is the highest in North Africa, followed by India, North America and East China.

Table 1 reports the detailed values of the annual mean anthropogenic and natural dust column burden from mixed dust areas over the semi-arid regions of East China, India, North America, and North Africa. In the semi-arid regions of India, the mean anthropogenic dust column burden is 0.38 g per m^2 and the natural dust column burden is 0.14 g per m^2; therefore, the percentage of anthropogenic dust is 73% of the mixed dust aerosols. The anthropogenic dust values of North Africa, East China and North America are 0.21, 0.18 and 0.14 g per m^2, respectively. The natural dust column burdens of North Africa, East China and North America are 0.20, 0.02 and 0.02 g per m^2, respectively, whereas the proportions of anthropogenic dust to mixed aerosol in these three regions are 51%, 90% and 87.5%, respectively. Therefore, the value of anthropogenic contribution in India is the greatest, much more than the other three selected regions.

4.2 Population variance in the semi-arid regions

Figure 6 is the distribution of mean population density. The population density in semi-arid regions exhibits dramatic regional variability. For the four selected semi-arid regions, both India and East China have higher population densities, most semi-arid regions of North Africa have relatively lower population density, and the population density in the semi-arid region of North America is the lowest. The regional difference of population indicates influences of human activities are not uniformly distributed in the semi-arid areas. Figure 7 illustrates the global distribution of population change between 1990 and 2010. India exhibits the most obvious population change, followed by North Africa and East Asia. North America exhibits an obvious difference between east and west areas, a similar spatial pattern of population change occurred in China. The difference between these respective western and eastern areas may be related to their economic status. The eastern areas of both North America and China are more industrialized than their western counterparts. Compare Fig. 6 and Fig. 7, the inconsistent distribution between population density and population change reveals that the regions with the higher population densities are not always have the more obvious population change. Population density and change are related to various factors, such as population policies, economic development status and political divisions.

Figure 8 compares the mean population density and change in the four selected regions; it is apparent that India has the highest population density, which reaches almost 290 persons per km^2. For the other regions, population densities from high to low are North Africa, East China, and North America. Population change appears to be the highest in India as well, followed by North Africa, East China and North America. More detailed population density and population change are illustrated in Table 2. It shows that India has the highest population density of 290 persons per km^2 with a population increase of 80 persons per km^2. The second largest population density is North Africa. It has a population of 53 persons per km^2, with a population growth of 22 persons per km^2. The population densities of East China and North America are 49 and 22 persons per km^2, respectively; and the population changes in East China and North America are 8 and 6 persons per km^2 respectively.

4.3 Relationship between anthropogenic dust with population density/ change

Figure 9 is the mean anthropogenic dust column burden as a function of population density. The population varies from 0 to 400 persons per km^2 on the x-axis with non-inform intervals, and the mean anthropogenic dust ranges from 0.15 to 0.35 g per m^2. The anthropogenic dust shows an increase from the population density of greater than 100 persons per km^2, and illustrates high population density greater than 100 persons per km^2 has significant effect on anthropogenic dust production. The standard deviation of anthropogenic dust is the highest for population greater than 400 persons per km^2 and the lowest for population of 25-50 persons per km^2. Basically, the standard deviation of anthropogenic dust is larger for high population density. The positive correlation indicates increasing population density may contribute to the production of the anthropogenic dust column burden. Figure 10 is the mean anthropogenic dust as a function of population change. The anthropogenic dust shows obvious increase from the population change that is greater than 25 persons per km^2, with a high standard deviation. The positive correlation reveals that the anthropogenic dust increase by population change tends to occur in the case of large population change, and confirms the positive contribution from high population increase to production of anthropogenic dust in the semi-arid regions.

In the semi-arid regions, four typical land covers in semi-arid regions are urban, grassland, cropland, and croplands mosaics. Figure 11 shows the global mean anthropogenic dust column burden in semi-arid region as a function of population density over cropland (blue line), cropland mosaics (which are lands with a mosaic of croplands less than 60% of the landscape according to Friedl et al., 2002; green line), urban (red line), and grassland (orange line). For population density less than 90 persons per km^2, the anthropogenic dust burden over different land covers all shows subtle changes. However, when the population density is larger than 90 persons per km^2, the anthropogenic dust exhibits an obvious increase as the population density increases. The anthropogenic dust increases the fastest in the croplands (blue line), followed by crop mosaics, urban and grassland. Differentt variability of anthropogenic dust as a function of population density over different land covers indicates that sensitivities of anthropogenic dust to population are quite different over four typical land covers.

And the percentage of different type of land cover in the semi-arid regions of East China, India, North America, and North Africa is illustrated in Fig. 12a-d. It shows the components of cropland, grassland, urban, and cropland mosaics are quite different. In the four selected regions, the Indian semi-arid region is dominated by croplands, which has an area of 5.92×10^5 km^2 (Table 3) and takes up 82.85% of total area (Table 4). The areas of croplands in East China, North America and North Africa are 0.94×10^5, 1.92×10^5, and 2.81×10^5 km^2, respectively and the corresponding percentages of croplands in East China, North America and North Africa are 6.29%, 11.51% and 16.66%, respectively. From both area and percentage, the croplands in India are more than in the other regions. The cropland mosaics have the largest area in North Africa (6.35×10^5 km^2), followed by India (0.73×10^5 km^2), North America (0.13×10^5 km^2) and East China (0.04×10^5 km^2); their percentages are 37.62%, 10.27%, 0.79%, and 0.29%, respectively. For grassland, it has the largest area in East China (13.67×10^5 km^2), followed by North America (13.51×10^5 km^2), North Africa (7.64×10^5 km^2), and India (0.08×10^5 km^2), with percentages of 91.86%, 45.22%, 80.75%, and 1.11%, respectively. The urban area is the largest in North America (1.16×10^5 km^2), followed by India (0.41×10^5 km^2), East China (0.23×10^5 km^2) and North Africa (0.08×10^5 km^2), and their percentages are 6.96%, 5.78%, 1.56%, and 0.50%, respectively.

Figures 13a-d illustrate the anthropogenic dust probability distributions are quite different in East China, India, North America, and North Africa with intervals of population and dust column burden are 20 persons per km^2 and 0.05 g per m^2. In these different regions, the semi-arid regions in India have the highest anthropogenic dust in the population density of 200-250 persons per km^2, and its anthropogenic dust column burden is concentrated around 0.4 g per m^2. The anthropogenic dust probability in East Asia (Fig. 13a) and North America (Fig. 13c) show that centers of anthropogenic dust are between 0.1 and 0.2 g per m^2, and the population density between 0 to 30 persons km^{-2}. Figures 13d is the anthropogenic dust in North Africa. The highest anthropogenic dust in North Africa is around 0.2 and 0.3 g per m^2, and the population density concentrated around 0-30 persons per km^2.

The comparison in Fig. 13 highlights the representative relationship between anthropogenic dust and population in India, and Fig. 14 shows quantified influences of population on anthropogenic dust probability in typical croplands of Indian semi-arid regions with intervals of population density/change are 20 persons per km^2. Figures 14a and b appears normal distribution of anthropogenic dust as a function of population/change. The population density and population change reach the highest anthropogenic dust probability at the values of 220 and 60 persons per km^2, respectively. Figures 14c and d compose both the impact from population density and change on anthropogenic dust probability and show the highest peak of anthropogenic dust probability is located in the population density of 220 persons per km^2 and population change of 60 persons per km^2. Such shape of 3-D figure (Fig. 14c-d) illustrated the impact from population does not always have a positive contribution to the production of anthropogenic dust, and overly excessive population will suppress the increase of anthropogenic dust. Meanwhile, the relationship in croplands of Indian semi-arid regions performs a direct influence of human activities on environment change. Moreover, as the total dust aerosol in India has been greatly increased by anthropogenic dust aerosol, it has changed the radiative effect of dust aerosol and the radiative balance as well. Eventually, it will contribute to regional climate change, if not already. Therefore, the relationship is shown in Fig. 14 has quantified the influence of human activities on regional climate for croplands in semi-arid regions.

5 Summary and discussion

In this paper, we focused on the relationship between anthropogenic dust and population. It was found that the total anthropogenic dust column of globe exhibited an obvious peak in the semi-arid regions, which were much higher than it in the other regions. Four geographical semi-arid regions of East China, India, North America, and North Africa were chosen as our study areas according to their anthropogenic dust levels and population. Both population density and population change were correlated with anthropogenic dust, indicating that these population features had effects on the production of anthropogenic dust column burden in these semi-arid regions. In particular, typical croplands in Indian semi-arid region showed a normal relationship between anthropogenic dust with population density/change, the relationship indicated the influence of human activities on environment can be quantified in the process of climate change. And it also proposed a typical influence of human activities on anthropogenic dust in cropland.

Dust aerosols exert a key impact on regional radiative forcing over semi-arid regions (Huang et al., 2006b), and are closely related to local climate change (Guan et al., 2015b). Historical statistics revealed that population change occurs in parallel with economic growth and with increases in energy consumption, GHG emission and anthropogenic dust. Further studies are needed to gain a better understanding of the influence of anthropogenic dust aerosols on climate change in semi-arid regions. Under the current dynamic economic conditions throughout the world, there are still many developing countries in semi-arid regions, which are undergoing extensive economic development or are in the process of transforming from an extensive economic mode to an intensive economic model. Developing countries exhibit high rates of population growth, which must be considered when forming economic development strategies. In the developed countries, population change may also result in increased consumption, higher energy demands and enhanced GHG production. Therefore, further investigations into the influence of human activities on anthropogenic dust aerosol production and the consequent impacts on regional climate change in semi-arid regions are needed, with an emphasis on understanding the feedback between regional climate change and societal development with the intent of applying more reasonable policies in the process of economic development.

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Table 1. Mean dust column burdens (g per m^2) in four geographical semi-arid regions.

Region	Anthropogenic dust	Natural dust
East China	0.18	0.02
India	0.38	0.14
North America	0.14	0.02
North Africa	0.21	0.20

Table 2. Mean population density/change (persons km^{-2}) in four geographical semi-arid regions.

Region	Mean population density	Mean population change
East China	49.18	8.15
India	290.07	79.69
North America	22.05	5.62
North Africa	52.73	21.85

Table 3. Different land cover areas (km^2).

Region	Urban area	Grasslands area	Croplands area	Cropland mosaics
East China	0.23×10^5	13.67×10^5	0.94×10^5	0.04×10^5
India	0.41×10^5	0.08×10^5	5.92×10^5	0.73×10^5
North America	1.16×10^5	13.51×10^5	1.92×10^5	0.13×10^5
North Africa	0.08×10^5	7.64×10^5	2.81×10^5	6.35×10^5

Table 4. Different land cover area percentage (%).

Region	Urban	Grasslands	Croplands	cropland mosaics
East China	1.56	91.86	6.29	0.29
India	5.78	1.11	82.85	10.27
North America	6.96	80.75	11.51	0.79
North Africa	0.50	45.22	16.66	37.62

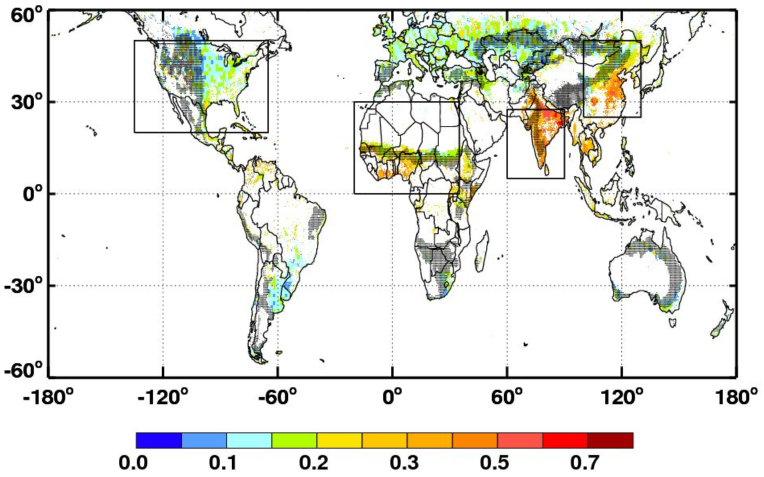

Figure 1. Global distribution of mean anthropogenic dust column burden (g per m^2) from 2007 to 2010. The gray hatching indicates semi-arid regions.

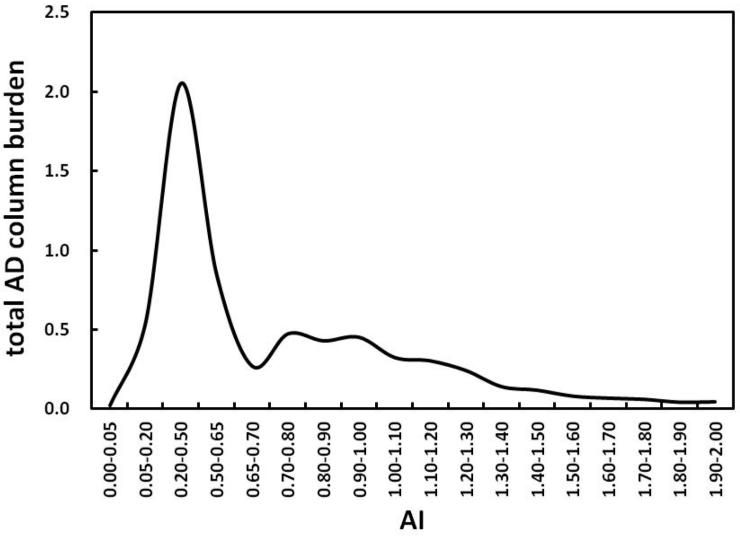

Figure 2. Total global anthropogenic dust column burden (Tg) as a function of the climatological mean aridity index (AI).

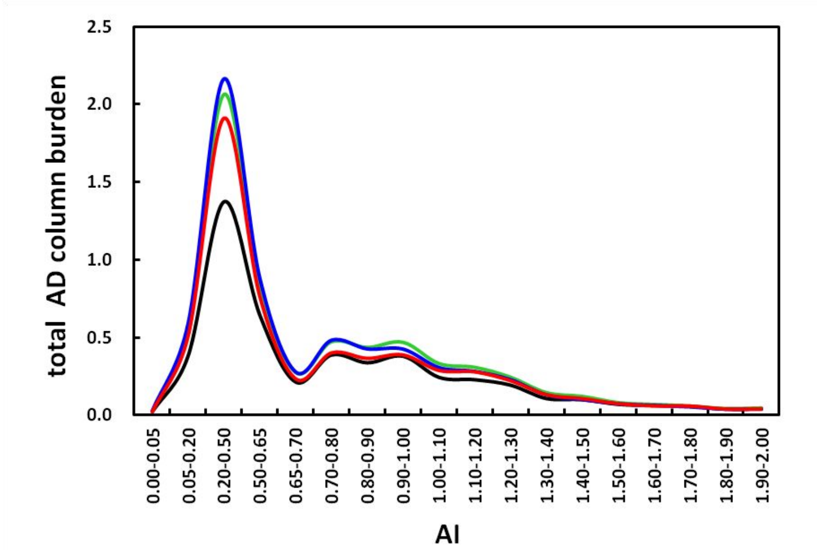

Figure 3. Comparison of the global anthropogenic dust column burden (Tg) in spring (green), summer (blue), autumn (red), and winter (black) as a function of the climatological mean aridity index (AI).

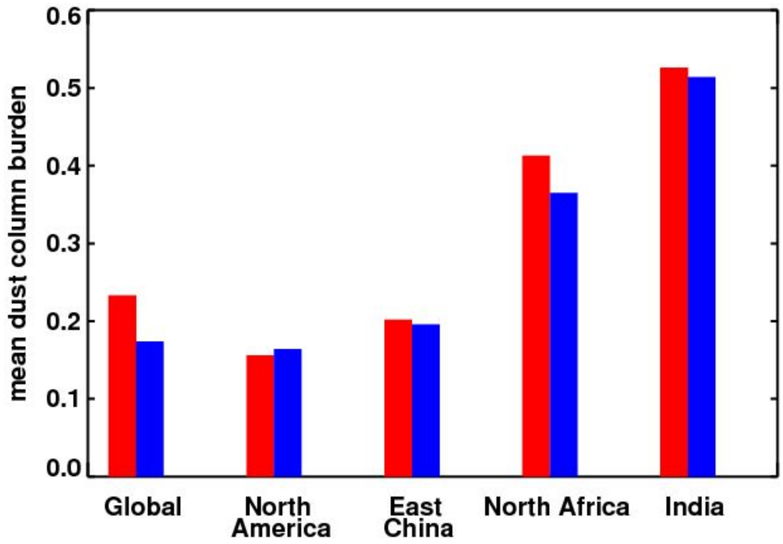

Figure 4. Mean dust column burdens (g per m^2) of mixed dust (red) and natural dust (blue) in the global and four geographical semi-arid regions.

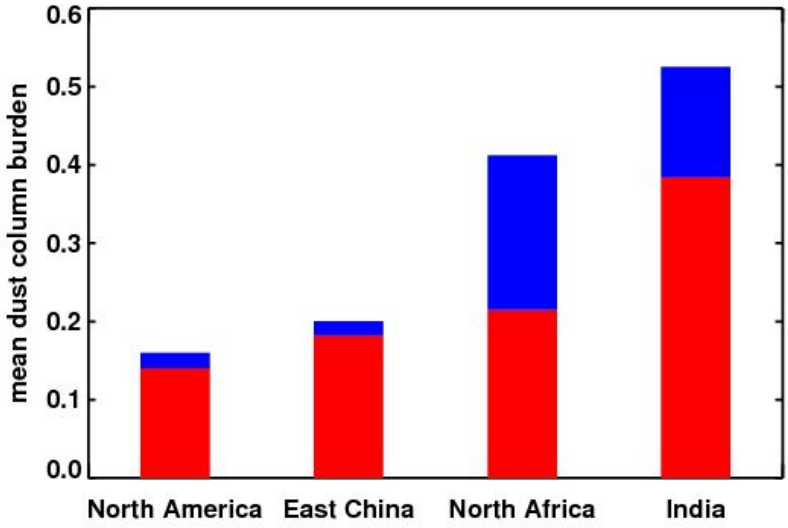

Figure 5. Mean anthropogenic (red) and natural (blue) dust column burdens (g per m^2) from mixed dust regions in the four geographical semi-arid regions.

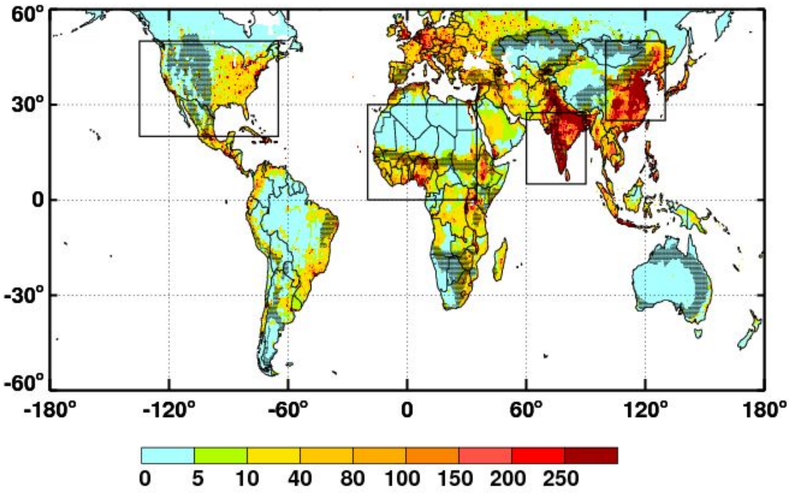

Figure 6. Global distribution of mean population density (persons per km^2).

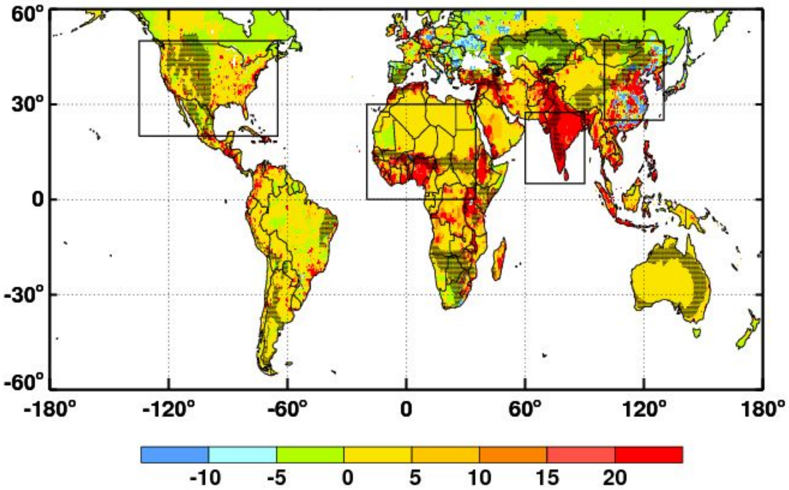

Figure 7. Global distribution of mean population change (persons per km^2).

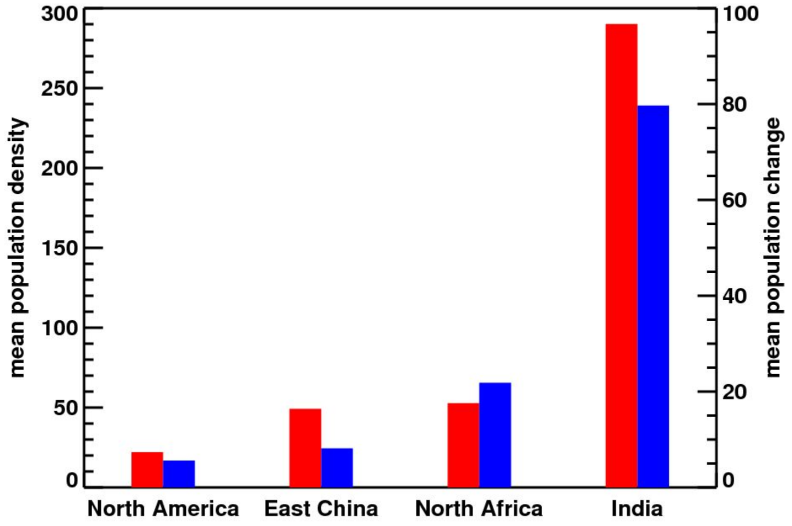

Figure 8. Mean population density (red) and population change (blue) in the four geographical semi-arid regions.

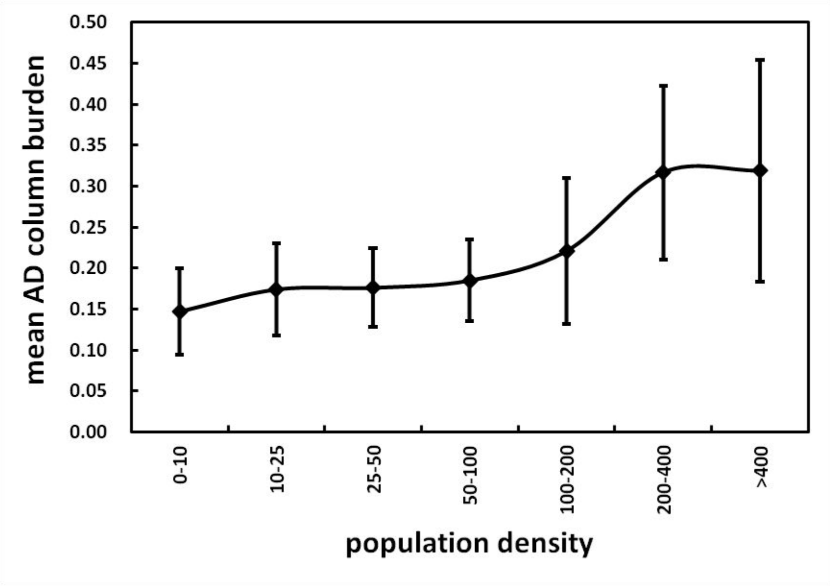

Figure 9. Mean anthropogenic dust column burden changes as a function of population density.

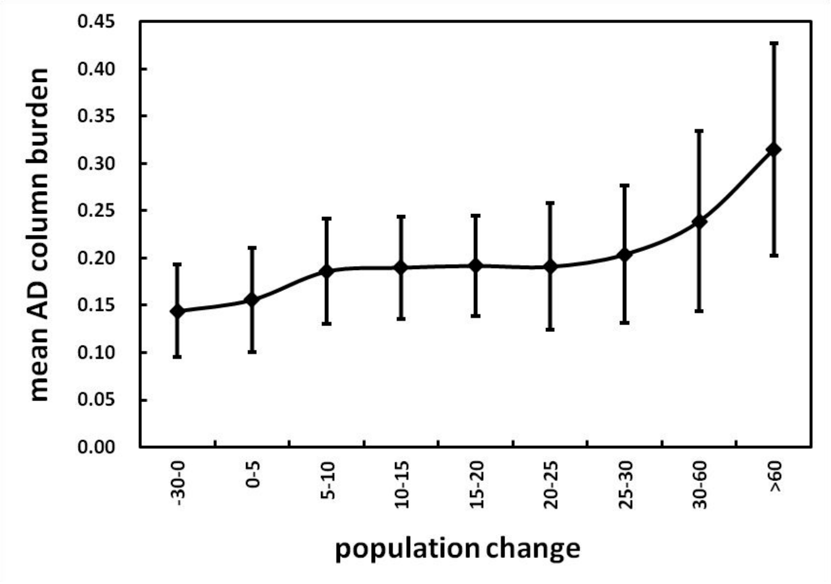

Figure 10. Mean anthropogenic dust column burden changes as a function of population change.

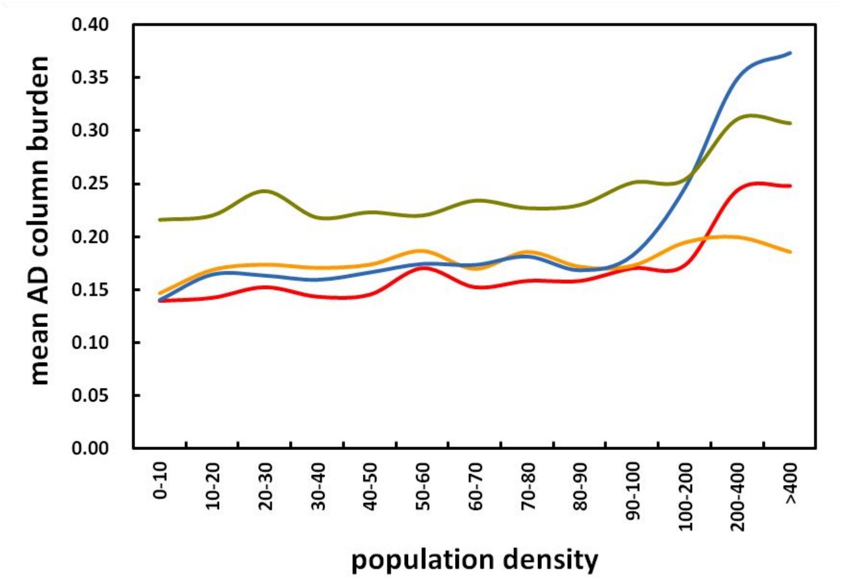

Figure 11. Global mean anthropogenic dust column burden (g per m^2) as a function of population density (persons per km^2) in semi-arid regions of croplands (blue), croplands mosaics (green), urban (red), and grasslands (orange).

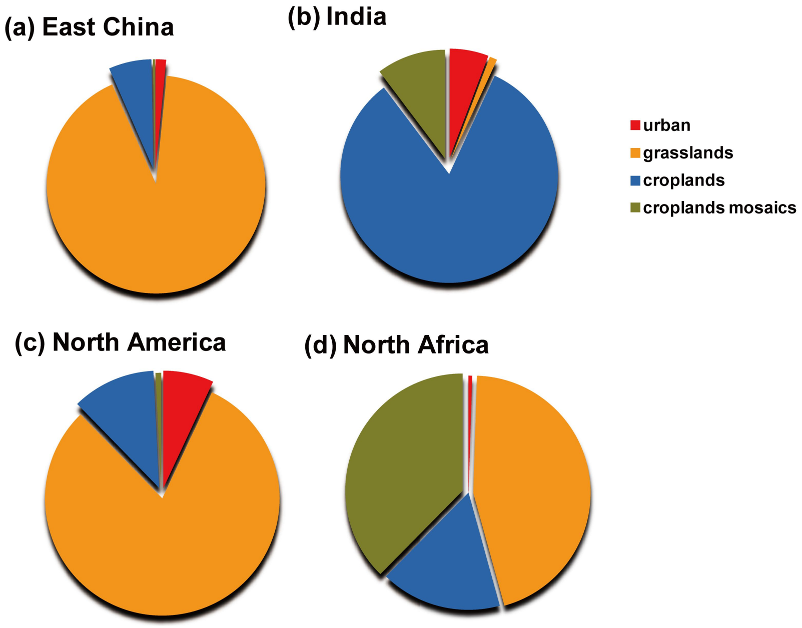

Figure 12. Percentage of different types of land cover in semi-arid regions of East China (a), India (b), North America (c), and North Africa (d).

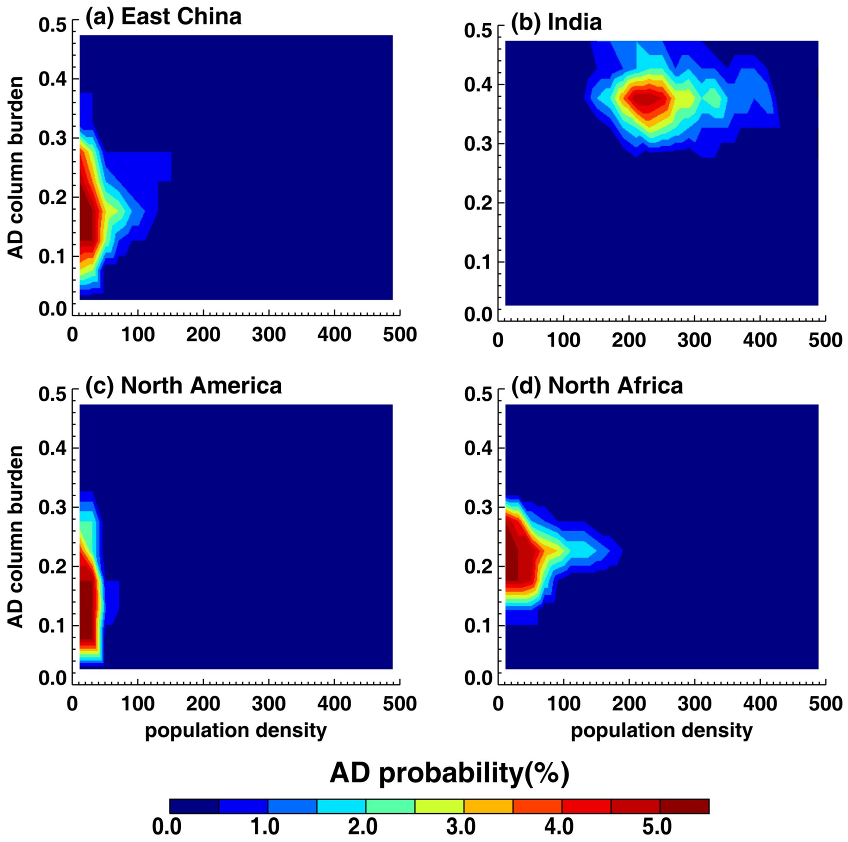

Figure 13. AD probability distribution in different population density and AD column burden value in semi-arid regions of East China (a), India (b), North America (c), and North Africa (d).

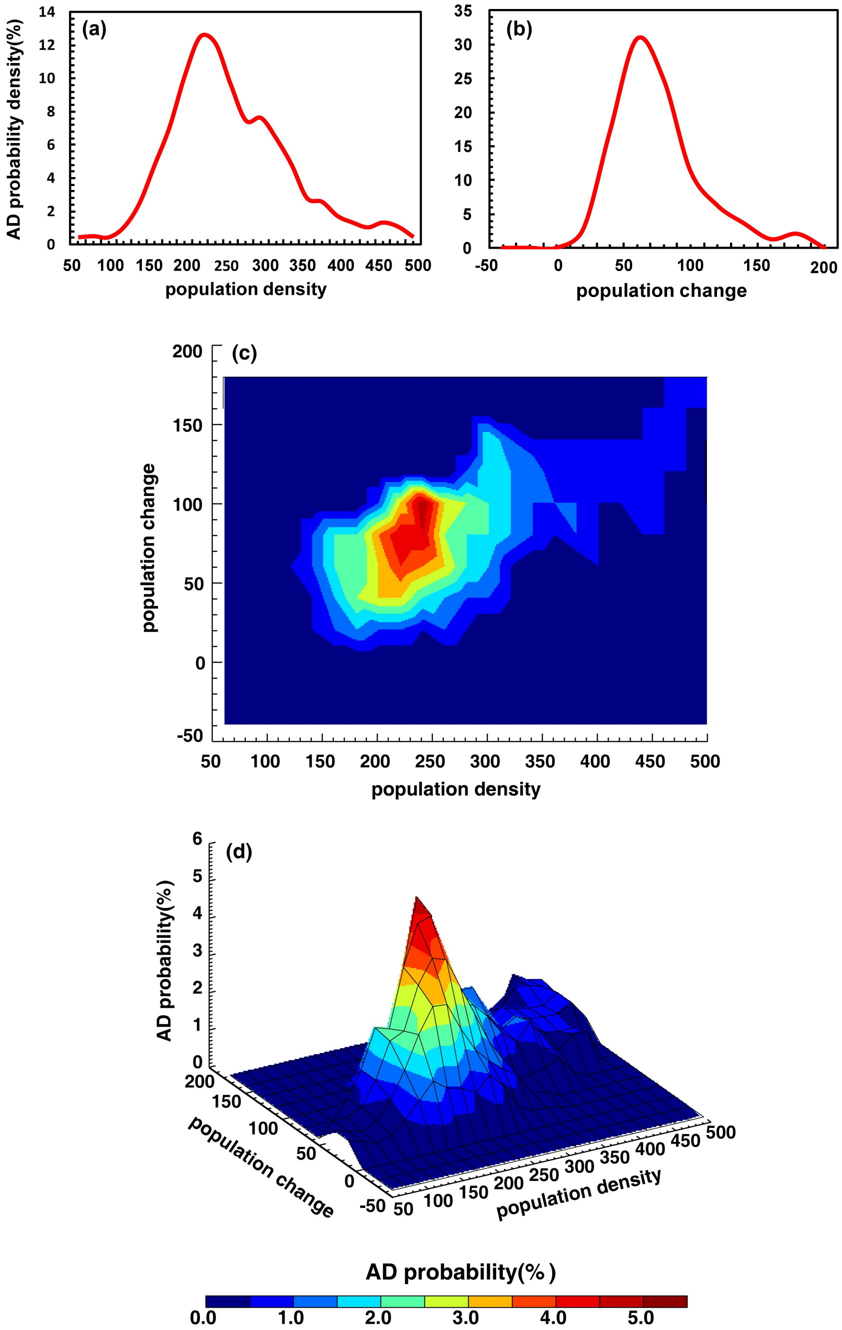

Figure 14. AD probability as a function of population density (a), population change (b), 3-D (c) and 2-D (d) of AD probability distribution as a function of population density and change in typical cropland-dominated semi-arid regions in India.