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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Joint spatial variability of aerosol, clouds and rainfall in the Himalayas from satellite data" *by* P. Shrestha and A. P. Barros

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Section 3. Satellite Data : It is well known that the MODIS aerosol retrievals over land use the dark-target approach, and no retrievals are performed when the surface reflectance is low. Your statement 'The MODIS aerosol retrieval is more accurate _' can be restated like 'The MODIS aerosol retrieval is less accurate where albedo is low compared to the region of high albedo (e.g., ocean and dark vegetation)'. The authors can mention what percentages are missing in the region of interest.

REPLY: We note there must be an inadvertent print mistake in the Reviewer's comment, when stated that MODIS aerosol retrieval is less accurate where albedo is low, when

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it is the opposite. Nevertheless, the statement to which the Reviewer refers to will be modified to read as follows: “Over land, MODIS aerosol retrieval is less accurate where albedo is high compared to the region of low albedo (e.g., dark vegetation , Kaufaman et al., 1997, Hsu et al., 2004)”

2. Section 4.1 Aerosol Variability: Before discussing aerosol variability, it would be helpful to remind the readers about the detailed description of the mean aerosol field. If it is already published in other work, pointing out a few characteristics would help. In general, authors did not discuss the inter-annual variability of the modes. EC1 time-series computed from MODIS aerosol optical depth (AOD) shows large year to year variability. The interannual variability is obvious within the 8 years of TOMS aerosolindex (AI) observations (Figure 4). Is it a natural variability or is there any other local influence? Is there any possibility of instrumental drift? If it is related with monsoon,the EC1 and/or EC2 must be connected with the monsoon variability. Is there any correlation between EC1 and EC2 with other climate or ocean variability indices, e.g., arctic oscillation (AO) and ENSO? This paper focuses on the intra-annual variability, but showing the inter-annual variability of aerosol, cloud, and rainfall by removing seasonal cycle from the ECs would be useful for interpreting the connection mechanism of the aerosol to the cloud and precipitation.

REPLY: The mean monthly aerosol optical depth used in this study is obtained from the MODIS Level 3 (L3) product. The monthly L3 product is computed from the complete set of daily files that span a particular month. Each daily L3 product contains statistics computed from Level 2 MODIS granules that span 24 hour period [see King et al. (2003), Hubanks et al. (2008)]. Regarding the TOMS data, there are known instrument problems and the manuscript was updated to include the following statement: Due to calibration issues associated with sensor performance degradation, trend analysis of the data after 2001 is not recommended by the NASA TOMS science team (http://daac.gsfc.nasa.gov/guide/tomsl3.dataset.gd.shtml) [see also Gautam et al. (2009)].

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Following Reviewer 1's suggestion, the EOF analysis of MODIS AOD was repeated using the DEEP BLUE Algorithm product to fill MODIS missing data over bright areas. However, note that the Deep Blue Algorithm itself requires the screening of the presence of subpixel clouds and aerosol retrievals over cloud-contaminated scenes are not provided (Hsu et al. 2006). Because the region of our interest has frequent cloud-cover, this will also create gaps in the data. Hence, both the dark target approach and the deep blue algorithm will have gaps in the monthly mean data, one effected by bright surfaces (desert), whereas, the other one effected by cloudy pixels. So, we used the MODIS Deep Blue aerosol retrieval (550 nm), wherever there was a missing value in the AOD using dark target approach. This fills up the missing AOD over bright reflecting areas like the Thar desert and the Taklaman desert. The analysis from the combined product produces similar results as previous analysis but it does improve the results over the Thar desert and the Takla Makan desert. The Deep Blue product from AQUA was available only from July 2002. The result from the EOF analysis of this combined data is discussed below:

The first EOF mode of the combined product is better able to capture the strong spatial mode developing over the Takla Man desert as well as the Thar desert during the summer monsoon season over India, peaking consistently during the month of July (Figure 1). The northern branch is bounded by the Takla Man desert. The southern branch is aligned north-west to the Aravalli range extending from the Arabian sea to the Indus Valley with peaks over the Thar desert.

The second mode does is very different from the original calculation when the missing values of AOD over the Takla Man desert were replaced with the spatial mean of the analysis domain (Figure 2). Here, strong variability of AOD is also observed in the Takla Man desert over the months of March-April-May. This variability is also present in the north-eastern part of India. The southern branch is aligned with the slopes of the Himalayas and extends to the eastern region of the IGP. This mode peaks around July consistent with EOF 1 and decreases sharply within the next two months, before beginning to peak again during the post monsoon followed by the winter season.

One of the most important outcomes of the EOF analysis using the combined product is that the third mode is able to capture the modes of variability of aerosol in the Ganges river basin along the southern slopes of the Himalaya over Nepal, peaking during the winter and the pre-monsoon season (Figure 3). The pre-monsoon aerosol loading over this region is processed by the cloudiness during the onset of the monsoon and aerosol below the cloud base is washed away by the monsoon rainfall. After the monsoon season is over, the aerosol again starts to peak during the winter season (Dec-Jan) [Gautam et al. (2007)].

Now, as suggested by the reviewer, standardized anomalies of the EC components was created as follows:

where and are the monthly mean and standard deviation for the monthly in question of data x. Also, Southern Oscillation Index (SOI) was downloaded from the Australian Bureau of Meteorology. The SOI index was divided by 5 to produce comparable plots with the standardized anomaly of the combined AOD product, which is first discussed below:

For SOI and the EC components of AOD, some periods have positive phase relationship, suggesting positive (negative) SOI with positive(negative) AOD anomaly, while some occasions have negative phase relationship i.e. positive(negative) SOI with negative(positive) AOD anomaly. Qualitatively, little information can be extracted from Figure 4,5 and 6, but when the data were binned to plot a monthly histogram, a negative phase relationship was present between SOI and AOD3 always for the month of June. Further, we present the monthly histogram plots obtained by comparing standardized anomalies of MODIS AOD with TRMM rainfall and MODIS AOD with MODIS COD.

During the period of 66 months considered above, 30 occasions showed positive phase relationship, i.e., PRECIP1 (first EC component of TRMM rainfall) anomaly is negative (positive) when AOD1 (first EC component of MODIS AOD) anomaly is negative

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(positive) [Figure 7]. The month of May had highest in phase relationship, which is a pre-monsoon season. On the other hand, 36 occasions showed negative phase relationship, i.e, PRECIP1 anomaly is negative (positive) when AOD1 anomaly is positive (negative). The month of January and October showed highest negative relationship and these periods are associated with winter rainfall and post-monsoon rainfall respectively. For COD1 (first EC component of MODIS COD) and AOD1 anomalies, 34 out of 66 occasion showed in phase relationship. The month of April and May had highest in phase relationship, again during the pre-monsoon season. And, 32 of 66 occasions showed negative phase relationship as described earlier with a maximum during the month of February and October i.e winter and post-monsoon season.

In the case for PRECIP1 and AOD2 (second EC component of MODIS AOD) anomalies, 39 out of 66 occasions where in phase, with maximum in phase relationship present during the month of June, July i.e. during the first half of the monsoon season (Figure 8). This does indicate that an increase in the precipitation during the monsoon season does have a positive impact on the increase in second mode of AOD. Similarly, 35/66 occasions showed in phase relationship between COD1 and AOD1 anomalies, with a maximum during the months of January, February and November, i,e the winter periods. And, 31 out of 66 occasions showed negative phase relationship with a maximum during the month of March and April i.e. the pre-monsoon season.

For PRECIP1 and AOD3 (third EC component of MODIS AOD), 27 out of 66 occasions showed in phase relationship with maximum for the month of February and April i.e the pre-monsoon season (Figure 9). And, 39 out of 66 occasions showed negative phase relationship, with maximum for the month of July (6 out of 6 years) suggesting increase in AOD anomaly for weaker monsoon rainfall in July. For COD1 and AOD3 anomalies, 27 of 66 occasions showed in phase relationship with 70% of maximum analyzed period for the month of September. Negative phase was observed for 39 out of 66 months with maximum for the month of July i.e during monsoon and again in December (winter month) as well. So a consistent strong negative phase relationship was observed between the AOD3 and PRECIP1/COD1 for the month of July suggesting increase in the AOD of this mode with weaker monsoon rainfall in July.

For PRECIP2 (second EC component of TRMM precipitation) and AOD1 anomalies, 39 of 66 occasions showed in phase relationship, with month of June and July having strongest relationship (Figure 10). And, 27 of 66 occasions had negative phase relationship with a maximum of for the month of May. This indicates that the increase in monsoon rainfall associated with the second mode of TRMM rainfall correlates with the increase in second mode of MODIS AOD. For COD2 (second EC component of MODIS COD) and AOD1 anomalies, 33 of 66 occasions showed in phase relationship with a maximum for month of April, during pre monsoon season. And, 33 of 66 occasions exhibited negative phase relationship with a maximum for the month of January i.e the winter period.

For PRECIP2 and AOD2 anomalies, 40 of 66 occasions showed in phase relationship. This is the highest in phase relationship observed between different modes of PRECIP and AOD (Figure 11). And, 26 of 66 occasions showed negative phase relationship with a maximum of around 70% for the month of November. Similarly, 38 of 66 occasions showed in phase relationship with a maximum for the month of July, during monsoon. And, 28 of 66 occasions showed negative phase relationship with a maximum for the month of April, during pre-monsoon season. This mode shows a strong positive relationship between the increase in AOD and the COD.

For PRECIP2 and AOD3 anomalies, 38 of 66 occasions showed in phase relationship with a maximum during the summer monsoon period (JJAS). And, 28 of 66 occasions showed negative phase relationship(Figure 12). For COD2 and AOD3, 28 of 66 occasions showed in phase relationship with a maximum of for the month of September. And, 38 of 66 occasions showed negative phase relationship with maximum for the month of April and July. The objective of this study is to identify the coupled modes of variability of aerosol, cloudiness and rainfall. The above studies again show that there are significant linkages between the observed modes during certain period of the months. A strong positive phase relationship was observed between PRECIP2 and AOD1 for the month of June, July indicating an increase in AOD associated with increase in rainfall during June, July monsoon rainfall. On the other side, a consistent strong negative phase relationship was observed between the AOD3 and PRECIP1/COD1 for the month of July suggesting increase in the AOD3 with weaker monsoon rainfall in July i.e. aerosols are less scavenged by rainfall during these periods. Also, a strong positive relationship was observed between the second mode of AOD and COD for the month of July and a strong negative phase relationship was observed between the third mode of AOD and second mode of COD.

3. Section 4.2 Rainfall and cloud variability: The discussion of the correlation among the first modes of MODIS AOD, COD and TRMM is confusing. Is the highest correlation (r_0.7) found to be the one between AOD and COD or between AOD and TRMM? Please add the explanation about the correlation length of six months. Most importantly, why this high correlation expresses the fact that the same large scale dynamics are governing aerosol and moisture transport in the region? The authors need to add reasoning for this.

REPLY:The Reviewer's point is well taken, and the text was revised. The highest correlation of r=0.7 was found between MODIS AOD EC1 and TRMM rainfall EC1, and also between MODIS AOD EC1 and MODIS COD EC1 at zero lag. The correlation length of six months here refers to time period in months during which the correlation was positive. Since the first spatial mode (EOF1) of clouds and the rainfall are aligned along the Bay of Bengal and the Western Ghats of India, and the first spatial mode (EOF1) of AOD is aligned parallel to the Himalayas with the main core in the Indus, these modes are at different locations but they are fuelled by the strengthening of the westerly winds during the summer monsoon, which also bring polluted air mass towards NW of the Aravalli Range all the way from the east coast of Africa and the Middle East [Lau et al. (2006)], and moist air below the Aravalli range that passes over the Western Ghats of India and finally veering Northwards along the Bay of Bengal. Hence, the same large

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scale dynamics governs the aerosol and moisture transport in the region.

4. Section 5 Joint variability: In section 4, the highest correlation between ECs of AOD and ECs of precipitation was found with a lag of three months. However, EC1's show a strong correlation at zero lag over the monsoon season in the joint variability between TRMM precipitation and AOD. Comments about this would be helpful for the readers.

REPLY:In Section 4, the EC1 of MODIS AOD showed high correlation with EC1 of TRMM rainfall and EC1 of MODIS COD at zero lag; this phenomenon was also strongly reflected in the joint variability between the TRMM precipitation and MODIS AOD, as the first pair of patterns resembles the first EOF modes of each of the variable analyzed. However, in Section 4, it was only the EC2 of MODIS AOD that had highest correlation with a lag of three months.

5. Section 5. 2 AOD and COD : The authors can discuss where the indirect radiative effect of aerosols on cloud properties is pronounced and explain why they think an aerosol-cloud indirect effect is significant in this region.

REPLY:Lau et al. (2008) provided evidence for aerosol indirect effect over the IGP using the MODIS derived cloud effective radius and AOD, showing smaller effective radius of cloud drops less than 10um over the regions of polluted cloud. Tripathi et al. (2007) examined the MODIS AOD and liquid/ice cloud effective radius from 2001 to 2005 over the IGP. In their study, for increasing cloud cover fraction, best correlation between liquid/ice cloud effective radius and AOD was obtained during pre-monsoon season, suggesting an increase in indirect effect with increase in cloud cover during the pre-monsoon season. The strongest correlation was obtained when cloud fraction was 0.6∼0.8 but then it decreased for higher values, suggesting a possible threshold for the aerosol indirect effect. These references have been added to the manuscript. In addition, the newly added Fig. 13 shows the area where aerosols, cloud and rainfall interactions are likely to be important.

6. Figure2: Enlarging the Figure 2 would help to identify the wind fields.

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REPLY:The figures were modified during the formatting for ACPD. We will request the publishers to enlarge the figures.

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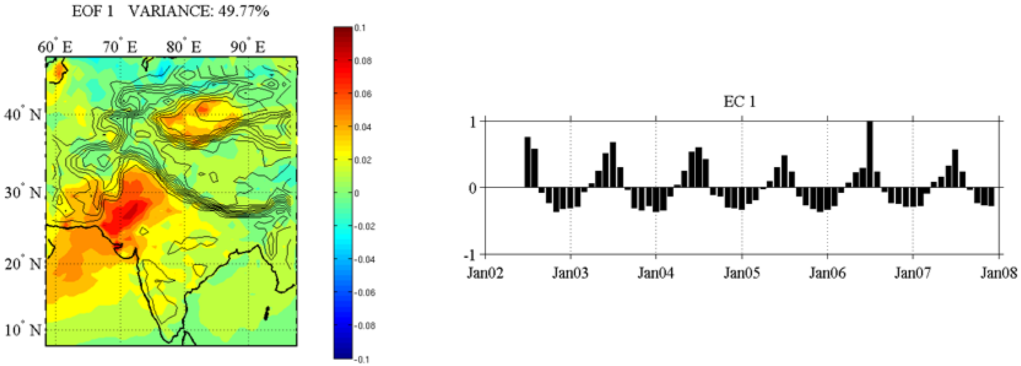

Fig. 1. EOF 1 and EC1 estimated from the MODIS Aqua by filling the missing values over land by the Deep Blue Algorithm retrieval at 550nm.

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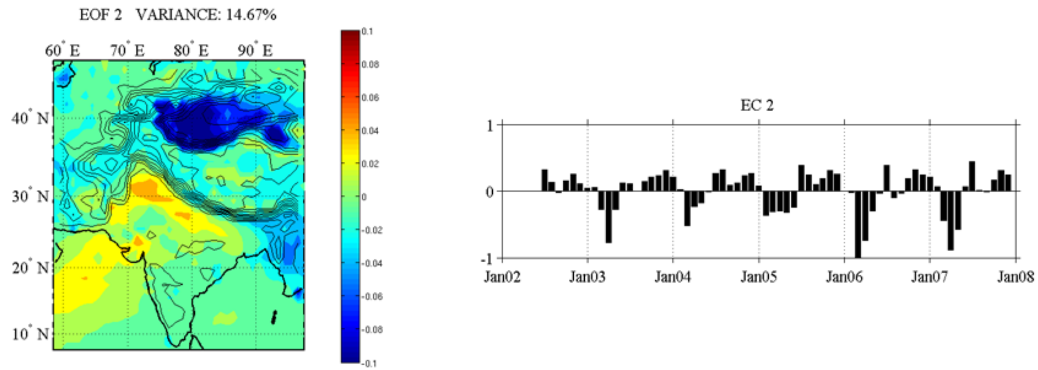

Fig. 2. EOF 2 and EC2 estimated from the MODIS Aqua by filling the missing values over land by the Deep Blue Algorithm retrieval at 550nm.

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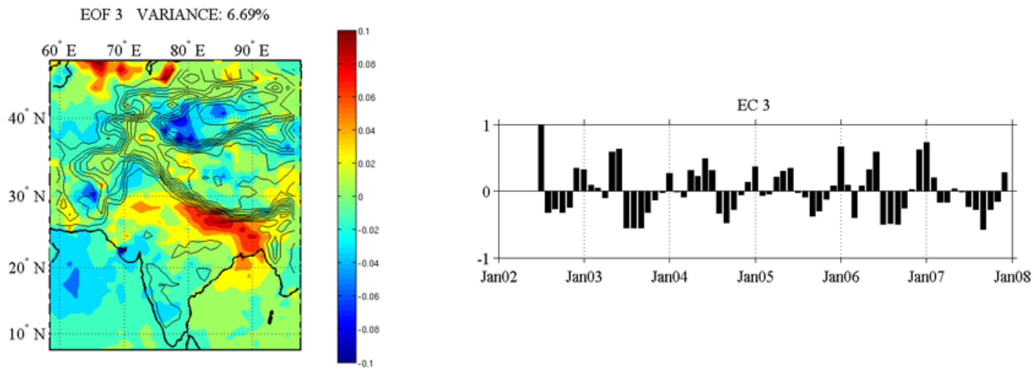

Fig. 3. EOF 3 and EC3 estimated from the MODIS Aqua by filling the missing values over land by the Deep Blue Algorithm retrieval at 550nm.

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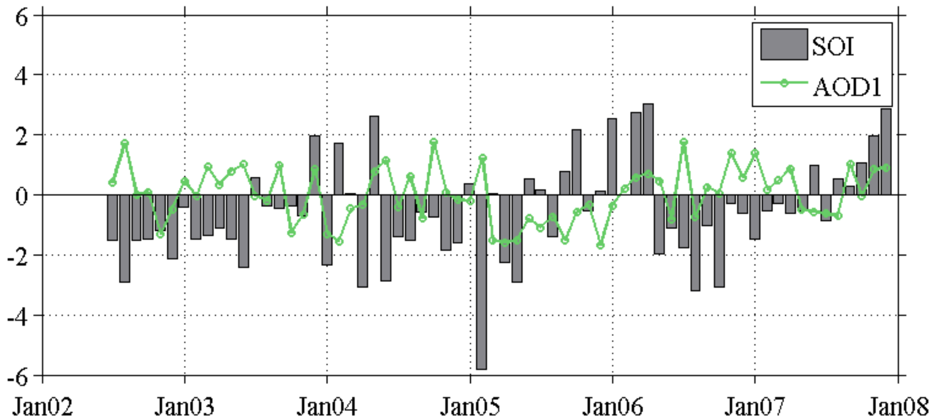

Fig. 4. Standardized anomaly of first EC component of MODIS AOD and SOI.

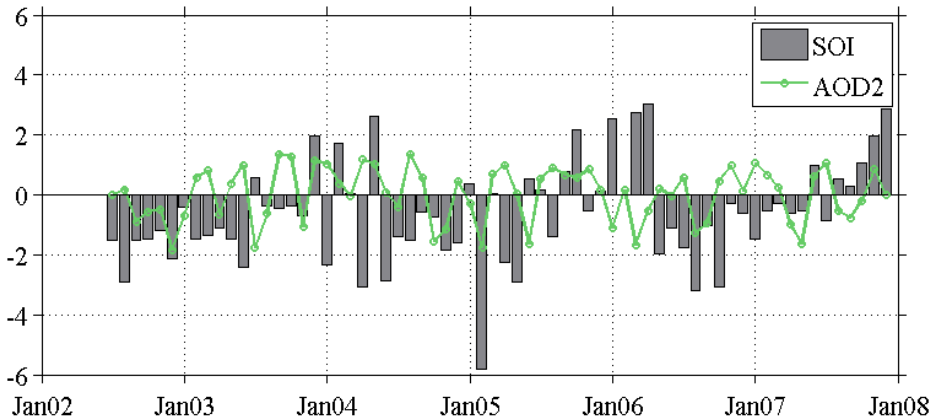

Fig. 5. Standardized anomaly of second EC component of MODIS AOD and SOI.

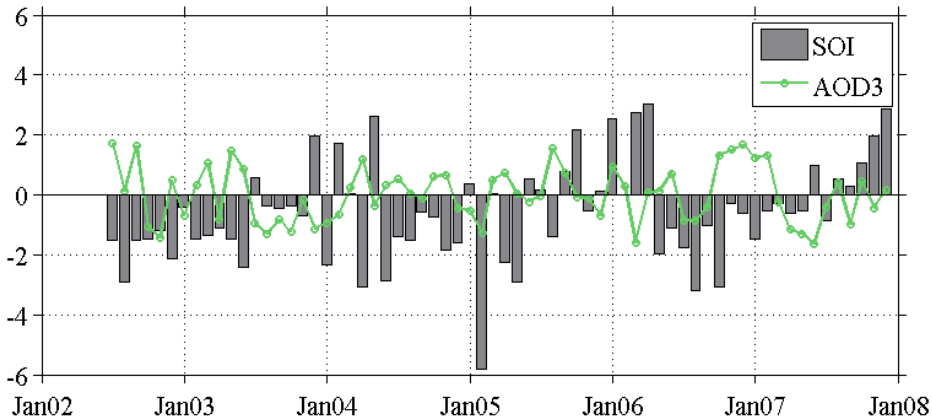

Fig. 6. Standardized anomaly of third EC component of MODIS AOD and SOI.

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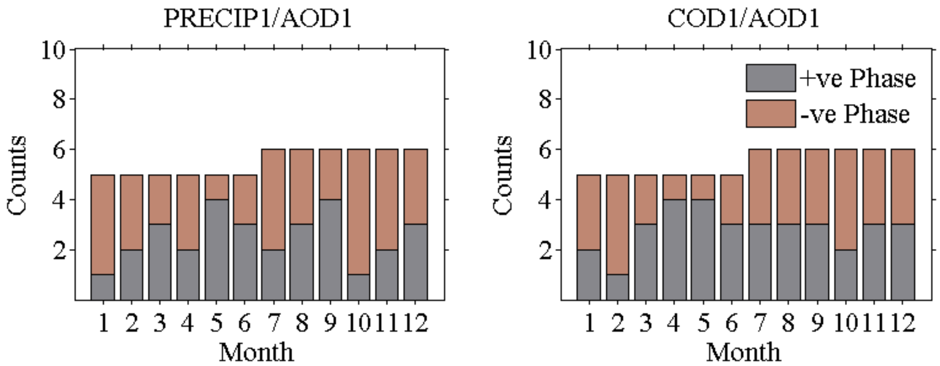

Fig. 7. Standardized anomalies of the first EC component of MODIS AOD and TRMM rainfall/MODIS COD.

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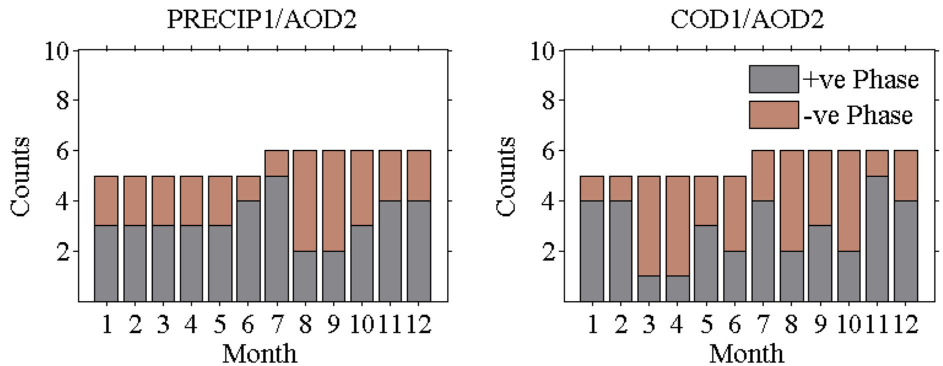

Fig. 8. Standardized anomalies of the second EC component of MODIS AOD and first EC component of TRMM rainfall/MODIS COD.

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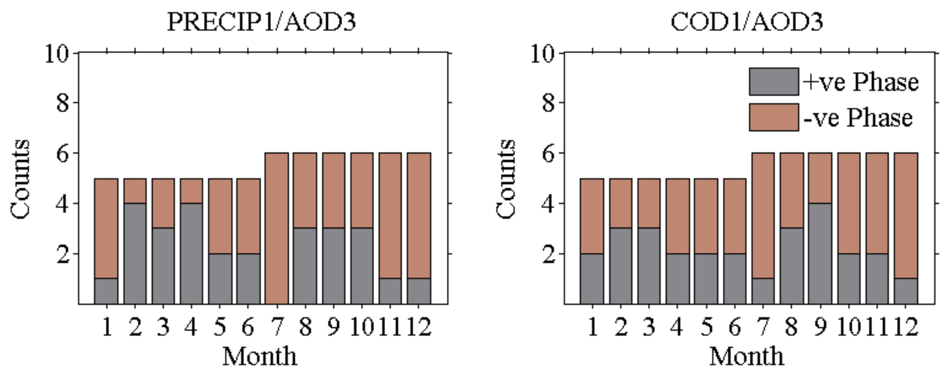

Fig. 9. Standardized anomalies of third EC component of MODIS AOD and first EC component of TRMM rainfall/MODIS COD.

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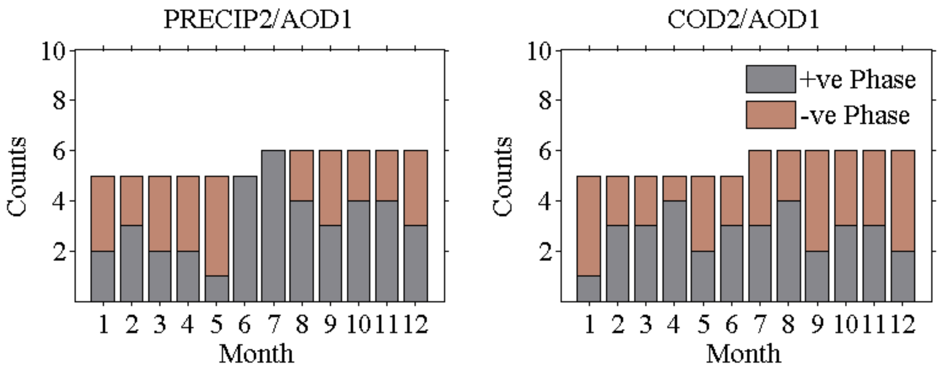

Fig. 10. Standardized anomalies of first EC component of MODIS AOD and second EC component of TRMM rainfall/MODIS COD.

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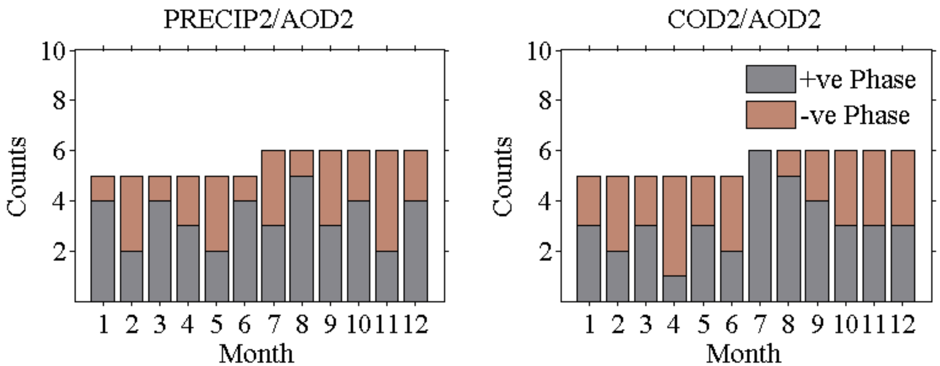

Fig. 11. Standardized anomalies of second EC component of MODIS AOD and second EC component of TRMM rainfall/MODIS COD.

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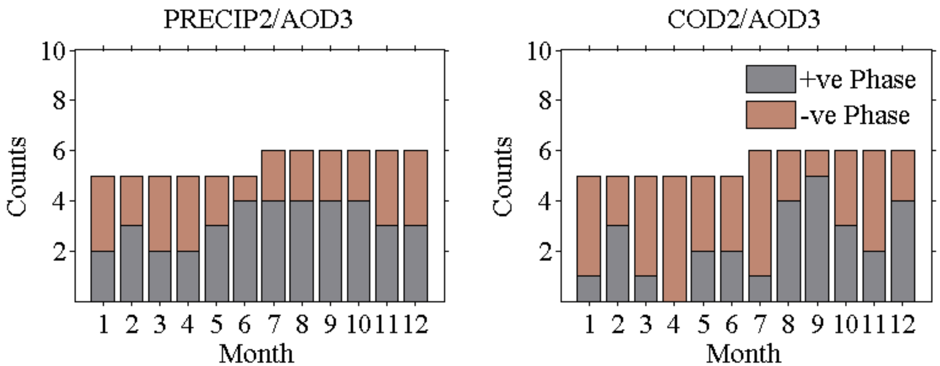

Fig. 12. Standardized anomalies of third EC component of MODIS AOD and second EC component of TRMM rainfall/MODIS COD.

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