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Atmospheric Chemistry and Physics Discussions

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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Note: Based on Comment#3 [Other comments], analysis was repeated using Deep-Blue algorithm product.

1.The description is limited to the annual cycle of aod and associated seasonal variation of cod and rainfall. In this regards, I do not see the merit of using EOF. As shown in the timeseries (EC), the first and second modes of EOF are associated with not only annual cycle but also the interannual variation. So, it may be beneficial to separate original timeseries into seasonall (annual and semi-annual) and interannual variation.

REPLY: In tropical climates, the seasonal signature of the monsoon dominates the

annual cycle and the semi-annual cycles. By contrast, if the study was for the eastern US it would be important to separate the different seasonal signatures in each data set to avoid ambiguity. However, there is no ambiguity in the interpretation of the data in the region of study. On the other hand, although there is clearly interannual variation as noted by the Reviewer, the length of the historical record does not allow for the analysis of interannual variability in a statistical sense. The number of points at the monthly time-scale is fewer than ten, which implies that the standard error of the mean is on the order of 40% (, where N=6 years) of the standard deviation for each month, which implies there is large uncertainty in the sample estimates of the monthly means. It is possible to interpret the observed year-to-year variability based on known features such as for example the effect of the drought of 2002. Nevertheless, to satisfy the Reviewer's concerns, the month-to-month variability of the standardized anomalies of the EC components of AOD, COD and Rainfall was assessed to better understand their relationships. This is discussed below in the answer to comment 2. In addition, some of the noted variability is actually caused by changes in retrieval algorithms and sensor calibration issues (e.g. TOMS), etc, that add further ambiguity. Specifically, the calibration issue with TOMS data is very pertinent and an explanatory sentence was added to the manuscript: "Due to the calibration issues associated with sensor degradation, trend analysis of the data after 2001 is not recommended as per the NASA TOMS science team (http://daac.gsfc.nasa.gov/guide/tomsl3.dataset.gd.shtml) and also mentioned in previous publications using TOMS data [Gautam et al. (2009)]." (Section 3 2nd paragraph in revised manuscript) . Finally, Eq. (1) for AI was incorrect as per Hsu et al. (1999), and this was fixed and the relevant reference added.

2.To identify the relations between aod and cod(or rainfall), the authors 1) calculate the lead-lag correlation between ECs and 2) use SVD computation between two variables. I found the approach is little confusing, especially when we have two different spatial patterns of cod that are associated with the same aod pattern (See Fig. 8 and Fig. 11. I'd like to suggest to use only the first two EOF ECs of AOD to calculated the regression map (with time lag(or lead)) with other variables (cod and/or rainfall) to show lead-lag relation between aod and cod(or rainfall).

REPLY: The objective of this study is to identify joint modes of variability of aerosol, cloudiness and rainfall toward elucidating coupling mechanisms. The SVD analysis was done to identify the joint variability between the two variables. We note that strong joint variability between monsoon rainfall and aerosol build up in the north-western part of India was observed. Besides, the first two patterns of COD and AOD show that the cloudiness pattern along the southern slopes of the Himalayas is consistent with the pattern of aerosol build up along the foothills. The second pair of patterns between COD and AOD shows that the cloudiness along the western and Eastern Ghats of India and aerosol build up north-west of Aravalli range all the way from the Arabian Sea to the Indus Valley go hand-in-hand. This is consistent with the climatology of regional monsoon circulations that bring moist air masses against the Ghats and transports aerosols (dust) from the Middle East to the Northwestern Sector of the subcontinent. A problem in Fig. 11 with regard to the EOF analysis of COD and AOD is that the area over which the SVD analysis was done includes a large portion of ocean including the Bay of Bengal and the Equatorial Indian ocean where, unlike AOD, the relative magnitude of COD is much larger than that over land and is influenced by other large-scale features such as ENSO and the Madden-Julian oscillation. There are however two important issues that required clarification in the manuscript: 1) note that lead/lag relationships evaluated via correlation analysis of different EC time-series beyond three months should not be considered due to the known strong seasonality of regional climate. This was corrected in the manuscript (Section 4.2, paragraph 3). Note that the relationships are only physically meaningful for aerosol-cloud rainfall-interactions when there is space-time consistency. That is, if the ECs exhibit high temporal correlation, this is only relevant for aerosol-cloud-rainfall interactions in the regions where the temporal correlation is supported by spatial agreement among the EOF patterns. Therefore, a statement noting “strong” correlation between say AOD3 and COD1 reflects the fact that the spatial patterns of EOF3 of AOD and EOF1 of COD are consistent. Note that the correlation between EOF3 of AOD and EOF1 of COD peaks at a lag

of 3 months due to the fact pre-monsoon aerosol build-up and maximum cloudiness take place at monsoon onset, but immediately the aerosol build-up is washed away by the monsoon rainfall Following the Reviewer’s suggestion, a study of the positive phase/negative phase relationships between the standardized anomalies of the different components from EOF analysis during the short period of study (see Appendix A in the supplement) was conducted. Although the data record is too short for robust statistics, there are physically meaningful linkages between the anomalies of observed EOF modes in months that are critical from the point of view of regional climate. A strong positive phase relationship was observed between PRECIP2 and AOD1 for the months of June and July indicating an increase in AOD northwest of the Aravalli range in contrast with the decrease linked to the increase in monsoon rainfall over Central India and southern slopes of the Himalayas. On the other hand, a consistent strong negative phase relationship was observed between the AOD3 and PRECIP1 and COD1 for the month of July suggesting increase in AOD3 with weaker monsoon rainfall in July (break phase of the monsoon), that is 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. (see Figures A1$\sim$A6 in Appendix A)

3. In their abstract, the authors claimed that they found, based on EOF analysis, that the areas where the indirect effect of aerosols are dominant. But, the authors did not provide adequate evidence and/or hypothesis to support the argument.

REPLY: The Reviewer’s comment is well taken. This study was motivated by earlier studies indicating the aerosol indirect effect over the region. 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. References to the above studies have been added to the manuscript. Building on previous work, what this study finds is an area focused on Central Nepal where there is consistent spatio-temporal agreement among aerosol, cloudiness and rainfall variability both in the pre-monsoon and monsoon seasons (see Figures 1 and 2).

4.On page 4385, the authors interpret the lead-lag correlation between ECs as cause and effect. ECs are supposed to be orthogonal each others, so the peak correlation can be found at a quarter of the period (3-month for annual cycle, or 9-month).

REPLY: We regret any confusion regarding the interpretation of lag-correlation as cause-effect. That was certainly not the intention. The intention was to discuss the observed lag-correlation between ECs of different variables in the light of the known regional climate dynamics.

5.Often, the authors refer their earlier works and emphasize that the current results are consistent with their earlier works. It would be nice for a reader to know what variables/ aspects the authors are referring to, without reading all of their previous work

REPLY: Check Corrections.

Pg. 4376, Ln 8, has been rephrased as follows: Liu et al (2008) could not find evidence of transport between northern India and the Tibetan plateau across the southern slopes of the Himalayas using CALIPSO data. However, their analysis was limited by the persistent cloud cover during the active phase of monsoon [Barros et al. 2004] which precluded detection of plumes associated with low-level flows aligned with major river valleys across the Himalayan range that permit transport from northern India to the Tibetan Plateau as shown by Barros et al. [2006] for two high-resolution simulations

of monsoon onset depressions (also see MODIS Rapid Response Image Subset over Nepal). Pg. 4377, Ln 22, has been rephrased as follows: Furthermore, the presence of elevated aerosol concentrations of remote origin at high altitudes beyond the edge of rainfall maxima signals the modulation of orographically enhanced precipitation processes upwind [Barros et al. 2004, Barros et al. 2006], and is consistent with transport from the northern Indian subcontinent to the High Himalaya and the Tibetan Plateau through both deep and shallow flow channels along the N-S oriented river valleys in the southern slopes of the Himalayas [as observed from MODIS Rapid Response Image Subset over Nepal and field experiment conducted during JAMEX09]. Pg. 4384, Ln 16 updated as follows: The first EOF mode of rainfall displays a strong gradient aligned with the lower foothills of the Himalayas during the JJAS period consistent with the orographic modulation of low level depressions that propagate westward from the Bay of Bengal and produce large rainfall [Lang and Barros (2002)]. In the analysis of summer monsoon rainfall in 1999 and 2000 in the Marsyangdi river basin in Central Nepal, Lang and Barros (2002) noted that the difference in precipitation associated with monsoon depressions was primarily dependent on the trajectory of the depression originating from the Bay of Bengal, and whether it veers NW as it approaches the mountains or propagates westward. On the other hand, large differences in event rainfall recorded at different raingauges (up to a factor of 8) over small distances indicates the role of small scale topographic features (ridge-valley orientation) in modulating rainfall. Pg. 4385, Ln 6, updated as follows: EOF2 also shows distinct cloudiness patterns in the Northern India Convergence Zone (NICZ, a convergence zone constrained to the Ganges valley and the Himalayan range, Barros et al. 2004) around May and then later in Oct-Nov. The May cloudiness pattern precedes the onset of the summer monsoon while the October-November cloudiness is associated with the retreat of the monsoon.

6.Wind fields shown in Fig. 2 should be masked out where the surface pressure is less than pressure level, especially for 900hPa winds. And 900hPa may be too low to discuss transport and convergence/divergence in northern India.

REPLY: The wind fields were masked for lower levels (900 hPa). The typical elevation of the IGP and Indus Valley where the dominant modes appear is less than 400m (see Figure 1a). There are only a few grid points over the Indus valley because the ERA Interim data whose resolution is around 1.5 degree.

7.During summer, AOD measurement may have a fair weather bias. And AOD can not be collocated with COD. The limitation of the MODIS/AOD measurement during active monsoon periods should be considered in interpreting the results.

REPLY: The MODIS algorithm over land uses at least 12 pixels out of 400 pixels to obtain the AOD at 10*10 km resolution after screening for clouds, snow, water and very bright areas. In this analysis, we rely on the third level MODIS AOD product obtained by aggregating these smaller chunks of data at the monthly time scale. Indeed, there is a limitation of MODIS AOD during the active summer monsoon period on the number of samples used by the monthly product for averaging in the 1x1 degree product. However, the strong precipitation observed during the monsoon season also suggests the aerosols are washed away consistent and the observed decrease in AOD during the summer monsoon at the monthly scale. The sharp gradient in the MODIS AOD (first mode) along with the phase lag of second mode of MODIS AOD reflects this behavior.

Other Comments:

1. Page 4374, line 22: It is not clearly documented what "the region of spatial overlap of the modes of variability" is.

REPLY: Collocated plot of the MODIS AOD (DeepBlue merged product, see answer to comment 2 below), TRMM rain and MODIS COD are shown in Figure 1 and 2 to clearly document the region of spatial overlap:

2. On page 4376: Liu et al. (2009) is not listed in the reference secion.

REPLY:Added.

3. Page 4380, line 15: Can you elaborate how the spatial mean is calculated? Rather

than fill the gap, the authors should consider repeating analysis with the deep blue product from Aqua. Another way is to use MODIS with missing over Tibetan Plateau. The variability of AOD over Tibetan Plateau will be very small anyway.

REPLY:The missing values in the current MODIS AOD product used for the study are in the Thar desert, India and the Tibetan plateau including the Takla Makan desert. The missing values were replaced with the spatial mean of the non-missing values for that month. This results in underestimation of AOD over the Thar desert and Takla Makan desert as observed from the TOMS EOF, but for the Tibetan plateau, the variability of AOD is very small as suggested by the reviewer. On the other hand, the Deep Blue algorithm is able to retrieve AOD over bright reflecting surfaces over land, like deserts, but it requires the screening of the presence of subpixel clouds and aerosol retrievals over cloud-contaminated scenes are not furnished (Hsu et al. 2006). Since, 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 due to bright surfaces (deserts), the other one due to cloudy pixels. Our strategy was to combine both, using the estimates from the MODIS Deep Blue aerosol retrieval (550 nm) wherever there was a missing value in the AOD using dark target approach. This fills the missing AOD over bright reflecting areas like the Thar desert and the Taklaman desert. The AQUA data was available only from July 2002. The result from the EOF analysis of this combined data is shown below:

By using this combined product, the EOF patterns are sharper, and the MODIS AOD is now 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 (Figure 3), peaking consistently during the month of July. The northern branch is bounded by the Takla Man desert. The southern branch is limited by the Aravalli range extending from the Arabian sea to the Indus Valley with maxima over the Thar desert.

The second mode (Figure 4) does not reflect the previous mode as discussed in the original manuscript. We reason this is due to the missing values of AOD over Takla

Man desert which we had replaced with the spatial mean of the analysis domain. 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 also appears here but is more aligned adjacent to the slopes of the Himalayas and extends to the eastern region of the IGP. This mode peaks around July consistent with the EOF 1 and decreases sharply within the next two months, and again starts to peak 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 5). 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)]. Similar results as presented earlier in the manuscript (Figure 9,10,11) were obtained when we did the SVD analysis to estimate the coupled variability between the new AOD and TRMM rainfall/MODIS COD, except the modes over Thar desert in India and Takla man desert are stronger and better defined as expected from the new MODIS AOD data used for the study. The results were updated in the manuscript.

4. Page 4384, lines 19-21: How do the signs of EOF related with the robustness of the mode?

REPLY: The Reviewer's question is well taken. The wording was confusing. It was meant to say that both the EOF1 and EC1 (63.5% variance explained) are positive during the monsoon season and thus the mode contribution to the overall precipitation signal is positive as expected during the monsoon season consistent with results from Barros et al. (2004) for the first mode of METEOSAT cloudiness, which is available at temporal resolution that allowed detecting the active and break phases of the

monsoon. The sentence was revised as follows: "..., the consistency of the spatial patterns of EOF1 and sign of EC1 with the EOF1 and EC1 of cloudiness data in Barros et al. (2004), which was available at time-scales that allowed detecting the active and break phases of the monsoon, indicates that the dominant mode of the JJAS seasonal variation of rainfall from TRMM 3B43 is robust."

5. The last sentence on Page 4384 (starting from line 27): It is not shown. Citation?

REPLY: M.L.Shrestha (2000), Kansakar et al. (2004), citations has been added.

6. Page 4385: This is the most confusing part. The authors' description may be right, but it is hard for me to draw the same interpretation based on the results(i.e. EOFs and ECs) shown in this paper. Few examples are:

1) we don't see the northward propagation from EOF, it just jumps when the sign of EC change.

REPLY: The following clarification has been made. (Section 4.2 paragraph 3): The May cloudiness pattern precedes the onset of the summer monsoon while the October-November cloudiness is associated with the retreat of the monsoon.

2) Line 13: Is the correlation length defined as the time the correlation become zero? If so, shouldn't it be around 3-4months?

REPLY: Yes. Figure 6 shows the correlation between the first EC component of MODIS AOD and TRMM rainfall. Note that due to the strong seasonality a cyclic correlation function is expected, but indeed it is about 4 months.

3) Lint 14: "the same large-scale dynamics"? It could be since they all have annual cycle as a dominant component in ECs. But, as shown in SVD analysis, the first EOF of cod may not related AOD and/or rainfall.

REPLY: Yes, they all have the annual cycle and these cycles have highest correlation at zero lag. On the analysis of the EC anomalies between the first modes of MODIS

AOD , TRMM rainfall and MODIS COD, approximately 50% of the occasions showed in phase relationship, with maximum for the month of May. It does indicate that there is a positive relationship between the monsoon rainfall and the development of the first mode of MODIS AOD but a longer observational record will definitely further clarify these findings. 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 NW of Aravalli range, these modes reflect different source areas for moisture (ocean) and aerosol (the Middle-East, deserts and urban areas in northwest India), but both are modulated by the same regional circulation patterns [Lau et al. (2006), Barros et al. 2004]. The anomalies of the first mode of the MODIS AOD and the second mode of TRMM rainfall showed consistent in phase relationship of large anomalies with most frequent agreement in June and July. This suggests that increase in monsoon rainfall over Central India and southern slopes of Himalayas, correlates with the (relative) increase in AOD over NW of Aravalli range as it is washed out elsewhere.

4) Lines 20-22: EC2 of AOD is dominated by the annual mode while EC2 of rainfall and COD are mostly semi-annual mode. I am not sure whether we can get any further information from the lead/lag correlation.

REPLY: The Reviewer's point is well taken. The temporal correlation length in this very strongly seasonal system should not exceed three months. Also see Appendix A for analysis of anomalies.

5) Line 27: Can you elaborate how the lag correlation suggests cloud-aerosol interaction?

REPLY: For aerosol-cloud-rainfall interactions, there is a need of spatial collocation between the spatial modes of variability of each aerosol, cloudiness and rainfall. Therefore, a strong correlation between say AOD3 and COD1 with a lag of 3 months, reflects the cumulative increase of aerosol during the pre-monsoon season (March-April-May)

peaking at the time of monsoon onset when cloudiness also peaks. Increased cloudiness leads to increased rainfall, which washes out the aerosol.

7. Page 4386, Line 10: Cross-correlation doesn't necessary mean causal relationships.

REPLY: There is no intention of suggesting causal relationship from correlation analysis. What is being done is to discuss the observed cross-correlation between ECs of different variables in the light of the known regional climate dynamics.

8. Page 4386 lines 24-27 & Page 4387 lines 15-18: There are little too far-fetched.

REPLY:Pg. 4386, lines 24-27 simply suggests that the aerosol build up in this region during the pre-monsoon season is washed away by the monsoon rainfall as observed from the EOF analysis in this study. Pg. 4387 lines 15-18 has been rephrased as follows: "This aerosol pattern is present during the non-monsoon season and suggests possible interaction with the clouds during the onset of the monsoon, which washes it away later. "

9. Page 4387 line 21: "landform" doesn't have temporal variability.

REPLY:At the temporal scales of this study, landform doesn't have temporal variability. The sentence has been rephrased: "The objective of this study is to identify the domain of joint space-time variability of aerosols, clouds and rainfall along the south facing slopes of the Himalayas."

10. Page 4387, line 24: COD is listed twice.

REPLY:Corrected.

11. Page 4388, lines 1-3: I am sure that the orography in this region plays important role in forming monsoon rainfall and circulation as well as aerosol distribution. But it is hard to draw this conclusion based on the results from the current study.

REPLY:The observed spatial modes of AOD, COD and Rainfall are organized along the southern slopes of the Himalaya from west to east as well as other terrain features observed in the EOF1, 2 and 3. Strong spatial gradients in EOF patterns are aligned with orographic gradients. So, the steep orography of the Himalayas does play a major role in the spatial organization of transport patterns by constraining the regional circulation (see also Barros et al. 2006, Barros et al. 2004), which causes the accumulation of aerosol in the region, separating it from the pristine air mass in the Tibetan plateau.

12. Page 4388 lines 4-8: This statement is not based on the current study.

REPLY:This statement refers to the discussion presented in Section 2 regarding the analysis of ERA Interim wind fields shown in Figure 2b of the manuscript.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/10/C4143/2010/acpd-10-C4143-2010-supplement.pdf

Interactive comment on Atmos. Chem. Phys. Discuss., 10, 4373, 2010.

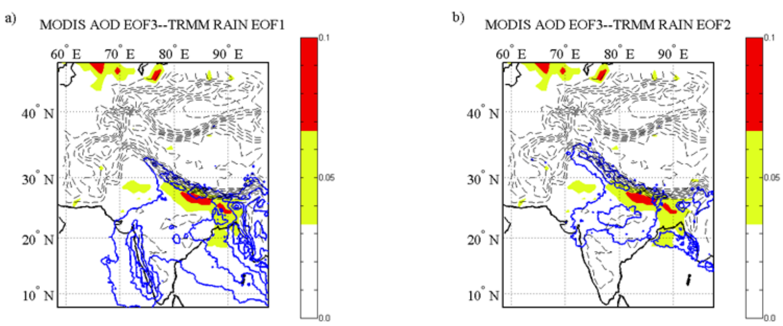

Fig. 1. Collocated plots of third mode of MODIS AOD (combined product of deep blue algorithm and dark target approach) and TRMM rainfall EOF 1 and EOF2. The contours of the TRMM rainfall EOFS are from 0.005

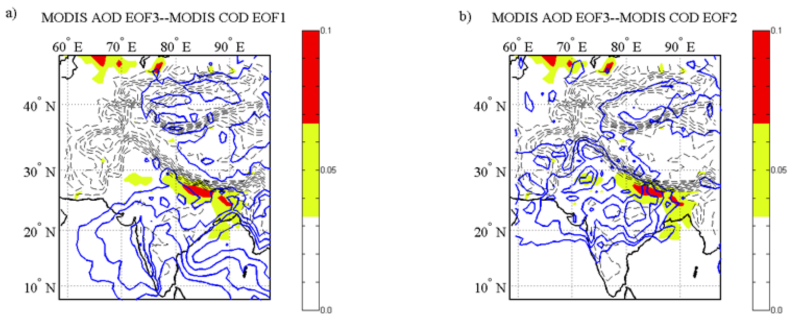

Fig. 2. Collocated plots of third mode of MODIS AOD (combined product of deep blue algorithm and dark target approach) and MODIS COD EOF 1 and EOF2. The contour of the MODIS COD is from 0.01 to 0.06 at an int

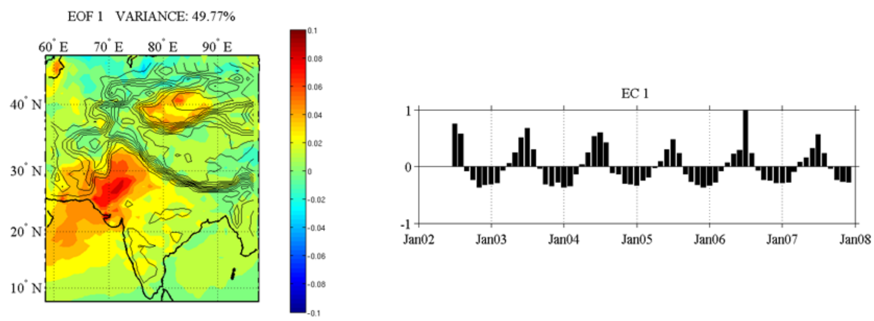

Fig. 3. EOF 1 and EC1 estimated from the MODIS Aqua by filling the missing values over land by the Deep Blue Algorithm retrieval at 550nm

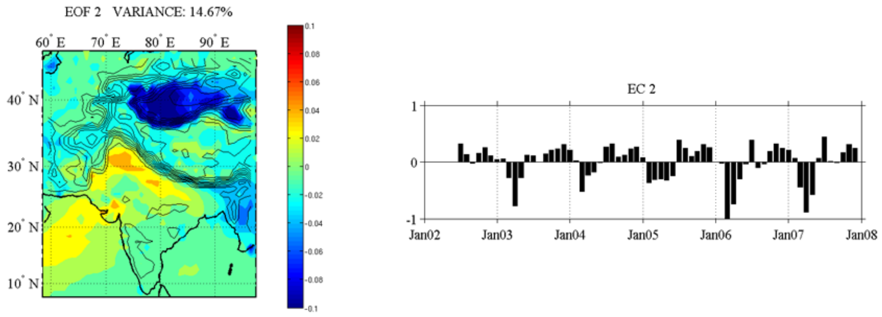

Fig. 4. EOF 2 and EC2 estimated from the MODIS Aqua by filling the missing values over land by the Deep Blue Algorithm retrieval at 550nm.

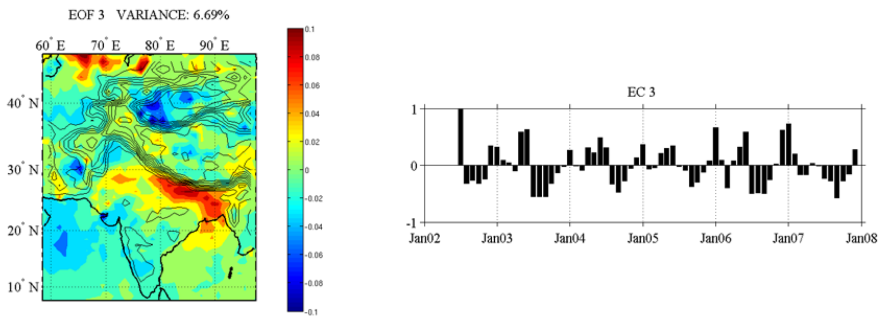

Fig. 5. EOF 3 and EC3 estimated from the MODIS Aqua by filling the missing values over land by the Deep Blue Algorithm retrieval at 550nm

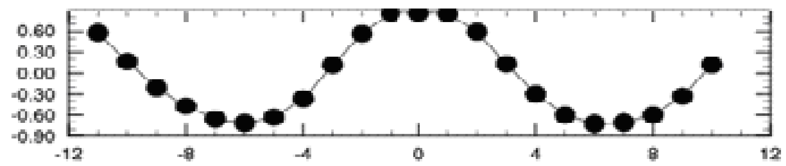

Fig. 6. Correlation between EC1 of MODIS AOD and TRMM rainfall with lag in the x-axis..