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YEAR 2 PROGRESS REPORT

Project Title "A Comprehensive Statistical Analysis System to Associate Local Land-Cover/Land-Use Change and Regional Aerosol Composition and Concentration"

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Abstract

Aerosols, particularly carbonaceous aerosols, will likely play an increasingly important role in the earth's energy balance and in global climate change. Much of these carbonaceous aerosols are generated by anthropogenic activities, including slash-and-burn agriculture, as well as fossil fuel combustion. The proposed research seeks to add to scientific understanding of the relationship between biomass burning and carbonaceous aerosols by estimating the spatial and temporal dependence structure of regional carbonaceous aerosol concentrations, given atmospheric circulation processes and observed fire occurrences. We examine these trends using a Bayesian hierarchical statistical framework coupled with a global chemical transport model in a manner that explicitly accounts for the uncertainty associated with these processes. While it is difficult to separate the contribution of biomass burning to regional carbonaceous aerosols due to the chemical and physical processes occurring within the atmosphere, our analytical technique allows us to estimate the contribution of biomass burning to regional carbonaceous aerosols via the local fire/regional aerosol space-time associations. Finally, we embed the statistical model into an integrated system that will allow the user to forecast aerosol distributions under various environmental policy scenarios. This integrated system will seamlessly retrieve and examine data on aerosols and fires from MODIS and MISR, and visualize the results. In developing our system, we will focus on fire/aerosol relation in mainland Southeast Asia from the end of 2000 to the present. Mainland Southeast Asia is currently experiencing much varied land-use/cover change (including urbanization), though forest clearing for agricultural and forestry activities remains a dominant pattern; our tool is designed to deal with these complex processes and multiple sources of carbonaceous aerosols, yet emphasizes the estimation of the fire-aerosol relationship. We expect to add to the scientific understanding on the processes and changes at work in the study region, but our tool will ultimately have broad applicability to other regions and applications. Thus, the project contributes to NASA strategic objectives to understand and protect the earth, to study the earth from space, and to use NASA's space-based technology to study to the interactions between land and atmosphere.

Keywords Bayesian hierarchical modeling, Biomass burning, Carbonaceous aerosols, Land-atmosphere interactions, Mainland Southeast Asia, MODIS, MISR, Spatio-temporal statistics

I. Research Objectives

1. To develop a hierarchical Bayesian framework to study the association between biomass burning and regional carbonaceous aerosol concentrations that incorporates a process-based description of aerosol transport over space and time;
2. To quantify explicitly the uncertainty involved in the relationship between biomass burning and regional aerosols, given available data and the nature of complex, circulatory atmospheric transport patterns;
3. To contribute to the understanding of the implications of current land-use changes in Southeast Asia given the measured effects of biomass burning in the last 5 years on regional aerosol concentrations; and
4. To conduct scenario and sensitivity analyses at a regional level that advance the understanding of the implications of biomass burning.

II. Year 2 -- Summary of Progress

GOAL Using MOZART output to characterize the spatial and temporal structure of aerosol transportation in and around our study region, which is an important component of the statistical models we are building.

Accomplishments:

- PI Darla Munroe and Co-PI Tao Shi met with collaborators Dr. Louisa Emmons and Dr. Gabriele Pfister in the Atmospheric Chemistry Group at NCAR in May 2007. We discussed details of the proposed statistical models and deliberated on several specific aspects of the MOZART model runs required for fitting the statistical model.
- During the NCAR visit, we also gave a talk in the Institute for Mathematics Applied to Geoscience at NCAR. Statisticians and atmospheric scientists provided us with helpful suggestion on our statistical model.
- We obtained MOZART output from Dr. Pfister and Dr. Emmons. These data consist of hydrophobic and hydrophilic black carbon emissions from MOZART output during the period between March 1, 2004 and March 12, 2004 on a T170 (0.7 degree) grid with 28 atmospheric pressure levels.
- We developed graphical and numerical summary tools for exploring the space-time dependence structure of the MOZART output. To streamline our exploratory analyses, these tools were imbedded inside a Matlab graphical user interface (GUI). We anticipate that these tools and GUI will also be of use when examining the results of our statistical analysis.
- We designed a novel Bayesian hierarchical statistical framework for modeling aerosol optical depth data that draws on the space-time dependence structure of the aerosol transportation process learned from the MOZART output. The process convolution, or moving-average, structure of this model readily accommodates the nonstationary and anisotropic behavior of aerosol transportation. We have performed simulation studies to verify that our model is sufficiently flexible for capturing the space-time dependence structure of the data and that it properly accounts for boundary effects. Currently, we are programming and testing a Markov chain Monte Carlo (MCMC) algorithm to fit the statistical model.

GOAL Exploring the local implications of using multiple data sources to describe fire-aerosol relationships across space and time. Specifically, we wanted to examine the differences in aerosol estimates from MISR and MODIS within our study region over the year 2005. Regional environmental analyses (such as ours) require significant data coverage, yet ground information on aerosols (from AERONET) is limited at a sub-continental scale. In addition, given the greater variability observable at lower resolutions, we expected that the differences between MISR and MODIS aerosol measurements are not likely to be randomly distributed across space or time.

Accomplishments:

- Developed a method for aligning MISR and MODIS aerosol estimates to explore the differences, and estimated several models of the spatial dependence in the difference between MISR and MODIS in our study region (see Results section for more details).
- These results were presented at the recent MISR Data Users Science Symposium.

GOAL Developing a web-based application that allows users to explore the database for our study area. Our ultimate goal is to make the web site available to the general public during the last year of this project. Year 2 was critical to achieving this goal because key techniques need to be configured and operational. Therefore, this year we focused on testing various enabling techniques and the creation of our database. We chose to develop our web site and programs on Linux, an open source system, so that our final package will be portable and useful for other users.

Accomplishments:

- We created a database for our study area that includes land use data, elevation, major roads and cities, MODIS fire occurrences for 2001-2005, and MODIS and MISR aerosols optical depths for 2001-2005.
- We created Java and C programs that can be used to extract information from this database.
- We created an initial web server that allows user to query individual data set and display the results in map images.
- We developed an AJAX framework that will be used to implement an interactive web site that can support dynamic querying and displaying of the database.

GOAL Exploring the potential for using surrogate information for fire occurrence and emissions. Due to incomplete spatial and temporal coverage of the satellite imagery and derived data products, we explored using several ancillary data sources to supplement the analysis and provide greater precisions for the forecasting we have planned for Year 3.

Accomplishments:

- <u>Burn scar data</u>. We evaluated whether the use of burn scar data would be worthwhile to supplement the data products for fire retrievals. After careful review of the literature, including Boschetti et al. (2004), we determined that the uncertainty of the fire products in our study region will probably not be improved by using burned area estimates.
- <u>Plume height data</u>. Plume height data is likely to be useful in the estimation of aerosol emissions from each fire event. Specifically, plume height is crucial to aerosol transportation patterns (Luderer et al. 2006). However, no products currently exist to provide estimates of this information, and it is not something we could easily estimate for our purposes. We are in conversations with Dr. Ralph Kahn (NASA Goddard Space Flight Center), Dr. David Diner (Jet Propulsion Laboratory) and other scholars working in this area, and should such products become available, we will incorporate such information if possible.
- <u>Estimated fuel loads</u>. Several field campaigns have been conducted in our study region to provide estimates of fuel load per land cover type, and we have compiled these estimates to use in our emissions scenarios. Often there is greater detail in the field data regarding land cover types than we have in the MODIS product which follows the IGBP land cover classification; therefore, we will have to conduct sensitivity analysis in parameterizing the model-derived aerosol estimates with these field estimates.

Significant results

Prior research has estimated significant average differences between MISR and MODIS related to processing methods (Abdou et al., 2005) and differences in the algorithms and in calibration (Kahn et al., 2007). Relatively little attention has been given to the variation in MISR and MODIS across a large region (larger than a field site, but smaller than the globe), and compared to local variation in environmental conditions and human activity. Therefore, we investigated these differences within our study region as we continue to work on techniques to combine disparate data sources in integrated analyses. Using the Level 2 MISR aerosol product (MISR_AM1_AS_AEROSOL) with the data field RegBestEstimateSpectralOptDepth and the MODIS aerosol product (MOD04) with the data field Corrected_Optical_Depth_Land, we estimated the differences in AOD (AOT, as appropriate) values for the blue, red and green spectral bands. To avoid day-to-day correlation in aerosols, we drew a temporally stratified sample by extracting data for the first and fifteenth days of each month in 2005, as well as other available dates along MISR path 129 from January - June 2005 (with the goal of more intensive sampling along this path).

We paired MISR and MODIS AOD values by matching MISR pixel centroids to the nearest MODIS pixel centroid. We estimated that within 9 km, two pixels (from MISR and MODIS, respectively) would have an overlap of greater than 50 percent. Therefore, in the analysis we used those pixels where the distance between MISR and MODIS pixel centroids was 9 km or less (Figure 1).

We explored the difference in the MISR and MODIS AOD retrievals over the course of 2005 (Figure 2). The mean of the difference between MISR and MODIS is close to zero overall, but significant variation around zero is evident. There are also notable variations in the differences between MISR and MODIS across the different spectral bands. Specifically, the variation in the differences is greatest for the blue band and least for the red band, with the green band falling in between. Oscillation of these differences across the year is also evident.

Plotting the differences between MISR and MODIS AOD values across our study region is also illuminating (Figure 3). It appears that there is spatial clustering in these differences (Figure 3a); large values for the difference (MISR > MODIS) appear to be proximate to each other in space, while small values (MODIS > MISR) also tend to be located close together. Figure 3b also indicates that differences in the values of AOD are evident: MISR AOD values are lower than MODIS when MODIS AOD values are high, and vice versa.

We ran a series of regressions, first to identify the extent of spatial clustering in the differences between MISR and MODIS. Then, we examined whether variation in these spatial patterns in the differences between MISR and MODIS could be explained by a set of factors that would capture the varying effects of the physical environment and human-related factors: the dry season (when biomass burning is prevalent), land cover, distance to major roads, distance to the coast, and distance to big cities (> 250,000 population) and other major cities.

We regressed the difference MISR - MODIS against the value for MODIS; controlling for dry season months (Reduced models); and against these variables plus other covariates (Complete model) at varying spatial neighbors (including pixels as "neighbors" in the weights matrix when they are within 50, 100 and 150 km, respectively). The estimated lambda value indicates that there is significant positive autocorrelation in the differences between MISR and MODIS. This autocorrelation remains significant when covariates are added, but does decrease slightly in magnitude. The differences between MISR and MODIS are thus also significantly related to differences in land cover, elevation, distance to roads and the coast, and large cities. Figure 4 displays a graphical plot of these regression analyses. These analyses will add the literature on aerosol modeling at regional scales (shedding light on the local effects of geophysical variation and human processes), as well as providing insights for us as we attempt to assimilate aerosol data from multiple sources in our statistical model. More details are to be found in Xiao et al. (in preparation).

Dissemination of Results

Publication

Peer reviewed

Munroe, D.K., Wolfinbarger, S.R., Calder, C.A., Shi, T., Xiao, N., Lam, C.Q., Li, D., 2007. The relationships between biomass burning, land-cover/use change, and the distribution of carbonaceous aerosols in mainland Southeast Asia: A review and synthesis. Department of Statistics Preprint No. 793, The Ohio State University. Conditionally accepted by *Journal of Land Use Science* (November 2007).

Xiao, N., Shi, T., Calder, C.A., Munroe, D.K., Berrett, C., Wolfinbarger, S.R., Li, D., in preparation. Spatial Characteristics of the Difference between MISR and MODIS Aerosol Optical Depth Retrievals over Mainland Southeast Asia. To be submitted to *Remote Sensing of Environment* (January 2008).

Other

Munroe, D.K., Calder, C.A., Shi, T., Xiao, N., Forthcoming. Fire-Land-Atmosphere Modeling and Evaluation for Southeast Asia (FLAMES). Global Land Project Sponsored Project Update. GLP Newsletter. Newsletter of the Global Land Project, International Project Office. GLP - a joint research agenda of IGBP and IHDP. Issue No. 3.

Presentations at technical meetings and conferences

Berrett, C., Calder, C.A., Shi, T. 2007. A statistical framework for synthesizing MISR AOD data and MOZART output. Poster at MISR Data Users Science Symposium, Pasadena, CA, December 6-7, 2007.

Shi, T., Calder, C.A., and Berrett, C. 2007 Spatial Characteristics of the Difference Between MISR and MODIS AODs over Mainland Southeast Asia. Talk at MISR Data Users Science Symposium, Pasadena, CA, December 6-7, 2007.

Shi, T. Space-Time Modeling of Biomass Burning and Regional Aerosols in Southeast Asia. Contributed talk at the 10th International Meeting on Statistical Climatology (Abstract accepted, but trip canceled due to personal reasons), Beijing, China, August 20-24, 2007

Berrett, C., Calder, C.A., Shi, T. 2007. Characterizing the Dependence Structure of Space-Time Processes Using Computer-Model Output and Sparse Observations. Joint Statistical Meetings, Salt Lake City, UT, August 1, 2007.

Calder, C.A., and Shi, T. Space-Time Modeling of Biomass Burning and Regional Aerosols in Southeast Asia. Invited Talk at the Joint Statistical Meetings, Salt Lake City, UT, July 31, 2007.

Shi, T., and Munroe, D.K. 2007 Spatio-temporal Statistical Modeling of Biomass Burning and Regional Black Carbon Aerosols in Southeast Asia. Invited Seminar at National Center for Atmospheric Research, Boulder, CO, May 3, 2007

Xiao, N., Munroe, D.K., Calder, C.A., Shi, T. Quin, E., Li, D., Wolfinbarger, S.R. 2007. Exploring the associations between biomass burning, land-cover/use change, and carbonaceous aerosols distribution in mainland Southeast Asia. Association of American Geographers Annual Meeting, San Francisco, CA. April 17-21, 2007.

Sessions organized at professional meetings

Munroe and Xiao organized the session "Modeling Coupled Human-Environment Systems: Regional Approaches" at the 102nd Association of American Geographers Annual Meeting, San Francisco, CA. April 17-21, 2007 (Five papers total).

Calder and Shi organized the session "Remote Sensing in Environmental Statistics" at the Joint Statistical Meetings, Salt Lake City, UT. July 29-August 2, 2007.

III. Year 3 – Summary of Goals

GOAL Developing realistic policy scenarios for the estimation of likely trends in aerosol emissions and transport given model estimates, and then disseminating our tools and findings to colleagues and collaborators in Asia.

Specific tasks

- Recognition of transboundary effects: Models linking regional aerosol emissions to local sources can inform discussions regarding the international cooperation that must take place to combat the locally detrimental effects of air pollution (see, for example the ASEAN Cooperation Plan on Transboundary Pollution [http://www.aseansec.org/8938.htm]).
- Biomass burning in the context of broader land-use changes: The literature suggests that many of the environmental impacts of biomass burning have increased in recent years due to changes in land-use practices in the region, namely, the reorientation of agriculture from smallholders to larger commercial farms producing crops for export (coffee, cashews, rubber, etc.). Smallholder biomass burning practices were less detrimental in that small areas were cleared at any given time, at specific times of the year. Conversely, Byron (2004) indicates that large-scale mechanized land clearing (as in plantation agriculture, which has expanded in the region) is a major cause of "dirty fires", or ones that generate a high level of smoke and haze.
- Collaboration with broader regional networks: We have made contact with colleagues at the MAIRS IPO in Beijing, and will be soliciting guidance and feedback from them directly on our webtools to coordinate with MAIRS activities in our study region.

GOAL Implementing the web site that allows users to retrieve information and explore the statistical model using a variety of environmental and policy scenarios. We have developed the framework of the web site and next year we will focus on migrating from our current web site to a new one that includes more features (e.g., querying multiple data sets and displaying search results in maps, tables, and charts). We will also focus on incorporating the statistical model, when it is ready, to the web service so that users can explore different modeling results.

GOAL As discussed above in our accomplishments for Year 2 of the project, we are currently developing algorithms to fit out statistical model to MOZART output in order to learn about regional atmospheric transport patterns. Once this step is complete, we will fix the model parameters that describe the dispersal of aerosols over space and time and refit it to the empirical satellite (MISR and MODIS) aerosol data and biomass burning data (MODIS). Using this fitted statistical model, we will be able to forecast regional aerosol distributions under the various policy scenarios discussed above.

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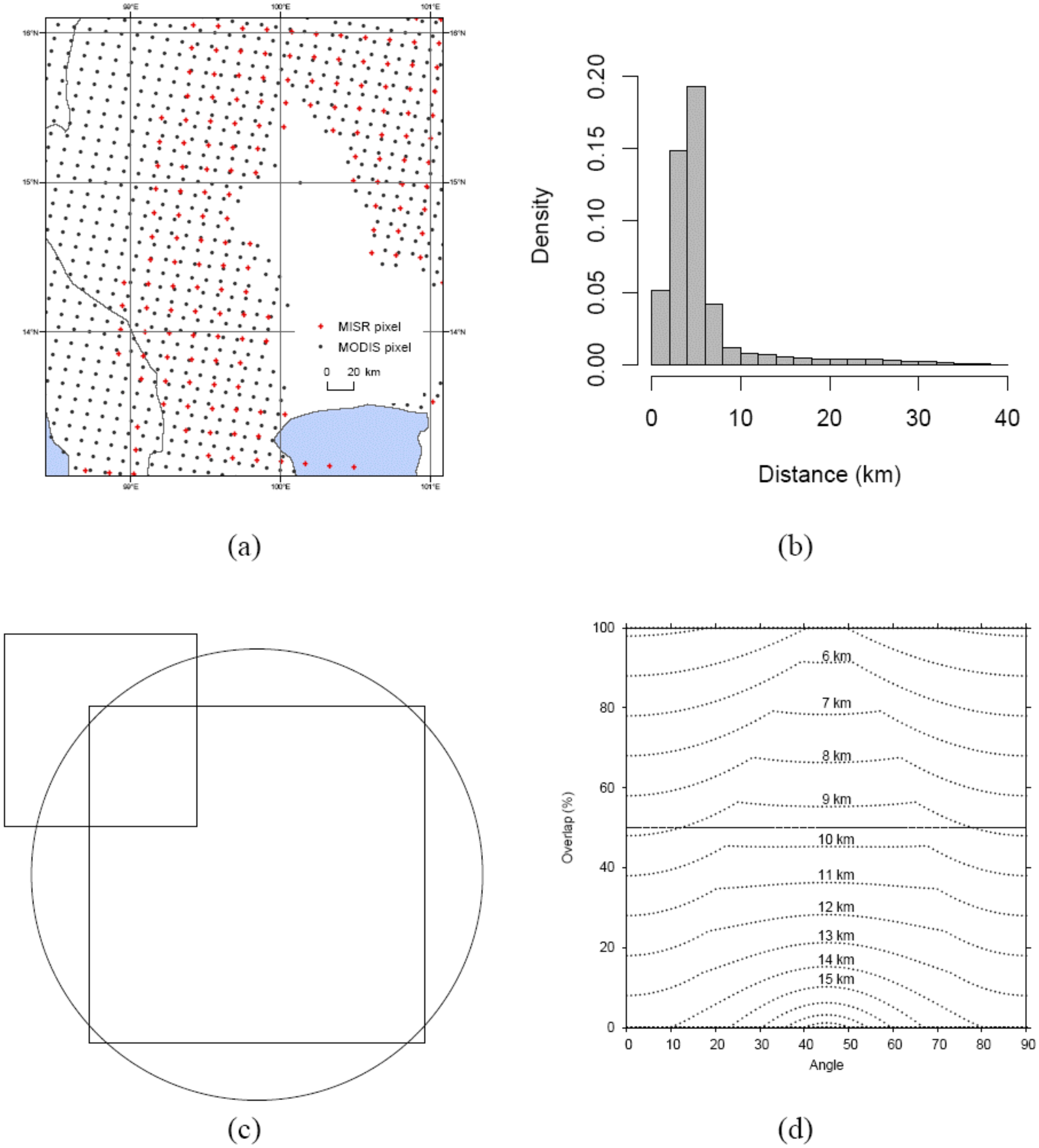
Luderer, G., Trentmann, J., Winterrath, T., Textor, C., Herzog, M., Graf, H.F., Andreae, M.O., 2006, Modeling of biomass smoke injection into the lower stratosphere by a large forest fire (Part II): sensitivity studies. *Atmospheric Chemistry and Physics*, **6**, 5261-5277.

Figure 1. Matching MISR pixels with MODIS pixels. (a) the locations of MISR and MODIS pixel centroids in a part of our study area. (b) The distribution of the nearest distance between MISR and MODIS pixel centroids [we used a cut-off distance of 9 km in our analysis]. (c) An approximation of calculating the overlap between a MISR pixel and MODIS pixel. (d) The relationship between MISR/MODIS pixel overlap with respect to their distance and relative position.



(a) (b)

(c) (d)

Figure 2. Box plots of the difference between MISR and MODIS AOD retrievals. The three bands are coded in corresponding colors. Dates shown include all days examined in this study, excluding days with no data.

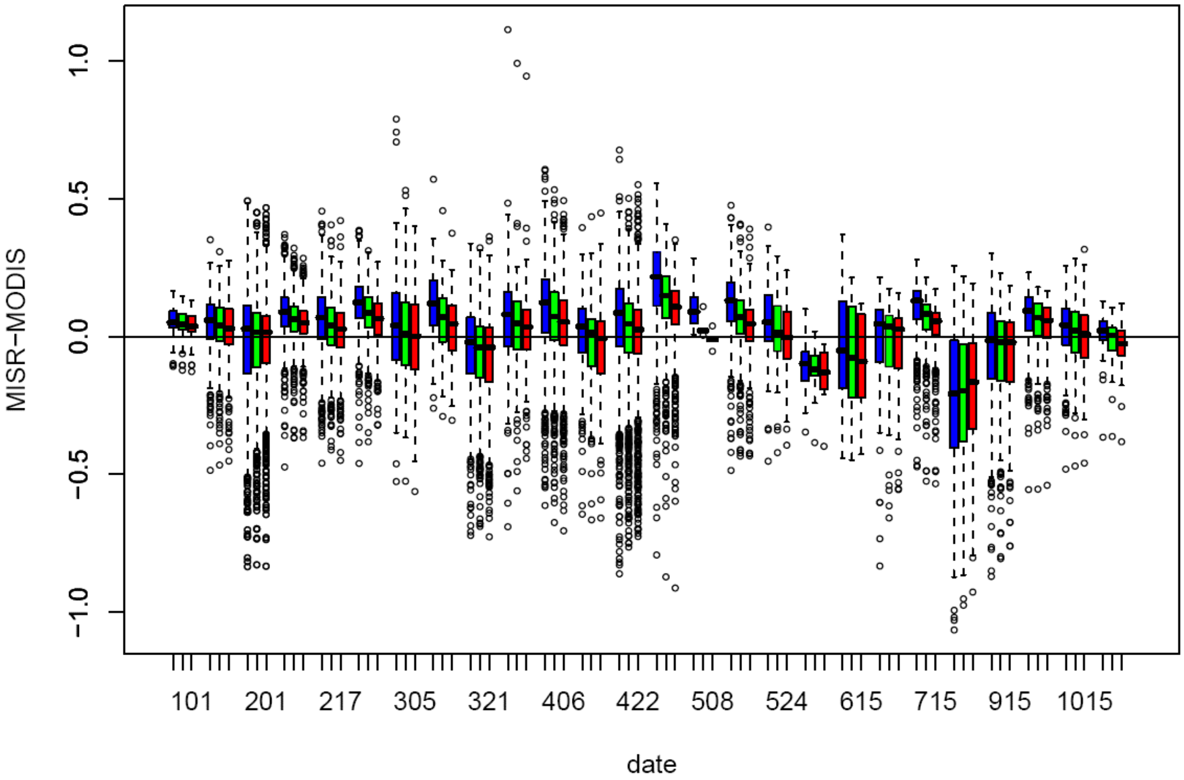
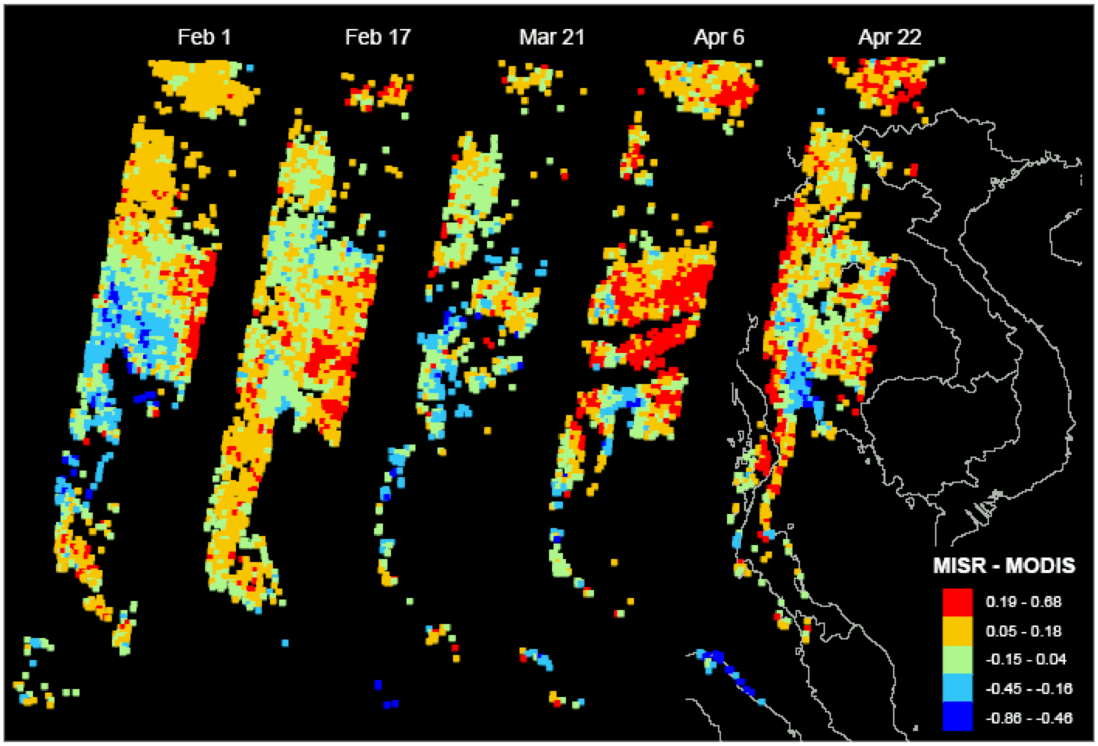
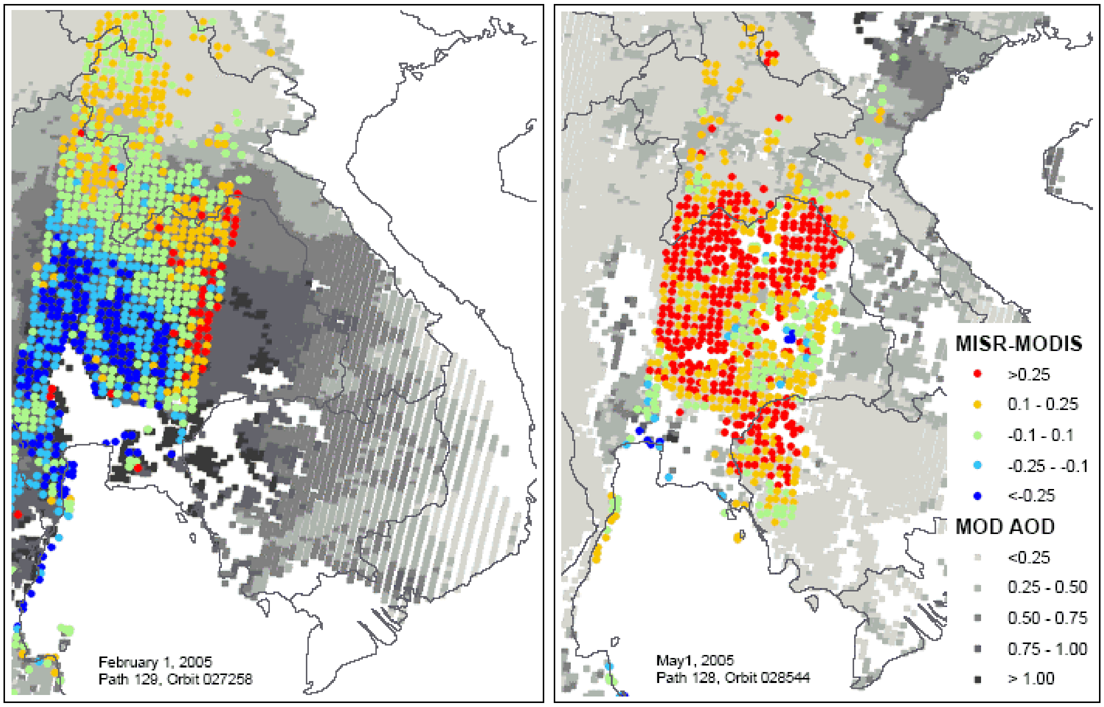


Figure 3. Spatial patterns of the differences between MISR and MODIS AOD retrievals (green band). (a) February 1 and May 1, 2005. (b) Five days on MISR path 120.



(a)



(a)

Figure 4. Results for regression model $x_{misr} = a + bx_{modis} + \varepsilon$ for valid 1 degree latitude/longitude boxes on February 1 and May 1, 2005. (a) Intercept. (b) Coefficient.

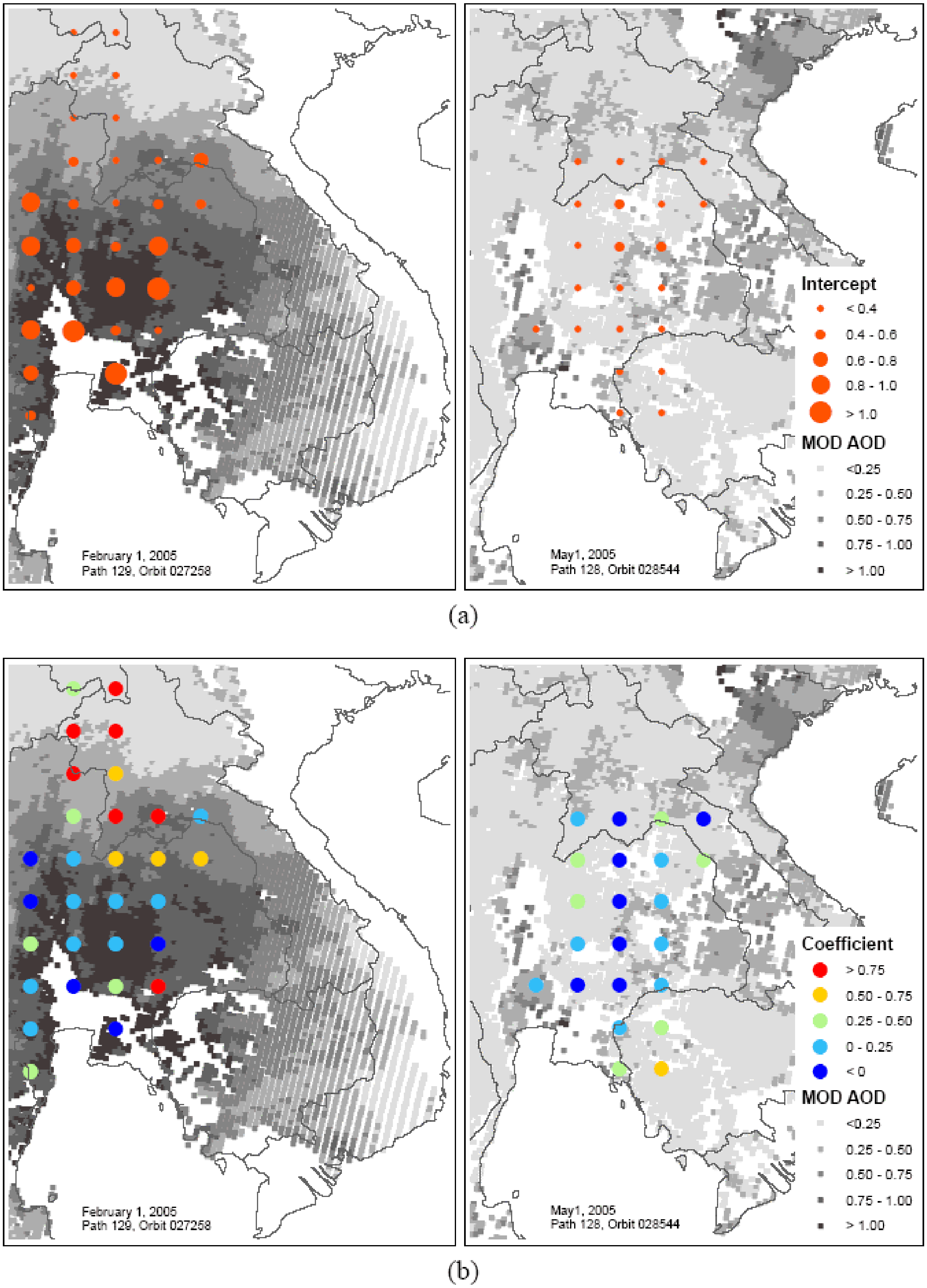


Table 1. SAR models of x_{misr} = a + bx_{modis} + ε, with varying neighborhood distances for the spatial weights matrices.

	50 km				100 km				150 km			
	Reduced model		Complete model		Reduced model		Complete model		Reduced model		Complete model	
Covariate	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
Intercept	0.227 ***	0.007			0.220 ***	0.014			0.188 ***	0.018		
x^{MODIS}	-0.776 ***	0.006	-0.780 ***	0.006	-0.762 ***	0.005	-0.776 ***	0.005	-0.725 ***	0.005	-0.741 ***	0.005
dry	0.058 ***	0.008	0.056 ***	0.008	0.072 ***	0.017	0.071 ***	0.017	0.064 **	0.023	0.060 **	0.022
Water			0.233 ***	0.010			0.228 ***	0.017			0.205 ***	0.020
Forest			0.225 ***	0.010			0.213 ***	0.017			0.190 ***	0.020
Shrub			0.245 ***	0.011			0.238 ***	0.017			0.217 ***	0.020
Savanna			0.253 ***	0.010			0.247 ***	0.017			0.228 ***	0.020
Crop			0.250 ***	0.010			0.245 ***	0.017			0.224 ***	0.020
Wetland			0.251 ***	0.028			0.262 ***	0.032			0.250 ***	0.035
Urban			0.219 ***	0.024			0.216 ***	0.028			0.181 ***	0.031
Elevation			0.000 ***	0.000			0.000 ***	0.000			0.000 ***	0.000
droads			-0.030 ***	0.006			-0.033 ***	0.006			-0.029 ***	0.006
dcoast			0.007 ***	0.002			0.000	0.003			0.002	0.002
dbcity			-0.004 **	0.002			0.004 *	0.002			0.001	0.002
docity			0.002	0.005			0.001	0.003			0.001	0.003
Lambda	0.893 ***		0.887 ***		0.939 ***		0.939 ***		0.949 ***		0.948 ***	

* Significant at the 0.01 level.

** Significant at the 0.005 level.

*** Significant at the 0.001 level.