Improving Aerosol and Visibility Forecasting Capabilities Using Current and Future Generations of Satellite Observations

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LONG-TERM GOALS

The long term goal of this research effort is to improve the Navy's aerosol and electro-optical propagation forecasting capability through the development of research and operational capabilities for assimilating both passive- and active-based remotely-sensed observations.

OBJECTIVES (abstract from proposal)

Critical to both military and civilian applications, the Navy Aerosol Analysis and Prediction System (NAAPS) is the world's only truly operational global aerosol and visibility forecasting model. Recent studies indicate that the assimilation of satellite observations significantly improves NAAPS aerosol forecasting capability and reliability. To fully utilize the wide breadth and depth of various current satellite observations, and prepare for future reductions in aerosol sensing satellites over the next decade, we propose to construct a multi-channel, multi-sensor, and multi-task assimilation system to improve NAAPS forecasts for both current and future applications. The specific objectives are to:

1. Finalize over-land and over-ocean aerosol assimilation methods using operational data assimilation (DA) quality Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) aerosol products, and develop a framework for considering current and future satellite aerosol products.
2. Develop forward models to enable a radiance assimilation capability by: 1) improving forecast performance over cloudy regions using the Ozone Monitoring Instrument (OMI) Aerosol Index; and 2) preparing for the post-MODIS/MISR era using the Geostationary Operational Environmental Satellite (GOES).
3. Improve model representations of aerosol vertical profiles and the accuracy of aerosol speciation in NAAPS through the use of a 3-D aerosol assimilation methods on satellite-based lidar observations and a generalized Angstrom exponent assimilation scheme.
4. Develop an improved 3-D parameterization for satellite observation and model forecasting error matrices using ground observations from the NASA Aerosol Robotic Network (AERONET) and the Micropulse Lidar Network (MPLNET).

APPROACH

Three main research themes are studied in this research effort, including: (1) exploring innovative approaches for applying satellite observations and satellite aerosol products to construct DA-ready data sources for operational aerosol model forecasts; (2) developing schemes for assimilating satellite aerosol products from passive- and active-based measurements; (3) developing a research/operational capability for directly assimilating GOES satellite radiances.

Strategies have been developed for constructing DA-grade satellite aerosol products using the Collection 5 MODIS Dark Target (DT), MODIS DeepBlue (DB), and the version 22 MISR aerosol products. Such efforts are critical to operational aerosol data assimilation and forecasting, as significant uncertainties exist in satellite aerosol products (Zhang and Reid, 2006, Shi et al., 2011a, Shi et al., 2011b; 2013; 2014). With the recent release of the collection 6 MODIS DT and DB products, as an ongoing research topic, research efforts have been conducted to fully evaluate the Collection 6 MODIS DT and DB products for constructing data-assimilation friendly products for use in operational aerosol forecasts.

We have attempted to apply satellite observations in new and creative research directions for aerosol-related applications. For example, in FY13, we studied the above-cloud aerosol phenomenon in relation to cloud optical depth retrievals (Alfaro-Contreras et al., 2014) and developed innovative methods for retrieving aerosol optical depth at nighttime using Visible Infrared Imaging Radiometer Suite (VIIRS) data (Johnson et al., 2013). Exploratory studies are continuous to develop new methods for retrieving aerosol properties at nighttime and studying spatial distributions and trends of the above-cloud aerosol events in FY14.

With the support of ONR funding, both 2-D and 3-D aerosol data assimilation capabilities have been developed for the use of passive-based (e.g. MODIS and MISR) and active-based (e.g. the Cloud-Aerosol Lidar with Orthogonal Polarization, or CALIOP) satellite aerosol products (e.g. Zhang et al., 2011). Research efforts have continued on studying the optimal approach of assimilating satellite aerosol products from multiple platforms for aerosol forecasts.

Lastly, research efforts have continued in FY14 for developing a research capability that directly assimilates GOES satellite radiance data for aerosol analysis and forecasts. The development of this research capability is necessary, as unlike research satellites such as MODIS and MISR, continuous and consistent observations are expected from observational satellites, such as GOES, for the foreseen future.

WORK COMPLETED

One of the main accomplishments of this study period is the development of a prototype model for directly assimilating GOES Channel 1 radiance data. This research capability is built upon the coupled NAAPS and Community Radiative Transfer Model (CRTM) system constructed in FY13. The prototype has been tested using simulated GOES radiance (Figures 1a-d) and details are shown in the Results section.

New advancements were also made for studying above cloud aerosol events in an attempt to explore the usage of above cloud aerosol data for aerosol analysis. Frequency distributions and the global and regional trends of above cloud aerosol events are studied using both OMI and CALIOP-based methods, and a journal paper is in preparation for submission in the near future.

Research progress was also made in studying the effect of submerged bubbles on satellite aerosol retrievals. Submerged oceanic bubbles, which have a much longer lifetime than whitecaps, can alter water-leaving radiance and thus impact satellite aerosol retrievals over oceans. However, subsurface oceanic bubbles have never been considered in satellite aerosol studies. For the first time, we have explored the impact of submerged oceanic bubbles on over-water aerosol retrievals using a linked oceanic and atmospheric radiative transfer model. A journal paper has been submitted.

In conjunction with GOES radiance assimilation, we have studied the sub-pixel cloud contamination in GOES imagery data. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data are collocated with GOES data and are used to estimate the effects of sub-pixel cloud coverage within a given GOES pixel to the observed GOES radiance. The results are documented in an M.S. thesis (Kaplan et al., Dec. 2013).

Lastly, continued from last year's efforts, we have finalized a study for evaluating the impact of multi-sensor (MODIS, MISR, and CALIOP) assimilation on aerosol analysis and forecasts. The strengths and weaknesses of including MODIS DT, DB, MISR and CALIOP aerosol products are investigated. Suggestions for future satellite missions are also proposed. This study is published in a peer-reviewed journal (JGR-A) this year (Zhang et al., 2014).

RESULTS

A Prototype Model for GOES Radiance Assimilation (Figure 1)

A prototype model for GOES radiance assimilation was developed as part of this year's research effort. The CRTM, coupled with NAAPS, is used as the radiation core of the model for calculating radiances and Jacobians for the GOES visible channel. A visible radiance-based NRL Atmospheric Variational Data Assimilation System (NAVDAS-VIS) is developed from the 3-D version of NAVDAS-AOD (Zhang et al., 2011). The inputs to NAVDAS-VIS are radiances and Jacobians calculated using the NAAPS 6-hour forecasts, as well as the GOES visible radiance data. The outputs of NAVDAS-VIS are in increments of the NAAPS-reported aerosol mass concentration.

Still, improvements are needed to use the prototype model in an operational mode. For example, the radiance assimilation scheme is only tuned currently for over-water scenarios. Also, simulated radiances from the coupled CRTM-NAAPS system have not been validated against observed GOES data. Still, initial tests of the developed radiance assimilation system show exciting promise. Figure 1a shows the NAAPS aerosol optical depth (AOD) distributions for NAAPS analysis with the assimilation of MODIS, MISR and CALIOP aerosol products, which are used as the reference for the study. Figure 1b shows the simulated GOES radiances using the NAAPS analysis from Figure 1a. Figure 1c shows the AOD distributions from a NAAPS natural run (without AOD or radiance assimilation).

Comparing Figures 1a and 1c, over water aerosol features that have been missed by the NAAPS natural run can be identified. For example, the aerosol plumes near Central America, as shown in Figure 1a, are not found in Figure 1c. Figure 1d shows the NAAPS analysis with GOES radiance assimilation using NAAPS aerosol mass concentrations from Figure 1c as the initial condition. The simulated GOES radiances from Figure 1b are used as the inputs for the radiance assimilation. The NAAPS analysis, after radiance assimilation, can successfully reproduce over water aerosol features, as shown in Figure 1a.

Although only simulated radiances are used in the study, the results shown in Figures 1a-d are very promising.

A Theoretical Study of the Effect of Oceanic Bubbles on the Enhanced Aerosol Optical Depth Band over High Latitude Southern Oceans as Detected From MODIS and MISR (Christensen et al., 2014)

Submerged oceanic bubbles, which could have a much longer life span than whitecaps or bubble rafts, have been hypothesized to increase the water-leaving radiance and thus affect satellite based estimates of water leaving radiance to non-trivial levels. Here we explore this effect further to determine if such bubbles are of sufficient magnitude to impact satellite Aerosol Optical Depth (AOD) retrievals through perturbation of the lower boundary conditions. Indeed, there has been significant discussion in the community regarding the high positive biases in retrieved AODs in many remote ocean regions. In this study, for the first time, the effects of oceanic bubbles on satellite retrievals of AOD are studied by using a linked Second Simulation of a Satellite Signal in the Solar Spectrum (6S) atmospheric and HydroLight oceanic radiative transfer models.

The results suggest an insignificant impact on AOD retrievals in regions with near-surface wind speeds of less than 12 ms^{-1}. However, the impact of bubbles on aerosol retrievals could be on the order of 0.02-0.04 for higher wind conditions within the scope of our simulations (e.g., winds < 20 m s^{-1}). This bias is propagated to global scales using one year of Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer - Earth (AMSR-E) data are used to investigate the possible impacts of oceanic bubbles to an enhanced AOD belt observed over the high latitude southern oceans (also called Enhanced Southern Oceans Anomaly, or ESOA) by some passive satellite sensors.

Ultimately, this study is supportive of the null hypothesis: submerged bubbles are not the major contributor to the ESOA feature. This said, as retrievals progress to higher and higher resolutions, such as from airborne platforms, in clean marine conditions the uniform bubble correction should probably be separately accounted for against individual bright whitecaps and bubble rafts.

Investigating Global Above-Cloud Aerosol Characteristics with CALIOP and OMI (Alfaro-Contreras et al., 2014; in preparation for submission)

Using seven and a half years (June 2006-November 2013) of Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aerosol and cloud layer products, as well as collocated Ozone Monitoring Instrument (OMI) Aerosol Index (AI) data and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) cloud products, we investigate the bi-annual and monthly variability in daytime above cloud aerosol (ACA) events over the globe and for several regions. The nighttime monthly and bi-annual global variability of ACA is also investigated using only CALIOP layer products.

Both OMI-MODIS and CALIOP-based daytime spatial distributions of ACA events show similar patterns during both periods of the study (December – May) and (June – November). Daytime cloudy-sky frequencies of ACA of up to 20% are found from CALIOP over Southeast Asia during June through November, while such events are non-existent from OMI-based AI. Year-round cloudy-sky

ACA frequencies of 20% are reported over Northern Africa from the OMI-based method, yet such events are undetected by the CALIOP-based method. Also, an increasing trend of 1% per year in the global monthly cloudy-sky frequency of occurrence of ACA events was found using the OMI-MODIS based method, yet the CALIOP based ACA frequency and aerosol optical depth trends are slightly negative. An in-depth analysis suggested that the OMI trend may be affected by a significant loss in the OMI AI data in the later years.

Lastly, a regional trend analysis was conducted for which a few regions are found to have increasing trends of cloudy-sky ACA frequency including southeast Asia, the Middle-East and India during daytime and nighttime analyses. Regions with negative ACA frequency trends are found for North and South Africa, as well as South America, during daytime and nighttime. However, none of the global and regional trends are statistically significant. A longer data record of ACA events is needed in order to establish a more significant trend of ACA frequency regionally and globally.

An Investigation of Sub-pixel Cloud/Clear-sky Contamination Using Hyper-spectral AVIRIS data (Kaplan, Dec. 2013, M.S. Thesis)

Cloud and clear-sky contamination of passive radiances due to sub-pixel clouds remains as a troubling issue for scientific applications that rely on remotely sensed data. Sub-pixel level clouds may not be detected by a standard cloud filtering process, and thus can cause uncertainties in satellite–based meteorological property retrievals. In this study, using collocated data from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and Geostationary Operational Environmental Satellite (GOES) data, sub-pixel cloud and clear-sky contamination was studied over the west coast of Northern California. The hyper-spectral data from AVIRIS have a spatial resolution on the order of 11.5 m for the study case, and thus can be used for carefully examining the sub-pixel cloud related bias in GOES data. This study suggests that significant sub-pixel cloud and clear-sky contamination exists, and should be considered for future applications that use measurements from passive sensors such as GOES. Lastly, simulated AVIRIS radiance values from a radiative transfer model were used to explore the possibility of using AVIRIS data for future aerosol studies.

IMPACT/APPLICATIONS

The prototype model for GOES radiance assimilation, once fully validated, can be implemented for operational aerosol forecasts. Our study, for the first time, explores the need to consider submerged oceanic bubbles for satellite aerosol studies.

TRANSITIONS

None.

RELATED PROJECTS

Research associate Ricardo Alfaro-Contreras is also partially supported by a NSF EPSCoRE grant.

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HONORS/AWARDS/PRIZES

Travis Toth has received the second place student poster award for his poster presentation "An Evaluation of Utilizing Passive and Active Satellite Aerosol Products as Proxies for Surface-Based PM2.5 Concentrations" at the 13th Annual Student Conference at the 94th American Meteorological Society Annual Meeting Feb 2-6, 2014.

Dr. Jianglong Zhang's coauthored paper, with Jeffrey Reid from NRL as the lead author, has received the 2013 Naval Research Laboratory Alan Berman Research Publication Award.

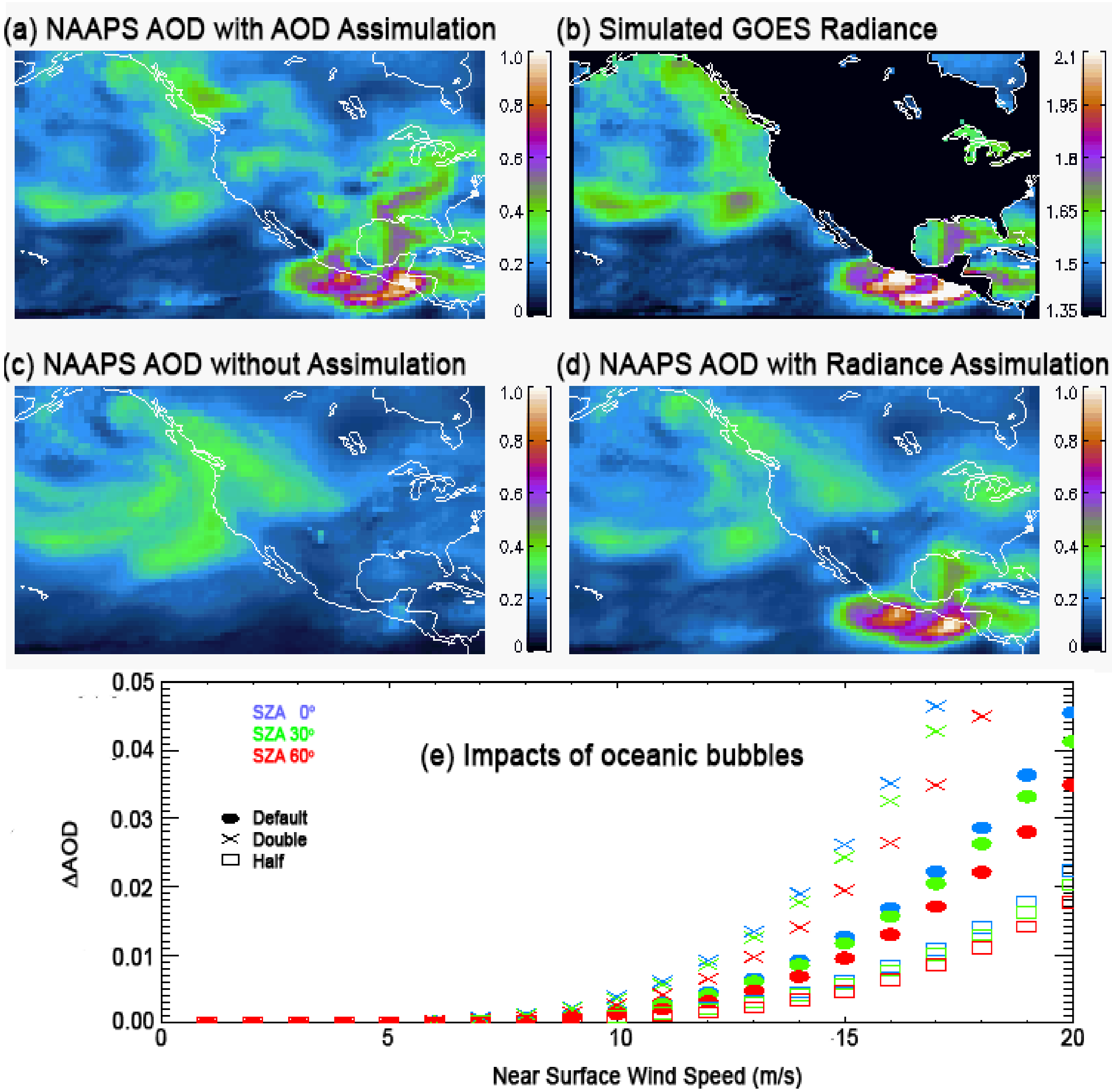

Figure 1. a). NAAPS aerosol optical depth (AOD) analysis (0.55 µm) with MODIS, MISR, and CALIOP aerosol product assimilation for 18UTC, May 15, 2007. b) CRTM simulated GOES-15 radiance (mW/m^2-sr-cm^{-1}) using the NAAPS aerosol analysis from Figure 1a. c) AOD distributions from the NAAPS natural run (without assimilation) for the same date as Figure 1a. d) AOD distributions from the NAAPS analysis with radiance assimilation using the simulated GOES-15 data from Figure 1b. e) The averaged aerosol optical depth uncertainties due to submerged oceanic bubbles (ΔAOD) as a function of wind speed for three solar zenith angles (SZA) of 0°, 30°, and 60° using default, half, and double bubble concentrations. The half and double bubble concentrations are constructed by doubling or halving of the default concentrations to allow analysis of two extreme conditions when compared to a normal set of conditions.

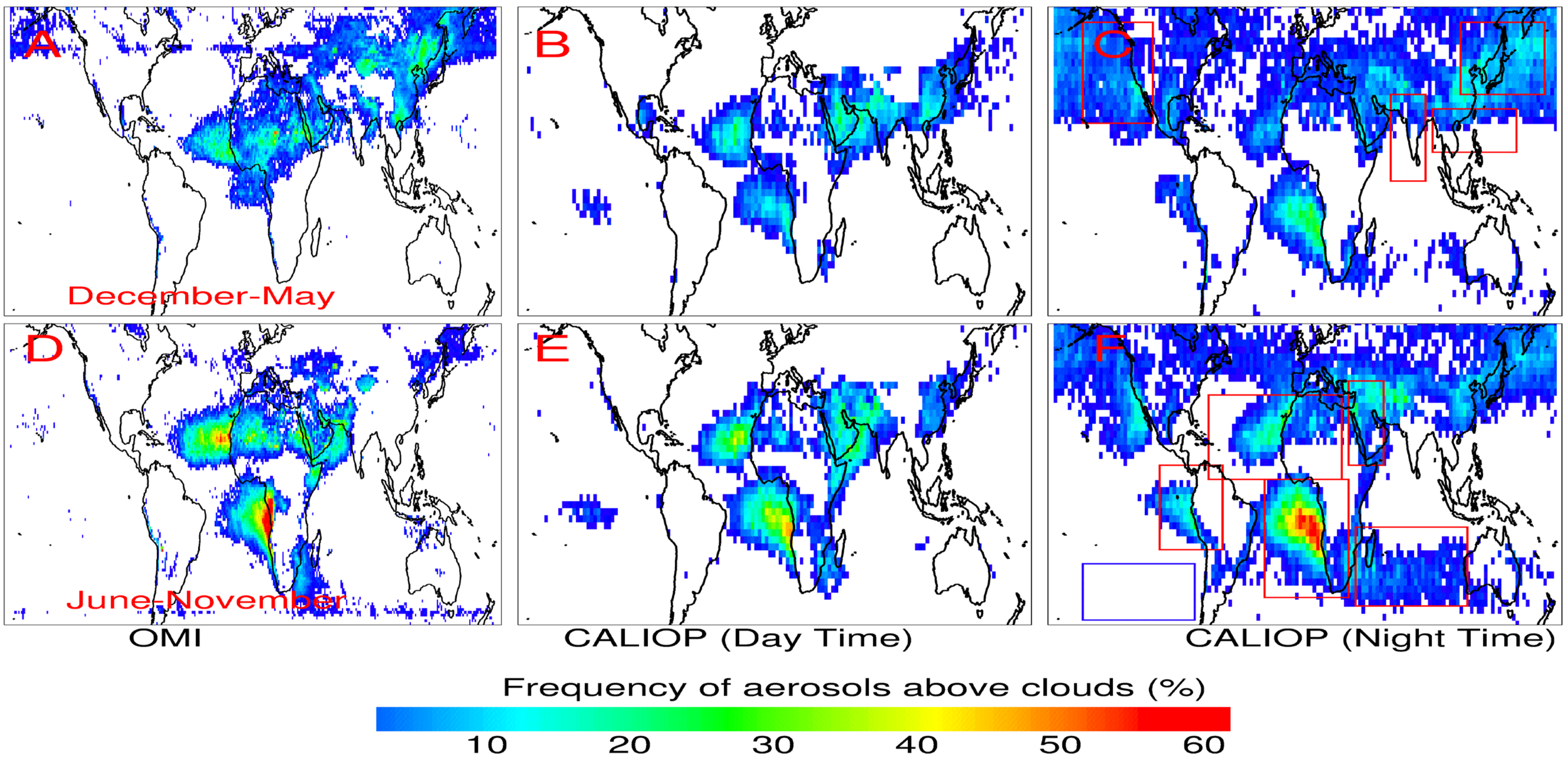

Figure 2. a).Seven year (December 2006- May 2013) frequency of occurrence of aerosol above-cloud events during December through May defined from OMI (ratio of opaque MODIS pixels with AI greater than 1.0 to the number of total opaque MODIS pixels). b) Day-time frequency of occurrence of above-cloud aerosol events over cloudy skies from CALIOP (ratio of CALIOP pixels with CALIOP above cloud aerosol optical depth ($AOD_{above\ cloud}$) > 0 to the number of CALIOP pixels with column integrated Cloud Optical Depth (COD) > 0 and $AOD_{above\ cloud}$ > 0) for the same temporal domain as Fig 1a. c) night-time frequency of occurrence defined similar to the day time frequency from figure 1b. d-f) shows the same information as figures 1a-1c during June 2006-November 2013. The red boxes show the areas selected for regional studies while the blue box shows the area chosen for the control study.