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939 Ellis Street, San Francisco, CA 94109

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Potential Uses of Satellite Data for Air Quality Studies

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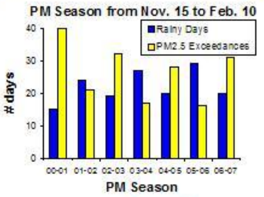

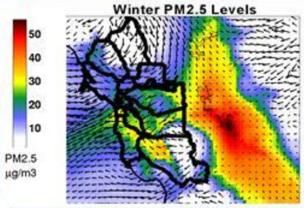

Prepared by:

Saffet Tanrikulu, Research and Modeling Manager
Scott Beaver, Atmospheric Modeler

Significant contributors:

Cuong Tran, BAAQMD
Yiqin Jia, BAAQMD
Su-tzai Soong, BAAQMD

Prepared for:

NASA Air Quality Applied Sciences Team
Physical Atmosphere Modeling Group

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Potential Uses of Satellite Data for Air Quality Studies

1. Introduction

This document presents ideas by which satellite data may be incorporated into air quality studies over the Western United States. Many specific examples are taken from central California. The document consists of four sections including this introduction section. In the second section we describe its purpose. In the third section we present specific examples where satellite data have been or can be used in central California modeling studies. In the fourth section we provide a discussion on unresolved data analysis and modeling issues that may be applicable to remote sensing studies.

2. BAAQMD purpose

The Bay Area Air Quality Management District (BAAQMD) has state-of-the-science air quality modeling and analysis capabilities. Our group actively applies photochemical air quality models (CMAQ and CAMx) coupled with prognostic meteorological models (MM5 and WRF) to conduct policy-relevant simulations over central California. The ability to understand how the weather impacts local to regional air quality is the core research issue for our group.

Modeling is conducted for two main purposes: (1) to comply with regulatory requirements and (2) to forecast high pollution events. For the regulatory requirements, modeling results are used for developing State Implementation Plans (SIPs) to address pollutant levels exceeding health-based thresholds set by the U.S. EPA and the California Air Resources Board. SIP development can have dramatic implications for both public health benefits and costs to industry. For example, the cost of the 2007 federal 8-hour ozone SIP developed for the San Joaquin Valley of California was estimated to be around $20 billion. The cost of the upcoming SIP for particulate matter (PM) for the same region is expected to be even higher. On the other hand, the health cost of 2010 PM levels in the San Francisco Bay Area was estimated to be about $13 billion a year, about $1 billion in direct morbidity costs and $12 billion valuation placed on premature death.

Forecasting high pollution events is very important for the region. Forecasts are used for promoting incentive programs for public transit and voluntary restrictions of household activities to mitigate high pollution levels and to comply with federal and State standards. Public participation in these programs grew significantly, reducing emissions when high pollution levels are expected.

Our main research area is central California. This region has high ozone levels in the summer and high PM levels in the winter. Federal nonattainment areas for ozone and PM are shown below in Figures 1 and 2. Three major air quality studies were conducted here at an expense exceeding $70 million. Central California also has an extensive network of continuous surface monitors for pollutant levels and meteorological parameters. These data have been invaluable for developing air quality simulations. To date, however, remote-sensing data have not been effectively utilized in our air quality modeling applications.

Our goal is to collaborate with other teams of investigators to identify projects for development. Project results must be readily integrated into our meteorological-photochemical modeling system (CMAQ/CAMx and MM5/WRF).

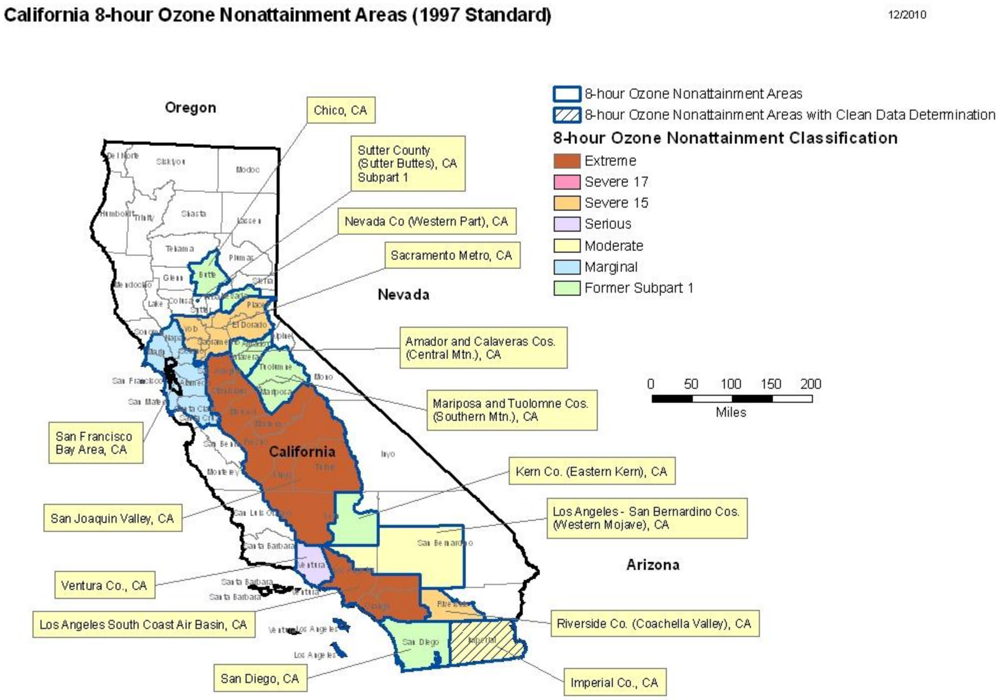


Figure 1. Map of federal 8-hour ozone nonattainment areas for California.

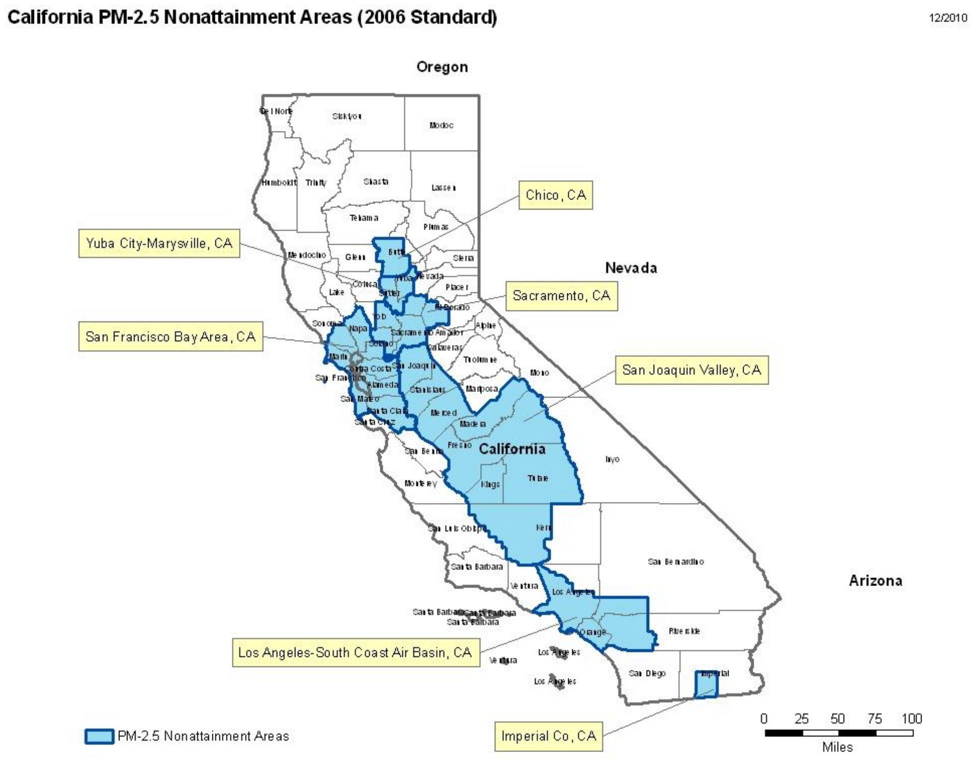


Figure 2. Map of federal 24-hour PM2.5 nonattainment areas for California.

3. Applications of remote sensing data for air quality modeling

3.1 Coastal clouds

Background: Coastal clouds may significantly impact ozone formation in coastal states. It is believed that there is a correlation between the areal extent and density of coastal clouds and levels of inland ozone. The proximity of the eastern edge of the offshore clouds to the shoreline can provide information on the development of the sea breeze air flow pattern. The time of day at which the sea breeze develops is often an indicator for peak daily levels of ozone reached in coastal areas.

Examples: If the summer sea breeze into the San Francisco Bay Area of California develops before 11:00 AM, it is unlikely that high ozone levels will occur on that day. On the other hand, if the development of the sea breeze is delayed until 3:00 PM, high ozone levels may exceed the thresholds for public health standards on that day.

Figure 3 shows a day (11 August 2010) with an early onset of the sea breeze air flow into the San Francisco Bay Area. Cloudy marine air was remotely sensed to flow over the Bay Area during morning and midday satellite overpasses. Corresponding model outputs are shown in

Figure 4. Figure 5 shows a day (8 August 2010) with relatively weak sea breeze. Winds were relatively calm over the Bay Area, and the morning fog had burned off by midday. Corresponding model outputs are shown in Figure 6.

A different example is the Arakawa clouds over Los Angeles Air Basin. The Arakawa clouds usually cover the basin in the morning hours of summer and lift between 11:00 AM and noon. Early dissipation of these clouds is typically associated with higher ozone levels. Delayed cloud dissipation, on the other hand, is associated with lower ozone levels in the afternoon of that day.

Recommendations: Satellite images (including cloud top temperatures) along with surface meteorological and air quality data can be studied to assess the impacts of the coastal clouds on summer ozone. The resulting information can be used for model evaluation. Simulated cloud cover can be compared to satellite observations to validate the model.

3.2 Orographic rain

Background: Orographic rain forms when moist air is driven upwards over elevated terrain such as large mountain ranges. It is common over the western United States. The resulting changes in the weather also impact air quality. The release of energy from the gaseous phase associated with water vapor condensation over mountain ridgelines can have important implications for meteorological modeling. It can influence the air flow patterns that are used to drive air quality models.

Example: Orographic rain often develops in the afternoon hours of summer days over the Sierra Nevada Range. This range extends from around 6000-9000 feet above the low-lying floor of California's Central Valley. The weather and air pollution characteristics over the Sierras provide the eastern boundary conditions for meteorological and air quality modeling over central California. Orographic rain can influence airflow patterns and temperatures over the Central Valley.

The right panel of Figure 5 shows this effect for 8 August 2010. Cloud formation and precipitation had intensified by midday over the ridge line of Sierra Range. The upwind Central Valley and Bay Area were clear. The meteorological model output (Figure 6) showed a similar effect.

Recommendations: Satellite images along with meteorological and air quality data can be studied to assess the impacts of orographic rain on air quality both upwind and downwind of large mountain ranges. This information can be used to evaluate both meteorological and air quality models. Spatial patterns for simulated and remotely sensed orographic rain can be compared to verify the model.

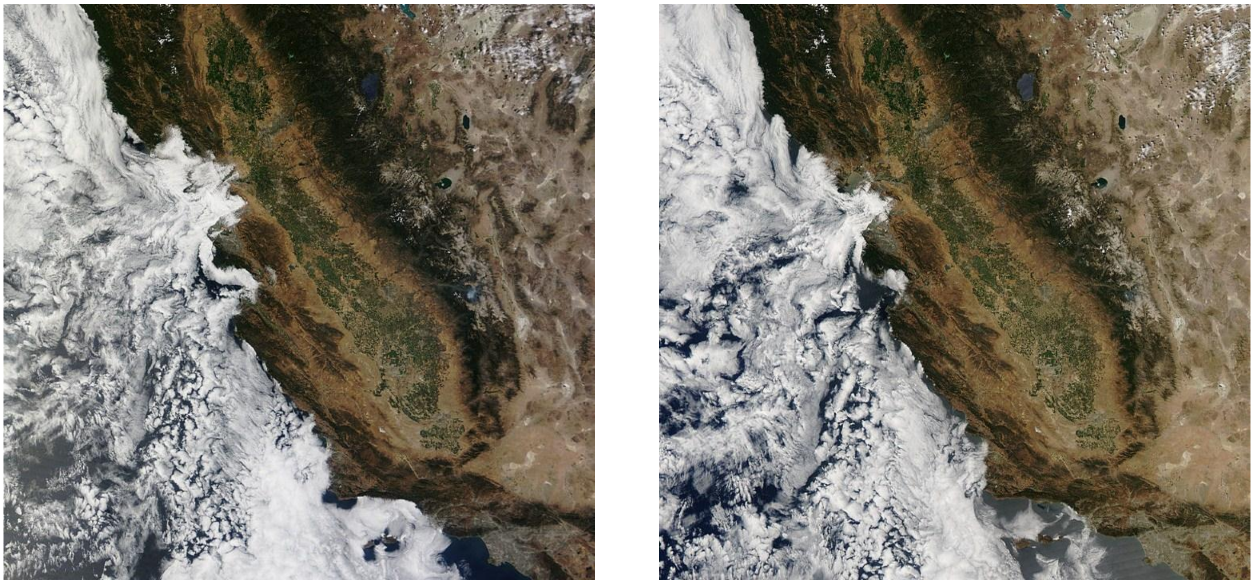


Figure 3. Satellite imagery for 11 August 2010 at 10:30 PST (left) and 12:30 PST (right) from the Terra and Aqua satellites, respectively. Cloud cover is present immediately offshore, over the San Francisco Bay Area, and to a lesser extent over the Monterey Bay at both times.

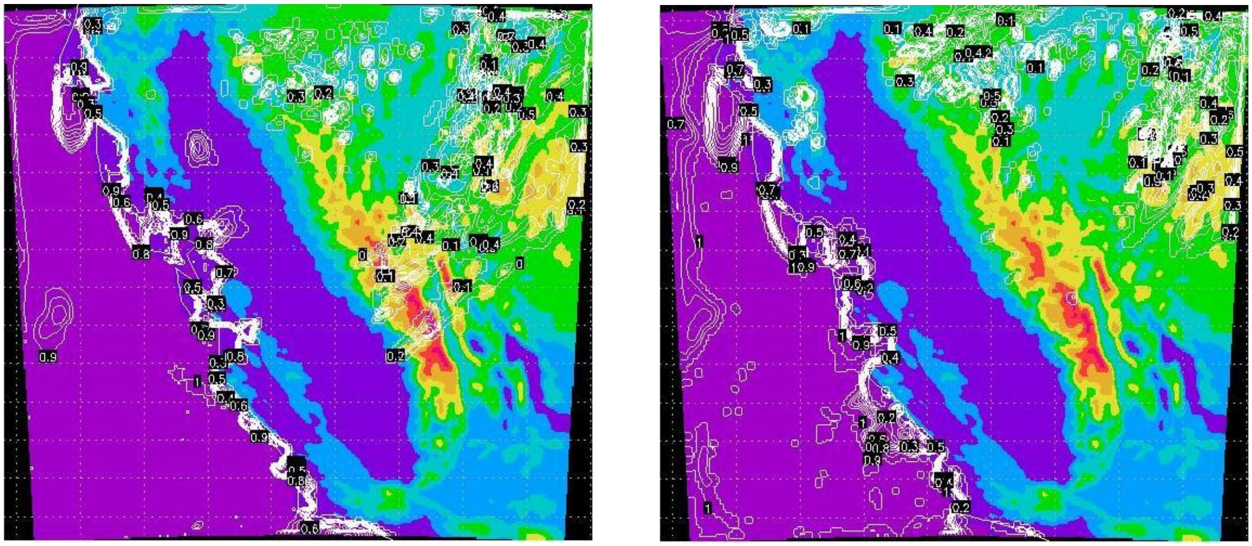


Figure 4. Meteorological model outputs corresponding to remote sensing data shown in Figure 3 for 11 August 2010 at 10:00 PST (left) and 12:00 PST (right). White contour lines indicate probability of cloud/fog formation on a scale 0 to 1. Values above approximately 0.5 indicate cloud/fog is likely. Terrain is indicated by the color shading.

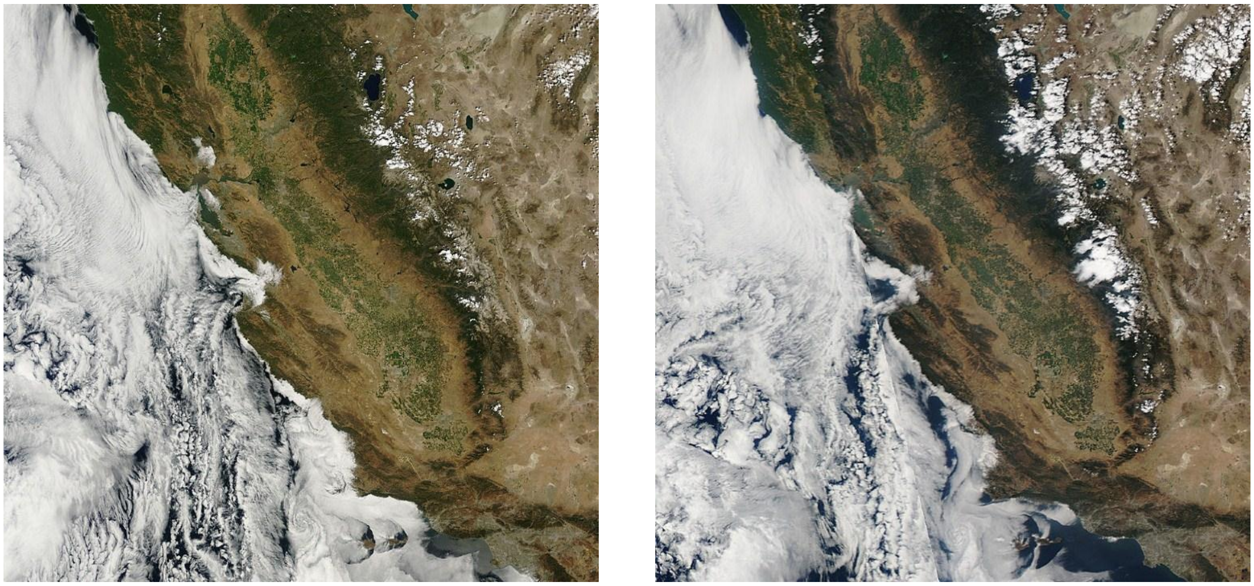


Figure 5. Satellite imagery for 8 August 2010 at 10:30 PST (left) and 12:30 PST (right) from the Terra and Aqua satellites, respectively. Much of the morning fog present over the San Francisco Bay Area has burned off by midday. Also, the later overpass shows orographic cloud formation over the Sierra Nevada range to the east of California's Central Valley.

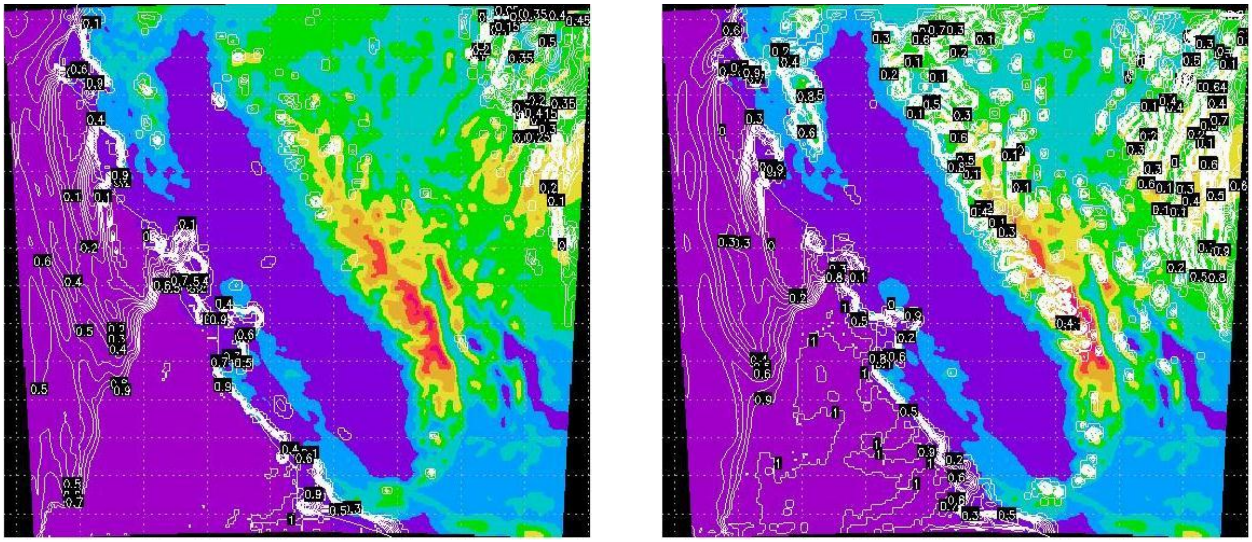


Figure 6. Meteorological model outputs corresponding to remote sensing data shown in Figure 4 for 8 August 2010 at 10:00 PST (left) and 12:00 PST (right). See Figure 4 caption for description.

3.3 Particulate nitrate formation

Background: Secondary $PM_{2.5}$ is formed by the reaction and condensation of gaseous precursors onto particles. Conversion of NO_x (the sum of NO + NO_2) emissions, mostly from combustion, into nitrate is the most important secondary $PM_{2.5}$ formation pathway throughout much of the western United States. (Conversely, sulfate $PM_{2.5}$ formation is characteristic in other states where coal-fired electrical generation is prevalent.) Plumes of nitrate $PM_{2.5}$ can impact large areas over and downwind of emission sources. Nitrate conversion may be especially enhanced over areas having strong ammonia emissions.

Examples: The Central Valley of California is approximately 800 miles long. A gradient of nitrate $PM_{2.5}$ typically occurs with lower levels toward the north and higher levels toward the south. Nitrate formation is especially prevalent over two areas about 100 miles in spatial extent, over which commercial dairying operations and associated ammonia emissions are concentrated. Surface monitoring networks are, however, not sufficiently dense to characterize the extent of nitrate plumes. The mixing of NO_x from combustion sources and ammonia from agricultural sources is an important process to understand in simulating Central Valley air quality.

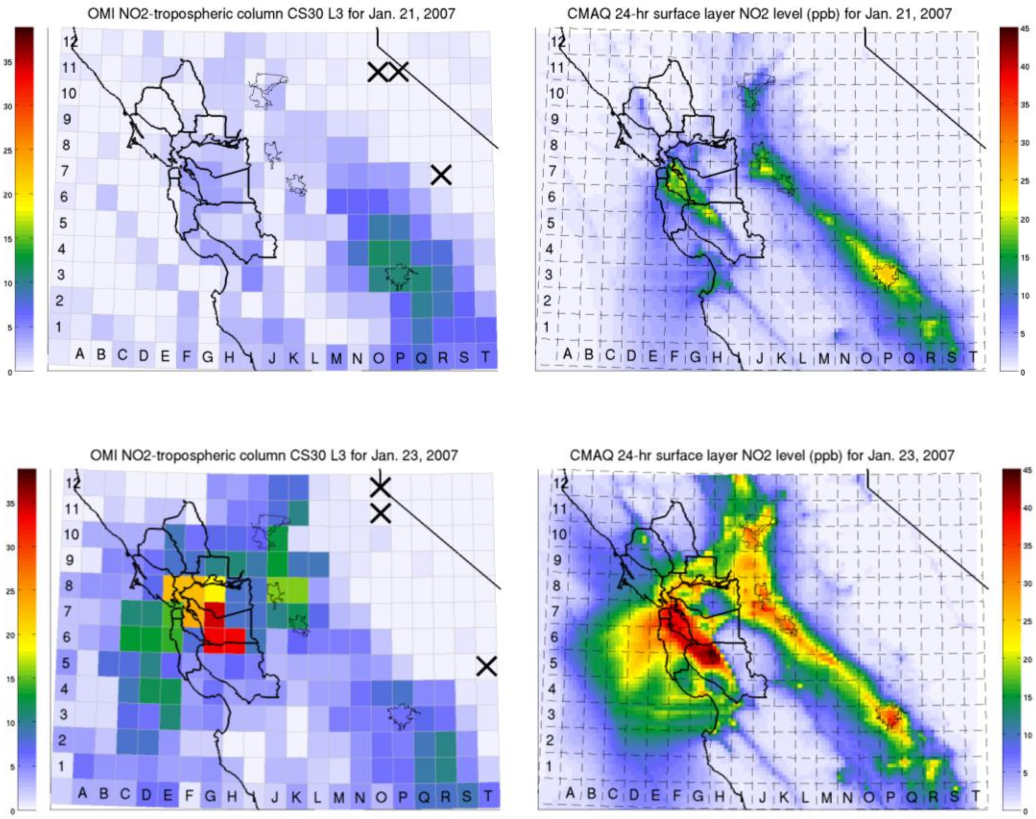


Figure 7. Remotely sensed NO_2-tropospheric columns (left side) and simulated NO_2 levels (right side) for 21 (top) and 23 (bottom) January 2007. The 0.25 degree remote sensing grid is shown on the modeling results, which was conducted at 4-km resolution. Black lines outline California and counties around the San Francisco Bay Area.

Remotely sensed NO_2 from the OMI instrument can be used to evaluate winter $PM_{2.5}$ simulations over central California. For this area in the winter, $PM_{2.5}$ and NO_2 tend to have similar lifetimes in spatial distributions. Figure 7 shows remotely sensed and simulated NO_2 for two days (21 and 23 January 2007). The remotely sensed and simulated spatial distributions are similar. During the former day, pollutant buildup occurred to moderate levels mostly in the southern San Joaquin Valley. During the latter day, high pollutant levels were widespread, especially over the San Francisco Bay Area. An outflow produced plumes downwind of the San Francisco Bay (mainly pixels C6, D6, E6) and the Monterey Bay (mainly pixels D4 and E4).

Recommendations: Remotely sensed NO_2 can be used to infer areas over which nitrate $PM_{2.5}$ formation occurs. Remotely sensed NO_2 plumes can provide an indication of the spatial extent of the reactive zone for nitrate formation. Additionally, ammonia-rich areas may be identified as areas depleted of NO_2 within a plume. This effect indicates that the available NO_x has been completely consumed by ammonia near its source of emission. Such information can be used for evaluating air quality models. We also recommend conducting this type of analysis across days associated with different weather patterns.

3.4 Winter fog and secondary PM

Background: An alternative particulate nitrate formation pathway is the conversion of NOx to nitric acid through the formation of N_2O_5 under very high humidity conditions in the absence of sunlight. Fog usually supplies the necessary humidity for this chemical transformation.

Examples: The formation of winter fog is very common in western states. In the San Joaquin Valley, fog develops on more than 80% of winter days when the region is influenced by a high pressure system. As a result, observed ammonium nitrate concentrations have been the highest in the nation.

Figure 8 shows an example of the day (7 December 2010) having thick surface Tule fog present through the morning hours. These conditions were likely to have favored nitrate conversion via the N_2O_5 pathway. Simulation results are shown in Figure 9. The simulation produced the surface fog over the San Joaquin Valley during the morning. The simulated fog remained through midday.

Recommendations: Uncertainty in the simulated fog and humidity is often large, resulting in incorrect estimation of NOx to nitric acid conversion in air quality models. Satellite imagery can be used to evaluate meteorological simulation modules for fog formation.

3.5 Snow cover

Background: Snow cover is one category of land-use types that is an input to both meteorological and air quality models. In the meteorological models, the estimation of several parameters including surface roughness, albedo, energy budget, planetary boundary layer processes, and air flows up and down the mountain slopes can be affected by this land-use type. It could also impact the surface pollutant deposition rate in air quality models.

Example: The cold surface caused by snow cover on top of the Sierra Nevada Range causes air to sink into the Central Valley at its base. This convergence of winds toward emissions sources on the valley floor is often associated with high fine particulate matter ($PM_{2.5}$) levels in the winter. Snow cover can vary markedly from winter to winter. As an example, Figure 10 shows winters with relatively high and low snow cover.

Figure 11 shows snow cover data for a day (5 December 2010) used to initialize the meteorological model. These data can be compared against imagery taken from the same winter shown in Figure 8.

Recommendations: Snow cover data is usually obtained from a seasonal average snow cover data file when model inputs are prepared. This seasonally averaged information is often unrepresentative. Satellite images can be used to update the seasonal average data with measurements to make improvements.

High resolution snow cover data may be available; however, it is unclear how to assimilate such data into the coupled photochemical-meteorological modeling system. Currently, snow cover data are used to initialize an outer 36-km meteorological modeling domain. Air quality simulations, however, are conducted on a nested 4-km domain using meteorological parameters such as winds and temperature.

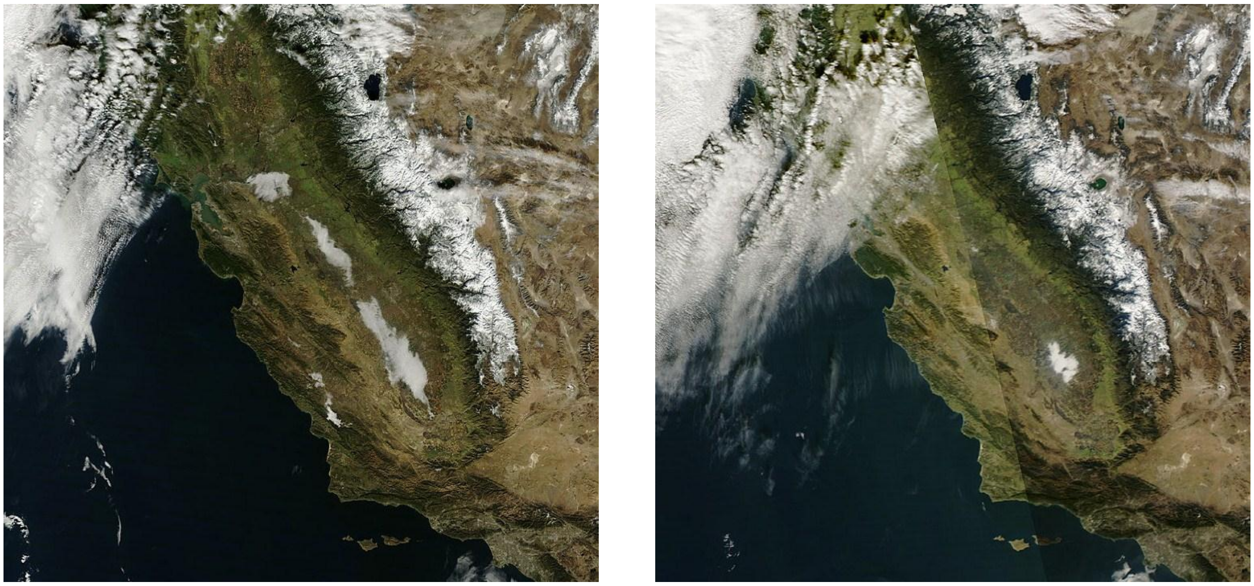


Figure 8. Satellite imagery for 7 December 2010 at 10:30 PST (left) and 12:30 PST (right) from the Terra and Aqua satellites, respectively. The morning overpass showed three dense patches of surface Tule fog along the San Joaquin Valley. Much of this fog had burned off by midday.

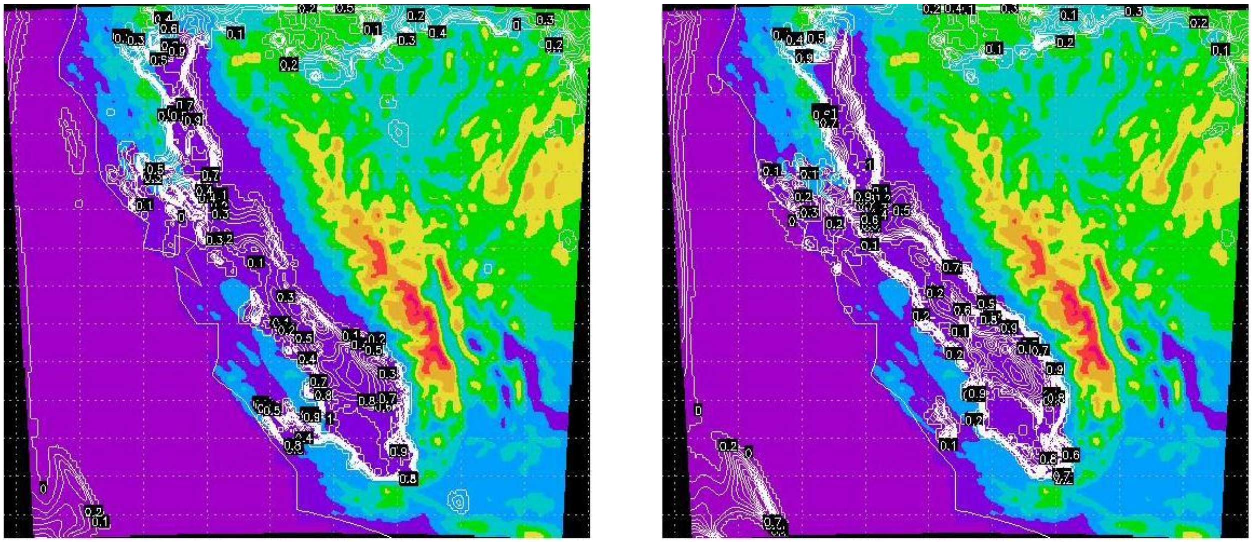


Figure 9. Meteorological model outputs corresponding to remote sensing data shown in Figure 8 for 7 December at 10:00 PST (left) and 12:00 PST (right). See Figure 4 caption for description.

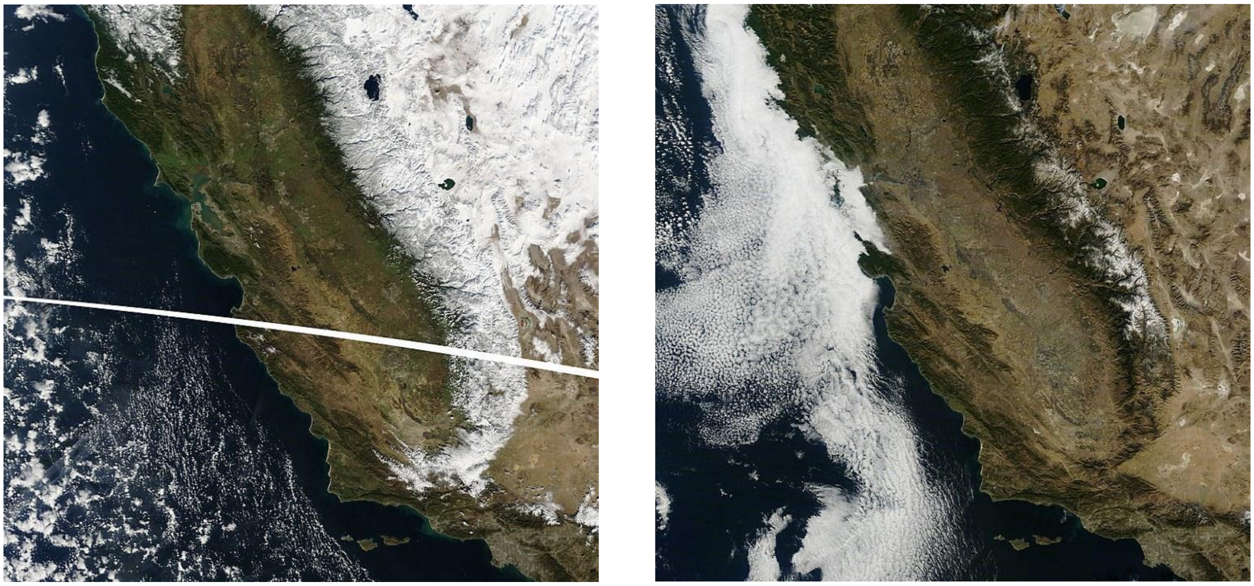


Figure 10. Satellite imagery for 26 December of 2008 (left) and 2011 (right) showing years with relatively high and low snow cover over the Sierra Range, respectively.

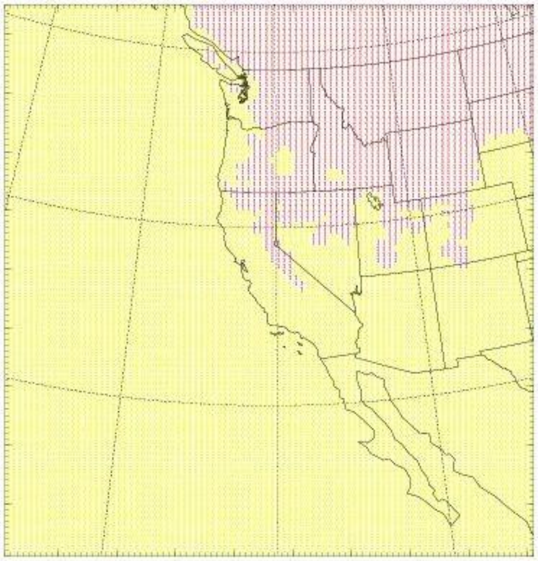


Figure 11. Snow cover data for 5 December of 2010 that were used to initialize the meteorological simulation. Red indicates snow, yellow indicates no snow cover. The snow cover spatial distribution can be compared against imagery in Figure 8 taken during the same winter.

3.6 Wood burning PM emissions

Background: Smoke from household wood burning can contribute strongly to $PM_{2.5}$ levels. Wood smoke is directly emitted as particles, as opposed to being formed by gaseous chemical reactions. As such, wood smoke accumulates and thus can be controlled effectively at a local scale. Activity levels and spatial patterns for wood burning, however, are highly uncertain.

Example: Wood burning emissions contribute to winter PM levels from 10% to 80% in various areas of California, except the Los Angeles air basin where winter wood burning has been banned. A number of air basins such as the San Francisco Bay Area, the San Joaquin Valley, and Sacramento have programs to curtail emissions on certain days (“Spare the Air Days”). For example, wood burning is restricted on days when the weather is conducive to high PM levels. The compliance rate for wood burning restrictions, however, is unknown and enforcement is problematic.

Emissions can vary considerably for different regions. Over the Bay Area, wood burning tends to occur during the clearest, coldest nights. Over the Central Valley, wood burning occurs more continuously and the wood smoke may be mixed with dense Tule fog blanketing the surface. Emissions estimates are uncertain because they are based on a limited sample size of random telephone surveys with volunteered information. These surveys tend to be unrepresentative over rural areas where wood burning is concentrated.

Recommendations: Satellite imagery may be used to investigate the Spare the Air Day compliance rate by comparing wood smoke on restricted activity (“no burn”) versus unrestricted (“burn”) days. It can be used to identify heavy burning areas so that public information staff can focus their education and outreach efforts. It can also be used to assess the uncertainty in emission estimates by comparing emissions at heavily surveyed areas with rural areas.

3.7 Agricultural irrigation

Background: Large agricultural areas represent human impacts on land use that can dramatically impact regional air quality. Agricultural fields can impact the estimation of a variety of meteorological parameters including planetary boundary layer processes, mixing depth, surface energy budget, soil moisture, and atmospheric humidity. Widespread irrigation practices can also impact pollutant deposition rates, biogenic emissions from any land cover, and NOx emissions from fertilizer application and microbial action in soils.

Examples: The Central Valley of California measures approximately 800 by 100 miles. The landscape is naturally arid in the summer and affected by flooding in other seasons. Extensive water management systems have allowed much of the valley to be dedicated to agriculture. The spatial distribution and thermal fluxes of areas impacted by irrigation, however, is largely unknown.

Recommendation: Irrigated areas may be determined from satellite imagery and remotely sensed temperatures. This information could help update model input data such as land-use category assignment.

3.8 Biogenic emissions

Background: Biogenic emissions of VOCs can be significant drivers of regional ozone formation. Biogenic emissions are important inputs for air quality models. They are, however, relatively uncertain due to unknown land use and vegetation characteristics, especially over remote areas.

Biogenic emissions for air quality modeling are estimated based on land use and the type of vegetation specified. These inputs are usually seasonal average data. However, depending on the location, the land-use and vegetation can change significantly from summer to summer, especially in wet vs drought summers. Emissions also vary throughout the season depending on spring rainfall and the growth of dormant natural vegetation under dry conditions in early to late summer.

Example: In the San Francisco Bay Area, it is unlikely to rain in July and August. Rain in late spring correlates well with ozone exceedances in August and September. This information, however, is not properly represented in the biogenic emissions inventories used for air quality modeling.

Recommendations: Several scientists have attempted to refine or verify estimated biogenic VOC emissions using a "greenness" index obtained from satellite measurements. Their study can be expanded to improve biogenic emissions estimate based on satellite data.

3.9 Dust storm impacts

Background: Dust storms can contribute to high regional $PM_{2.5}$ levels for certain areas with exposed soils.

Example: Inyo County of California has a dry lake bed that contributes to windblown dust. These emissions, however, are uncertain in magnitude.

Recommendations: Dust can be tracked from satellite imagery to identify sources. Large areas subject to desertification can be reclaimed to mitigate dust storms.

3.10 Ocean boundary conditions

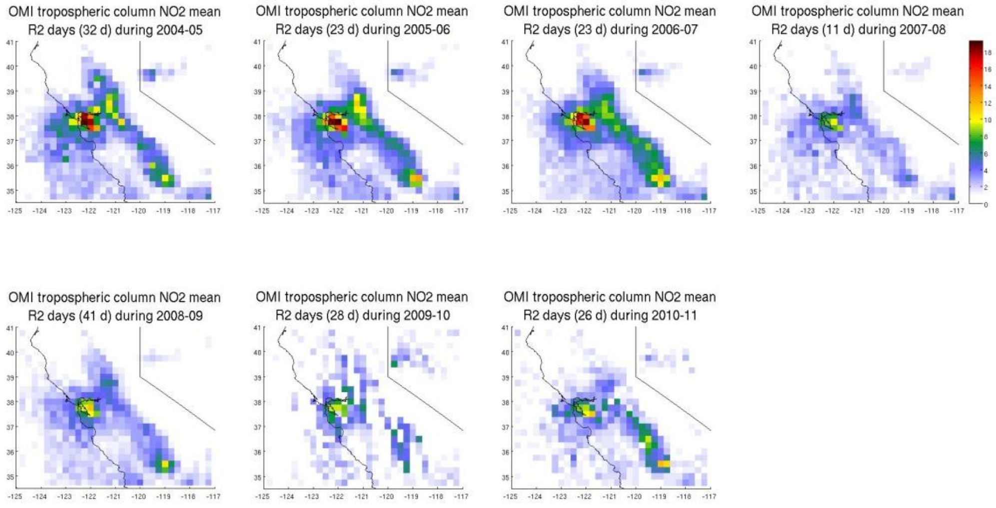
Background: No air quality data is measured over the Pacific Ocean routinely. Air quality model boundary conditions are set there based on a few aircraft measurements.

Recommendation: Specify air quality and meteorological variables over the Pacific Ocean and update model boundary conditions from the specified values.

3.11 Trend analysis

Background: Assessing how pollutant levels change over time is important to assess control strategy efficacy and identify new pollution problems. Trends are impacted by the weather in addition to changes in emissions.

Example: The meteorologically normalized trend was examined for the tropospheric NO_2 column remotely sensed by the OMI instrument. Figure 12 shows the mean spatial distribution for each winter from 2004-05 through 2010-11, averaged for the days assigned to an "episodic" weather pattern typically associated with high $PM_{2.5}$ levels. Over the San Francisco Bay Area, there appeared be two superimposed trends related to changes in emissions. First, NO_2 was more widespread and reached higher levels for 2004-05 through 2006-07 as compared to the latter years. This downward "step" was likely caused by a prolonged economic recession. Second, both before and after the downward step, the NO_2 spatial distribution generally appeared to contract somewhat from one winter to the next. These slow, gradual changes may have reflected the impacts of implemented emissions controls to slightly outpace the region's growth.



OMI tropospheric column NO2 mean R2 days (32 d) during 2004-05

OMI tropospheric column NO2 mean R2 days (23 d) during 2005-06

OMI tropospheric column NO2 mean R2 days (23 d) during 2006-07

OMI tropospheric column NO2 mean R2 days (11 d) during 2007-08

OMI tropospheric column NO2 mean R2 days (41 d) during 2008-09

OMI tropospheric column NO2 mean R2 days (28 d) during 2009-10

OMI tropospheric column NO2 mean R2 days (26 d) during 2010-11

Figure 12. Aerial plots of means for observed OMI tropospheric NO_2 column for "episodic" $PM_{2.5}$ weather pattern for winters 2004-05 through 2010-11. Sample sizes for each mean shown above plot. Same scale used for each winter.

Recommendations: NO_x and VOC trends can be tracked using remotely sensed NO_2 and formaldehyde (HCHO), respectively. Tracking of ammonia trends would also be useful. Analysis of weather patterns can be used to achieve meteorological adjustment of trends to better reflect changes in atmospheric pollutant loadings and related emissions changes.

3.12 Wildfire emissions

Background: Wildfires are very common in the western states during the summer. Typically 10 to 40 separate wildfires are reported on a given day. Wildfire NOx and VOC emissions can lead to poor air quality, contributing to ozone exceedances. The U.S. EPA excludes any high ozone levels influenced by wildfire emissions from adversely impacting a region's status to attain air quality standards.

Example: Wildfires have historically influenced high ozone levels in the Central Valley of California. One such wildfire occurred during a Central California Ozone Study intensive measurement period. The collected data were used to develop air quality model inputs to evaluate regulatory strategies for ozone. Regulatory strategies could be better evaluated by removing the influences of naturally occurring wildfires from such air quality simulations.

Recommendations: Satellite images can be used to estimate wildfire emissions and their transport in the atmosphere. This information can be used to document the influence of wildfire emissions on high ozone levels. In addition, wildfire emissions can be simulated and compared against satellite observations to verify the diffusion and dispersion algorithms of both meteorological and air quality models.

3.13 Pollutant transport

Background: Pollutant transport is a very important and often controversial issue. Most downwind districts and states claim that they are being polluted by upwind sources. Therefore, upwind sources may need to be regulated in order for downwind areas to attain air quality standards. However, there is no commonly accepted method to quantify transport.

Example: The relative contributions of transported versus local emissions sources is sometimes calculated using a model. A typical strategy is to "zero out" the emissions from upwind sources to determine the effects on downwind areas. Such modeling applications, however, are unrealistic and cannot be verified by any existing measurements.

Recommendations: Remote sensing can be used to investigate visible plumes and also trace gases such as NO_2 that that may suggest transport between different areas. (Tracking sulfur dioxide transport would only be applicable for other states where coal-fired electrical generation is prevalent.) Long-term records can be used to assess the frequency of an representative spatial patterns for different types of pollution transport events. This information can help assess the representativeness of various air flow patterns that may have different pollutant transport characteristics.

4. Summary and discussion

The use of satellite data in air quality studies can complement the traditional surface based measurements. In a broader scope, we group the potential areas in three categories.

4.1 Analyzing atmospheric features impacting air quality

The most important groundwork for conducting an air quality simulation is to first develop a "conceptual description" of pollutant formation. A conceptual description represents the fundamental science behind air quality modeling. Air quality simulations are codified representations of the conceptual description.

The existing conceptual descriptions of pollutant formation are mostly based on surface observations. They should be updated with satellite based data and new results should be evaluated.

As an example, we further consider the effect of coastal clouds discussed throughout section 3. Imagery of cloud cover could first be evaluated to determine if any correlations exist between remotely sensed clouds and surface-level air quality. An investigator would then determine how cloud cover data would impact the meteorological simulation, and then evaluate the downstream impacts on the air quality simulation. Alternatively, further inland, such as over the Rocky Mountains, the density in proximity of coastal cloud cover may reflect large-scale weather patterns setting the upwind boundary condition for inland pollutant levels. Again, these boundary conditions would impact the meteorological simulation, which would impact the downstream air quality simulation. Such cascaded effects need to be explored systematically and rigorously.

4.2 Preparing air quality simulation inputs

An air quality simulation executes the codified conceptual description of pollutant formation. There are many technical aspects to conducting an air quality simulation. Therefore, increased scientific knowledge does not necessarily directly translate into an improved air quality simulation. For our purposes, we desire to integrate remote sensing data into an existing air quality modeling system. This modeling system uses a standardized data format. Tremendous effort is often required to format data into this system. Therefore, for a developed methodology to be widely adopted, a computer program or "patch" must be available for operational use of remote sensing data with minimal user effort.

As examples, land use categories may be remotely sensed with high accuracy. This information, however, needs gridded onto the air quality simulation domain. Some form of “process analysis” to examine the inner workings of the model may be necessary to understand the model sensitivity to inputs.

4.3 Evaluating air quality simulation outputs

Rigorous evaluation of air quality model outputs is necessary to identify its strengths and weaknesses. Various types of comparisons between remotely sensed and simulated quantities may be conducted. Comparisons can be made for point estimates, averages (e.g. seasonal or annual), or by weather pattern. Our fundamental research interest is to understand how air quality is impacted by changing weather patterns. Satellite-based measurements supporting this objective are highly desirable.

Additionally, satellite data may suggest potential policies that could be explored using simulations. For example, remote sensing data may help suggest alternative transportation routes to mitigate congestion and emissions. Potential alternative transportation routes could be simulated to evaluate their impacts on population exposure to pollutants.