ENGINEERING SATELLITE DATA FOR ENVIRONMENTAL HEALTH ISSUES

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ABSTRACT:

Environmental health and public health are often linked in the scientific and popular literature even though they require different scientific skill sets, technologies, and models for their study. *Environmental health* includes not only the health and sustainability of natural ecosystems, but the environments of built landscapes, home and building environments, and of the Earth system processes that promote or retard environmental change. To study them, one needs education in atmospheric physics and chemistry, water chemistry, geophysics, and biology. *Public health* is related in large measure to degraded environmental parameters (mostly induced by modern economic, social, and human pressures on landscapes). To study public health, one needs medical training and an appreciation of those processes that impact environments and that may in turn influence populations whose health might be at risk. Using satellite-acquired data and imagery to study environmental health has many immediate attractions; however, the extension of these studies for better understanding public health patterns and outcomes lags far behind, and does not yet embrace medical communities. This paper describes an engineering system for linking atmospheric dust episodes to specific public health outcomes that can be verified and validated in medical terms. It requires forging new scientific partnerships from the environmental and medical professions.

1. COUPLING ENVIRONMENTAL HEALTH WITH HUMAN HEALTH

1.1 Background and Stimulus

Articles appear frequently in the popular press that link space technology to environmental and public health issues. A recent example by Wright (2005) lists several human activities that force increases in atmospheric dust episodes and the ability of these to carry viruses, bacteria, radioactive isotopes, and pesticides deleterious to human health. While such articles add to the public's general appreciation of Earth system processes, they often imply higher than true levels of scientific understanding of these processes; and in some cases draw premature conclusions about cause and effect relationships. Behind these popular press contributions is a body of national and international evidence citing the perils of doing "business as usual" at the expense of environmental and public health. Among the noteworthy in this category is Woerden (1999).

In 2002, the National Aeronautics and Space Administration's (NASA's) *Earth Science Applications Division* (now part of the *Science Mission Directorate*) began an integrative program called Research, Education and Applications Solutions Network (REASoN) that echoes closely the views expressed by Woerden regarding core datasets, the collection of data having high quality, and their use for environmental policy.

1.2 Guiding Principles

The first principle to emerge from the United Nations Conference on Environment and Development held in Rio de Janeiro (UN, 1992) was that "*Human beings are at the center of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.*" Here, perhaps, is an early convergence of environmental with public health. Ten years later at the 2002 World Summit on Sustainable Development (WSSD), the Johannesburg Plan of Implementation (POI) was adopted (UN, 2004). In this Plan, paragraphs 53-57 refer specifically to human health issues. It is stated (p. 31) that "there is an urgent need to address the causes of ill health, including environmental causes, and their impact on development, and to reduce environmental health threats."

Many challenges in Earth system science require not only integrating complex physical processes into system models, but also coupling environmental biogeochemical and chemical phenomena that trigger human health responses. The next generation of modellers will be required to form teams that partner members from the biogeophysical realm with those from the medical realm to assess quickly changing and highly vulnerable situations.

People and Pixels (Liverman et al., 1998) was among the early publications to draw humankind into the arena of satellite remote sensing. Most earlier scientific literature focused on physical and natural applications in agriculture, forestry, rangeland, hydrology, and mineral exploration. After *People and Pixels,* interest has migrated to people-oriented issues like

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food security, environmental health, public health, disasters and hazards, and most recently on security and antiterrorism. Because of their immense humanitarian and policy implications, remote sensing and geospatial programs are moving quickly to address the consequences of climate change on human health, air and water quality degradation, and diseases following natural disasters.

1.3 Context

For the photogrammetry, remote sensing, and geospatial information sciences, the key language in Paragraphs 53-57 in the POI includes the following (especially the underlined phrases). For the most part they are general aims and goals, but a few are quite specific.

§-54:

- Integrate health concerns into strategies, policies, and programs for sustainable development;
- Provide technical and financial assistance for health information systems and integrated databases;
- Target research efforts and apply research results to priority public health issues and reducing exposures to public health risks;
- Start international initiatives that assess health and environment linkages; and,
- Develop preventive, promotive, and curative programs for non-communicable diseases (like chronic respiratory diseases.

§ 56:

- Reduce respiratory diseases and other health impacts resulting from air pollution;

2. ENGINEERING AN EARTH SCIENCE/PUBLIC HEALTH SOLUTION

2.1 Project Goals and Structure

Goals for the NASA REASoN project reported here are to (a) assimilate satellite data into a regional weather forecasting model; (b) baseline the value added to this model by incorporating satellite data products; (c) partner with health care scientists and public health authorities to verify and validate the Earth system science coupling mechanisms between environmental health and public health; and (d) benchmark quantitatively the scientific and societal benefits of this engineering effort.

The project has three thrusts moving along a parallel front. The first focuses on assimilating satellite data from MODIS Terra and other sources into the Dust Regional Atmospheric Model (DREAM) developed at the University of Malta. DREAM, in turn, is driven by the National Centers for Environmental Prediction (NCEP)/Eta weather forecasting model, widely used around the world. The aim of this effort is to: (a) verify that advanced satellite image data from current research sensors can replace model parameters from traditional non-satellite sources, or from earlier (coarser resolution) satellite sources; and, (b) validate that parameter replacements lead to more reliable model forecasts of dust episodes.

The second front focuses on optimizing DREAM model outputs by iterating model inputs with a variety of satellite products and assessing incremental improvements. The aim of this effort is to partner with a prototypical public health decision support system called the Rapid Syndrome Validation Project (RSVP) developed by Sandia National Laboratories. For this project, interest is concentrated on respiratory diseases that are known clinically to be triggered, at least in part, by atmospheric dust (asthma, Hantavirus Pulmonary Syndrome, and Acute Respiratory Distress Syndrome). The questions of greatest interest to the research team are: (a) how well and with what degree of sensitivity can NCEP/Eta and DREAM forecast that dust will be lifted from a landscape? (b) how well can these models predict the speed and direction of moving dust clouds? (c) can medically sound evidence be generated that couples dust episodes to documented respiratory health responses at the population level? and, (d) can areas affected by dust clouds be forecast in a timely fashion to alert health officials and populations at risk?

The third front involves working with public health authorities to determine whether there are statistically valid relationships between dust episodes and records for increased respiratory complaints. This is a difficult effort in the United States because public health authorities are distributed throughout all levels of government (city, county, state, and federal), and because standardized record keeping is not mandatory for all types of records within or between these levels. Furthermore, because of patient confidentiality, it is impossible to know exactly the environmental circumstances or the geospatial coordinates behind any given record. These circumstances led developers of RSVP to design a decision support system that encourages public health officials, air quality monitoring offices, doctors, and clinicians to coordinate their information electronically, and in appropriate ways to protect patient confidentiality; but also that allows group attributes to emerge in such a geospatially explicit way that populations at risk can be forewarned.

These three thrusts are interactive. For effective application of satellite observations to public health, physicians and clinicians need to be motivated to report non-confidential patient information in such a way that emerging spatial patterns at a broader scale can be recognized by public health and safety offices early in the development of an episode. For its part, satellite-based dust forecast models must be recognized as a reliable source of information to issue medical alerts. Epidemiologists across the world are fearful of a pandemic flu outbreak and are very aware that devastating respiratory diseases can span the globe in 24 hours (Oxford et al., 2005; Selinus et al., 2005; Taubenberger et al., 2005).

2.2 Coupling Framework

For this project, the framework for coupling atmospheric dust processes with human health responses begins with experimental NASA satellite data products and modifies them for assimilation into DREAM. The output from DREAM becomes input to RSVP. This support system is queried by doctors and clinicians who desire additional corroborating information about similar cases being reported by their local or regional colleagues. The ultimate goal is to have the output from RSVP delivered to public health decision makers for announcing appropriate health alerts.

2.3 Coupling Challenge

Direct satellite observations have confirmed through numerous studies that moderate and severe dust events can be detected, and that dust can be traced in the atmosphere across continents and oceans (e.g. Lee, 1989; King et al., 1999; Prospero, 1999;

Kaufman et al., 2000; Chu et al., 2003; Grousset et al., 2003; Gu et al., 2003; Miller, 2003; Kaya et al., 2004; Stefanov et al., 2003). Likewise weather forecasting models, augmented with regional dust forecasting capabilities, show promise for better predicting the onset and tracking of dust events. Lastly, there is growing recognition that naturally dusty environments have long-term human health impacts (e.g., Policard and Collet, 1952; Bar-Ziv and Goldberg, 1974; Norboo et al., 1991; Goudie and Middleton, 2001; Xu et al., 1993; Mathur and Choudhary, 1997; Wiggs et al., 2003; Wright, 2005). What remains to be demonstrated is the direct coupling of specific dust episodes with health response statistics. Whereas long-term (lifetime) exposures to dusty environments may lead to desert lung (silicosis), or pneumoconiosis in high altitude or desert dwelling populations, asthma is a chronic respiratory disease triggered by numerous indoor and outdoor environmental attributes. Asthma is a rapidly growing illness among children and elders throughout the industrialized world. It remains to be demonstrated that these populations respond to individual dust events in numbers high enough to issue public health alerts; or that such events can be forecasted and tracked in adequate time to issue effective alerts.

3. ELEMENTS AND INITIAL RESULTS

3.1 Dust Regional Atmospheric Model (DREAM)

DREAM is based on a Eulerian modelling approach (Nickovic et al., 2001). Its dust concentration module consists of three static surface parameters: topography and vegetation cover at 1x1 km resolution, provided by the U.S. Geological Survey; and soil types converted into texture classes at 2x2 minute resolution provided by the UN/FAO. Atmospheric inputs include both wet and dry deposition parameters, and seven ZOBLER soil texture classes at 1.0° resolution, provided by the NCEP/Eta model. Other NCEP/Eta parameters include lat/lon, 32 pressure levels from the surface to 100 hPa, geo-potential height, wind components, specific humidity, and soil temperature, moisture, and albedo. Resolution of the atmospheric inputs range from 0.1° to 1.0° lat/lon.

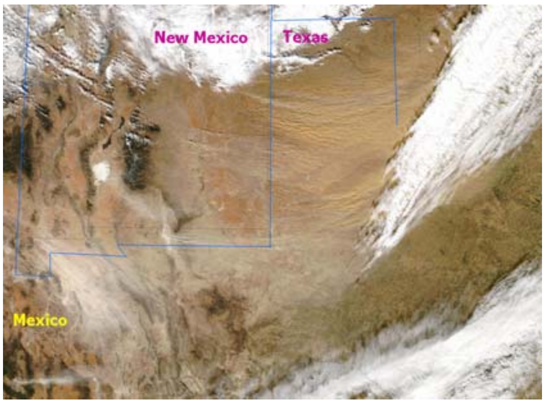

Figure 1. Terra MODIS image of the December 15, 2003 dust storm that swept into the panhandle of Texas. The bright circular spot at left center is White Sands National Monument. Both siliceous and calcareous dust, and their points of origin, are seen clearly in the cloud-free areas.

This set of inputs has been used to model a severe dust event that arose abruptly in Eastern New Mexico and West Texas on December 15, 2003 (Figure 1). A Pacific cold front swept through the region bringing gale force winds and dry conditions, causing one of the worst dust storms in recent years. Since it was installed in 2001, Continuous Air Monitoring Station (CAMS) in Lubbock measured its highest $PM_{2.5}$ one-hour average (485.6 $\mu g/m^3$) between 1300-1400 hrs Central Standard Time. It also measured a daily average $PM_{2.5}$ of 76.7 $\mu g/m^3$. The PM_{10} daily average concentration of 384 $\mu g/m^3$ was estimated to be five times higher, than is considered "healthy" by the U.S. Environmental Protection Agency.

Results of this model run are shown in Figure 2, and are used here as a baseline for DREAM's capability.

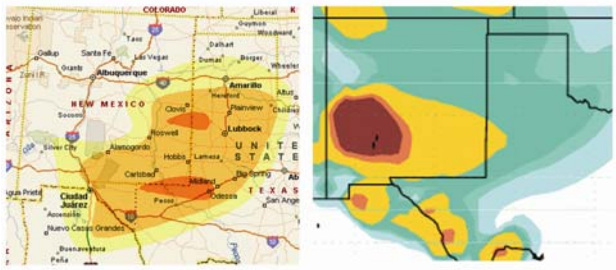

Figure 2. (Left) A geostatistically generated map of visibility classes as recorded at 12:00pm CST by a network of only six $PM_{2.5}$ monitoring stations in the area shown (yellow = < 7 miles, orange = < 3 miles, and red = < 1 mile visibility); (right) The same area as modeled by DREAM, also for conditions at 12:00pm showing six categories of dust loading.

Considering that DREAM was used to model hundreds of weather reporting stations across more than 10° of latitude and 20° of longitude, the output is encouraging. Both outputs in Figure 2 show that a dust event was evolving in southeastern New Mexico, but DREAM fails to show the heavy concentrations of $PM_{2.5}$ already spreading eastward.

3.2 Satellite Data Assimilation into DREAM

Name	Sensor/ Origin	Original Format	Time Period
Leaf area index - LAI	MOD15	HDF	Dec 2003
Land cover - LC	MOD 12	HDF	Dec 2003
Enhanced vegetation indices - EM	MOD 13	HDF	Dec 2003
gclayh – max clay content	STATSGO	Coverage	
gclayl – min clay content	STATSGO	Coverage	
gsurflex – USDA surface texture	STATSGO	Coverage	
gweg – wind erodiblity	STATSGO	Coverage	
Shuttle Radar Topography Mission	Space Shuttle	DTED	Feb 2000

Table 1. Initial products for testing improvements of input parameters for DREAM.

Table 1 is an initial list of products prepared for assimilation into DREAM. These are intended to replace equivalent surface parameters in the baseline version to achieve finer landscape resolution and more dynamic temporal resolution. These products include MODIS (MODs 12, 13, 15) as possible replacements for land cover, coupled with finer resolution on soil texture derived from the U.S. Natural Resources Conservation Service (NRCS) STATSGO. The most difficult parameter to engineer as a replacement has been "z_o", the length associated with surface roughness. The team has tried to derive this value from Shuttle Radar Topography Mission (SRTM) data and from digital elevation data, but are not satisfied yet with either result.

Data assimilation is a multifaceted process, hampered by the general absence of metadata. One must first compare the attributes of existing model inputs and of possible satellite data replacements. Like DREAM, many models currently used for Earth system science were designed without benefit of data sets acquired remotely. Data compatibility issues therefore must be considered including: (a) measurement units, (b) x,y,z resolution, (c) temporal frequency, (d) map projection and ease of re-projection to fit model requirements, (e) file formats, (f) error and error propagation, and (g) validity of the replacement data in terms of enhancing or improving model outputs. Table 1 includes inputs that are direct replacements for baseline data sets, assuming the data are compatible in the model. If yes, then the second and following tasks for assimilation are to iterate the process with different kinds of products and resolutions, and to measure the incremental improvements in model outputs.

In Figure 3, four replacement data sets are visualized. These are: (a) 17 classes of 1x1 km land cover (MOD 12) and (b) 1x1 km leaf area index (MOD 15), both from MODIS Terra; (c) 10m elevation data from SRTM; and, (d) surface soil texture from STATSGO (NRCS).

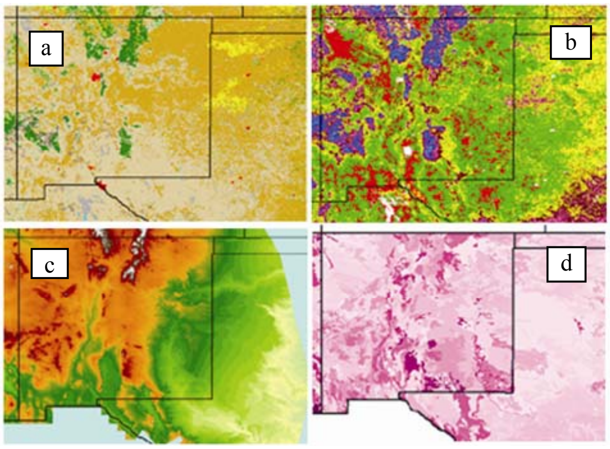

Figure 3. Visualizations of four data sets to replace the baseline DREAM surface data sets.

3.3 Health Data

Health data are being assembled in two ways: (a) a review of the literature on windborne contaminants and health; and (b) a review and analysis of retrospective health data from the panhandle of West Texas.

The aim of the literature survey is to validate that atmospheric dust is coupled to human health in scientifically measurable ways. The review addresses five categories of concern:

- the physical properties of dust storms from a geophysics perspective;
- Aerobiology—how far organisms and chemical compounds are transported on the wind;
- Fungi (including indoor molds and outdoor mycoses) with particular reference to natural histoplasmosis, coccidioidomycosis, and blastomycosis;
- Bacteria, and their ability to be carried by dust; and,
- Chemicals (including human-made, funga, and bacterial toxicants).

Search results have been narrowed to about 950 primary references focused on anthropogenic factors relevant to West Texas and Eastern New Mexico. This region is sparsely populated, which means that land disturbances (like overgrazing, the addition of fertilizers and pesticides, and other practices on the land) lead to industrial and agricultural pollution (e.g., cotton gin dust and aerosolized cattle feed-lot waste) that are aggravated by periods of drought.

Dust from Eastern New Mexico is such a perennial problem in West Texas that validating its medical impacts on populations at risk is a core goal. Records have been kept in West Texas for the past two decades. Over 100,000 records of respiratory illnesses have been drawn from a variety of sources and aggregated to the census block level. These records include detail on asthma, influenza, mortality, behavioural- and risk-factor surveys, clinic files, and hospital discharges. Companion research also is underway in West Texas on the implications of cotton gin dust, cattle feedlot dust, and crop pesticide spraying on human health. Results from all of these should augment understanding of the coupling between atmospheric dust contaminants and human health.

3.4 RSVP Decision Support

At present, science and technology increasingly support the *practice* of medicine; but, appropriate technology for medical *reporting* seems trapped in the paper world of the 20th Century. RSVP is one of several decision support systems aimed at modernizing health care reporting. It is an Internet-based syndromic surveillance system designed to facilitate rapid communication between epidemiologists (public health officials in local jurisdictions) and health care providers (physicians, physician assistants, and nurse practitioners). It is a reporting and discovery system for primary care physicians and clinicians who want to determine if their patient's syndrome has been reported by others in the local or surrounding area. It provides medical and environmental information in a geospatially explicit architecture in three modules: (a) a syndromic information collection module whereby doctors can submit an inquiry, (b) a communication module whereby a public health official can respond to an inquiry; and, (c) a data visualization module that permits both parties to review collective inputs in the medical and geographic domains.

The prototype system has been successfully beta-tested for six syndromes in several states in the U.S.A. and internationally (Singapore), and has on-going testing on respiratory syndromes in Texas. Beta testers have expressed a universal desire for more visualization tools, especially those of a geospatially explicit kind. In response, this project is partnering with developers of RSVP to insert an imagery and geospatial module into which outputs from DREAM can be placed and made available via the Internet. Future design elements include analytical tools like data mining, 3-D visualizations, and disease analysis algorithms; and expanding the range of data types to Internet-based sources for prescriptions, patient complaints, and lab results (all on a patient confidential basis).

3.5 Early Results

A point-by-point comparison between *in-situ* observations and baseline model output has been performed across reporting stations from Santa Fe in central New Mexico to South Padre Island on the Texas Gulf Coast for the two-day dust event of December 15-16, 2003. Three comparisons were made: (a) magnitude (highest 1-hour mean $PM_{2.5}$ $\mu g/m^3$); (b) peak hour (the UTC time the 1-hour peak $PM_{2.5}$ occurred); and (c) duration (the length of exposure to $PM_{2.5} \geq 65\mu g/m^3$).

Figure 4 (a-b) shows results from these comparisons. At some reporting stations (Figure 4-a), it appears the model overestimated the magnitude of the highest 1-hour average $PM_{2.5}$ during the early stages of the episode, and underestimated the concentrations during the later stages, sometimes by an order-of-magnitude. The correlation coefficient for all data from 40 sites for the UTC Peak hour was $r^2 = 0.60$ (Figure 4-b), indicating that the model performed only moderately well forecasting the time of heaviest dust concentration. However, there is solid evidence that the model performed very well ($r^2 = 0.96$) for stations in central and east Texas, as the storm progressed southeastward toward the Gulf of Mexico. For all reporting stations, the peak $PM_{2.5}$ concentrations lasted for only a few hours, and only one station exceeded the National Ambient Air Quality Standard of $65\mu g/m^3$ (Lubbock, $76.7\mu g/m^3$). The model tends to over-estimate the duration at most sites.

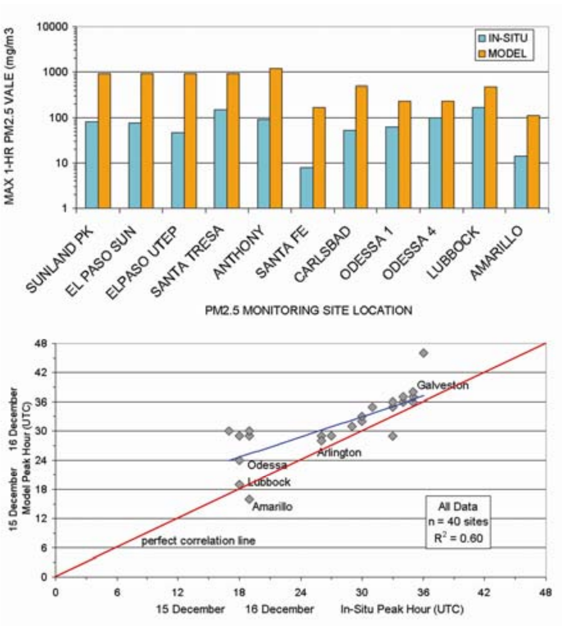

Figure 4 (top) Magnitude of the highest 1-hour $PM_{2.5}$ for 11 stations in eastern New Mexico and West Texas; (bottom) Correlation of occurrence of UTC peak hour.

Figure 5 is a comparison of modelled dust concentrations with measured visibility from reporting stations in the region. It appears that DREAM successfully predicted the meteorological field with regard to the patterns and values at individual sites. Further, time series comparison of radiosonde versus modelled profiles of wind speed, direction, temperature and specific humidity show good statistical agreement, though at heights above 20,000 meters, the model shows considerable scatter for wind speed and direction.

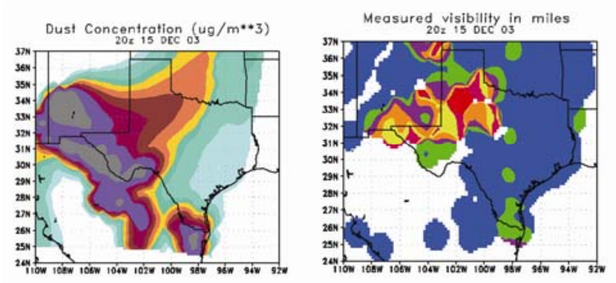

Figure 5. (left) Modeled dust pattern and concentrations; (right) measured visibility at weather reporting stations in the same region.

While DREAM performs well with predicting meteorological patterns, it has mixed performance predicting the onset of dust events. The team hopes to improve this performance by deriving a better estimate of aerodynamic surface roughness length (z_0) through remote sensing. Understanding and measuring this parameter is crucial for understanding surface friction and the ability of wind to lift dust from a surface.

The project team is convinced from these early results that there is ample room for improving the model with better resolution data for surface parameters. Future reports will document the incremental improvements to DREAM and RSVP. Hopefully, these reports also will document the medical impacts of atmospheric dust events.

4. SUMMARY

Coupling biogeochemical processes that lift dust into the atmosphere with the ecology of airborne pathogens will allow epidemiologists to better understand the medical consequences of dust transport across regions and continents Through Internet- and Intranet-accessible syndromic surveillance and reporting systems, medical professionals someday will better diagnose individual patient symptoms in a geospatial context for early warning of disease outbreaks and deteriorating environmental conditions that put populations at risk. The role dust storms play in human health is an important part of Earth system science that has fundamental socioeconomic and political importance.

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