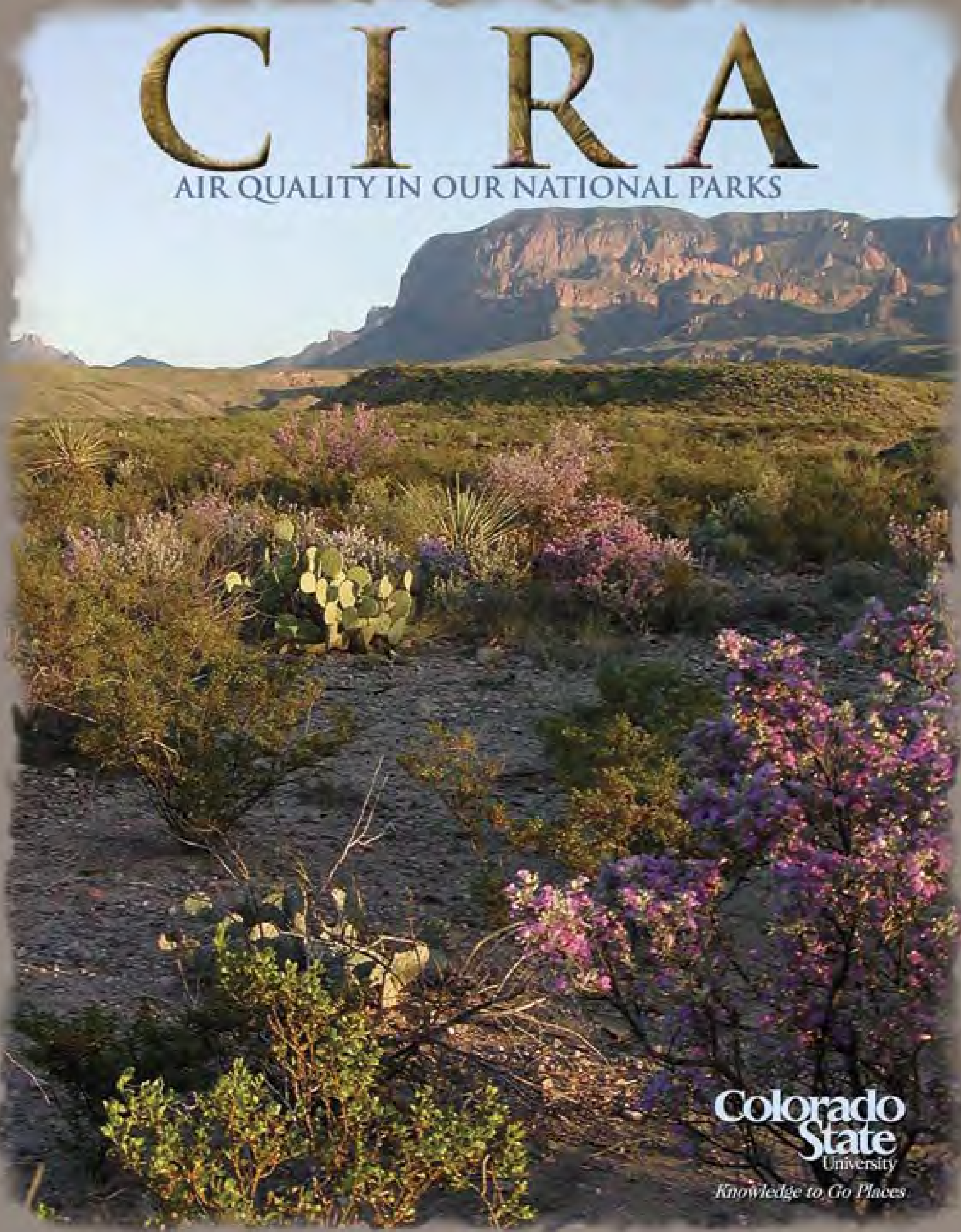
CIRA

AIR QUALITY IN OUR NATIONAL PARKS



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Contents

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Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study Results

Doug Fox, Bret Schichtel, Mike Barna, Kristi Gebhart, Bill Malm

Big Bend National Park is located in southwestern Texas along the Mexican-Texas border (Figure 1). During the 1990s, increased haze at Big Bend obscured Big Bend's and the region's scenic beauty and challenged the Regional Haze regulations designed to eliminate human-caused haze in Big Bend and 155 other National Parks and Wildernesses around the U.S.

Figure 1. A terrain map of Texas and Mexico as well as some major cites and points of interest to the BRAVO study.

The Big Bend Regional Aerosol and Visibility Observational (BRAVO) study, an intensive monitoring program sampling aerosol physical, chemical and optical properties, including special atmospheric tracers, was conducted from July-October 1999. The monitoring was followed by a multi-year assessment to identify haze sources and to learn about the chemical, physical, and optical properties of aerosols responsible for the Big Bend NP haze. Study participants included the National Park Service (NPS), the U.S. Environmental Protection Agency (EPA), the Texas Commission on Environmental Quality (TCEQ), and the Electric Power Research Institute (EPRI), among others.

In support of BRAVO, NPS and CIRA scientists analyzed the measured aerosol data and conducted qualitative and quantitative haze source apportionment analyses. All source apportionment techniques went through extensive validation and evaluation tests and only those techniques which passed these tests were applied to Big Bend's haze. In addition to the analysis of the BRAVO study data, long-term Big Bend air quality and meteorological data were analyzed to determine the representativeness of the BRAVO time period to other seasons and years.

In this article, key findings from the analyses and their implications concerning Big Bend's haze with a focus on the apportionment of particulate sulfate are presented. This paper is adopted from the Executive Summary of the BRAVO technical report where more details can be found (BRAVO Study Results: Air Quality Data and Source

(continued on page 4)

Fellowships in Atmospheric Science and Related Research

The Cooperative Institute for Research in the Atmosphere at Colorado State University (CIRA) offers a limited number of one-year Associate Fellowships to research scientists including those on sabbatical leave or recent Ph.D. recipients. Those receiving the awards will pursue their own research programs, collaborate with existing programs, and participate in Institute seminars and functions. Selection is based on the likelihood of an active exchange of ideas between the Fellows, the National Oceanic and Atmospheric Administration, Colorado State University, and CIRA scientists. Salary is negotiable based on experience, qualifications, and funding support. The program is open to scientists of all countries. Submitted applications should include a curriculum vitae, publications list, brief outline of the intended research, a statement of estimated research support needs, and names and addresses of three professional references.

CIRA is jointly sponsored by Colorado State University and the National Oceanic and Atmospheric Administration. Colorado State University is an equal opportunity employer and complies with all Federal and Colorado State laws, regulations, and executive orders regarding affirmative action requirements. In order to assist Colorado State University in meeting its affirmative action responsibilities, ethnic minorities, women and other protected class members are encouraged to apply and to so identify themselves. The office of Equal Opportunity is in Room 101, Student Services Building.

Senior scientists and qualified scientists from foreign countries are encouraged to apply and to combine the CIRA stipend with support they receive from other sources. Applications for positions which begin January 1 are accepted until the prior October 31 and should be sent via **electronic** means only to: Professor Thomas H. Vonder Haar, Director CIRA, Colorado State University, humanresources@cira.colostate.edu. Research Fellowships are available in the areas of: **Air Quality, Cloud Physics, Mesoscale Studies and Forecasting, Satellite Applications, Climate Studies, Model Evaluation, Economic and Societal Aspects of Weather and Climate.** For more information visit www.cira.colostate.edu.

Attribution Analyses Results from the National Park Service / Cooperative Institute for Research in the Atmosphere. Schichtel, B.A. and others. CIRA report ISSN 0737-5352-65. 2004.)

Characterization of Big Bend's Haze

Haze is caused by the scattering and absorption of light by suspended fine liquid or solid particles in ambient air, known collectively as atmospheric aerosol. The sum of the light scattering and absorption is known as light extinction, and can be thought of as the fraction of light lost per unit of distance. The units of light extinction are inverse distance, e.g., 1/million meters or Mm^{-1}. Higher light extinction levels correspond to hazier conditions.

Detailed particle size and chemical composition measurements made at Big Bend during the BRAVO study were used to develop advanced estimates for each day's contributions to light extinction by the major aerosol components. These compare well to direct optical measurements of light scattering and light extinction. Figure 2 shows the daily particulate light extinction (sum of light scattering and absorption) contributions by the major aerosol components. As shown, there is a distinct difference in the particulate extinction budget in the first and second half of the BRAVO study. From July 1-August 15, the light extinction is primarily due to ammoniated sulfates (35%), organics (20%), and coarse mass (30%). In the second half of the study, post-August 15, the ammoniated sulfates account for 50% of the particulate extinction while organics and coarse mass each account for about 20%. On the haziest 1/5th of the days, a measure relevant for the Regional Haze Regulations, sulfate compounds accounted for about 55% of the particulate b_{ext} and organics 15%.

The BRAVO study period can be put into a larger climatological context by examining Big Bend's extinction budget over a long period of time. Figure 3 shows the five-year (1998 through 2002) light extinction budget from measurements made every three days at Big Bend National Park in the IMPROVE monitoring network. In general, there are two periods of high haze at Big Bend National Park – one in the spring when particulate sulfate and carbonaceous compounds contribute equal amounts to haze, and another in late-summer/fall when particulate sulfate compounds are the largest contributors to haze. As in the BRAVO period, the particulate sulfate compounds usually contribute more to haze than any other individual aerosol component. Carbonaceous particulate matter – organic compounds and light absorbing carbon (LAC) – generally constitute the second largest individual aerosol component contributing to haze at Big Bend NP, and on some days are the single largest contributor to haze. Information from other studies shows that during late spring episodes, concentrations of carbonaceous compounds are increased due to biomass burning in Mexico and Central America. Dust, represented by a combination of fine soil and coarse mass, contributes as much to haze as particulate sulfate compounds during the months of March and April.

On average, sulfate compounds contribute more to light extinction on the haziest days (53%) than for average days (48%). The contribution of carbonaceous (i.e., organic and light absorbing carbon) compounds to light extinction remained about the same: 23% on average on the haziest days. Coarse mass

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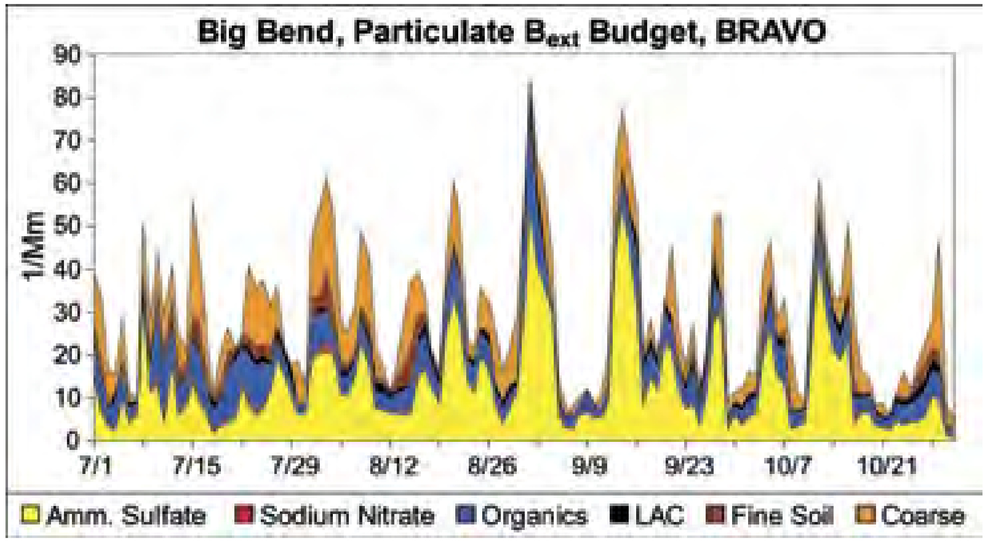
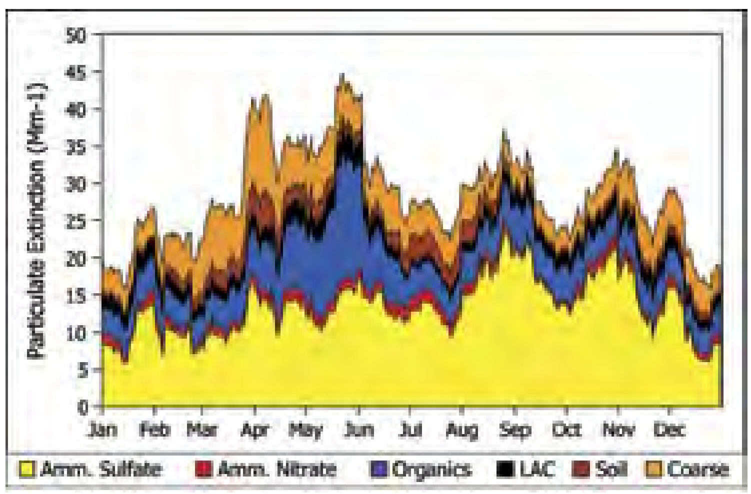


Figure 2. Big Bend's particulate light extinction budget during BRAVO.

Big Bend Extinction Budget (1998-2002)

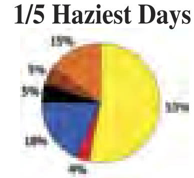


Overall

All Days

Part. b_{ext} = 28.8 Mm^{-1}

1/5 Haziest Days



Part b_{ext} = 54.4 Mm^{-1}

Figure 3. Big Bend National Park five-year light extinction budget. All days with that fall on the same day of the year were averaged together, then the data were smoothed using a 15-day moving average.

is also a major contributor to the particulate light extinction accounting for about 17% on average days and 15% on the haziest days. Since the sulfates accounted for more than half of the particulate extinction on the highest haze days, the lower contribution of organics and the fact that they have a potentially large contribution from smoke and other natural sources lead us to focus on understanding the source attribution of sulfate.

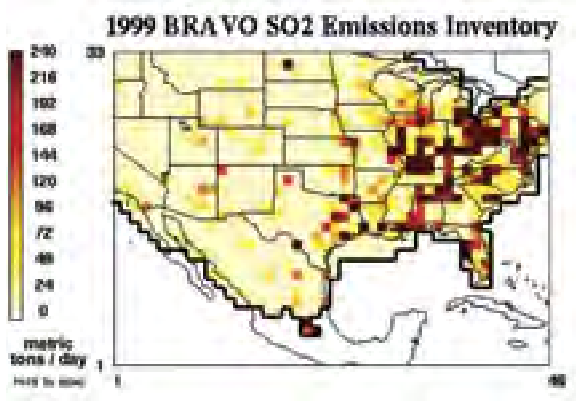


Figure 4. SO_2 emissions based on the 1999 BRAVO emissions inventory used in the REMSAD and CMAQ-MADRID modeling. No emissions were included beyond the black outline shown in the figure. Mexico City and Popocatepetl volcano emissions are located in the three most southern emission grid cells.

Apportionment of Big Bend's Sulfate Haze

Ambient particulate sulfate compounds originate from direct emissions of sulfate (primary sulfate) or are produced by chemical transformation (oxidation) of SO_2 emissions in the atmosphere (secondary sulfate). Secondary sulfates constitute most of the particulate sulfate compounds measured at ambient monitoring sites, such as Big Bend National Park. The extent of the oxidation of SO_2 to secondary sulfate depends on the oxidative capacity of the atmosphere, which is influenced in large part by nitrogen oxides (NO_x) and volatile organic carbon emissions. Oxidation of SO_2 to sulfate can be slow, often requiring one to two days to convert about half of the SO_2 to particulate sulfate compounds. However, transformation can occur much more rapidly, from hours to minutes, in the presence of mists, fog, and clouds. Meanwhile, atmospheric dispersion and deposition processes are reducing the ambient SO_2 and sulfate concentrations. Consequently, it is challenging to establish causal relationships between measured ambient particulate sulfate concentrations and SO_2 emissions sources.

Figure 4 presents the SO_2 emission inventory used in the BRAVO study. Sources outside the modeling domain were accounted for by using a four-month average boundary condition obtained from global model simulations. The largest SO_2 emissions are in the eastern U.S. where about 14 million metric tons per year are emitted. In Texas, approximately 1 million metric tons of SO_2 are emitted each year, almost all in eastern Texas. In the western U.S., emissions are about 1.7 million metric tons per year. In Mexico, SO_2 emissions are estimated to be about 2.5 million metric tons per year, with about 60% contributed by the Popocatepetl Volcano. There are a few high emitting locations in northern Mexico, including the Carbón I & II coal-fired power plants located about 200 km east-southeast of Big Bend and at urban and industrial areas near Monterrey in northeastern Mexico.

SO_2 emission inventories in the U.S. are considered to be of a reasonable quality, however, significant uncertainties in the Mexican SO_2 emissions remain. In addition, the Popocatepetl Volcano near Mexico City is the largest single SO_2 emissions source in North America and it has been active for a number of years including during the BRAVO study period. But because of atmospheric flow patterns, it likely had little effect on Big Bend haze during the BRAVO study period.

Airmass Transport to Big Bend during BRAVO Days with High and Low Particulate Sulfate Concentrations

All things being equal, a source region's potential to contribute to haze at Big Bend increases in time periods when air parcels frequently pass over and linger over the source region before transport to Big Bend. These air mass transport characteristics can be estimated from trajectories, where a trajectory gives the estimated location of air parcels every hour prior to being transported to Big Bend. Residence time analysis is used to aggregate the number of air parcels that resided over an area for selected periods of time at Big Bend (e.g., a month) or selected receptor site conditions (e.g., haziest days at Big Bend). This is related to the aggregate of time all trajectories resided over a given area. While the residence time is dependent on airmass transport frequency from a given region to Big Bend and the time it spends over the region, it has been shown that the difference in the residence time from one region to another is primarily dependent on different transport frequencies.

On days with the 20% highest particulate sulfur concentrations during the BRAVO study, air parcels were most likely to have previously resided over northern Mexico, Texas, and the eastern U.S. (Figure 5a). These tended to be low level and low speed air parcels which are conducive to the accumulation of pollutants from sources. In contrast, on days with the 20% lowest particulate sulfate concentrations, air parcels most often originated over northern Mexico and the Gulf of Mexico as well as over the western U.S., and infrequently over eastern Texas or the eastern U.S. (Figure 5b). The transport over Mexico tended to be low level but high speed which is not conducive to the accumulation of emissions into the air parcels.

The examination of transport pathways during individual particulate sulfate episodes showed that there were three common pathways associated with elevated sulfate at Big Bend: from eastern Texas, the southeastern U.S., and northeastern Mexico (Figure 6). The largest concentrations occurred when transport over several of these regions occurred. For example, the September 1 episode had transport over all three regions and had the highest concentrations during the BRAVO study. Elevated sulfate was also associated with prior transport over the Midwest (Missouri, Kentucky, and Tennessee), though this was infrequent and airmasses tended to be elevated and had higher speeds relative to the other three regions.

These results show that the transport from eastern Texas and the southeastern U.S. is associated with elevated sulfate concentrations at Big Bend and not with low sulfate concentrations. These results, combined with the fact that eastern Texas and the Southeast

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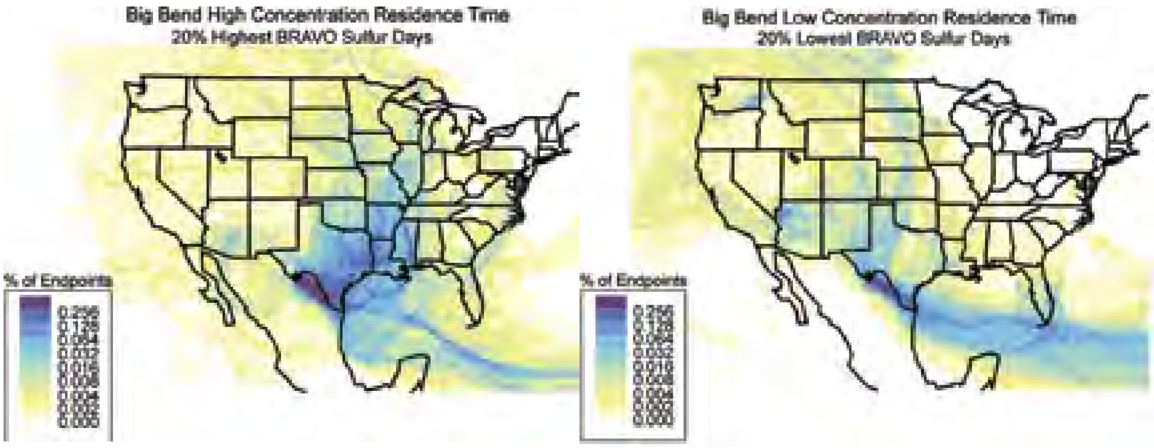

Figure 5. Fraction of time that air parcels spent during ten-day trajectories for periods with the a) 20% highest concentrations of particulate sulfate compounds and b) for the periods with the 20% lowest concentrations of particulate sulfate during the BRAVO study period July through October 1999.

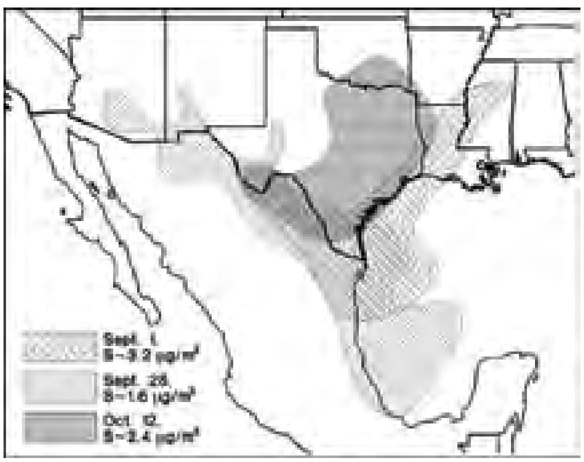

Figure 6. Air mass transport patterns to Big Bend, TX, during three sulfate episodes. Each isopleth shows the most likely pathway the air mass traversed prior to impacting Big Bend.

have high sulfur dioxide emissions, support the notion that these areas contribute to the sulfate concentrations and haze at Big Bend. Transport from Northeastern Mexico appears to be a common pathway during both high and low sulfate days. However, the time air masses spend over northern Mexico prior to reaching Big Bend is greater on the high sulfate days than the low sulfate days. The increased time allows for potentially greater accumulation of SO_2 emissions and for transformation to sulfate.

Quantitative Source Apportionment of Big Bend's Sulfate Haze

NPS/CIRA scientists employed three different methods (receptor-oriented modeling, source-oriented modeling and hybrid modeling combining features from both) to quantify source types (e.g., power plants) and source regions (e.g., Texas, the eastern U.S., the western U.S., and Mexico) that contribute to Big Bend haze.

Air Mass History Based Receptor Models:

These methods developed statistical relationships between the Big Bend particulate sulfate concentrations and airflow before reaching Big Bend. Variations included the use of two estimates of North American wind fields (EDAS from the National Weather Service and MM5 applied specifically for the BRAVO study) and the use of back-trajectories from Big Bend (Trajectory Mass Balance - TrMB), and forward transport and dispersion from all potential source regions (Forward Mass Balance Regression – FMBR).

Regional Air Quality Source Oriented Models:

The REMSAD regional air quality model was used to estimate the effects of transport, dispersion, chemical transformation, and deposition on emissions, thereby predicting particulate sulfate concentrations throughout the modeling domain, including at Big Bend. The difference in predicted concentrations between air quality model prediction with all emissions (base case) and those with emissions for a specific source or source region set to zero (emissions sensitivity case) is interpreted as the particulate sulfate attributed to the specific source or source region.

A second regional air quality model, CMAQ-MADRID was applied by scientists from EPRI and Atmospheric and Environmental Research (AER) in the study. The models were tested against the BRAVO tracer data finding that they could reproduce tracer concentrations within the inherent uncertainty of the tracer data. Both models tended to underestimate particulate sulfate compound concentrations in the first half of the BRAVO study period when sources in Mexico were determined to have the largest contribution and both models tended to overestimate particulate sulfate concentrations when flow was from the eastern U.S.

Hybrid Modeling – Synthesis Inversion Analysis of Air Quality Models: Concerns about possible systematic biases that could be the result of Mexico's SO_2 emissions and/or transformation chemistry biases resulted in the development of a hybrid modeling approach. This approach entailed the development of statistical relationships between the daily source attribution results from REMSAD and CMAQ-MADRID and the measured particulate sulfate concentrations in and around Big Bend. Synthesized CMAQ-MADRID combined with the attribution of Carbon power plants from Synthesized REMSAD provided the best available estimates of the source attribution for particulate sulfate at Big Bend during the BRAVO study period and, henceforth, it is referred to as the BRAVO Estimate.

Figure 7 presents a smoothed daily attribution using the BRAVO Estimate method. The top plot in Figure 7 shows attribution in absolute concentrations for direct comparison to the measured particulate sulfate concentrations, while the bottom plot shows the percent fraction of the predicted amount by each source region. As shown, each source region's contribution to Big Bend particulate sulfate had unique characteristics over the BRAVO study period. Sources in Mexico were the largest contributors to sulfate in

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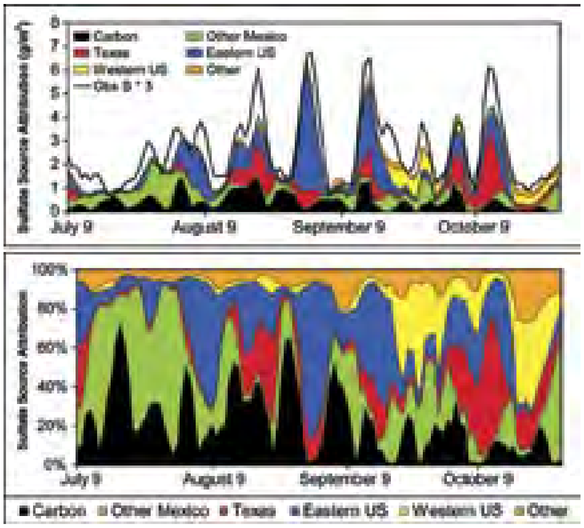

Figure 7. Smoothed daily estimates by source regions to particulate sulfate concentration (top plot) and fraction of total predicted particulate sulfate (bottom plot) at Big Bend during the study period.

July and August, contributing from 0.5 to 1.5 μg/m$_3$ every day. During the largest peak in late July, sources in Mexico contributed to about 2 μg/m^3, constituting about 90% of the modeled particulate sulfate. In September and October contributions by sources in Mexico decreased to less than about 1 μg/m^3. Sources in Texas contributed very little to sulfate concentrations in July, with three episodes in the middle months of the study period having peak values from about 0.8 to 1.5 μg/m^3. During two episodes in October, sources in Texas had peak contributions of about 1.2 to 2.8 μg/m^3 of particulate sulfate and constituted over 60% of the largest peak in October. Sources in the eastern U.S. contributed to sulfate concentrations mostly in the middle two months of the study period with several peak contributions exceeding 1 μg/m^3. The largest of these contributions is greater than 5 μg/m^3 and constitutes about 80% of the largest peak particulate sulfate measured during the BRAVO study period.

The Contribution of Sulfur Source Regions to Particulate Haze Levels at Big Bend National Park during the BRAVO Study Period

Both the fraction of light extinction associated with particulate sulfate (see Figure 2) and the fraction of particulate sulfate attributed to each source region (see Figure 7) varied considerably throughout the BRAVO study period. This information was combined to show variation in the absolute and percent fractional contribution by sulfur source regions to Big Bend light extinction (shown in the top and bottom plots of Figure 8 respectively). Pie diagrams are shown in Figure 9 to illustrate the differences in particulate sulfate contributions by various source regions to light extinction for the study period's 20% haziest days compared to the study period's 20% least hazy days. The numbers of 20% haziest days during each month of the BRAVO study from July through October are 1, 8, 10, and 4, respectively, while the numbers per month for the 20 least hazy days were 3, 1, 10, and 9, respectively.

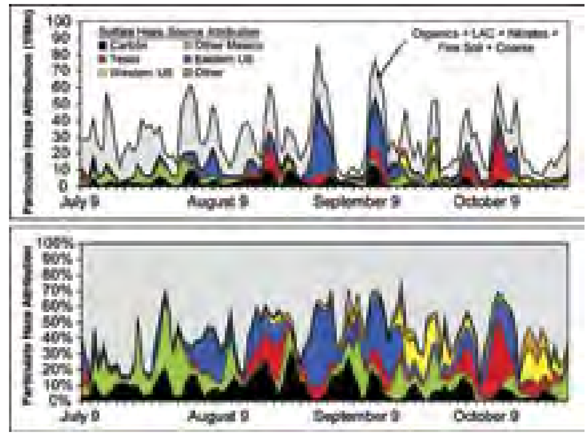

Figure 8. Estimated contributions to particulate haze by various particulate sulfate source regions. The top plot shows the absolute haze contributions by the various particulate sulfate sources as well as the total particulate haze level (black line). The bottom plot shows the fractional contribution to haze by the various sources.

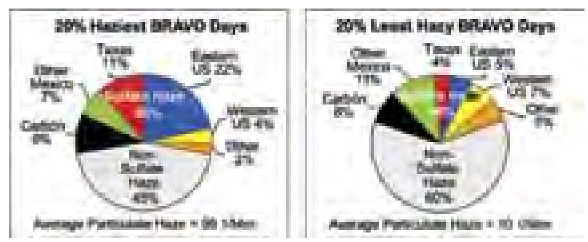

Figure 9. Estimated contributions by particulate sulfate source regions to Big Bend particulate haze levels for the 20% haziest days and the 20% least hazy days of the BRAVO study period.

Application of the Source Attribution Results to Other Months and Years

In order to assess the applicability of haze attribution results for the BRAVO study to other years or other times of year, it is necessary to compare the four-month study period with the same months in other years and with other months of the year. Emissions and meteorology are the two most important factors that influence haze levels. Between 1999 and the present the annual emissions responsible for particulate sulfate concentrations in North America have not appreciably changed (U.S. emissions have decreased about 15%, but less is known about emission trends in Mexico). Seasonal variations in SO_2 emissions and in the SO_2 to particulate sulfate oxidation rate make extrapolations of the BRAVO study results to other months of the year prone to additional uncertainty. One of the most influential meteorological processes affecting the haze at Big Bend is the airflow patterns that determine which potential source regions are upwind of Big Bend. In spite of the uncertainties inherent in such a simple approach, comparisons of the meteorological flow patterns from the residence time analysis were used alone in an attempt to assess the applicability of BRAVO study results to other years and times of year.

During the BRAVO study period, airflow to Big Bend was mostly similar to the airflow conditions during the five-year period. However, in September 1999 there was typically less flow over the eastern U.S. than for the five-year average, implying that the BRAVO results may underestimate the average haze contributions by that region's sources. Furthermore, in October 1999 there was typically more flow over Texas and less flow over Mexico, implying that the average October BRAVO haze contributions may be overestimated for Texas and underestimated for Mexico compared to the five-year average. While the estimated average contributions by these source regions may change, the peak contributions are likely not affected by the atypical frequency of flow.

(continued on page 13)

Heavy Snowfall . . . in the Midst of a Drought

John Weaver

On the morning of 19 March 2003, residents living just east of the Rocky Mountains in north-central Colorado awoke to find themselves buried under two-to-four feet of extremely wet, heavy snow. The snow was so heavy that in Fort Collins alone 37 structures were completely destroyed and more than 200 severely damaged as roofs, walls, and entire buildings collapsed. Had this been a large tornado outbreak, the massive amount of destruction that occurred in dozens of Colorado cities up and down the northern Front Range[1] would have made national news for days. However, other than for a couple of thirty second spots on the networks, very little national attention was given the event. In large part, the lack of interest in the wide ranging impact of this record-breaking snowstorm[2] prevailed locally. Perhaps the explanation lies in the absence of violence that characterized the two-day-plus affair. After all, snow is nothing more than white crystals floating to earth. Ironically, the storm occurred during the worst drought in Colorado history, so most local residents were simply glad to have the moisture.

From a forecast point of view, the storm was not a surprise. The occurrence of a heavy snow event was accurately predicted, as was the fact that the storm would last for at least 48 hours. Computer model guidance correctly indicated that the heavier precipitation would begin over the Front Range on the evening of Monday, 17 March, and continue for at least 48 hours (Figs. 1, 2). The guidance even hinted at two periods of heavier activity. The first would start on the evening of the 17th, and taper off late the next morning. A second round would begin on the late afternoon of the 18th, and continue into the morning of the 19th. That's pretty much what occurred, though the model forecast precipitation amounts were significantly understated for the populated areas along the Front Range corridor (Fig. 2).

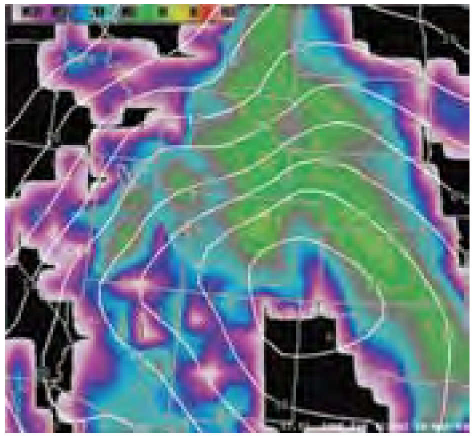

Figure 1. Computer-model output (eta 24-hr, forecast from 12:00 UTC, 17 March 2003) depicting forecast precipitation and surface pressures. The precipitation forecast is for the period 11:00 pm on 17 March through 5:00 am LST on 18 March 2003. The output shows 0.95" of liquid precipitation, or around 10"-12" at the snow: liquid ratios that were expected to occur. The interim, 6-h map (not shown) indicates that the precipitation would be spread evenly over the 12-h period. (1 in = 25.4 mm)

There were misgivings among forecasters as to when (and in some cases whether) the changeover from rain to snow would occur. All of the computer models predicted that the 1000-500 hPa thickness (a measure of the "coldness" of the lower and middle layers of the atmosphere) was theoretically too high (i.e., too warm) to allow frozen snow crystals to reach the ground. In fact, several indicators suggested that snow levels would go no lower than about 6,000 feet (1830 m). The majority of the larger northern Front Range cities are situated about a thousand feet lower than that. Nevertheless, most Colorado forecasters ultimately agreed that diurnal cooling, combined with the cold precipitation, would chill things sufficiently to allow the changeover to occur just after sunset. My own assessment was that the rain would turn to snow around 6:00 pm, with snow totals reaching upwards of 10"-15" (25-38 cm) by the time the storm was over.

A pre-event, light rain, began falling in northern Colorado early on the morning of 17 March (Fig. 3), and continued generally light-to-moderate throughout most of the day. It tapered off completely just before 4:00 pm

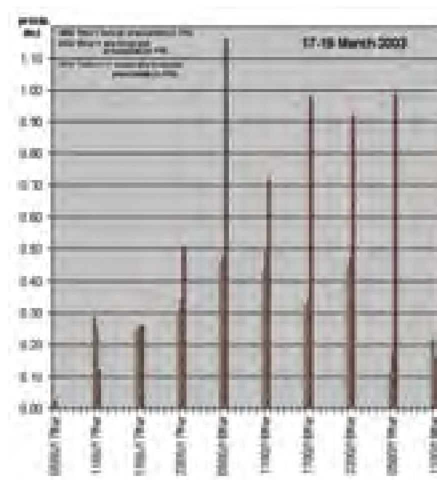

Figure 2. a) Meso-eta model (amounts from the eta-12 km grid output, extrapolated to a 29 km grid increment), and standard 80 km eta model (amounts from the eta-12 km grid output, extrapolated to an 80 km grid) precipitation forecasts (in inches) from the morning of 17 March 2003, plotted in yellow and blue, respectively. Plotted in red are actual liquid-equivalent precipitation amounts in 6-hr increments from observations taken at the Colorado State University Campus in central Fort Collins (FCL). (1 in = 25.4 mm)

(continued on page 9)

[1] The geographical designation "Front Range" refers to the easternmost range of peaks of the Rocky Mountains, but the terms "Front Range," or "Front Range corrid -
ing will apply.

[2] The March 2003 snowstorm has erroneously been called a "blizzard," and there was certainly enough snow involved to qualify. However, to meet the official definition there would have to have been either sustained winds, or frequent gusts, to at least 35 mph (56 km/h) for a significant period of time, and there were not.

Heavy Snowfall *(continued from page 8)*

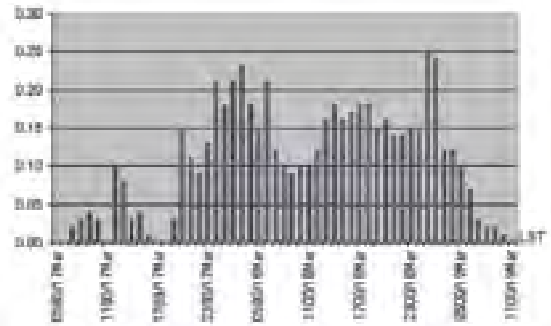

Figure 3. Hourly precipitation (in inches) measured at the Colorado State University site (FCL) in central Fort Collins. Amounts shown are for the hour ending at the times appearing on the abscissa. (1 in = 25.4 mm)

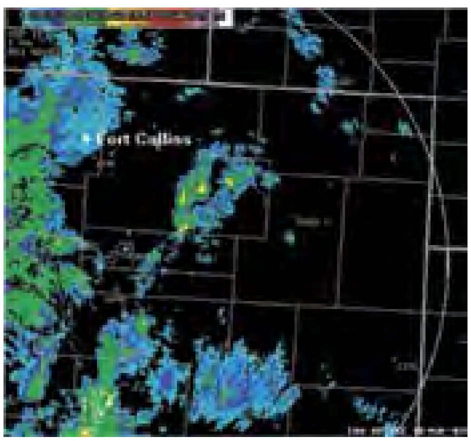

Figure 4. One line of convection moves off to the west of Fort Collins (squall lines were moving westward) as a second line forms to the east. Figure shows the 0.5 degree tilt, PPI reflectivity scan taken from the Denver, Colorado WSR-88D at around 6:00 pm on the evening of 17 March 2003.

local standard time (LST), but showers began again around 7:00 pm, as several north-south-oriented bands of convective precipitation moved across the area from east to west (Fig. 4). The new showers were heavier than those which had occurred earlier (Fig. 2), even producing a small, short-lived tornado about 25 miles (~40 km) east of Denver. However, as dusk transitioned to dark, all of the precipitation on the plains continued to fall as rain. Just fifty miles to the north – across much of southeastern Wyoming – it had been snowing most of the afternoon. This was troubling, since the region where it was snowing is situated at elevations of 6,000 feet, or greater. This is the precise elevation where the models predicted the rain/snow line would be found. As temperatures and dewpoints hovered in the upper 30s (Fahrenheit) throughout northern Colorado, forecasters began to worry about their predictions of heavy snow. Denver television stations had played up the coming winter weather, but by this time there seemed a strong possibility that the official National Weather Service forecast for a 12-20" (~30-50 cm) snowfall could turn to nothing more than 2-3" (~50-75 mm) of cold rain.

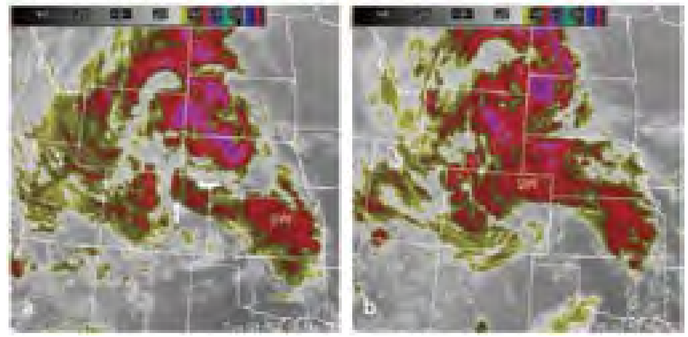

Figure 6. GOES, 10.7 µm infrared window images taken on the evening of 17 Mar 2003. a) image taken at 6:45 pm LST showing infrared view of banded convection in northeastern Colorado (arrows) and approaching shortwave disturbance to the east-southeast, over Kansas (SW), and b) image taken at 10:00 pm LST showing infrared view of shortwave at the time the rain changed over to snow along the Front Range in northern Colorado.

The problem may have been in the anticipated, versus actual, location of key synoptic features. Here, the computer models were only a few miles off, but it was a critical few miles. The eta-model presented a scenario wherein a so-called "warm conveyor belt" (i.e., a warm, moist stream of air being drawn into a developing extratropical cyclone) would move moist air up from the Gulf of Mexico into southeast Wyoming. The developing extratropical cyclone would then wrap heavy precipitation over the top of the cold air, and back into Colorado from the north (recall Fig. 1). GOES satellite imagery showed that the center of the developing system was actually a little further south than expected, and that the warm conveyor belt was feeding directly into northeast Colorado (Fig. 5). By 9:00 pm, as a second line of relatively heavy convective rain moved across the northern Front Range, a failed forecast was beginning to look more and more likely. It was raining steadily – relatively hard at times – but the temperatures and dewpoints were all staying well above freezing.

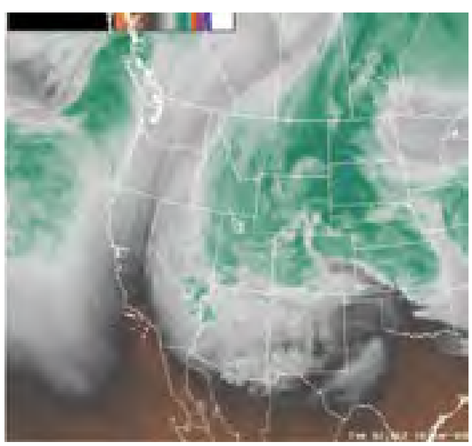

Figure 5 . GOES, 6.7 µm water vapor image taken at 7:45 pm on 17 March 2003. The image shows the moisture associated with the warm conveyor belt stretching from northeastern Oklahoma, across most of Kansas, and westward into northern Colorado. At this time the surface low pressure is moving into southeast Colorado.

Satellite imagery offered a clue that changes were on their way. Figure 6 presents two GOES 10.7 µm images that reveal an enhanced area of colder cloud tops associated with a shortwave trough (marked SW in the figure) approaching from the east. This disturbance didn't arrive along the Front Range until about 10:00 pm LST, but its arrival had a profound effect. It was at that time when most reliable observers at elevations around 5,000 ft. reported a changeover from mostly rain to 100% snow. By this time, FCL (on the Colorado State University campus in central Fort Collins) had reported 0.76" (~19 mm) of rain. There'd been a little ice mixed in with the rain off-and-on throughout the evening, though it all melted on contact. But at 10:00 pm, the changeover took place, and snow began in earnest. By 7:00 am on Tuesday, 6"-12" (15-30 cm) were measured at various locations in Fort Collins, and it

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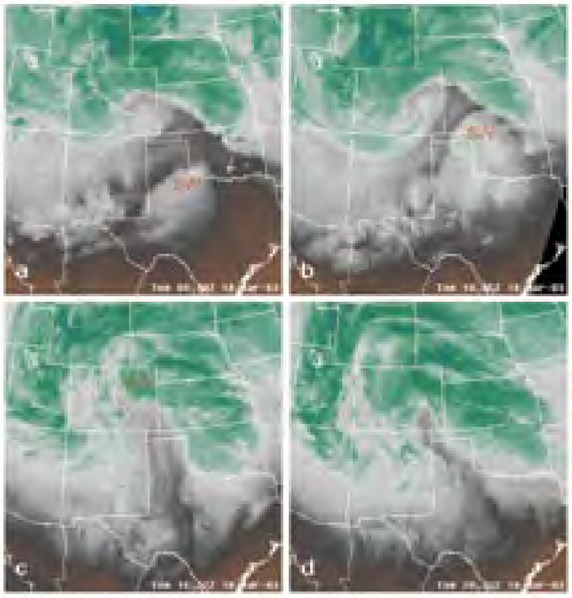


Figure 7. GOES, 6.7 ?m water vapor image taken at a) 9:30 pm on 17 March, b) 3:05 am on 18 March, c) 9:22 am on 18 March, and d) 1:22 pm on 18 March 2003 showing an intensifying shortwave (marked SW in red) as it makes its way around the deepening cyclone which is still centered over southeast Colorado. Snow rates increased dramatically as this feature arrived along the Front Range. Note the expanding warm conveyor belt, especially over Kansas and Oklahoma.

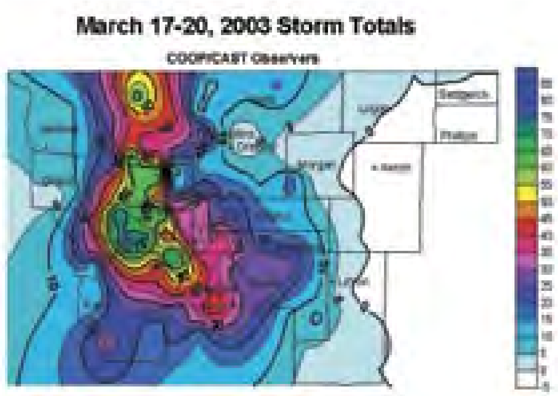


Figure 8. Map showing total snowfall (in inches) for the March 2003 snowstorm in north central Colorado. Observations were collected by National Weather Service (NWS) co-operative observers and members of the Colorado All-Season Spotter Team (CAST) – a volunteer spotter network that provides real-time weather information, year-round, to forecasters at the NWS office in Boulder, Colorado. Map courtesy of the Boulder, Colorado, NWS forecast office. (1 in = 2.54 cm)

was still coming down[3]. The liquid equivalent at FCL (where 8" fell overnight) was 1.5" – yielding a snow/water ratio of about 5:1. Other observers in the region all reported ratios ranging from 5:1 to 7:1. These included several experienced observers who are part of the Colorado Climate Center's CoCo RaHS (Community Collaborative Rain and Hail Study) project. CoCo RaHS is a network of trained volunteers with observers in most of the cities affected by the storm.

The intensity of the snowfall trickled off to less than half an inch per hour over the next four hours, but a second shortwave was rotating around the now extremely robust cyclone (Fig. 7). This second disturbance – accompanied by deeper moisture in a reinvigorated warm conveyor belt – arrived in central Colorado around noon local, and snow rates increased dramatically. This was the beginning of the second, and most persistent, segment of the event. As the hours passed, and the snow continued up and down the Front Range corridor, tree limbs began snapping, wide-expanse roofs bowed downward, and cars on the street morphed into massive white mounds. Heavy snow continued for another 24 hours, with some particularly heavy convective bursts just after midnight on the 19th. When it was over, central Fort Collins had received an additional 24" of snow, and several foothills observers reported more than 40".

By midday on Wednesday, 19 March, north central Colorado was buried (Fig. 8). Roads throughout the region were impassable, and most businesses were closed. The northern Front Range had been hit with its second largest snowfall in the region's history (Wilson 2003), and, according to *Claims* magazine, Colorado sustained the highest nationwide insured losses for the entire first quarter of 2003 as a result. The snow itself was so heavy that municipal snow plows in most cities were at first unable to clear roads. Many plows were damaged while trying. Thousands of residents in Jefferson County (west and southwest of Denver) were trapped in their homes for several days, and deep snow closed the major interstates. Yet – other than for hospitals and emergency responders – no one that I've spoken with locally ever felt any real sense of danger. From a more personal perspective, I certainly didn't feel threatened at any time. The storm, to most, seemed more of an interesting phenomenon – partly fun, and partly an inconvenience. Figures 9 and 10 illustrate the absurdity of the situation. I broke two snow shovels, and finally succeeded in shoveling out my driveway, only to find deep, extremely heavy snow blocking the street. Figure 11 is an example of building damage in Fort Collins. And this was one of the salvageable structures.

CIRA research associates working for the Virtual Institute for Satellite Integration Training (VISIT) have been tasked with developing a winter weather teletraining course for National Weather Service forecasters. The course is meant to focus on satellite imagery as a value-added tool within the short-range forecast/nowcast suite of products. The March 2003 storm is one of the examples chosen for presentation. Two questions concerning the case remain partially unanswered. First, and most important, why was the changeover from rain to snow delayed for so many hours (alternatively, why did it change, at all)? Second, why did precipitation amounts right along the Front Range exceed all of the model forecast values by nearly a factor of two? The solution to neither is trivial. The "late" changeover probably had to do with the fact that northeast Colorado was directly beneath the feed of warm, moist Gulf air aloft. The warmer rain may have been modifying the cold air that was trying to move in from the north. The changeover was probably due to layer lifting (and consequent adiabatic cooling) associated with the arrival of the shortwave disturbance illustrated in Fig. 6. Once the changeover occurred, the colder air from the north gained a foothold, and the precipitation never changed back.

(continued on page 11)

[3] Interestingly enough, this first round of snow didn't present much of a problem for motorists along the urban corridor. In the week prior to the storm, daily high temperatures had ranged in the high 60s to low 70s (F), and the 2" (5 cm) soil temperatures had reached 50°F (10°C) the day before the storm. By early Tuesday morning, however, snow was finally beginning to accumulate on the roads.

Heavy Snowfall *(continued from page 10)*

Figure 9. Now what?! Shoveling the driveway doesn't help very much when the street has nearly thirty inches (~75 cm) of snow blocking it. Photo taken by the author in northeast Fort Collins late on the morning of 19 March 2003.

Thousands of buildings were damaged, and five people were killed. The largest snowstorm in north-central Colorado history occurred on 1-5 December 1913 (Wilson 2003). It dumped 30"-45" of snow onto communities all along the northern Front Range, including Fort Collins and Denver, and that storm was accompanied by strong, gusty winds. It was a true blizzard. Worse, since it occurred near the beginning of winter, the snow was slow to melt off. The aftermath caused serious continuing problems for nearly two months.

The March 2003 snowstorm would certainly be classified as an extreme event anywhere in the country. A three-foot-deep, one-foot-square column of snow, at a snow-to-water ratio of 5:1 to 7:1, weighs from 27-38 pounds (12 - 17 kg). Putting that much weight on every square foot of a wide-expanse roof challenges even the most advanced engineering. As a witness to the event, I find it surprising that more structures

(continued on page 13)

It is likely that model underestimates of precipitation amounts just east of the foothills are directly related to local topography. The excessive precipitation in this region most probably resulted from a locally deepened boundary layer associated with cold air damming along eastern slopes of the Front Range – a phenomenon that occurs regularly in upslope precipitation situations (Richwien 1980, Gage and Nastrom 1985, Dunn 1987, or Wesley et al. 1990). The "piling up" of cold, moist air serves to extend the effect of the foothills several miles eastward. In Weld County – whose western border is just a few miles east of the mountains – both snow and liquid precipitation totals were closer to the model-predicted values. For the VISIT training, that aspect of the case will be heavily emphasized when the session participants include offices near mountainous terrain.

The March 2003 snowstorm was a wonderful example of the extreme weather events that occur frequently on the High Plains of the United States. The average annual precipitation along most of the Front Range corridor runs around 15" (~380 mm) per year, yet exceptionally heavy precipitation occurs somewhere in the region nearly every season. The most notable event for the City of Fort Collins was a flash flood which took place on the evening of 28 July 1997 (Petersen et al. 1999). That remarkable weather system dropped 14.5" (~370 mm) of rain onto portions of the urban area in less than 30 hours; 10.5" (267 mm) fell in just over five.

Figure 10. Ironically, the athletic fields at Colorado State University had been closed until the Fall term due to drought conditions. Watering restrictions made it impossible to revitalize the dry, brittle grass. This photo of a six-foot sign was taken on the morning of 19 March 2003. Photo courtesy of Stacey Seseske (NOAA/FSL), former CSU graduate student.

Comparing Two Storms

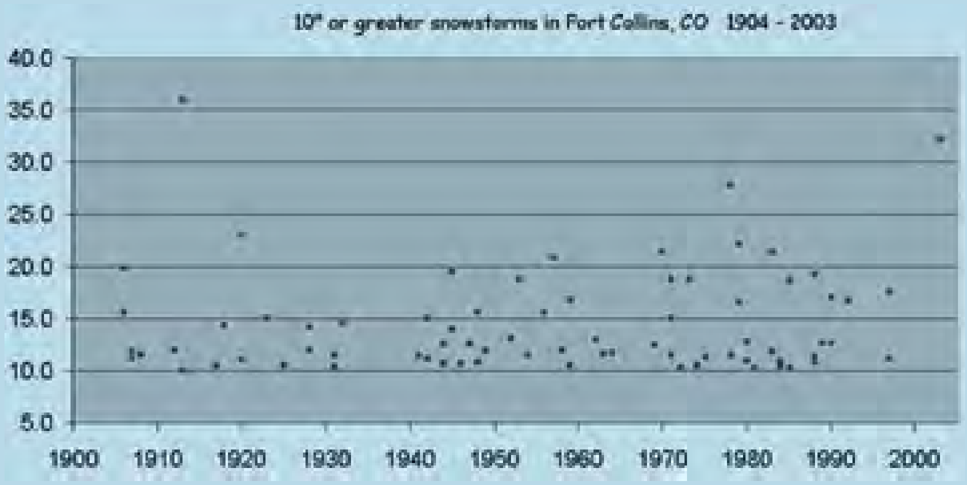
Not only did the all-time record blizzard of 1-5 December 1913 produce more total snowfall over a slightly larger area than did the 2003 storm, but it also occurred at the beginning of the cold season instead of near its end. According to Wilson (2003), persistent cold following the December 1913 storm caused deep snow to linger well into the following year. Its effects were adversely affecting various aspects of life in Denver well into February of 1914. The deep snow associated with the 2003 event, coming as it did at the beginning of spring, disappeared quickly.

Within a week, most of the snow along the Front Range was gone. The quick melt-off is evident in the two visible wavelength satellite images taken one week apart. On the left is a GOES-12 visible image taken at 17:45 UTC on 20 March 2003 showing snow cover along the eastern Front Range of Colorado the day after the storm. A cloud field covers extreme northeast portions of the state. On the right is a GOES-12 visible image taken at 15:45 UTC on 26 March 2003. More than 80% of the snow cover along the Front Range has vanished.

What Constitutes the "Worst Storm?"

It is nearly impossible to rank snowstorms in any general way, simply because there are so many ways to do it. Trying to assess a storm's intensity in terms of so-called human impact is a serious challenge. For example, you might decide to compare storm-related deaths/injuries as a measure of severity, but this would lead to a long series of questions. One would need to consider differing and/or changing population densities, time of day that the storm hits (nowadays, a one foot snow during rush-hour would have much more impact than the same storm in the middle of the night), available communications technology, response and rescue resources, and many others. Dollar damage assessment might be another part of the equation, but then one would have to consider such variables as inflation, differing/changing building codes, the size of the urbanized area affected, and so on.

Making comparisons based on objective weather variables might (at least at first glance) seem a better approach, but in this arena the problems can be even more complex. Is a two-foot snow, at a 20:1 snow-to-water ratio, "worse" than a one-foot snow at a heavier, 5:1 ratio? Should one simply consider the greatest snow depths reported for large storms, or should the assessment include the size of the total area affected? Is one storm "worse" than another if it is followed by a period of very cold weather that causes snow to linger an inordinate amount of time, instead of melting away quickly? Would a one-foot snow, accompanied by strong winds and six-foot drifts, be "worse" than a three-foot snow with modest winds and small drifts?



What constitutes a single "storm?" Should a break in snowfall of some arbitrary length of time suffice to represent the "end" of one storm, and the beginning of another? Should meteorologists make the determination based on whether a restart of snowfall is part of the same weather system?

Some climatologists contend that the snowstorm which occurred during the first week in December 1913 was actually two separate events. Snow fell on the 1st and 2nd, then there was a period on the morning of the 3rd where the precipitation stopped entirely. By this time there was 16.5" (42 cm) of new snow on the ground in Fort Collins. Light snow began again late in the day, and continued to increase until it became heavy on the 4th and 5th. By the time the five day period was over, a total of 36" (91 cm) had fallen. Looking back at the crude surface maps available for 1913, my guess is that both snows were part of the same low pressure system that moved up from the southwest. It's a judgment call, but in the point-data shown below, I've chosen to classify the entire five day event as a single storm. My criteria, for this case and a few others, was as follows: 1) if there were two or three consecutive days upon which similar amounts of snow fell (within the same order of magnitude), I would classify these days as a single event, and 2) if there were *more* than three days in a row with snow, then I would try to find maps that would confirm or deny a "single storm" interpretation. There were only five cases in category (2), and none seemed ambiguous.

The graph below shows snowstorms which produced 10" (25 cm), or greater, snowfall in Fort Collins over the period 1904 through 2003. Of the one hundred years compiled, 49 had at least one such event, and several produced deep snow events. The months in which double-digit snowstorms occurred were as follows: March (17 times), April (15), December (10), November (9), February (8), January (7), October (5), May (2), and September (1). The graph clearly shows that, for Fort Collins, the March 2003 snowstorm (32.2", or 82 cm) was second only to the blizzard of 1913 (36.0", or 91 cm). The third greatest total shown on the graph occurred in early May 1978, when a total of 27.8" (71 cm) was recorded.

Heavy Snowfall *(continued from page 11)*

Figure 11. Collapsed roof of the large Bed, Bath, and Beyond store on south College Avenue in Ft. Collins, CO. The roof on this structure was replaced and the store re-opened several months later. Photo courtesy of Ron Phillips, City of Fort Collins.

weren't damaged. It was a large and quietly-ferocious beast.

But another way to look at it is to remember that the March 2003 snowstorm brought 5" (~127 mm), or more, of welcome precipitation to large portions of a drought parched state, and may have represented the first glimmers of hope for an end to Colorado's long and deadly drought.

Acknowledgments

The author would like to express his thanks to Drs. Mark DeMaria and Don Hillger (NOAA/CIRA), Dr. John Knaff (CIRA), Dr. Roger Pielke and Mr. Nolan Doesken (Colorado Climate Center), and Mr. Robert Glancy (NWS forecast office, Boulder, CO). When writing informally there is a tendency to be a little more relaxed than when writing for a refereed journal. These folks not only kept me honest, but also helped make the piece a little more interesting with a number of valuable suggestions. Chad Gimmestad of the NWS forecast office in Boulder, CO went out of his way to provide model output data that we'd overlooked when we assembled the data set for the case here at CIRA. Finally, I'd like to thank Ms. Odie Bliss of the Colorado Climate Center, without whose help none of the fascinating statistics presented herein would have been available.

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Implications

There is no single answer to the question of what sources are responsible for the haze at Big Bend National Park. Sources in both the U.S. and Mexico have been found to be responsible. Mexican SO_2 emissions contribute to the sulfate haze most frequently, but the haziest events that occur in the late summer and fall include contributions from Texas and the eastern U.S. The largest single contribution to haze is from the Carbon power plant in northern Mexico. Substantial reductions of that facility's emissions would likely result in small but noticeable improvements in Big Bend haze on many days, but it would not make much difference to the worst haze episodes during late summer and early fall. SO_2 emission reductions in both Texas and the eastern U.S would likely reduce the worst haze episodes during the late summer and fall. Emission reductions southeast of Big Bend on both sides of the Rio Grande River have a potential to reduce haze at Big Bend during the June through September period when transport from this region is most frequent.

The clearest days at Big Bend have low sulfate concentrations. The visual scene on a clear day is more sensitive to small changes in haze than a hazy (or moderately hazy) day. On these clear days, the Carbon I & II power plants and other sources in northeast Mexico appear to be the largest contributors to Big Bend's sulfate haze. Thus, reduction in emissions from Carbon would likely result in creating more clear days. However, growth along this border region will probably further reduce the number of clear days.

CIRA Communiqué: Employee News

2004 CIRA Research Initiative Award Recipients

This year, CIRA was proud to announce a new group of CIRA Research Initiative Award winners. Michael Hiatt, CIRA Research Infrastructure Group Manager, won in recognition of his "outside-the-box" thinking in creatively managing CIRA's infrastructure. And the GLOBE group was recognized for their exceptional work in supporting the GLOBE Program through its growth spurts and changing needs. A more complete description of each of the winners' outstanding achievements follows.

The CIRA GLOBE Systems Team consistently demonstrated exceptional initiative throughout its involvement with the GLOBE Program. Team members **Travis Andersen, Matt Hansen, Mike Leon, Karen Milberger, Maureen Murray, Dave Salisbury, Mike Turpin,** and **Ali Zimmerman** were honored with a research initiative award for their many accomplishments.

Beginning with the Program's initial deployment in 1995, the Team assumed ever-increasing responsibilities as the Program increased from 500 U.S. schools at its inception to more than 15,000 participating schools in 106 countries in 2004. The Team designed, developed, and implemented the GLOBE interactive website comprised of more than 1500 pages, the central database containing more than a million observations, and all of the key data distribution functions. Their dedication and innovative efforts culminated this past year in the Team's acceptance of a large number of new responsibilities to support the transition of the Program from NASA to the new UCAR/CSU management team. The most challenging of these new responsibilities was assuming control of the NASA/GSFC GLOBE visualization software, comprised of thousands of lines of "home-grown" computer code. In addition to all of the hardware and software issues related to the transition, the team worked long hours to accommodate more than 10 new GLOBE protocols – including arctic bird migration, fire fuel, macroinvertebrates, and seaweed reproduction. Together with these new protocols came the release of a new electronic version of the GLOBE Teacher's Guide, new data entry pages, new email data entry code, and many modifications to the database to accommodate the new parameters. In addition to these development tasks, the Team also assumed responsibility for training new GLOBE staff members on the use of the Help Desk user interface and the GLOBE website administrative pages and web tools.

GLOBE Team winners: Karen Milberger (top) and Maureen Murray (middle) were unable to attend the award presentation. Above: (l to r) Mike Leon, Ali Zimmerman, Dave Salisbury, Mike Turpin, Matt Hansen, Travis Andersen.

In summary, the GLOBE Team consistently employed many new innovative techniques and technologies in all of their development endeavors. Their accomplishments over the years have played a large and critical role in the success of this ever-expanding international science education program.

On October 4, 2004, Mr. Sean O'Keefe, Administrator of the National Aeronautics and Space Administration (NASA) and Mr. Yannick d'Escatha, President of the Centre National D'Etudes Spatiales (CNES) signed an agreement making France an official partner in the GLOBE program. The announcement came during a ceremony held in conjunction with the International Astronautical Congress in Vancouver, British Columbia, Canada, and makes France the 107th country to participate in this effort.

An Individual award was presented to **Michael Hiatt**, CIRA Research Infrastructure Group Manager. Michael's continuing creativity and initiative have been critical to CIRA's long-standing success in atmospheric research. Michael has single-handedly managed and developed the infrastructure upon which all research and administrator efforts depend. Michael's contributions have improved the efficiency of CIRA researchers as well as made resources available (data and computational systems) at a level usually associated with institutions many times larger than CIRA. Some of his recent achievements are as follows:

(continued on page 15)

Michael Hiatt

1. Michael developed a DVD-based archive system which went into operation in December 2003. His new system has further reduced the cost per gigabyte for our satellite data storage activities by better than 50%. Additionally, the data availability of this random-access system far surpasses the utility of older tape-based systems for our researchers.
2. Michael has implemented a new MSG Earthstation. In this instance a portion of the system was purchased off-the-shelf but his improvements in data compression and hands-off system monitoring have made the system one of the first to begin the actual archival activities.
3. During the last year, the University and the computer user communities have undergone massive worm and virus attacks. Michael's work on firewalls and up-to-date inoculation systems has minimized the impacts of these national-level problems.

Prior to 2003, Michael also instituted several other noteworthy actions that have improved CIRA's infrastructure to the benefit of all our research projects. Among these is a build-your-own strategy for computers (saving CIRA money by upgrading rather than replacing computer systems), tight management of LAN, e-mail, earth station, and computer system's configurations (producing the most cost effective support possible), an automated data library/retrieval system, a custom-designed hardware component for CIRA's upcoming CloudSat Data Processing Center, an innovative video camera/tape system to monitor building security (Michael engineered a motion-sensing algorithm for the web-cam-based system that reduced the overhead so much that all entrances are now covered throughout the Atmos/CIRA complex), and the quality of our satellite data (dropouts, noise etc.) has vastly improved due to Michael's improved architecture and the judicious selection of high quality components where necessary.

In short, Michael Hiatt's work has been both highly creative and more importantly, responsive to CIRA's needs. Michael's work has been singled out by other University departments and NASA/JPL as exceptional.

FSL Team Member of the Month – September 2004

Sher Schranz

Sher Schranz, Technology Outreach Division/FX-Net Program Manager, was selected as FSL's Team Member of the Month for September 2004. Sher received this recognition for outstanding efforts in furthering the utility of the FX-Net technology. Since transferring to TOD about a year ago, Sher has provided strong leadership in the creation of new features in FX-Net and has worked to establish contacts and projects with new air quality customers. She is also applauded for expanding support for the National Interagency Fire Center.

Aviation Meteorology Award

The National Weather Association announced that their Aviation Meteorology Award goes to the Fort Worth, Texas CWSU staff and the FSL Aviation Division for "exceptional sustained efforts to develop and implement operational enhancements in the area of aviation services." CIRA members sharing the award in the Aviation Division's Aviation Systems – Development and Deployment Branch include Jim Frimel, Lisa Gifford, and Young Chun. Congratulations to Jim, Lisa and Young for the well-deserved recognition!

Jim Frimel

Lisa Gifford

Young Chun

(continued on page 16

Science Teacher Receives CIRA Grant

by Margi Cech and Nolan Doesken

Joe Willey, a middle school teacher from the panhandle of Texas, recently spent two weeks in Colorado developing weather related educational resources for teachers. A grant from the Cooperative Institute for Research in the Atmosphere allowed Joe to team up with atmospheric scientists working with the Community Collaborative Rain and Hail Study – CoCo RaHS.

Joe developed an interest in weather while growing up as the son of a Strattford, Texas farmer. He vividly remembers sitting on a tractor watching his cousin's barn get blown away by a tornado. It didn't scare him; it fascinated him. After high school, Joe joined the Army, completed Signal School and worked with a radar installation in Ethiopia. After a few years of civilian work, Joe went back to school and got his Bachelor's Degree in Science Education and a Master's degree in Natural Science. He has translated his love for Meteorology into a 17-year career teaching 8th grade Earth Science at Tulia Junior High School in Tulia, Texas where he also serves as Head of the Science Department.

Mr. Joe Willey cheerfully checks the raingauge.

As a result of a CIRA grant, Joe spent 2 weeks this summer working with Nolan Doesken and other CoCoRaHS staff members to review and produce educational materials that can be easily included in teachers' weather-related curriculum. Joe's passion for the weather has caused him to challenge students and teachers alike: "Tell me a subject that doesn't somehow include or relate to the weather. When one teacher suggested choir, I replied, 'How about Singing in the Rain, Raindrops Keep Falling on My Head, or Stormy Weather?' In all my years teaching, no one yet has been able to come up with a subject that I can't find some way to include weather!"

In pursuing continuing education in meteorology, Joe has attended the Earthworks program for earth science teachers sponsored by the Cooperative Institute for Research in Environmental Science at the University of Colorado. That is where he first connected with Nolan Doesken and CSU's CoCo RaHS project. Joe has also completed both the DataStreme and Project Atmosphere courses offered through the American Meteorology Society, and spent 7 years designing teacher workshops related to math and science.

Mr. Willey thinks that there is a lot more that needs to be done to update meteorology education. He believes most science textbooks present meteorology from an east coast perspective, and don't do an adequate job of describing the climate and weather events of the southwest. He will continue to work to improve teaching resources for teachers from this part of the country, and hopes to come back to CIRA in the future.

Lesson plans can be viewed via the Colorado State University Community Collaborative Rain and Hail Study website: http://www.cocorahs.org and click on "For Teachers."

Communiqué

(continued from page 15)

CIRA Promotions

CIRA is pleased to announce that 13 employees were recognized for excellence with promotions this July. Those promoted were:

Randall Collander from Research Associate II to Research Associate III
John Dietz from Research Associate II to Research Associate III
Leslie Ewy from Research Associate II to Research Associate III
John Forsythe from Research Associate II to Research Associate III
Jim Frimel from Research Associate III to Research Associate IV
Lisa Gifford from Research Associate I to Research Associate II
Brian Jamison from Research Associate II to Research Associate III
Andrew Jones from Research Scientist II to Research Scientist III
Chris MacDermaid from Research Associate III to Research Associate IV
Don Reinke from Research Associate III to Research Associate IV
Karll Renken from Research Associate II to Research Associate III
David Salisbury from Research Associate II to Research Associate III
Dan Schaffer from Research Associate III to Research Associate IV
Milija Zupanski from Research Scientist II to Research Scientist III

The Increasing Role of Satellite Data in the GLOBE Program

Renate Brummer, Cliff Matsumoto, and Debra Krumm

Introduction

The GLOBE Program is an international science education program designed to increase scientific understanding of the Earth as a system, support improved student achievement in science and mathematics, and enhance environmental awareness through inquiry-based learning activities. Under the guidance of their teachers, students worldwide collect environmental data around their schools and post these findings on the Internet. GLOBE scientists design protocols for measurements that can be accomplished by K-12 students, and are also useful in scientific research. As scientists respond to the major environmental issues of today, laboratory and classroom collaboration help unravel how complex, interconnected processes affect the global environment. GLOBE's unique global database holds more than 11 million student measurements and associated metadata records that offer atmospheric, soil, land cover, hydrological, and phenological information accessible universally on the Web for research and visualization. Since its initiation, the GLOBE Program has grown from 500 U.S. schools in 1995 to more than 15,000 schools located in 106 partner countries as of September 2004.

Since October 2003, GLOBE has been managed by the University Corporation for Atmospheric Research (UCAR) in partnership with Colorado State University (CSU) under a NASA Cooperative Agreement. Along with the new GLOBE management structure, the responsibilities for the CIRA GLOBE team have also changed significantly. The Team has now assumed responsibility for the entire systems infrastructure previously handled by four different groups (CSU/CIRA, NASA Goddard Space Flight Center, NASA Ames Research Center, and the National Geophysical Data Center). The list of systems tasks now performed by the CIRA team includes the administration of the main GLOBE Webserver, development of data acquisition tools, maintenance of the central GLOBE database, coordination and collaboration involving the mirrored GLOBE Web and database systems, and design, development and enhancement of all data access and visualization functions.

Simultaneously, the CSU Atmospheric Science Department (ATS) assumed a predominant role within the GLOBE science team. ATS is now directly responsible for developing and supporting all GLOBE science measurement protocols, including detailed description of protocols and instrument specifications, in collaboration with NSF-funded science Principal Investigators (PIs). ATS also plays the role of a liaison to the science community and ensures the scientific validity of GLOBE data. ATS members are also in charge of the GLOBE Help Desk.

GLOBE and Satellite Data

GLOBE students around the world have the opportunity to assist scientists in their research on Earth as a system. Since the early years of GLOBE, participating schools have worked closely with satellite data. The GLOBE land cover and biometry protocols were introduced to the Program in 1996. These protocols ask students to define a land cover sample site (90m X 90m) and to determine the dominant vegetation for this area. The biometry protocol (Figure 1) measures detailed properties of the vegetation found around the land cover study site. As part of the data analysis, students are encouraged to use LandSat imagery to compare their data collection results with the high-resolution satellite image.

Figure 1. Students measuring a tree circumference as part of the GLOBE land cover/biometry protocol.

The data collected by GLOBE students on the ground for the land cover study site helps land cover scientists create and properly label land cover maps produced from satellite images and aerial photography. Additional independent groundcover samples help verify the accuracy of these maps. Data such as detailed biometric observations from groundcover sample sites help Earth systems scientists improve their ability to accurately interpret satellite imagery. More specifically, GLOBE land cover data are used by scientists to "ground truth" images taken by Terra – the first NASA satellite to monitor daily, and on a global scale, how Earth's atmosphere, land, ocean, biosphere, and solar radiation influence each other.

Data, including maximum/mean air temperature and 5 cm/10cm soil temperature, collected by GLOBE students help augment NDVI data derived from SPOT4 vegetation imagery to drive and validate Soil-Vegetation-Atmosphere (SVAT) models. Simulation modeling is an excellent tool for understanding processes and feedback within water and energy cycles, testing various scenarios, and interpreting satellite imagery.

Another group of satellites continues to play an important role in GLOBE. Since 1997, infrared imagery from the geostationary satellites GOES (East and West), Meteosat, and GMS are accessed several times a day and are imported into the GLOBE reference database. These 30km resolution images are mosaicked and offered four times a day (0000, 0600, 1200, and 1800 UT) to provide a more detailed image of the Earth than other GLOBE reference datasets, i.e., maximum and minimum temperatures, clouds, precipitation, soil

(continued on page 18)

moisture, evaporation, and albedo, obtained from global numerical prediction model output. These satellite images can be found on the GLOBE Website (www.globe.gov) under the Maps&Graphs section and can be displayed with GLOBE student data.

NASA's Earth Science Enterprise, with its many satellite missions and high priority on education, offers excellent avenues for collaboration with GLOBE's hands-on measurements and classroom learning activities to help students better understand Earth system science concepts. As an example, NASA's education programs developed to accompany three of their upcoming satellite missions – CloudSat, CALIPSO and Aura – have teamed up with GLOBE to help teachers in the U.S. better understand the atmosphere through a series of lead educator workshops. The first workshop was held at Colorado State University in Fort Collins, Colorado, in July 2004. The workshops bring together long-time GLOBE teachers and trainers with teachers new to the program (including teachers from NASA Explorer Schools). The educators are also brought together with NASA mission scientists and GLOBE science PIs.

GLOBE and CloudSat

Colorado State University's Atmospheric Science Department is the home of the CloudSat PI, Dr. Graeme Stephens, who is also a GLOBE Science (Atmosphere) PI. The CloudSat satellite (Figure 2) is currently scheduled to be launched in April 2005. As its name implies, CloudSat will collect data on clouds with an instrument known as a Cloud Profiling Radar. Clouds are one of the least understood elements of climate and the hydrological cycle. Yet, without an understanding of clouds, weather forecasting and climate modeling become extremely difficult. For millennia, clouds have been studied from the ground. Over the last century, it has become possible to study clouds from above. Until now, though, there was no good way to study what goes on inside of clouds. CloudSat will use a special type of active microwave radar (94 GHz) to provide a global survey of cloud properties to aid in improving cloud models and the accuracy of weather forecasts, with the long-term goal of improving global climate models. This cloud-profiling radar will provide vertical distribution of cloud physical properties, including liquid water content, ice content, and cloud optical depth (Stephens et al., 2002). The CloudSat mission is a cooperative effort that includes its international partner, Canada, and its industry partner, Ball Aerospace and Technologies Corporation. CIRA, as the CloudSat Data Processing Center (DPC), is expecting to ingest approximately 26 GB of data per day and produce and store approximately 52 GB of nine standard data products. In addition, the DPC will distribute a significant portion of those data to scientists and students around the world. Among CloudSat's other partners are Jet Propulsion Laboratory, Canadian Space Agency, the U.S. Air Force, U.S. Department of Energy, Goddard Space Flight Center and scientists from France, United Kingdom, Germany, Japan and Canada.

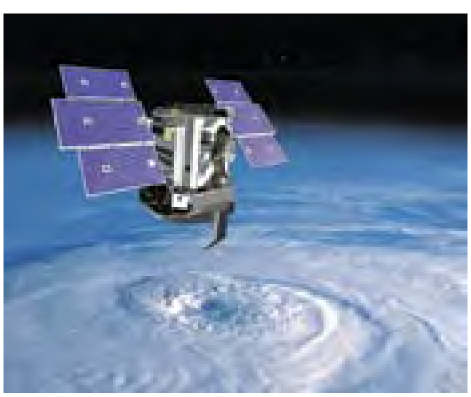

Figure 2. NASA ESSP satellite CloudSat (courtesy of Ball Aerospace).

CloudSat's Education Network

The CloudSat Education Network (Krumm et al., 2004) provides the opportunity for schools to partner with the CloudSat Science and Education teams and is working closely with the GLOBE Program. The Network will use proven science and education programs like GLOBE to partner scientists, teachers, students and the communities where they live to give students meaningful, authentic and contemporary educational experiences. Student activities and learning outcomes are being designed to meet both general education outcomes and specific standards or objectives from school curricula. The main focus of the knowledge development component of the project is to help students better understand long-term climate change and the climatic processes that maintain the Earth's energy balance.

The base level of participation in the CloudSat Education Network is the reporting of cloud cover, cloud type, temperature and precipitation data every 16 days, coinciding with the satellite overpass. Participation in the Network is expected to give GLOBE teachers the tools to provide students the opportunity to:

- Develop basic numeracy skills by gathering and processing environmental information that can be used by scientists to complement the measurements taken by the CloudSat satellite (Scientists will also benefit from this ground-based reference data).
- Develop practical science skills by measuring, recording and analyzing local environmental measurements.
- Communicate and learn with other students from around the world using appropriate information and communications technologies.
- Interface with the CloudSat Education Network Website which will offer student friendly materials and ideas to support the educational goals of member schools.
- Liaise with, ask questions and offer ideas to the CloudSat Science Mission team.

The network will be international in nature targeting up to 100 schools. Currently, schools in Australia, New Zealand, Ghana, Cameroon, Croatia, Germany, and the United States are prepared to participate. Existing and new contacts are being pursued in Malaysia, Thailand, Taiwan, South Africa, the United Kingdom, and Pakistan. Schools through existing networks have also been targeted and contacts are being made in Russia,

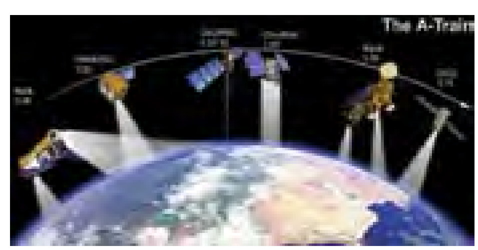

Figure 3. The "A-Train" will consist of six satellites flying in formation for the purpose of studying Earth's atmosphere (NASA Facts, 2003).

(continued on page 19)

GLOBE Program *(continued from page 18)*

Iceland, Sweden, Finland, Estonia, Canada, and China.

The NASA "A-Train"

For the first time, NASA will fly six satellites in a tight formation like railroad cars on a train (Figure 3).

Officially known as the Afternoon Constellation, the A-train will study the Earth's atmosphere in order to improve weather forecasting and climate prediction, among many other advances. The A-Train is an international effort similar to the GLOBE Program. Table 1 lists the six satellites, their primary research areas, approximate launch dates and affiliations. These polar-orbiting A-Train satellites will fly 705 kilometers above the Earth's surface in a sun-synchronous orbit.

Many of these A-Train satellites (as well as other environmental satellites) will be (and have been) sources of data for visualization and comparison with locally measured observations by GLOBE students. For example, the aerosol optical thickness (AOT) measurements by the MODIS instrument on Terra and Aqua satellites have been shown to agree well with AOT measurements conducted by GLOBE students using sun photometers. Some cloud data from the CERES instrument aboard Aqua have been merged into the GLOBE cloud database. GLOBE student observations of cloud type have also been compared to coincident satellite-derived observations using the MODIS Cloud Product data from Terra. In addition, GLOBE snow data have been used to validate the snow detection algorithm from MODIS on the Terra satellite. The GLOBE sun photometers will be used by GLOBE students to report aerosol data for comparison with CALIPSO's lidar measurements. A ground validation plan has also been proposed to use inexpensive GLOBE hand-held UV-A instruments to help ESO/Aura scientists understand the temporal and spatial variability of UV-A radiation under a satellite instrument "footprint."

Future Plans

With the recent launch of Aqua and Aura, and additional new satellite missions like CloudSat, CALIPSO, PARASOL, and OCO over the next few years, GLOBE students around the world will have more opportunities to participate in these missions and assist scientists in their research on the Earth's atmosphere. Mission scientists will be comparing GLOBE data on clouds, aerosols, ozone, precipitation, water vapor, UV, and CO2 to images and measurements collected by these orbiting satellite sensors. The GLOBE Program is also expected to expand over the next few years to incorporate networks involving citizen groups, Scouts, and other informal "after school" organizations. The Program will also likely see the addition of more marine protocols to support the concepts of Earth system science.

SPACECRAFT	MISSION	INTERNATIONAL PARTNERS	LAUNCH DATE
Aqua	Synergistic instrument package studies global climate with an emphasis on water in the Earth's atmosphere system including its solid, liquid and gaseous forms	France, Australia, Italy, Brazil	May 2002
CloudSat	Cloud Profiling Radar will allow for most detailed study of clouds to date and should better characterize the role clouds play in regulating the Earth's climate	Canada, Japan, Germany, United Kingdom, The Netherlands, France	April 2005
CALIPSO	Observations from space-based lidar will lead to improved understanding of the roles aerosols and clouds play in regulating the Earth's climate	France	April 2005
PARASOL	Polarized light measurements will allow better characterization of clouds and aerosols in the Earth's atmosphere, in particular distinguishing natural from man-made aerosols	France	October 2004
Aura	Synergistic instrument package studies atmospheric chemistry, focusing on the horizontal and vertical distribution of key atmospheric pollutants and greenhouse gases	The Netherlands, United Kingdom, Finland	July 2004
OCO	Will make global space-based observations of the column integrated concentration of CO2, a critical greenhouse gas	France, Germany, New Zealand, Australia, The Netherlands	August 2007

Table 1. Summary of A-Train missions.

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CIRA Mission

The Mission of the Institute is to conduct research in the atmospheric sciences of mutual benefit to NOAA, the University, the State and the Nation. The Institute strives to provide a center for cooperation in specified research program areas by scientists, staff and students, and to enhance the training of atmospheric scientists. Special effort is directed toward the transition of research results into practical applications in the weather and climate areas. In addition, multidisciplinary research programs are emphasized, and all university and NOAA organizational elements are invited to participate in CIRA's atmospheric research programs.

The Institute's research is concentrated in several theme areas that include global and regional climate, local and mesoscale weather forecasting and evaluation, applied cloud physics, applications of satellite observations, air quality and visibility, and societal and economic impacts, along with cross-cutting research areas of numerical modeling and education, training and outreach. In addition to CIRA's relationship with NOAA, the National Park Service also has an ongoing cooperation in air quality and visibility research that involves scientists from numerous disciplines, and the Center for Geosciences/Atmospheric Research based at CIRA is a long-term program sponsored by the Department of Defense.

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