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The 2001 Asian Dust Events: Transport and Impact on Surface Aerosol Concentrations in the U.S.

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A transport event in April 2001 brought substantial quantities of mineral dust from Asian deserts to the U.S. atmospheric boundary layer (ABL). The dust was seen in large amounts throughout the ABL in the U.S., with almost no reduction in concentrations. It was estimated that the amount of Asian dust in the continental U.S. ABL in mid-April 2001 was 1.1 E5 metric tons, a value comparable to the daily emission flux of all U.S. sources of particulate matter (PM) less then 10 μm diameter (PM10). In some regions, the Asian dust, combined with local pollution, elevated urban PM to levels associated with adverse health effects. The April 2001 event appears to be the largest Asian dust event ever observed in the U.S., and its effects provide evidence that air pollution issues must be viewed in a global context.

In late April 1998, satellites, ground-based lidar, and surface sites observed a large cloud of dust as it moved from Asia to North America. At the time, this was believed to be the largest Asian dust event ever seen in North America [*Husar et al.*, 2001]. An even larger Asian dust cloud was observed in April 2001. The concurrent ACE-Asia experiment provided a large number of observations as this air mass left the Asian continent [*Huebert et al.*, 2003]. The arrival of this air mass over North America has been documented using surface and satellite-based, remotely sensed data [*Thulasiraman et al.*, 2002], aircraft observations [*Price et al.*, 2003], and with a transport model [*Gong et al.*, 2003]. This article describes the influence this dust event had on the U.S. ABL.

For this study, aerosol data was used from the Interagency Monitoring Program for improved Visual Environments (IMPROVE) network, with more than 100 sites located throughout the U.S. (http://vista.cira.colostate.edu/improve). The sites are primarily in national parks, in national wildlife refuges, or other Class I areas.

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IMPROVE filter samples are collected in two size ranges (PM10 and PM2.5) for 24 hours every 3 days. A complete chemical analysis is conducted on the PM2.5 samples, whereas only mass is routinely measured on the PM10 samples. Many of these sites have been operating since the late 1980s.

From analysis of sunphotometry measurements and a satellite-based aerosol index, *Thulasiraman et al.* [2002] conclude that the dust first arrived in the free troposphere over the U. S. on 12 April. Aircraft observations in the Pacific Northwest on 14 April 2001 [*Price et al.*, 2003] found a substantial mineral dust layer above 4 km a.s.l., mixed with carbon monoxide and non-methane hydrocarbons. Two days later, the dust was seen at the surface. Figure 1 shows data from a selection of IMPROVE sites in the west, central, and eastern United States for 2001. Clearly present is the large spike in PM10 and Si concentrations in mid-April. A surprising and important result is the similarity of peak PM10 and Si concentrations at sites across the U.S. The highest concentrations are in the central west coast, the Rocky Mountains, and the southeastern U.S. At the same time, the dust is clearly seen in northern sites from Washington state (North Cascades National Park) all the way to Maine (Acadia National Park). PM10 and Si concentrations at the Okefenokee IMPROVE site in Georgia are comparable with the highest concentrations seen anywhere in the U.S. Generally, sites in the western U.S. show their peak concentration on 16 April, and those in the eastern U.S. have peaks on 19 or 22 of April, keeping in mind that IMPROVE samples are only collected every 3 days.

The composition of the dust using the IMPROVE chemical data (PM2.5 only) was evaluated. Figure 2 shows the relationship among Fe, Ca, Al, and Si from 110 sites on 16 April. The consistent relationship among these elements and the fact that the ratio is similar to previous observations of Asian dust [e.g., *Husar et al.*, 2001] support the idea that a single dust source is impacting concentrations throughout the United States. On 16 April, 70 out of the 110 sites are shown to have Si concentrations of 0.3 μg/m^3 or greater, compared to only three sites a week earlier. In addition, a linear regression of PM2.5 versus PM10 for these 110 sites for 16 April (plot not shown) yields a slope of 0.47, and an R^2 of 0.89. So while there is likely some local contributions to the PM10 and PM2.5 concentrations on 16 April, the analysis indicates that the largest component of the PM mass was due to mineral dust, and this component had a consistent composition across most of the 110 IMPROVE sites considered.

Air quality data from urban sites around the country was also examined. Shown in Table 1 are the highest PM10 concentrations for the month of April 2001 for several urban locations. At virtually all sites examined, PM10 concentrations peak between 16 and 20 April. As expected, these urban locations have higher PM concentrations than the IMPROVE sites. However, the consistency in the peak date and concentrations indicates a substantial dust influence. Comparing the PM10 concentrations from the days before the dust arrived, the Asian dust increases concentrations at these sites by 30–40 μg/m^3. At some locations, the combination of local sources plus the Asian mineral dust push the PM10 concentrations to levels associated with health impacts [e.g., *Delfino et al.*, 1994].

For mid-April 2001, the arrival of the dust above North America is well documented [*Thulasiraman et al.*, 2002; *Price*, 2003; *Gong et al.*, 2003]. Expanding on the earlier results, a detailed trajectory analysis was conducted to determine the meteorological processes that transported dust from the Asian ABL to the U.S. ABL. Between 5 April and 9 April, thousands of forward trajectory particles were released every 12 hours from the lowest 2 km of the troposphere over the desert regions of China. The dust source regions were determined from the analysis of *Gong et al.* [2003] and the remotely sensed TOMS (Total Ozone Mapping Spectrometer) aerosol index (http://jwocky.gsfc.nasa.gov/aerosols/today_plus/yr2001/asia_dust.html). Trajectory calculations were based on the global NCEP FNL 1x1 degree wind field analyses, available very 6 hours. A visualization of the dust transport is provided on the *Eos* Electronic Supplement (http://www.agu.org/eos_elec/000319e.mov).

The transport process was initialized by two mid-latitude cyclones that entrained dust from the Gobi Desert region between 6 and 9 April. The cyclones merged over the western Pacific and sheared apart over the eastern Pacific, producing several transport pathways into the

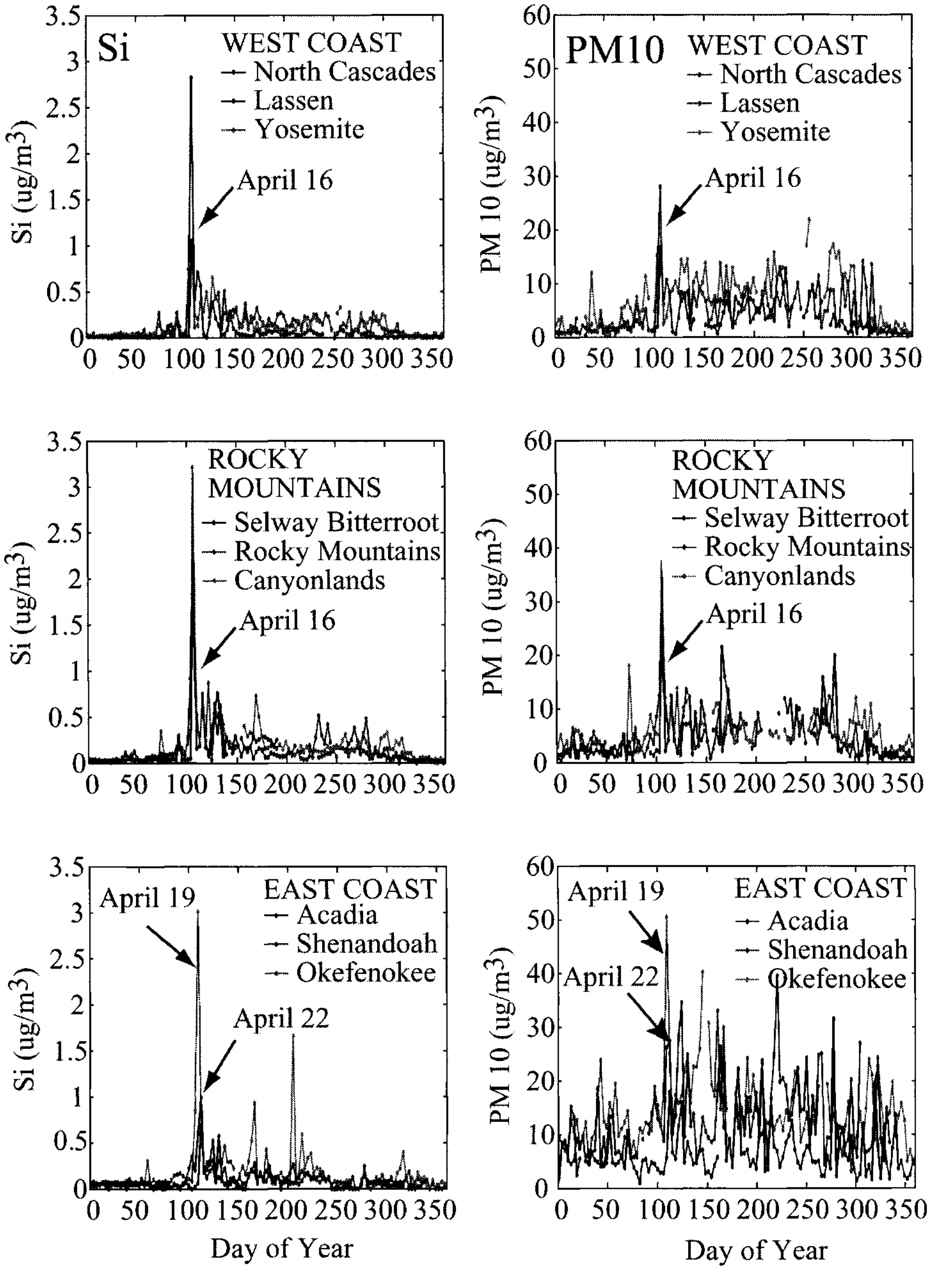

Fig. 1. PM10 and Si (ug/m³) for 2001 from IMPROVE sampling locations in the western, central, and eastern U.S. Original color image appears at back of volume.

U.S. ABL. The remainder of this article focuses on the processes that brought dust to the ABL of the west coast on 16–17 April.

Transport of the Dust

On 6 April, trajectory particles were lofted ahead of a surface cold front, and within the warm conveyor belt (WCB) of a mid-latitude cyclone above the Gobi Desert region. These particles traveled across the Pacific within the WCB until it decayed over the eastern Pacific as it flowed anti-cyclonically into an upper level ridge. Caught in the descending flow typical of the eastern side of upper level ridges, the particles descended into a surface anti-cyclone just west of California. Meanwhile, trajectory particles that were released above the Gobi Desert region behind the surface cold front wrapped into the center of the cyclone, mixed with some of the WCB trajectories, and were transported to the lower troposphere of the western Pacific. Many of these particles remained in the lower troposphere and were rapidly transported across the Pacific parallel to a strong surface pressure gradient. On 15 April, these particles became entrained in a new surface cyclone west of California. The cyclone formed just west of the surface anti-cyclone containing the trajectory particles that descended from the WCB. As the cyclone moved ashore on 16 April, it pushed the WCB trajectory particles into the west coast, while the particles within the cyclone affected the west coast on 17 April. This analysis demonstrates that dust can be transported to the U.S. ABL by both high- and low-altitude trans-Pacific pathways.

For the 110 IMPROVE sites, the mean PM10 value shows a peak on 16 April of 19 μg/m³. This compares with a mean value for 1–13 April of 10 μg/m³. Therefore, the Asian dust increased the mean PM10 concentration in the U.S. boundary layer by 9 μg/m³. On 16 April, we find evidence that the dust affected 80–90 of the 110 IMPROVE sites considered. Assuming a height of 1500 m, it is calculated that the continental U.S. ABL contains 1.1 E5 metric tons of PM10 from Asian mineral dust and 5.2 E4 metric tons of PM2.5. For comparison, all U.S. sources contribute 8.6 E4 metric

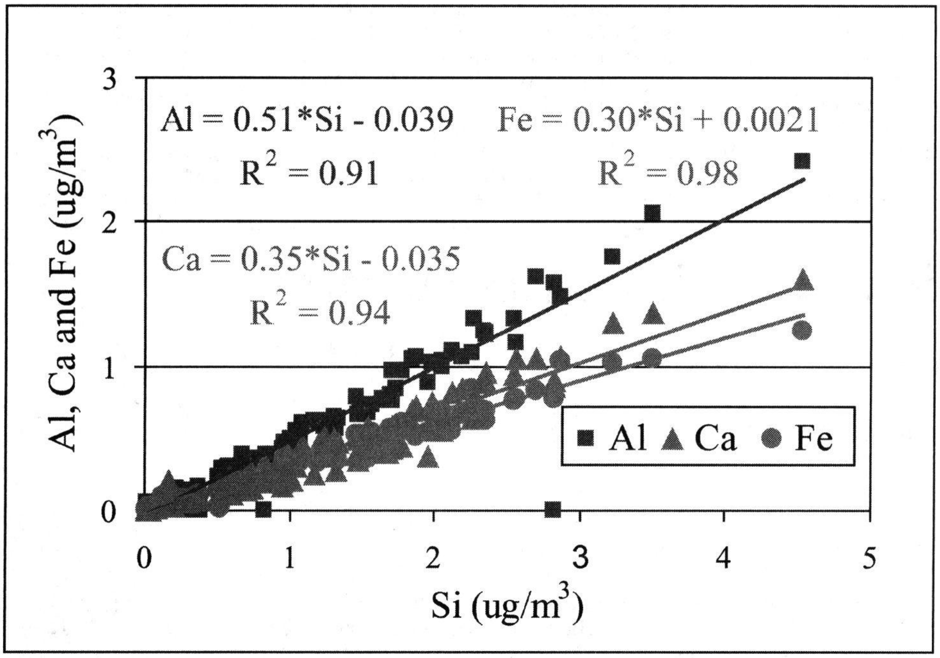

Fig. 2. Scatter plot of Al, Ca, and Fe versus Si in 110 IMPROVE samples from 16 April 2001. Original color image appears at back of volume.

Table 1. Highest PM10 Value (24-Hour Average) for Each Site for the Month of April 2001.

Site	Date	PM 10 ug/m^3	Site	Date	PM 10 ug/m^3
Tucson, AZ	17-18 April	85	Savannah, GA	20 April	85
Salt Lake City, UT	16 April	78	Atlanta, GA	20 April	67
Aspen, CO	16 April	71	Winston-Salem, NC	20 April	74

tons/day of PM10 and 2.1 E4 metric tons/day of PM2.5 [*U.S. EPA*, 2000]. So for the week starting 16 April, Asian dust sources contributed an amount of PM to the U.S. ABL which was comparable to all U.S.-based sources. Since elevated PM10 and Si concentrations persist at most sites for several weeks and dust transport to North America continues through early May [*Gong et al.*, 2003], it is likely that the total Asian dust source to the U.S. ABL is significantly larger then the value given above. For comparison, *Gong et al.* [2003] calculate that the total flux of mineral dust from Asian deserts during the spring of 2001 is 2.5 E8 metric tons. Thus, only a very small percentage of the Asian dust released has reached the U.S. ABL.

Using a similar approach, it was found that the April 1998 dust event, while also quite substantial, had about two-thirds of the impact on PM concentrations in the U.S. that the 2001 event had. Examining the IMPROVE aerosol data back to the mid-1980s, we found no other comparable events. Thus, while these events are extreme in the amount of transported PM, they appear to be infrequent.

Nevertheless, this case study shows that extreme episodes of inter-continental transport can adversely impact air quality in regions far from the original emission source.

Acknowledgments

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Communicating with Uncertainty: A Critical Issue with Probabilistic Seismic Hazard Analysis

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Probabilistic seismic hazard analysis (PSHA) is a widely used method for seismic hazard assessment. PSHA predicts a relationship, called the seismic hazard curve, between the maximum ground motion or response spectra and the annual frequency of exceedance (return period). Generally, the smaller the annual frequency of exceedance, meaning the longer the return period, the larger the ground motion—seismic hazard—PSHA will predict, and vice versa. PSHA is the most widely used method for assessing seismic hazards for input into various aspects of public and financial policy.

For example, the U.S. Geological Survey used PSHA to develop the national seismic hazard maps [*Frankel et al.*, 1996, 2002]. These maps are the basis for national seismic safety regulations and design standards, such as the National Earthquake Hazards Research Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures [*BSSC*, 1998], the 2000 International Building Code, and the 2000 International Residential Code (IRC).

Adoption and implementation of these regulations and design standards have significant impacts on many communities in which estimated hazards are high, such as the New Madrid area in the central United States. For example, the Structural Engineers Association of Kentucky found that if IRC-2000 were adopted in Kentucky, it would be impossible to construct residential structures in westernmost Kentucky without enlisting a design professional. It also would not be feasible for the U.S. Department of Energy to obtain a permit from federal and state regulators to construct a landfill at a facility near Paducah, Kentucky.

It is well understood that there is uncertainty in PSHA because of the uncertainties inherent in input parameters that are used in the hazard analysis, especially for the central United States. In the central United States, the question is not whether there is any seismic hazard, but how high the hazard is. Scientists and engineers, including *Frankel* [2003] and *Stein et al.* [2003a, b], have long discussed this issue and will continue to do so. Although the products of PSHA are widely used and accepted, our experience is that few practitioners, let alone users, have an in-depth understanding of the limits of applicability of PSHA or their sensitivity to assumptions in the underlying parameters. Because PSHA influences policy decisions on issues ranging from building codes to science funding, an appreciation for the uncertainties and assumptions underlying it is valuable for the user and decision makers.

Functions of PSHA

Since its introduction in 1968, PSHA has been widely used in seismic hazard assessment [*Algermissen and Perkins*, 1976; *Frankel et al.*, 1996, 2002]. PSHA incorporates ground motions and occurrence frequencies for all earthquakes in a region through a mathematical model (triple integration). As an example, Figure 1 shows a hypothetical region in which there are three seismic sources (A, B, and C faults) and a site of interest. It is assumed that only characteristic earthquakes will repeat along the faults in certain time periods (recurrence times). This simple example was used to

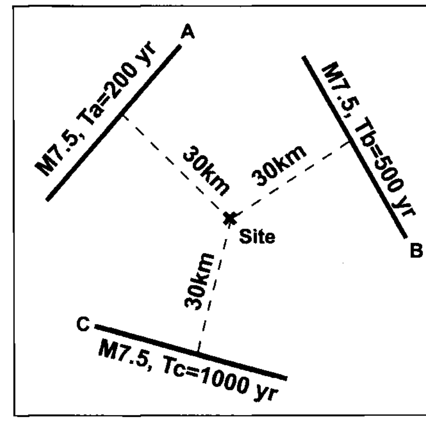

*Fig. 1. A hypothetical region with three seismic sources (**A**, **B**, and **C** faults) and a site of interest within 30 km of the faults.*

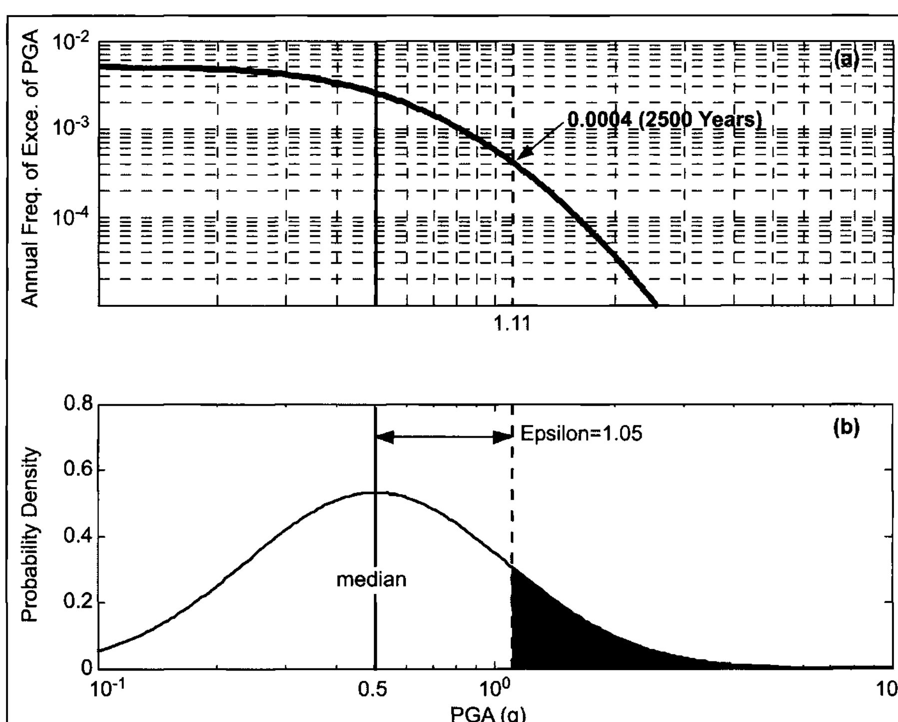

*Fig. 2. Steps for calculating the annual frequency of exceedance for the peak ground acceleration of 1.11g from fault **A**. (a) The annual frequency of exceedance (0.0004) is shown for the peak ground acceleration of 1.11g from fault **A**, and (b) probability (0.08) that the peak ground motion will exceed 1.11g (shaded area under ground-motion density function) is shown. The median ground motion (μ) is 0.5g, and the standard deviation (σ_{ln}) is 0.75. Epsilon=$(\ln y - \ln \mu)/\sigma_{ln}$.*

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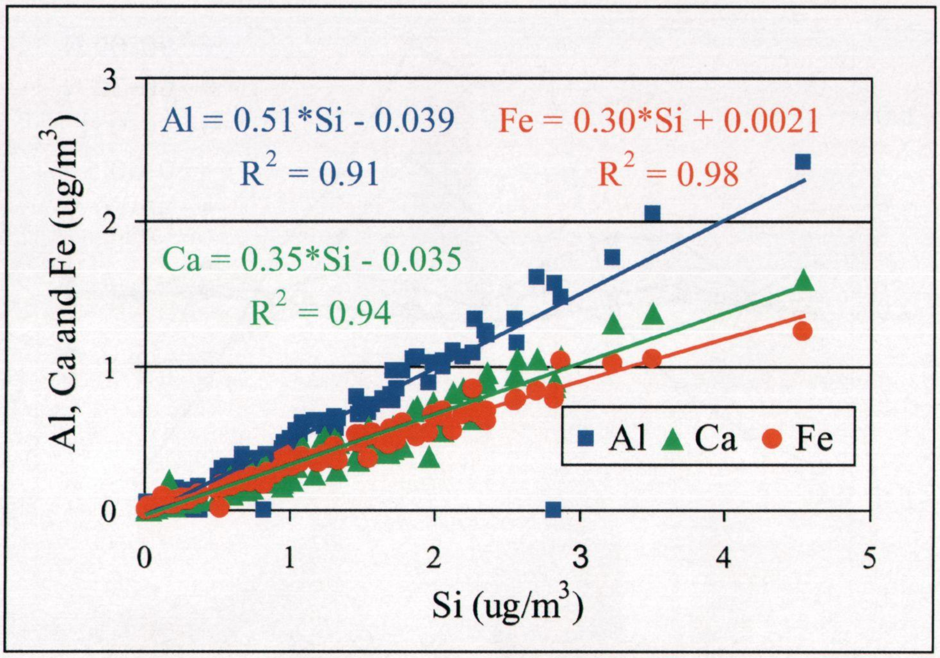

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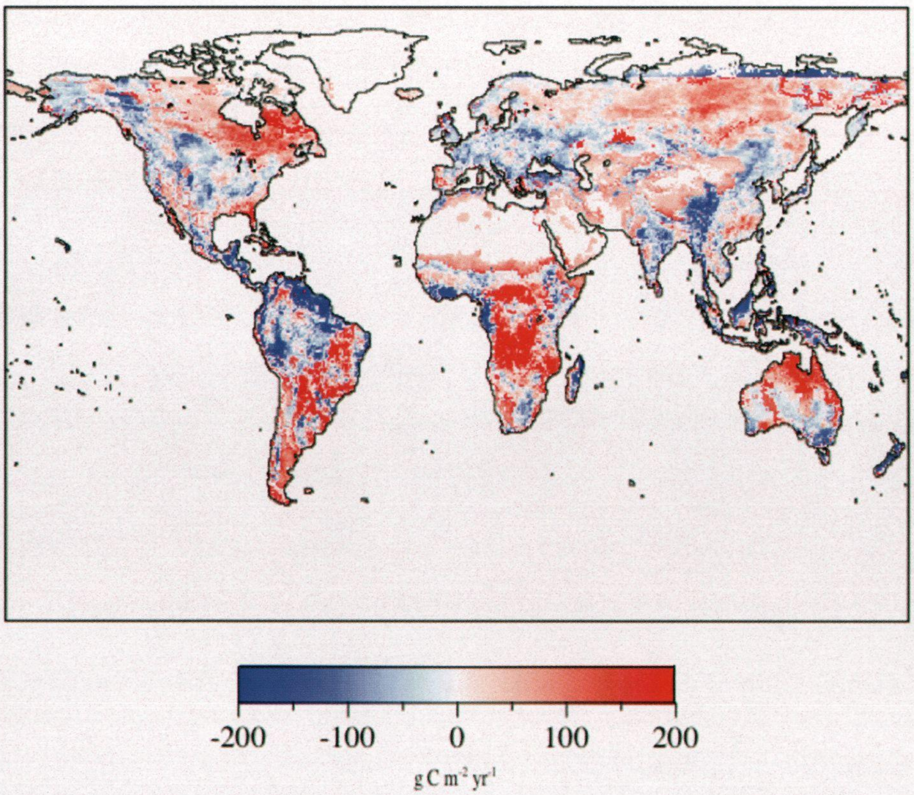

Fig. 1. Predicted global distribution of annual net ecosystem production fluxes in 2001. Net annual source areas are shown in blue, while net annual sink areas are shown in red.

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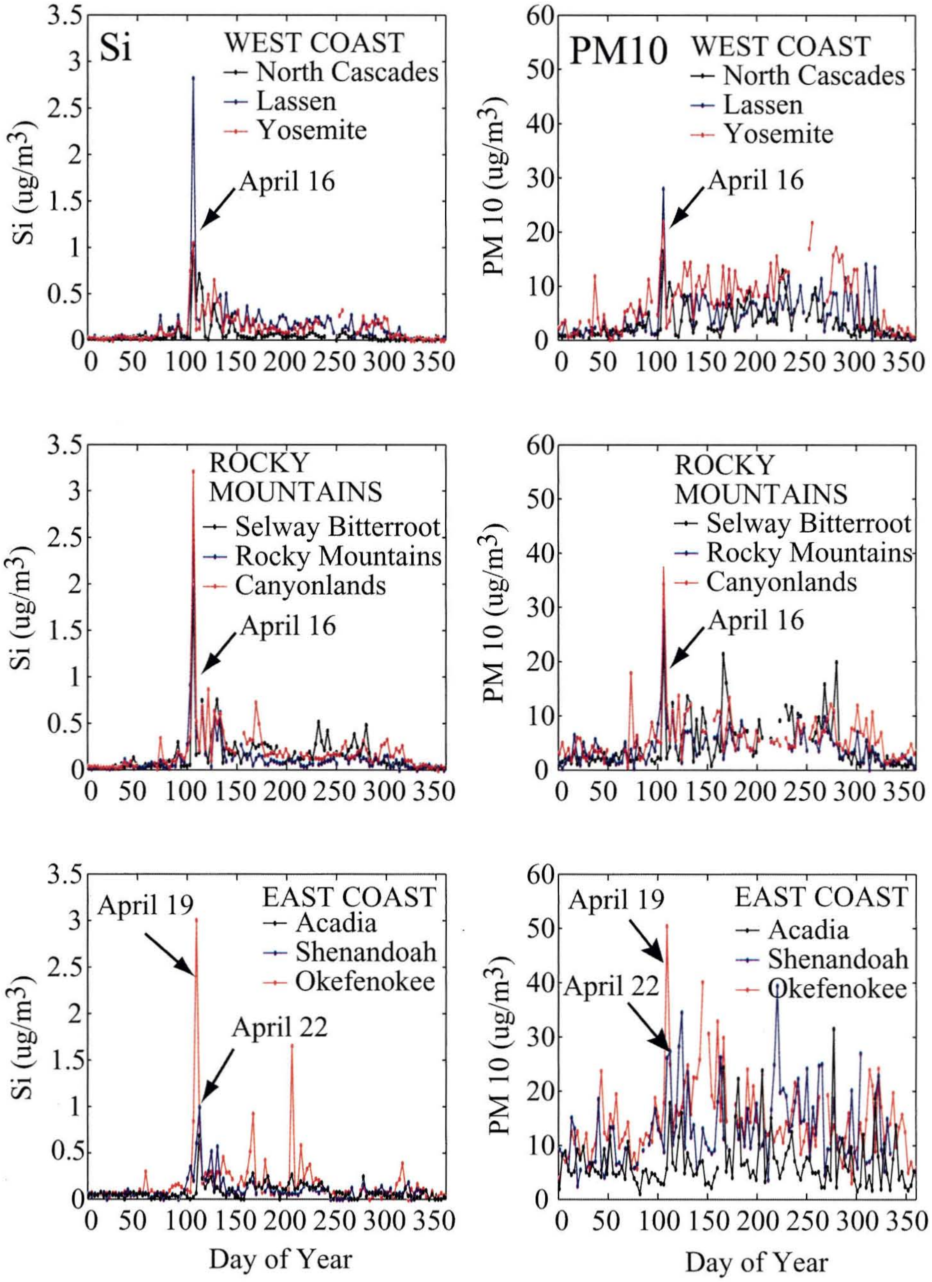

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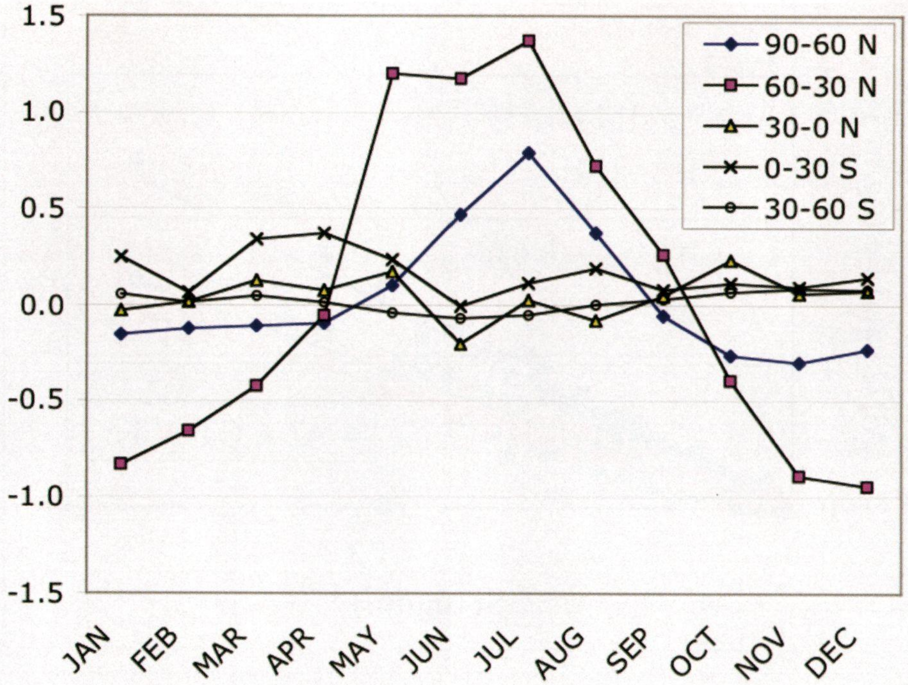

Fig. 2. This graph compares predicted monthly net ecosystem production fluxes in 2001 for 30° latitude zones. Units are Pg C mo^{-1}.