Transport of smoke from the Central American fires of 1998

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Abstract. During the spring of 1998, smoke produced by biomass burning in Central America was transported northward, where it eventually affected the continental United States. To quantify this event, this study analyzes the presence of aerosols using the Total Ozone Mapping Spectrometer (TOMS) aerosol index. Unusually large amounts of UV-absorbing aerosols were present over parts of Central America during 1998 compared to a climatology created from the 13-year Nimbus 7 TOMS data set (1979-1992). The role of transport is studied by computing trajectories for air parcels initialized in the area with the most widespread fires. Comparison of the TOMS aerosol index maps and the parcel trajectories indicates that the trajectories adequately represent the smoke transport. Analysis of the TOMS data, the meteorological observations, and the trajectories indicates that the source region of the smoke is influenced by two prevailing transport regimes: one northward and one westward. The transport alternates between the two flow patterns. Statistical analysis of the transport shows that May 1998 and the climatology contain similar patterns of northward and westward flow regimes. The northward flow regime in 1998, however, is among the strongest of the 20-year period analyzed. The combination of unusually large smoke production and stronger than normal northward transport led to significant smoke concentrations over large areas of the central and southern United States.

1. Introduction

From July 1997 through June 1998, Mexico and Central America experienced the driest conditions for that length of time since 1945, the beginning of the historical record [Bell et al., 1999]. During the latter part of that period, intense heat added to the dryness and produced enhanced drought conditions. Additionally, Bell et al. [1999] noted that the beginning of the 1998 monsoon season was delayed for 4-6 weeks. These factors, in combination with traditional agricultural practices, culminated in widespread biomass burning. Lyons et al. [1998] estimated from satellite imagery that during April, May, and June there were more than 10,000 fires that consumed a total area greater than 4000 km². Figure 1 is an infrared image from the advanced very high resolution radiometer (AVHRR) aboard the NOAA 12 satellite. It shows numerous hot spots (fires) throughout Guatemala and southern Mexico.

During April through June of 1998, smoke produced by the fires was transported northward, where it eventually affected the continental United States. Regional impacts of the smoke included a reduction of visibility and possible negative health effects from particulate matter. Peplier et al. [2000] verified the presence of biomass burning aerosols during this time period at the Atmospheric Radiation Measurement (ARM) program Southern Great Plains Cloud and Radiation Testbed in Oklahoma and Kansas using multiple instruments. In addition, biomass burning emissions can contain carbon monoxide, hydrocarbons, and nitrogen oxides, which can cause increased tropospheric ozone through chemical reaction pathways [Crutzen and Andreae, 1990]. Another possible effect of the smoke was an increase in the fraction of positive-polarity cloud-to-ground lightning flashes in thunderstorms that formed in smoke-filled air masses [Lyons et al., 1998; Murray et al., 2000].

The burning season in Central America is part of the annual agricultural cycle of the region. Biomass is incinerated in the land clearing and preparation process before planting takes place. If this burning occurs annually during the dry season, why was smoke so much more noticeable in Texas and much of the central and southeast United States during 1998 compared with other years? Two possible hypotheses are unusually large smoke production due to the dry conditions and anomalous northward transport of smoke. The increased amount of smoke in the continental United States could also be due to a combination of those two processes.

In order to investigate this phenomenon, we use a combination of satellite aerosol retrievals from Total Ozone Mapping Spectrometer (TOMS) instruments and air parcel trajectory calculations. The TOMS aerosol product was initially used by Hsu et al. [1996] to detect biomass burning smoke and Saharan dust. Dave [1978] first documented that aerosols could cause a wavelength-dependent error in retrieving ozone from backscattered ultraviolet radiation measurements. Hsu et al. [1996] discovered that because of this error the presence of aerosols that absorb ultraviolet radiation could be deduced from the Nimbus 7 TOMS data based on the reflectivity difference, known as the residue value, between the 340- and 380-nm channels. TOMS reflectivity is determined by using the measured radiance-irradiance ratios for channels not sensitive to ozone absorption and removing from it the Rayleigh scattering

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component. The channels at which ozone does not absorb ultraviolet radiation include 331, 340, 360, and 380 nm. The reflectivity measurement is overcorrected for multiple Rayleigh scattering when absorbing aerosols are present, with the overcorrection being greater at shorter wavelengths. Therefore, for an atmosphere bounded by a wavelength-independent Lambertian reflecting surface, this reflectivity difference is a measure of the amount of absorbing aerosols present [Hsu et al., 1996].

Several previous studies have coupled trajectory calculations with TOMS data. Schoebert et al. [1993] compared the TOMS sulfur dioxide data of the Cerro Hudson eruptions of August 14-15, 1991, with parcel trajectories computed using the Goddard trajectory model [Schoebert et al., 1992]. Hsu et al. [1996] also used the Goddard trajectory model to diagnose the transport associated with the seasonal variations of biomass burning in South America. More recently, Allen et al. [1999] combined the TOMS aerosol index measurements with multiple-level parcel trajectories to create an aerosol trajectory model that was used to study the eruption of Alaska's Mount Spurr in 1992.

In order to test the two hypotheses discussed above, monthly mean TOMS aerosol retrievals for 1998 are compared with a 13-year TOMS aerosol climatology, and 1998 trajectories are compared with a 20-year trajectory climatology. In addition, to validate the trajectory calculations, we compare 1998 trajectories initialized in the biomass burning region with the daily TOMS aerosol retrievals for the same period.

2. Data

The TOMS aerosol product is produced by the Ozone Processing Team at NASA's Goddard Space Flight Center. TOMS retrievals are used because of their effectiveness over most surface backgrounds, including both land and water [Herman et al., 1997]. The aerosol product, which is produced once daily, is available on a 1.25°×1° global longitude-latitude grid with values averaged over each grid box from the instantaneous fields of view. Because the aerosol index represents the total column aerosol concentration, there is no information about the vertical distribution. For this study, we use data from two of the five TOMS instruments that have been carried on different satellites since 1978: the Nimbus 7 TOMS (1978-1993) and the Earth Probe TOMS (1996 to present). The Earth Probe TOMS instrument differs from the Nimbus 7 TOMS instrument in that it does not contain wavelengths at 340 and 380 nm. Instead, the reflectivity difference between the 331- and 360-nm channels is utilized [Hsu et al., 1999].

The TOMS aerosol index is designed so that positive values are associated with ultraviolet-absorbing aerosols and negative values are associated with nonabsorbing aerosols [Hsu et al., 1999]. Absorbing aerosols include dust and
biomass burning aerosols, while sea-salt particles and sulfate aerosols are examples of nonabsorbing aerosols [Torres et al., 1998]. Because aerosols from biomass burning produce positive residue values, indices in the range from 1.5 to 7.5 are the focus of this study. Positive values below 1.5 are not considered because this range includes background levels of aerosols present throughout much of the atmosphere.

Trajectories are computed using winds from the National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis Project data set [Kalnay et al., 1996]. The NCEP/NCAR reanalysis data set was chosen because of its temporal and spatial coverage and its availability. The reanalysis process uses a frozen, state-of-the-art, global data assimilation system. For this study we use data from the 21-year period 1978-1998. The quality and quantity of data used in the assimilation vary with time. Data sources include global rawinsonde data, Comprehensive Ocean-Atmosphere Data Set (COADS) surface marine data, aircraft data, surface land synoptic data, satellite sounder data, and Special Sensing Microwave/Imager (SSM/I) surface wind speeds. Individual sources are incorporated into the reanalysis when available.

Reanalysis variables include $u$ (zonal wind), $v$ (meridional wind), $T$ (temperature), and $Z$ (geopotential height) at 17 pressure levels from 1000 to 10 hPa; $\omega$ (vertical velocity in pressure coordinates) at the 12 lowest pressure levels; and $q$ (specific humidity) and RH (relative humidity) at the lowest pressure levels. The reanalysis is archived at 6-hour intervals for each day. Data are stored on a global $2.5^\circ \times 2.5^\circ$ longitude-latitude grid.

3. Methods

Figure 2 is a map of the area of interest of this study, which ranges from 10° to 42°N and from 78° to 115°W. For the entire study area, maps of daily, monthly, and climatological monthly mean TOMS aerosol index values are used to characterize the distribution of smoke during April and May. In addition, three subregions, labeled A, B, and C are identified in Figure 2. Region A is the area of most intense biomass burning during 1998 as estimated qualitatively from the advanced very high resolution radiometer (AVHRR) and Geostationary Operational Environmental Satellite (GOES) imagery (see below). Region B (10°-25°N, 85°-110°W) covers the larger area where smoke from seasonal biomass burning is common. Various statistics of the aerosol indices within this region are used to evaluate whether smoke production in 1998 was higher than normal. Similar statistics are computed for Region C (30°-40°N, 80°-100°W) in order to verify that the quantity of smoke present in the United States during 1998 was, in fact, anomalously large.

While the TOMS data are used to evaluate the occurrence of smoke itself, trajectories are used to evaluate the transport. The trajectory model used is from Bowman [1993] and is similar to other Lagrangian models in widespread use. Trajectories are computed using a standard fourth-order Runge-Kutta scheme with velocity components linearly interpolated in space and time to the location of the parcels.

Because the initial distribution of smoke is not well known quantitatively, parcels are initialized in a rectangular volume approximating the area into which the smoke is initially injected. On the basis of examination of the locations of fire hot spots as indicated by AVHRR and GOES infrared imagery, the horizontal boundaries of this area (Region A) are 16°-19°N and 90°-95°W. As shown below, this source region produced the aerosols that affected North America. There were other areas of fire activity in Central America, but the associated smoke was not transported northward.

Vertically, the initial volume extends from 950 to 700 hPa and thereby includes most of the lower troposphere. In the zonal, meridional, and vertical direction, parcels are arranged in a regular grid with 20, 12, and 6 parcels respectively, totaling 1440 parcels for each initial time. Forward trajectories are computed for time periods of 9 days. For the 1998 calculations, parcel positions are initialized and saved at 6-hour intervals. For the climatological reference period (May 1978-1997), trajectories are initialized and saved at 24-hour intervals. The possible vertical transport of aerosols by deep convection (and subsequent horizontal transport in the upper troposphere) is not considered due to the prevailing drought conditions affecting the region.

There are multiple sources of error associated with the calculation of trajectories. The largest of these errors is due to uncertainties in the wind fields. The variables contained within the NCEP/NCAR reanalysis are classified based on their susceptibility to model influences. Horizontal winds are graded Class A as they are generally well defined by available observations. Vertical velocity data in pressure coordinates, however, are classified as B, signifying they are only partially defined by observations and therefore subject to greater influence from the model characteristics [Kalnay et al., 1996]. Uncertainties can also be attributed to the spatial and temporal resolution of the wind data.

In order to help visualize the atmospheric flow field and its fluctuations, monthly mean wind and geopotential height maps are produced from the NCEP/NCAR reanalysis data set.
at 925, 850, and 700 hPa. Instantaneous vector wind, geopotential height, and vertical velocity fields are generated daily at 900, 800, and 700 hPa for the times 0000, 0600, 1200, and 1800 UTC.

4. Results

4.1. Occurrence of Aerosols During 1998

Analysis of the TOMS aerosol index imagery reveals that there were several significant episodes of smoke production and transport in Central America during April and May 1998. Because the month of May contains multiple episodes that include examples of transport similar to those that occurred in April, the rest of this study focuses solely on May and on the variations in transport that occurred during that month.

The TOMS data show that there were two distinct transport regimes affecting the source region during May 1998. The first regime, which directly impacts the United States, involves the northward advection of aerosols from the source region. Figure 3a shows the aerosol distribution on May 14, which is the result of the northward transport prevalent during the first 12 days of the month. The gray scale indicates aerosol index values between 1.5 and 7.5. All values less than 1.5, which fill most of the domain, are designated by the lightest gray, which is not included in the gray scale. Missing values are unshaded. The second transport regime is characterized by westward transport of the aerosols over the Pacific Ocean as shown by the TOMS image for May 18 (Figure 3b). Overall, the month of May can be separated into five episodes during which the direction of transport alternates between these two regimes (Table 1).

4.2. Climatological Aerosol Distribution

The monthly-mean aerosol distribution for May 1998 is shown in Figure 4a. This can be compared with the climatological monthly mean distribution from the Nimbus 7 TOMS for May of the climatological reference period 1979 through 1992 (Figure 4b). Both 1998 and the climatological distributions show the two transport regimes, one to the north-northwest along the coast of the Gulf of Mexico, and one westward over the tropical Pacific Ocean, consistent with the daily maps in Figure 3. The mean values for 1998 are clearly larger than the climatological values, indicating that smoke was present in greater than average amounts during May 1998.

To provide further information on the unusual nature of the smoke production during 1998, Figure 5 shows the probability distribution of the daily maximum aerosol index value within Region B for 1998 and for the climatological period. That is, Figure 5 shows the number of days during which the maximum daily aerosol index in Region B fell within a range of values. Recall that the aerosol indices are averaged over $1^\circ \times 1.25^\circ$ boxes, so values are smoothed to that scale. To compare 1998 with the climatological period, the results are expressed in terms of days per month. It is important to note that other UV-absorbing aerosols, such as Saharan dust transported across the Atlantic Ocean, are reflected in these statistics. It is apparent that the two distributions are very

| Table 1. General characterization of the flow from the smoke production region during May 1998 |
|---|---|---|
| Period | Dates | Direction of Transport |
| 1 | May 1-4 | split, primarily northward, southern part moves westward |
| 2 | May 5-12 | northward |
| 3 | May 13 | transition |
| 4 | May 14-19 | westward |
| 5 | May 20 | transition |
| 6 | May 21-23 | northward |
| 7 | May 24-31 | split northward and westward |
dissimilar. During 1998, 18 days had maximum aerosol indices greater than 4.2. On average, only ~1 day per month had values that high during the climatological reference period. While more than half of the days during the climatological period have an aerosol index below 2.0, there is no single day during May 1998 in this range. The mean daily maximum for May 1998 is 4.17, while the mean daily maximum for the Nimbus 7 climatology is 2.11, approximately half of the 1998 average. These data show that there are anomalously high concentrations of aerosols present during the spring of 1998 in Region B. Assuming that this signal is mostly due to biomass burning aerosols, it can be concluded that more smoke than average was produced during May of 1998, and that large amounts of smoke were present on many more days than average.

4.3 Trajectory Validation

We turn now to the question of the role played by transport during the 1998 event. Because the initial distribution of smoke near the fires is not well known, it is necessary to confirm that our simplified initial condition for the trajectories provides a reasonable approximation to the initial smoke distribution. To do this, plume maps from the trajectory calculations are compared qualitatively with the daily TOMS aerosol maps. A plume map for a given time shows the instantaneous distribution at that time of all parcels released within the source region during the previous 9 days. Recently released parcels are typically still in or near the source region, while parcels released earlier may have been transported completely out of the study region. The purpose of these
Plate 1. TOMS aerosol index maps (gray scale) and trajectory plume maps (colored parcels) for selected days in May 1998. The initial pressure of a parcel is given by the color scale.
Figure 6. Trajectories for parcels initialized at 850 hPa on selected days during May 1998. Tick marks represent parcel positions at 6-hour intervals.

maps is to represent the distribution of smoke from a steady, continuous source. A steady, continuous source is approximated in this case by releasing new “puffs” of parcels every 6 hours within the source region. For this purpose we use the three-dimensional trajectories. Plume maps are created at 1800 UTC to most closely match the time of the TOMS satellite overpass for the region (approximately 1700 – 1800 UTC). Note that the TOMS is not sensitive to aerosols that lie underneath continuous cloud layers, so aerosols in some locations may not be detected by the TOMS.

Plate 1a displays the TOMS aerosol index for May 9 overlaid with the plume map for May 9 at 1800 UTC. It is important to note that fires are also present on the west coast of Mexico (directly west of Region A) that contribute to the plume over the Pacific. These fires are not specifically represented in the trajectores with our initial conditions. In general, agreement between the TOMS aerosol data and the plume maps is good, particularly over the western Gulf of Mexico. Over the southeastern United States, the modeled plume does not widen as much as is shown by the TOMS data, and parcels initialized at the lowest two levels (colored black and magenta) are transported too far northward. The differences could be due to errors in the trajectories, errors in the initial locations of the parcels, or unobserved smoke. However, the locations of modeled parcels do capture the essence of the northward moving plume’s turn to the east and southeast. The passage of the cold front through North America on May 10 is also modeled adequately (Plate 1b).

Plates 1c, 1d, and 1e show TOMS aerosols and plume maps for May 15, 16, and 17, respectively. May 15 shows the
greatest northward extent of the plume, as deduced from the TOMS data, and the beginnings of a westward plume emanating from the source region. The westward transport regime over the source region is firmly established by May 16, and both TOMS data and the trajectories indicate the progression of a cold front through North America. The plume grew significantly to the west after May 15. Finally, on May 17, a cold front progressed to the north coast of the Gulf of Mexico. From the TOMS data it is evident that many of the aerosols previously covering the midwestern United States were dispersed. Local observations and the measurement by the Raman lidar of the total aerosol scattering coefficient at 550 nm at the ARM site document the passage of the cold front and the resulting improvement in visibility [Pepper et al., 2000]. The remnants of the northward plume were concentrated over the northern half of the Gulf of Mexico. The westward plume more than doubled in size during the last 24 hours.

The maximum westward coverage of the aerosol plume occurred on May 20 (Plate 1f). Again, the modeled parcels acceptably depict the location and extent of the aerosol plume. Some parcels, especially at 750 and 700 hPa, initially move westward across Mexico and curve north and east into the central United States. These parcels tend to be widely dispersed, and the associated aerosol index values may have been too low to be registered by the TOMS.

Given the observational limitations, the uncertainties in the winds, and the simplifying assumptions (steady smoke source represented by discrete, 6-hour puffs), the agreement between the TOMS observations and the trajectories is quite good. The collocation evident in the previous examples shows that the three-dimensional trajectory plumes adequately model the aerosol plumes measured by the TOMS instrument. The best agreement between the trajectories and the TOMS data is for parcels initialized between 850 and 750 hPa.

4.4. Trajectory Analysis

Having established that the trajectories provide a reasonably good representation of the smoke transport for 1998, that transport can be compared with the climatological transport for the preceding 20-year period. On the basis of the comparison in the previous section, we use the trajectories of air parcels initialized at 850 hPa to represent the smoke transport.

Figure 6 shows the trajectories of parcels initialized in the source region at 1800 UTC on selected days in May 1998.

![Figure 7. Time-mean horizontal wind fields in m s⁻¹ at 850 hPa for selected periods during May 1998.](image-url)
During the first four days of May, the transport was primarily northward (Figure 6a). Most parcels move northward, while those on the southern edge of the source region move southwest and west. Over the 4-day period, this pattern gradually changes, and all parcels experience northward transport.

The predominately northward flow continues for the week beginning May 5. On May 5, 6, and 7, trajectories make an eventual turn to the east as the air reaches the United States. Figure 6b shows that trajectories initialized on May 12 remain northward from the source region but diverge over eastern Texas. During May 13 and 14, the initial direction of transport changes from northward to westward. Parcels initialized on May 18 move southwestward away from the source region (Figure 6c).

The flow changes to northward once again around May 20, as can be seen in Figure 6d. Parcels initially move to the west, but after several days the flow reverses and parcels are carried back toward the source region before moving northward. The northward flow continues through May 23 with parcels eventually turning east near 40°N (Figure 6e). During the last few days of the month there is a split transport pattern. As shown by Figure 6f, parcels initially located in the southwestern half of the source region move southwestward, while parcels initialized in the northeastern part move north and east across the Gulf of Mexico and the southern United States. The trajectories generally agree with the back trajectories from the Oklahoma ARM site presented by Pepler et al. [2000].

These variations in the flow regime are reflected in the mean winds averaged over periods of a few days. Figure 7a shows the mean horizontal wind field at 850 hPa for May 2 to May 12. During this period the winds are predominately from the south-southwest across the source region with southwesterlies off the southern coast of Mexico.

The mean winds are significantly different for the period between May 14 and May 20. As shown in Figure 7b, the mean wind is east-northeasterly over the source region. To the south of the source region, there is an area of very strong easterlies associated with the southern edge of a closed high centered over the northern Gulf of Mexico. The mean vector wind field for the third time period, May 21 through May 26 (Figure 7c), is similar to the first period discussed in this section with southeasterly winds over the source region.

Finally, Figure 7d shows the mean fields calculated for May 27 to May 31. The winds over the source region average out to reveal no strong overall pattern. Winds near the northeast corner of the source region are light and from the southeast, while winds over the rest of the area are also light and generally north-northwesterly. Winds directly to the east of the source region are from the southeast and are significantly stronger.

The climatological mean wind field at 850 hPa for May of 1978 to 1997 is shown in Figure 8. The mean winds across the source region are diffuent. The flow in the northern part of the source region and across the Gulf of Mexico is associated with the clockwise circulation around the subtropical high. The flow across the southern part of the source region is primarily easterly. To the west of the source region, there is an area of very light winds surrounded by a slight clockwise circulation. The diffuence between the air that remains in the tropical easterlies and the air that circulates northward around the subtropical high is located near the source region. As the flow fluctuates, it is natural that the transport from the source region is sometimes northward and sometimes westward.

In order to determine whether the transport in 1998 was unusual, we compare the transport for May 1998 with a climatology of transport for May from 1978-1997. The probability distributions of parcel locations are estimated by counting parcels in $2\times2$ longitude-latitude grid boxes. The resulting values indicate the probability of a parcel released in Region A being located in a specific grid box at any time during the month. Parcels between the 975- and 725-hPa pressure levels are used to represent the lower troposphere.

Figure 9 illustrates the parcel location probability density function for May 1998 (Figure 9a) and for the climatology (Figure 9b). Because of the larger sample size, the climatological field is smoother than that for 1998. Both averages exhibit similar features overall, including an area of higher probabilities extending from the source region to the northwest and a second arm extending from the source region to the west-southwest. These arms are indicative of the prevailing northward or westward transport from the source region both in May 1998 and during the climatological period (Figures 4 and 8). Neither distribution shows any significant eastward transport.

We compare 1998 with the climatology by subtracting the climatology from the 1998 field (Figure 9c). Compared to the climatology, the probability of northward transport is larger in 1998, while the probability of westward transport is smaller. The difference in northward transport is most obvious in the
Figure 9. (a) Probability of transport to a given location for May 1998. (b) Same as Figure 9a except for the 20-year climatology for 1978-1997. (c) May 1998 transport probability anomaly (1998 minus climatology). Positive values are shown by solid lines and negative values by dashed lines. (d) Standard deviation of the monthly mean transport probabilities during the climatological period. All values are scaled by $10^5$. To avoid clutter, contours representing large values were omitted.

Figure 10. Average number of parcels per day in Region C. May 1998 has the highest value during the 21-year period.
central and eastern United States. To gauge the magnitude of these differences, Figure 9d shows the standard deviation of the monthly mean parcel location probabilities for the 20 years of the climatological period. The shape of the standard deviation's spatial distribution is very similar to the probability density function for the climatology. Comparison of Figures 9c and 9d indicates that both the westward and northward anomalies for 1998 are large compared to the standard deviation. While the character of the transport in 1998 is similar to the climatology, the intensity of the northward flow is unusual.

In order to further compare the intensity of the northward transport during May 1998 to the climatology, the number of parcels within Region C and below 700 hPa is calculated for each day during the month. Figure 10 shows the daily average number of parcels within Region C for the month of May for each year. May 1998 has the highest value of any year with 947 parcels per day, which represents 65% of the 1440 parcels released daily as a part of this comparison. That value is more than 2 times larger than the 20-year average of 384 parcels per day. Figure 11 shows the number of days with specific parcel counts for May 1998 and for the climatology. Attention is immediately drawn to the numerous days with large numbers of parcels in the 1998 distribution. From this information, it can be concluded that the transport from the source region into Region C during May 1998 was unusually strong in 1998.

5. Conclusions

During April through June of 1998 large amounts of smoke were transported northward from Central America into the central and southern United States. The smoke can be traced back to biomass burning in Central America that is part of the seasonal agricultural cycle. In this study we investigate whether the unusual amounts of smoke reaching the United States were due to exceptional smoke production or to anomalous northward transport.

Smoke production in May 1998 is evaluated by using the aerosol indices retrieved by the Earth Probe Total Ozone Mapping Spectrometer. The 1998 values are compared to a climatology from 1978-1992 from the Nimbus 7 Total Ozone Mapping Spectrometer. Statistical comparison shows that there are significantly more aerosols in Central America (Region B) during May of 1998 than is typical of the climatology. Both monthly mean amounts and the number of days with large daily maximum values are larger in 1998.

The role of transport is evaluated by computing parcel trajectories from the region of widespread burning (Region A) for 1998 for the 20-year period from 1978 through 1997. During both May 1998 and the preceding years, transport from the region tends to alternate between northward transport into the United States and westward transport into the tropical Pacific Ocean. The intensity of northward transport during May 1998 is unique with respect to the 20-year record from 1978 to 1997. Other years, however, have had strong northward transport from the source region. The fact that large amounts of smoke were present on many days during 1998 meant that when the flow turned toward the north, there was smoke present to be transported. On the basis of these results, we conclude that anomalously strong flow helped to carry the smoke northward into the United States, but that the unusually widespread burning and smoke production was necessary for the anomalously large amounts of smoke in the United States.

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References


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