

New Directions: Eruptive Transport to the Stratosphere: Add Fire-Convection to Volcanoes[☆]

As this piece is being written (August 2003) hundreds of fires are raging in the boreal forests of Russia and Canada, and in the temperate forests of the western USA. Interested scientists across the globe are monitoring them from space. Satellite instruments such as NASA's venerable TOMS monitor the smoke aerosols from these fires, some of which emitted smoke plumes that were traceable over a distance of more than 5000 km (Russia to the USA). Clearly such smoke plumes were thick enough and/or lofted high enough to survive scavenging forces and elongate sedimentation time.

In the northern summer of 1998, similar fires occurred in the boreal zone of Russia and Canada. According to Fromm et al. (2000, *Geophysical Research Letters* 27, 1407–1410) these fires were responsible for creating plumes of smoke that entered the lower stratosphere in July and August, and resided in detectable amounts well into October. The postulated mode of entry: a combination of intense (and extensive) crown-fire burning, and extreme convection in thunderstorms. At its greatest extent, the stratospheric smoke layers resided at 16 km (430 K potential temperature), a full 6 km above the tropopause. In late summer and early fall this stratospheric smoke cloud was seen to spread completely around the globe at middle and high latitudes. There were no reported volcanic eruptions in 1998 to explain such an extensive, deep intrusion.

As remarkable as 1998 was, it was not a singular event. In 2001 a similar phenomenon occurred. Detailed vertical profiles of aerosol extinction from the Naval Research Laboratory's Polar Ozone and Aerosol Measurement (POAM) III and NASA's Stratospheric Aerosol and Gas Experiment (SAGE) II, as well as an assortment of ground-based lidars in Europe, North America, and the high Arctic recorded an extensive and enduring stratospheric aerosol enhancement. Once again, there was no reported volcanic eruption of sufficient magnitude to explain these observations. The

TOMS aerosol index data helped identify a localized blowup in Canada on 29 May, and a suite of other satellite-borne imagers (SeaWiFS, MODIS, AVHRR, DMSP, and GOES) allowed Fromm and Servranckx (2003, *Geophysical Research Letters* 30(10), 1542, doi:10.1029/2002GL016820) to trace the stratospheric smoke cloud back to an individual pair of supercell thunderstorms that erupted over a noteworthy boreal forest fire in Alberta. One of the remarkable revelations of this case was that the smoke cloud on the day immediately following the "eruption" was optically opaque to the nadir viewers at the tropopause level. This finding alone is sufficient to require a new look at the power of extreme convection to exacerbate combustion and smoke production, and then deposit copious amounts of boundary layer material deep into the atmosphere.

In addition to the extensive observations in 1998 and 2001, there is evidence of extreme fire conditions leading to long-distance and/or stratospheric intrusion in other years as well. In 1992, a fire in Idaho, USA, was found to be the origin of stratospheric measurements of methyl cyanide (Nathaniel Livesey, personal communication, 2003), a gas emission known to be related to biomass burning. As far back as 1950, a long-burning fire in western Canada was known to be the starting point for a smoke plume that darkened skies in the eastern USA and caused observations of blue suns and moons over Europe. In that case, aircraft observations of the plume were made over Scotland at an altitude of 11 km. The scientific literature contains multiple references to observations of mystery clouds in the stratosphere (i.e. in the absence of a known source such as a volcano). Perhaps an explanation of these puzzling observations is to be found in the above-mentioned recent discovery.

The work of Stocks et al. (1998, *Climatic Change* 38(1), 1–13) projects a significant increase in the frequency and severity of boreal fires under a changing climate. In fact, there is speculation that climate change has contributed directly to the severe forest fire seasons across Russia and Canada in recent years, including an unprecedented 21 million hectares burned in Siberia in 2003. Projected climate change will result in longer fire seasons, and greater areas burned under drier

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conditions, resulting in greater fuel consumption and fire intensity levels (both major contributors to convection column development) resulting in more extensive hemispheric transfer of boreal fire smoke. Larger areas burned will also result in a younger age-class structure in boreal forests and a net loss of carbon from the biosphere to the atmosphere, creating the likelihood of a positive feedback loop between climate change and boreal fire activity.

The discovery that smoke from boreal forest fires has been injected into the stratosphere is fundamental in atmospheric science, with far reaching potential implications in many important areas of atmospheric science including climatology and atmospheric chemistry. First, aerosols in the atmosphere reflect light from the sun back to space, resulting in a cooling of the earth's surface. The added significance of stratospheric aerosols is that, in the stratosphere, aerosols can be efficiently disbursed globally because winds are strong and because aerosol residence times are long (gravitational settling times are long and the aerosols are elevated far above tropospheric scavenging mechanisms such as clouds and precipitation). The potential importance of large stratospheric aerosol loading on global climate has been known for quite some time. The most extreme example occurred after the eruption of Tambora in 1815, which is believed to have injected the largest amount of aerosol material in the stratosphere of any volcano in the historical record. The following summer (1816) has become known as the "year without a summer" in the USA and Western Europe, with snow in July, frost in all summer months, and total crop failures.

It has long been accepted that there are only two sources of stratospheric aerosol (Brasseur and Solomon, 1986, *Aeronomy of the Middle Atmosphere*, Reidel, Dordrecht, 452pp.). Namely: (1) slow upward transport of carbonyl sulfide (OCS) generated at the surface and eventually oxidized into sulphuric acid droplets, and (2) injection of ash and SO₂ (which also produces sulphuric acid droplets) from volcanic eruptions.

Our results show that intense convection, spawned by a combination of heating due to forest fires and weather disturbances, must be added to this list of potential sources of stratospheric aerosol. However, the global magnitude of this source, compared to the other known sources, is by no means clear. It is also important to point out that the implications of the stratospheric forest fire smoke discovery is not limited to the stratospheric aerosol budget. Transport of material (both aerosol and gaseous compounds) from the troposphere to the stratosphere is a key issue in atmospheric science for a number of reasons. For example, the global ozone depletion problem is primarily the result of the transport into the stratosphere of chlorofluorocarbons (CFC) compounds produced anthropogenically and released into

the atmosphere near the surface. These chemicals are inert and long-lived in the troposphere, but become photochemically active in the stratosphere, and take part in catalytic chemical cycles that destroy ozone. In addition, the transport of greenhouse gases into the stratosphere is a critical part of the atmospheric global warming conundrum. It is generally assumed in models used to study these phenomena that transport from the troposphere to the stratosphere occurs only in the tropics—outside of the tropics only transport from the stratosphere to the troposphere is considered. Our findings show that the extratropical tropopause is not an iron lid, and that transport across it can and does occur.

As we have discussed here, the discovery that boreal forest fire smoke can be injected into the stratosphere via intense thunderstorms is very surprising, and has a large range of potential ramifications for key atmospheric science problems. Because the details of this potentially important process remain largely unexplored, this finding has opened a whole new class of atmospheric research issues and studies. First and foremost, the global significance of this source of aerosol needs to be ascertained. To do this, studies need to be done to understand the meteorological and forest fire conditions necessary to effect stratospheric injection. From this information, it will be possible to make estimates of the total mass loading of stratospheric aerosol from this source, and compare this to the other known stratospheric aerosol sources. The radiative effect of this class of aerosols also needs to be calculated, which will require detailed knowledge of their composition. An important goal of this research would be to develop a quantifiable understanding of this phenomenon, which can be incorporated into global atmospheric climate models and, thereby, to begin to study its climatic significance.

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