An Analysis of the Physical, Chemical, Optical, and Historical Impacts of the 1908 Tunguska Meteor Fall

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A detailed analysis of the physical nature and photochemical aftereffects of the explosive cometary meteor Tunguska is presented. The physical manifestations of the event (the acoustic and seismic waves, forest damage, and so on) are shown to be consistent with the entry of a 5-million-ton object into the Earth’s atmosphere at 40 km sec$^{-1}$. The meteor apparently had a very low effective density ($<0.01$ g/cm$^3$) due either to its intrinsic porous structure, to shattering in orbit far from the Earth, or to breakup upon initial impact with the Earth’s upper atmosphere. Aerodynamic calculations are used to demonstrate that the shock waves emanating from the falling meteor could have generated up to 30 million tons of nitric oxide (NO) in the stratosphere and mesosphere.

The photochemical consequences of such an immense Tunguska-related NO injection are investigated with the aid of a fully interactive one-dimensional chemical-kinetics model of atmospheric trace constituents. The first year after the Tunguska fall (from mid-1908 to mid-1909) a 35–45% hemispherical ozone depletion is predicted with the model: declining but still substantial ozone depletions are calculated in subsequent years. Atmospheric transmission data collected by a research team of the Smithsonian Astrophysical Observatory (APO) at Mount Wilson, California, from 1908 to 1911 are analyzed for ozone absorption in the Chappuis bands. Statistical analysis of the APO data reveals an ozone variation of 30–15% over this period, supporting the theoretical predictions.

The optical anomalies which followed the Tunguska event are reviewed for evidence of NO$_2$–O$_2$ chemiluminescent emissions, NO$_2$ solar absorption, and meteoric dust turbidity. The chemical afterglows are shown to be intense enough to account for some of the unusual night-time light displays seen after the fall, but not widespread enough to explain the “light nights” and glowing skies reported throughout Eurasia. These phenomena appear to be related to the dust and water vapor deposited by the meteor at the cold summer mesopause, resulting in the formation of dense noctilucent clouds. Only circumstantial optical evidence for a large Tunguska NO$_2$ enhancement is found, which can not be used to calibrate independently the NO injection by the meteor. The suggestion of a dust veil created by the Tunguska explosion is revealed by the APO transmission data. We deduce that nearly 1 million tons of pulverized dust may have been deposited in the mesosphere and stratosphere by the Tunguska fall, which agrees with previous estimates of the meteor mass influx.

Possible climate changes triggered by the Tunguska event are investigated. The most important climate anomaly identified in the post-Tunguska era is a 0.3° K cooling of the Northern Hemisphere which lasted for almost a decade. Several large volcanic eruptions occurred during this period which also played a role in the temperature change. However, radiation transport calculations are reported which suggest that Tunguska contributed to the cooling trend. The lessons of Tunguska for other important geophysical problems, such as ozone/weather coupling and the ancient extinction of the dinosaurs, are also explored. It is concluded that more rigorous investigations of the physics and chemistry of the Tunguska event are warranted.
1. INTRODUCTION

On the morning of June 30, 1908, at 7:17 AM local time, a huge bolide plunged toward Earth over Central Siberia (60° 55' N, 101° 57' E) and exploded with tremendous force high in the atmosphere. The blast devastated nearly two thousand square kilometers of dense Siberian forest. A local trader sixty kilometers away was thrown to the ground by the blast wave and seared by the heat. The brilliant falling meteor was seen for hundreds of kilometers around, the explosion was heard a thousand kilometers away, and the pressure disturbances traveled twice around the globe.

Scientific knowledge of the Tunguska event has been reviewed by, among others, Krinov (1966) and Hughes (1976). Theories of the event have included cosmic objects as different as antimatter rocks (Cowan et al., 1965), black holes (Jackson and Ryan, 1973), near-critical fissionable masses (Hunt et al., 1960) and small comets (Whipple, 1930). It is now widely believed that the Tunguska meteor was a small cometary fragment (Wick and Isaacs, 1974; Brown and Hughes, 1977; Kresak, 1978), although an alternative model assuming a highly porous heat conductive meteoroid has been forwarded (Liu, 1978). Theoretical and experimental simulations of the event demonstrate that an object of very low density flying at hypersonic velocity can produce the observed ground tremor, acoustic wave, and forest damage (Korobeinikov et al., 1976; Petrov and Stulov, 1975; Ben-Menahem, 1975).

Following the Tunguska explosion, anomalous atmospheric emissions brightened the night-time sky over Europe and Asia on several consecutive evenings (Krinov, 1966). Two weeks after the event, moreover, sunlight was noticeably dimmed for several weeks over North America (Fe senkov, 1949). Park (1978) suggested that both of these unusual phenomena may have been the result of nitric oxide (NO) generated during the meteor fall. In air heated by the shock waves surrounding a high-velocity meteor, the temperature can reach tens of thousands of degrees Kelvin, and the N₂ and O₂ molecules can be fully dissociated. As the meteor trail expands and cools, most of the N and O atoms recombine into N₂ and O₂, but some recombine into NO. Park (1978) estimated that the amount of nitric oxide generated by the Tunguska meteor may have been several tens of millions of tons (1 ton = 10³ kg = 10⁶ g), which is certainly enough to have triggered widespread atmospheric disturbances.

In this paper, we explore some of the atmospheric phenomena associated with the Tunguska meteor fall. In Section 2, the physical nature of the Tunguska meteor is discussed. This provides a basis for estimating the quantity of nitric oxide produced by the event—using the approach of Park (1978)—in Section 3. In Section 4, we describe the stratospheric/mesospheric photochemical model which is utilized to calculate the Tunguska-induced ozone–NOx perturbations. These calculations are reviewed in Section 5. Section 6 is devoted to an analysis of the atmospheric transmission data recorded from 1908 to 1911, which bear on the Tunguska problem. The “light nights” and other optical anomalies are addressed in Section 7. Possible climatological, environmental, and historical implications of the Tunguska fall are raised in Section 8. Our major findings are summarized in the concluding Section 9.

2. THE NATURE OF THE TUNGUSKA EVENT

2.1. The Tunguska Meteor Parameters

The Tunguska event caused many unusual and widespread disturbances, some of which were recorded scientifically. Four reliable pieces of information relate to

1. the magnitude and direction of the seismic waves produced by the meteor explosion,
2. the magnitude of the accompanying acoustic (barometric) wave,
(3) the speed of propagation of the acoustic wave, and
(4) the pattern of forest damage and lack of impact craters.
Additional information about the event is obtained from
(5) the discovery of microscopic spherules of iron, nickel, and silicate compounds at the site of the event,
(6) eyewitness accounts,
(7) meteorological anomalies, and
(8) astrophysical and geophysical constraints.

A comprehensive scientific study of all of the recorded information has not yet been carried out. Instead, various investigators have analyzed parts of the available data in order to determine the nature and physical parameters of the meteor. Table I summarizes most of the significant published results of this research. There is a general consensus on the entry velocity of the meteor, $U_0$ (30 to 40 km sec$^{-1}$), and the angle of incidence (15 to 40°). Moreover, data pertaining to the velocity dispersion of the acoustic waves generated by the meteor indicate that the approximate center of the high pressure that produced the waves was located at an altitude of 6 to 9 km (Krinov, 1966; Ben-Menahem, 1975). Simulations of the pattern of forest destruction corroborate this height range (Korobeinikov et al., 1976). There is, however, significant disagreement over the other characteristics of the Tunguska body, most importantly its mass, density, and composition. Below, we attempt to synthesize the available information in order to determine these remaining uncertain meteor parameters. Table II gives these properties, and reviews how they were determined.

Ben-Menahem (1975) accurately deduced the ground impulse of the meteor explosion using recorded seismographic data. The vertical and horizontal momentum components are, respectively, $7 \times 10^{18}$ and $1.4 \times 10^{18}$ dyne-sec. The presence of a horizontal component suggests that the impulse was caused by a moving object as opposed to a spherical explosion. The horizontal impulse detected by the seismographs, moreover, would be only a small fraction of the total momentum of the meteor; the initial horizontal momentum imparted to the atmosphere is only weakly coupled to the ground. The vertical impulse ($7 \times 10^{18}$ dyne-sec) is more likely to represent the original vertical momentum of the falling body, because the bulk of the air entrained downward by the entry flight could efficiently transfer its momentum to the ground. Neglecting the effects of buoyancy and assuming an angle of incidence of 30°, the momentum of the body along the direction of flight would be $7 \times 10^{19}$ /sin 30° = 1.4 $\times 10^{19}$ g cm sec$^{-1}$. For an entry velocity of 40 km sec$^{-1}$, the initial mass, $M_0$, would be $3.5 \times 10^6$ tons. If, on the other hand, the angle and velocity of entry were 20° and 30 km sec$^{-1}$, respectively, the initial mass would be $7.9 \times 10^6$ tons. Considering the dissipative effects of air motions and buoyancy, therefore, it may be concluded that the initial mass of the Tunguska meteor was $M_0 \approx 3.5 \times 10^6$ tons. Such values are in close agreement with the initial mass of ~2 $\times 10^6$ tons deduced by Bronshten (1976) using an extrapolation of the properties of bolides observed by the Prairie Network.

The initial kinetic energy of the meteor, which follows from the momentum analysis, is $\approx 2.8 \times 10^{25}$ ergs. This energy is considerably larger than the frequently quoted "blast energy" (equivalent energy of a point explosion) of $5 \times 10^{23}$ ergs (or 12.5 megatons nuclear equivalent) deduced by Hunt et al. (1960), Ben-Menahem (1975), and others. Ben-Menahem estimated the blast energy by comparing the vertical component of the ground impulse for the Tunguska fall with a known impulse from a nuclear explosion. A nuclear explosion, however, is spherical and does not generally create a horizontal impulse unless the terrain is highly irregular. Hence, a nuclear explosion is not a good analogy to the Tunguska event.
### Tunguska Meteor Parameters

<table>
<thead>
<tr>
<th>Initial mass $(10^{12} \text{ g})$</th>
<th>Initial velocity $(\text{km sec}^{-1})$</th>
<th>Effective density $(\text{g cm}^{-3})$</th>
<th>Initial (final) energy $(10^{20} \text{ ergs})$</th>
<th>Angle of incidence $^\circ$ elevation</th>
<th>Flight azimuth $^\circ$ E from N</th>
<th>Type and size (radius) of the body</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Solid ice meteor</td>
<td>Grigoryan (1979)</td>
</tr>
<tr>
<td>$0.5^a$</td>
<td>$31 \pm 2$</td>
<td>$&lt;1.0^a$</td>
<td>—</td>
<td>$-0.1$</td>
<td>$-30$</td>
<td>Extinct comet fragment (Encke) (~50 m)</td>
<td>Kresak (1978)</td>
</tr>
<tr>
<td>~0.4</td>
<td>40</td>
<td>0.1</td>
<td>—</td>
<td>15</td>
<td>—</td>
<td>Porous meteoroid $^b$ (~100 m)</td>
<td>Liu (1978)</td>
</tr>
<tr>
<td>~2</td>
<td>25</td>
<td>$&lt;1.0$</td>
<td>—</td>
<td>11</td>
<td>—</td>
<td>Microcomet (porous, low-density object)</td>
<td>Bronshten (1976)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(0.039-0.052)^c$</td>
<td>$35-40^d$</td>
<td>100-115</td>
<td></td>
<td>Korobeinikov et al. (1976)</td>
</tr>
<tr>
<td>0.004–1.1</td>
<td>40</td>
<td>$&lt;0.01$</td>
<td>—</td>
<td>20</td>
<td>—</td>
<td>Bound crystalline object like snow (100–300 m)</td>
<td>Petrov and Stulov (1975)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt;0.001$</td>
<td>$&lt;0.05 \pm 0.01$</td>
<td>—</td>
<td>—</td>
<td></td>
<td>Ben-Menahem (1975)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$&lt;1.0$</td>
<td>—</td>
<td>—</td>
<td>Pre-type 1 carbonaceous chondrite</td>
<td>Whipple (1968)</td>
</tr>
<tr>
<td></td>
<td>35–40</td>
<td></td>
<td>—</td>
<td>$28 \pm 12.5$</td>
<td>115</td>
<td></td>
<td>Zotkin (1966)</td>
</tr>
<tr>
<td></td>
<td>$1.0^e$</td>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Small comet or comet fragment (100–350 m)</td>
<td>Zotkin and Tsikulin (1966)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
<td>Fesenkov (1966)</td>
</tr>
<tr>
<td></td>
<td>20–47</td>
<td></td>
<td>—</td>
<td>17</td>
<td>105</td>
<td></td>
<td>Krinov (1966)</td>
</tr>
<tr>
<td>0.1–10</td>
<td>28–40</td>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
<td>Bronshten (1961)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(0.02-0.06)$</td>
<td>—</td>
<td>—</td>
<td></td>
<td>Hunt et al. (1960)</td>
</tr>
<tr>
<td>4.9</td>
<td>40</td>
<td>0.002</td>
<td>4.0</td>
<td>30</td>
<td>115</td>
<td>Cometary meteoroid, loose crystal matrix with embedded dust (850 m)</td>
<td>Present study</td>
</tr>
</tbody>
</table>

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$^a$ A "conservative" estimate according to Kresak (1978).

$^b$ The body of the meteoroid is required to have a very large heat conductance.

$^c$ Only the last 20 km of the flight path are considered.

$^d$ Shurshalov (1978) has recently extended this work and found that an angle of incidence of 40$^\circ$ best fits the observed forest destruction pattern.

$^e$ Fesenkov's estimate for the dust component of the total mass.

$^f$ Based on the model of Park (1978).
The Tunguska Meteor Fall

Table II
Properties Deduced for the Tunguska Meteor

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry velocity $U_0$</td>
<td>$40 \text{ km sec}^{-1}$</td>
<td>Celestial orbital parameters, and typical meteor velocities.</td>
</tr>
<tr>
<td>Entry angle</td>
<td>$30^\circ$</td>
<td>Eyewitness accounts, ground blast effects, and association with comet Encke.</td>
</tr>
<tr>
<td>Altitude of explosion $h$</td>
<td>$6-9 \text{ km}$</td>
<td>The pattern of forest destruction, and the velocity of the acoustic waves.</td>
</tr>
<tr>
<td>Entry mass $M_0$</td>
<td>$5 \times 10^6 \text{ tons}$</td>
<td>The measured ground impulse in conjunction with the deduced entry velocity and flight angle.</td>
</tr>
<tr>
<td>Initial energy $E_i$</td>
<td>$4 \times 10^{18} \text{ ergs}$</td>
<td>Calculated as $\frac{1}{2} M_0 U_0^2$.</td>
</tr>
<tr>
<td>Final energy $E_f$</td>
<td>$5 \times 10^{21} \text{ ergs}$</td>
<td>The equivalent blast energy required to produce the observed seismic disturbance.</td>
</tr>
<tr>
<td>Effective radius $R_0$</td>
<td>600-1000 m</td>
<td>Inferred from the requirements of a low air speed to produce an &quot;explosion,&quot; and a large air mass to stop a hypersonic body.</td>
</tr>
<tr>
<td>Effective density $\rho$</td>
<td>$\sim 2 \times 10^{-3} \text{ g cm}^{-3}$</td>
<td>Identification of the meteor as a dessicated cometary fragment shattered in flight; computed from the deduced mass and radius.</td>
</tr>
</tbody>
</table>

* Values deduced by previous workers; see Table I and the text.

The rapid energy loss of the meteor, and the poor analogy of the event to a spherical explosion, are best understood by analyzing the primary mode of dissipation of the initial kinetic energy of the Tunguska object. At hypersonic velocities, the shock waves generated by a meteor are highly anisentropic. This causes most of the kinetic energy lost to the air to be converted into heat rather than into mechanical work of compression, which is the source of the "blast" energy. The anisentropy is caused by the fact that the increases in temperature and pressure across a strong shock wave are both (roughly) proportional to the square of the Mach number. Thus the pressure increase is proportional to the temperature increase, as opposed to the isentropic case where the pressure increase varies as the $\gamma/(\gamma-1)$th power of temperature, where $\gamma$ is the specific heat ratio (note that $\gamma/(\gamma-1) > 3.5$). The resultant pressure rise across a shock wave is much smaller than the equivalent isentropic compression with the same temperature rise. It can be shown that, at $40 \text{ km sec}^{-1}$, only about $10^{-9}$ of the dissipated kinetic energy is converted into pressure work. At low Mach numbers, the conversion of kinetic energy to pressure work can become more efficient—potentially 14% at Mach 3 and 100% at Mach 1. In the case of the Tunguska meteor, the production of pressure work would be sharply peaked at a Mach number $\sim 3$ for two additional reasons. First, at high altitudes, where the Mach number is high, the absolute density of the atmosphere is too small to create a high pressure. Secondly, at Mach numbers $< 3$, the drag of the body is reduced to the point that kinetic energy is not efficiently transformed into pressure waves. Note that the heat dissipated by the flight of a body the size and velocity of the Tunguska meteor could, on average, raise the global atmospheric temperature by less than 0.002$^\circ \text{K}$, which is undetectable.

Because it is essential for a body to slow to $\sim \text{ Mach 3}$ before substantial pressure work can be produced, evidence that the Tunguska meteor was decelerated by the atmosphere is provided by the observed forest destruction and lack of impact craters. As we will show, this deceleration is critical to the generation of large quantities of NO.
It also implies that the Tunguska object was quite unusual in having a very low equivalent density. For slowing to occur, the momentum conservation law dictates that the body displace along its flight path an air mass much greater than its own mass; the necessary air mass may be approximated as 10 times the meteor mass (Baldwin and Scheaffer, 1971). Now, assuming that the meteor is a nonablating sphere with a mass of $3.5 \times 10^6$ tons and an incident angle of 30°, the equivalent average radius and density of the body are calculated to be $6.7 \times 10^4$ cm and 0.003 g cm$^{-3}$, respectively. We performed more sophisticated calculations, including factors such as ablation and fragmentation, and conclude that the initial equivalent radius of the meteor, $R_0$, was $\geq 6 \times 10^4$ cm, and its effective density, $\rho$, $\leq 0.003$ g cm$^{-3}$. The exact values depend on, among other things, the ablation properties of the meteor.

The size and density of the meteor can also be deduced by knowing the initial energy of the body from the momentum impulse and initial velocity and by knowing the blast energy able to produce the observed seismic waves. In this case, the meteor's energy at an altitude just above the observed explosion center is equated with the apparent blast energy observed at the ground. This procedure implicitly assumes that an object flying at a low supersonic velocity can create roughly the same pressure disturbance as a spherical explosion, which is reasonable. The size and density of the meteor are then related to the kinetic energy lost by the meteor above the explosion altitude. Park (1978) and Petrov and Stulov (1975) made detailed aerodynamic calculations of the slowing-down and ablation of the Tunguska meteor. They concluded that only a large body ($\sim 10^5$-cm radius) of low effective density ($\sim 0.002$ g cm$^{-3}$) could be stopped by the atmosphere yet carry the necessary "blast" energy to the upper troposphere.

The absence of impact craters at the fall site obviously supports the idea that the meteor was stopped by atmospheric drag. On the other hand, O'Keefe and Ahrens (1982) have shown that an ice meteor of very low density could impact a planetary surface at high velocity without producing a deep crater. In the case of Tunguska, for example, a density $\leq 0.01$ g cm$^{-3}$ would be called for. However, as noted above, such a meteor would interact strongly with the atmosphere and probably disintegrate above the ground.

In summary, the physical disturbances accompanying the Tunguska event point to a body of low effective density ($\sim 0.002$ g cm$^{-3}$), high initial velocity ($\sim 40$ km sec$^{-1}$), and substantial intrinsic mass ($\sim 5 \times 10^6$ tons). The flight of such an object through the atmosphere can explain most of the recorded data.

### 2.2. The Nature and Origin of the Tunguska Meteor

The parametric model of the Tunguska meteor described above does not specify its shape, structure, or origin. The proposed low effective density might be explained by a structure consisting of a loose agglomeration of crystals, or a swarm of separate small particles. The aerodynamic interactions between closely spaced particles can make the assembly behave like a single, solid body of low average density. In order to obtain the required effective density of $10^{-3}$ g cm$^{-3}$, a swarm of bodies of unit density separated by 10 times their mean radius is required. There are basically two possible origins for such an object: i.e., a cometary meteor of intrinsically low density, or a meteor of relatively high density broken up during flight through the atmosphere. These alternative hypotheses are examined below.

At the Tunguska fall site, Russian investigators collected meteoric debris consisting of submillimeter-sized spherules of iron, nickel, and silicates (Krinov, 1966). Most of the meteoric globules were found 20 to 80 km downwind of the explosion epicenter,
THE TUNGUSKA METEOR FALL

which is consistent with the theory that a meteor disintegrated at high altitude.

A question arises as to the means by which a large, dense, stony meteoroid can be decelerated in the atmosphere. As mentioned earlier, a high-density object of substantial size is not easily slowed-down by air friction. It must be assumed that extensive breakup occurs at high altitudes. Hunt et al. (1960) discussed the breakup of water droplets in high-velocity air streams caused when the stagnation pressure "punches out" the center of the drop to form a torus. The time for torus formation is roughly given by

$$t_b \sim 50 \frac{R}{U} \left(\frac{\rho}{1000 \rho_a}\right)^{1/2} \text{sec},$$

(1)

where $R$, $U$, and $\rho$ are the body radius, velocity, and density, respectively, and $\rho_a$ is the density of air at the altitude of torus appearance. Hunt et al. (1960) also reviewed evidence for this breakup mechanism in collected meteorite fragments. For a body having a density $\sim 0.1$ g cm$^{-3}$ (a typical value for a low-density stony meteoroid), (1) predicts that breakup can occur fast enough ($< 1$ sec) at 10 km to explain the observed Tunguska phenomenon, provided that the meteor’s original radius $R$ is $\leq 30$ m or, equivalently, its initial mass is $< 10^6$ tons. For higher meteor densities, even smaller radii and masses would be required. This explanation thus conflicts with the minimum mass of $3.5 \times 10^6$ tons established by the seismic data.

Theoretical studies of the breakup of solid meteors by aerodynamic stress have been carried out. The breakup depends critically on the bulk strength of the body, the presence of fractures, its shape, rotational velocity, and so on (Passey and Melosh, 1980). Grigoryan (1979) and Melosh (1981) have shown that kilometer-sized meteors could be significantly fragmented and dispersed at high altitudes, particularly at low angles of incidence, even if they possess great strength. The most common type of meteors, carbonaceous chondrites, may have tensile strengths as low as $10^7$ dynes cm$^{-2}$, compared to iron meteorites with strengths $\sim 10^8$ dynes cm$^{-2}$ (Baldwin and Sheaffer, 1971). As a result, carbonaceous chondrites seldom reach the ground intact. When a fragile, high-velocity meteor is crushed in flight, the fragments may separate "explosively" (Krinov, 1966). A large ($\sim 1$ kiloton TNT equivalent) explosion, which occurred near Revelstoke, Canada, in 1965, left behind only a fine carbonaceous chondrite powder on a field of fresh snow (Folinsbee et al., 1967). Folinsbee et al. (1969) argue that such phenomena are fairly common.

If the Tunguska event was due to the fall of a stony meteor which broke up in flight, the breakup had to commence at high altitude in order to allow sufficient time for the body to be crushed. For a relatively small body (i.e., one with a radius $\leq 10$ m) early breakup is compatible with theory. For a body with a mass $\geq 10^6$ tons, however, the hypothesis is difficult to reconcile with the necessary deceleration and heating of the meteor. At high altitudes, the body is unlikely to split and slow down because the force-to-mass ratio is too small to cause a significant lateral movement of the fragments in the short time available. The time required for heat to penetrate the body increases roughly as the square of the radius. For a meteor with a radius $\geq 5$ m, heating of the interior leading to enhanced breakup would be virtually impossible unless the material has an extraordinarily high thermal conductivity (Liu, 1978).

A cometary origin for the Tunguska meteor is more plausible and therefore has been accepted by numerous investigators (e.g., Whipple, 1930; Fesenkov, 1969; Wick and Isaacs, 1974; Brown and Hughes, 1977; Kresak, 1978), though not without some reservations. It is generally believed that a comet is composed primarily of a loose agglomeration of frozen crystals of water, ammonia, carbon dioxide, and methane interspersed with cosmic dust. However, the density deduced above for the Tunguska
object (~0.002 g cm$^{-3}$) does not match that of either a comet nucleus (~0.1 g cm$^{-3}$) or tail (~10$^{-4}$ g cm$^{-3}$). It is unlikely that tidal disruption could break up a comet nucleus the size of the Tunguska meteor as it was engaged by the Earth's gravitational field, because the Roche limit dictates that the tensile strength be less than 1 dyne cm$^{-2}$ (Aggarwal and Oberbeck, 1974). Likewise, it is improbable that a comet which was disrupted near the Sun would reach the Earth as a well-contained swarm of particles.

Extraterrestrial bodies possessing intrinsic densities much lower than that of a comet core have not been identified. One possibility is a so-called “coreless” comet, which is theoretically possible but has yet to be identified, or a virgin comet in its initial circuits of the Sun. Another possibility is a fragment of a larger comet nucleus, which might be shattered yet spatially localized to such a degree that, upon entering the Earth's atmosphere, the shock waves of individual fragments merge into a single shock wave. Alternatively, a comet with a large fraction of volatile material might slowly sublimate on successive passes near the Sun, leaving behind a highly porous matrix. A piece of such a matrix could retain enough cohesion to reach the Earth intact. Comet Encke is a prime candidate as the parent comet for the Tunguska meteor (Kresak, 1978). Although the probability of such low-density objects colliding with the Earth is obviously quite small, the cometary hypothesis is more plausible than the alternative suggestion of a stony meteor. Accordingly, the cometary explanation of the Tunguska event is adopted in the present work. This theory does not conflict with the apparent discovery of meteoric debris at the fall site. A comet with a mass of several million tons would contain large quantities of metallic and stony materials.

2.4. The Aerodynamic Model

Park's (1978) aerodynamic model of the Tunguska meteor fall was adopted to make new calculations for the event. The model is consistent with most of the recorded data, as discussed earlier, and with the collision scenario just described. Park's model calls for an initial effective meteor density of 0.002 g cm$^{-3}$, mass of $5 \times 10^6$ tons, velocity of 40 km sec$^{-1}$, and flight elevation of 30°. Park's model is predicated on the sudden slowing-down of the meteor in the upper troposphere, leading to rapid breakup by thermal and mechanical forces (although the physical processes of breakup are not treated in the model). In Park's calculations, the residual kinetic energy of the me-
A meteor at ~10 km is equated with the energy of the terminal “explosion.”

Park’s model for Tunguska is similar to that of Petrov and Stulov (1975) except that Park utilizes a more realistic meteor ablation rate. Petrov and Stulov assumed a priori that convection governs the heat transfer to a falling body. Park (1978) and Biberman et al. (1980) showed that the radiative heat transfer rate is several orders of magnitude greater than the convective rate, which results in much faster ablation of the meteor.

Park (1978) made his aerodynamic calculations for altitudes up to 50 km. At greater heights, his assumption of an optically thick radiation field in front of the meteor is invalid. In an opaque field, the rate of radiative heat transfer to the stagnation point, and hence the ablation rate of the meteor, increases as the ambient air density decreases. However, as the radiation field approaches the optically thin regime, the heat transfer rate becomes proportional to the air density. In passing from the optically thick to the optically thin radiation environment, the fraction of the available kinetic energy of flight which is radiatively transferred to the body increases toward a maximum value. For the Tunguska meteor fall, this fraction is about 0.20 according to Petrov and Stulov (1975). By taking into account the differences in the radiative heating regimes above and below 50 km, Park’s model was improved and his calculations were extended to 100 km.

3. GASES AND DUST PRODUCED BY THE TUNGUSKA EVENT

The Tunguska meteor deposited large quantities of gaseous and particulate matter in the upper atmosphere during its flight. The ambient composition of the atmosphere was also altered by the intense shock waves surrounding the meteor. In this section, we discuss the NO produced in the meteor trail by thermochemical processes, the contribution of ablated meteor material to the background trace gas composition, and the magnitude of the Tunguska dust intrusion.

3.1. NO Production

Using Park’s improved aerodynamic model, the mass of NO generated by Tunguska-like meteors of different chemical composition were computed, holding the initial size, density, and velocity of the meteor fixed at the nominal values (see above). The composition of the meteor affects the predicted NO deposition profile because of the influence of material thermodynamic properties on bulk ablation rates. Meteors of pure H_2O, NH_3, CO_2, and CH_4 were assumed, as these are the most likely constituents of icy comets (Whipple, 1976, 1978). The NO produced by a composite meteor consisting of equal masses of the four basic substances was estimated by adding together one-fourth of the NO production figures calculated for each of the pure substances.

The oxidation of ammonia can lead to some additional NO production. However, Park’s (1978) calculations indicate that the mass of NO produced by the shock waves (generally) exceeds the initial mass of the meteor by a large factor. Thus a possible small NO contribution from NH_3 oxidation can be ignored.

Figure 1 shows the resulting NO deposition profile for the composite Tunguska meteor. The total mass of NO generated is roughly 30 million tons. Several small peaks appear in the profile because each pure substance generates a peak at a unique altitude. Although the peaks are somewhat artificial, their presence is not critical to an assessment of photochemical effects, as long as the total quantity of injected NO is correct, because atmospheric mixing acts to redistribute the NO in any case.

For the nominal values of \( \rho, M_0, \) and \( U_0 \) (Section 2), the present NO calculation is estimated to be accurate to within a factor of about 2 above 50 km; below 50 km, it is accurate to within 35%. However, Park’s
(1978) calculations indicate a great sensitivity of NO production to the intrinsic density and mass of the meteor and its initial velocity and composition. By choosing the most likely velocity of 40 km sec\(^{-1}\) and a mixed composition, we believe that the residual uncertainty in the NO yield due to these two parameters is less than a factor of 2. The effect of composition depends largely on the optical properties of the vaporized meteor substance. In Park's (1978) work, a CO\(_2\) meteoroid produced 2–3 times as much NO as an H\(_2\)O meteoroid because of differences in opacity. Our assumed composite meteor probably strikes a reasonable balance between the gaseous opacity characteristics of a variety of materials.

In Park's earlier calculations, the constraint of a terminal "explosion" energy of \(5 \times 10^{23}\) ergs was applied to the meteor at 10 km. Park then found that an increase in the effective meteor density from 0.002 to 0.01 g cm\(^{-3}\) reduced the NO yield by a factor of 5–7, due mainly to the fact that the denser meteor produced less frictional heat in the atmosphere. However, Park also noted that the denser body is more likely to reach the ground, in contradiction to the conspicuous absence of impact craters.

An important fact which arises from Park's calculations is the nearly constant energy efficiency of NO production as the meteor parameters are varied (as long as the body is appreciably decelerated in the atmosphere). For a large number of combinations of initial velocity (20–60 km sec\(^{-1}\)), density (0.002–0.01 g cm\(^{-3}\)), and composition, Park found that roughly 30–60 eV of
initial kinetic energy are required to produce each nitric oxide molecule in the meteor trail. Thus the major uncertainty in the total NO yield for Tunguska is related, within a factor of ~2, to the uncertainty in the initial kinetic energy of the meteor. Inasmuch as the documented explosion energy is $\sim 10^{23}$ ergs, while the initial flight energy assumed by Petrov and Stulov (1975), Park (1978), and in this work is $\sim 10^{25}$ ergs, the NO yield in Fig. 1 could conceivably be overestimated by a factor of 100. Guided by the discussion in Section 2, however, such an error seems unlikely, although a factor of 10 overestimate is possible, due principally to the uncertainty in $\rho$.

It is interesting to contrast the energy efficiency of NO production by meteors with that by other physical mechanisms. Here, the initial kinetic energy of the Tunguska meteor is estimated to be $\sim 4 \times 10^{25}$ ergs, and about 42 eV are expended for each NO molecule formed. Nuclear bombs, by comparison, require $\sim 250$ eV/NO. Highly energetic particles (electrons, protons) and photons (X rays, $\gamma$ rays) generate roughly one NO molecule for each ion-electron pair formed in air (Nicolet, 1975); thus the energy efficiency is close to 35 eV/NO. Lightning requires 40–80 eV to generate one NO molecule (Griffing, 1977; Chameides, 1979; Hill et al., 1980), although this relatively high yield has been questioned recently (Dawson, 1980). The efficient production of NO in high-velocity meteor trails is due to the extreme turbulence of the wake, which allows a relatively large volume of ambient air to be quickly heated above 3000° K. This heated air is then rapidly quenched by further mixing with the ambient atmosphere, causing NO to be “frozen out” (Park, 1978; Park and Menees, 1978; Menees and Park, 1976; Park and Rakich, 1980).

The $3 \times 10^7$ tons of NO generated above 10 km by the Tunguska meteor are equivalent to $6 \times 10^{35}$ molecules of NO. By comparison, the total ambient $\text{NO}_x$ ($\text{NO} + \text{NO}_2 + \text{HNO}_3 + 2\text{N}_2\text{O}_5$) burden of the stratosphere is $4-15 \times 10^{34}$ molecules (Bauer, 1979). The average stratospheric production rate of NO by all natural processes (mainly $\text{N}_2\text{O}$ decomposition) is about $5 \times 10^{34}$ molecules year$^{-1}$ (Johnston et al., 1979). Aurora may produce $2 \times 10^{35}$ odd-nitrogen molecules annually in the upper mesosphere (Bauer, 1978), and meteors may contribute $10^{32}-10^{34}$ molecules per year in this region (Park and Menees, 1978), but only a fraction of this mesospheric NO can reach the stratosphere.

During the US/USSR nuclear test series of 1961–1962, nearly 300 megatons of explosive energy were expended in the atmosphere and roughly $3 \times 10^{34}$ NO molecules were deposited in the stratosphere (Bauer and Gilmore, 1975). Crutzen et al. (1975) determined that one of the largest solar proton events (SPEs) on record (August, 1972) produced about $3 \times 10^{33}$ NO molecules through the dissociation and ionization of air. Therefore, in comparison to other natural and anthropogenic sources of $\text{NO}_x$, the Tunguska event may represent the most massive impulsive $\text{NO}_x$ loading of the stratosphere to occur in recent history.

The physical consequences of very large stratospheric $\text{NO}_x$ injections have never been suitably calibrated by atmospheric events. For example, nuclear bomb-generated $\text{NO}_x$ has never been shown to cause widespread depletions of stratospheric ozone (Johnston et al., 1973; Goldsmith et al., 1973; Chang et al., 1979). Heath et al. (1977) linked the NO produced by the large August 1972 SPE with the coincident ozone reductions observed in the upper stratosphere by the Nimbus 4 satellite; however, an effect on the total ozone column was not observed. The Tunguska meteor fall, by contrast to past nuclear bomb tests and SPEs, may have caused a much larger NO injection over a much wider altitude range. For example, the Tunguska event may be compared approximately to a large-scale 6000-megaton nuclear “war” in terms of the mass of NO deposited in the stratosphere (e.g., see Whitten et al., 1975). Hence the corresponding perturbations of
the stratospheric photochemical system are expected to be quite significant.

3.2. H₂O and Other Trace Gases Generated by the Tunguska Event

Besides NO, other chemical species could have been formed in the atmosphere by the Tunguska meteor fall. We assume that the mass ablated from the meteor and deposited along its flight path was primarily CO₂ and H₂O, in proportions dictated by the initial C–H composition of the meteor. Any frozen CH₄ and NH₃ in the body of the meteor would have been oxidized to CO₂ and H₂O in the entry plume.

The equivalent H₂O deposition profile calculated for the composite Tunguska meteor is shown in Fig. 1. The CO₂ deposition can be neglected because of the large atmospheric CO₂ inventory, but the H₂O deposition may be significant. Our estimate of the total mass of water vapor released by the Tunguska meteor is ≈1.5 × 10⁶ tons, or 5 × 10³⁴ molecules. While this amount of H₂O is small compared to the total stratospheric water vapor burden (≈10³⁸ molecules, within a factor of 3), it could cause important local perturbations. For example, the global abundance of water vapor above 80 km, where noctilucent clouds occur, is only of the order of 10³³ molecules. Possible enhancements in noctilucent clouds are discussed in Section 7.

Odd-oxygen and odd-hydrogen generation in the heated meteor plume are ignored. The quantities of these species deposited by the meteor are not likely to be large; ozone is unstable in heated air, and hydrogen radicals tend to recombine quickly. Moreover, the stratospheric abundance of odd-oxygen is in excess of 10⁹⁷ O atoms. Johnston (1977) considered the problem of ozone production by nuclear explosions, and found some potentially important short-term chemical effects in the nuclear cloud. We are interested in some of the prompt (~1–2 days) aftereffects of the Tunguska meteor fall, but we will neglect the contribution of thermochemical odd-oxygen production, as there is no accurate way of estimating the quantity involved. The possible meteoric deposition of ozone-destuctive halogens—most notably chlorine—is also ignored. Chlorine is only a minor (<10%) constituent of cosmic bodies (Whipple, 1978), while the stratosphere (of 1908) probably held a million tons or more of Cl. Thus ambient chlorine could not have increased more than a few percent worldwide as a result of the Tunguska event.

3.3. Dust from the Tunguska Meteor

The enhancement in stratospheric dust caused by the Tunguska meteor can be crudely estimated by comparing the meteor mass influx with the stratospheric aerosol burden. According to the present estimate, the Tunguska meteor weighed about 5 × 10⁶ tons. Most of this material consisted of H₂O, NH₃, CH₄, and CO₂ ices, in accord with the composite meteor model. Thus an estimate of ~1 × 10⁶ tons of meteoric dust deposited by Tunguska in the upper atmosphere appears reasonable. However, a large fraction of the Tunguska dust mass might have resided in very large particles (~100-μm diameter) having short atmospheric residence times (~ hours). Large meteoritic spherules attributed to Tunguska were found in abundance near the fall site (Florensky, 1965).

The total mass of background stratospheric aerosols is approximately 10⁶ tons. Accordingly, the Tunguska meteor could have caused large local perturbations in atmospheric turbidity. The ambient optical depth of the aerosol layer at 550 nm is about 0.005. If, for example, the dust from the Tunguska meteor were confined to one-fifth of the Northern Hemisphere, and if the dust optical properties corresponded to those of the ambient aerosols, then the perturbed dust optical depth could have approached 0.05. By comparison, if all of the NO produced by the Tunguska meteor were converted into NO₂ and confined to one-fifth of the Northern Hemisphere, then the optical depth at 550 nm would be ~0.1 In the next
section, however, it is shown that only a small fraction of the injected NO is actually converted into NO₂.

The tenuous coma of gases and dust surrounding a comet body is stripped away by air resistance high in the atmosphere. Only the core of the body penetrates into the stratosphere. The ionosphere might therefore be affected by the material deposited along the meteor's high-altitude flight path. Ivanov (1966) contended that the explosion of the Tunguska meteor produced a buoyant cloud that rose into the lower thermosphere (~150 km), causing the worldwide ionospheric and geomagnetic disturbances which were noted at the time. Fesenkov (1966) suggested that the dusty cometary tail of the meteor stopped several hundred kilometers high in the atmosphere and produced, by reflection of sunlight, the anomalous glowing skies seen over Europe.

The subject of high-altitude dust layers, and their possible role in noctilucent cloud formation, is deferred to Section 7.

4. THE ATMOSPHERIC PHOTOCHEMICAL MODEL

4.1. Description of the Model

To estimate the impact of the NO and H₂O deposited by the Tunguska meteor on the composition of the upper atmosphere, simulations of the event were made with a comprehensive one-dimensional (1-D) photochemical model. The model extends from 10 to 120 km altitude and treats a fully interactive set of 53 trace constituents using the latest photochemical data (e.g., DeMore et al., 1981). The background atmospheric temperature and density were taken from the U.S. Standard Atmosphere (1962). Detailed aspects of the model are documented in a series of reports (Turco, 1975; Turco and Whitten, 1975, 1977, 1978).

The global average tropopause height in the model lies at 13 km, whereas the tropopause height over Siberia (61°N) is closer to 10 km. This difference causes a negligible error in the NO and H₂O stratospheric deposition inventories.

The model is photochemically "averaged" over the diurnal cycle. That is, the average rates of chemical reactions corresponding to day and night conditions are determined separately and averaged. Species concentrations are calculated as a function of time using the average chemical rates, which are updated periodically to reflect the changes in average composition [see Turco and Whitten (1978) for a full description of the diurnal averaging technique]. The diurnal averaging scheme yields values for the average daytime and average night-time species concentrations and chemical rates. A diurnally averaged solution was chosen over a full-diurnal calculation for two reasons. First, at very early times (~1 day to 1 week) when detailed time dependences might be of interest, the perturbations are dominated by expansion and mixing of the meteor plume, which cannot be treated accurately in a one-dimensional model. Second, a major goal of the present work was to study the long-term effects of Tunguska extending over several years, for which a full-diurnal computation is impractical. One fully time-dependent calculation, which extends through the first night following the Tunguska fall, is discussed in Section 7.

Average photodissociation rates for the present Tunguska simulations were determined for 30° latitude equinoctial and 50° latitude equinoctial and solstitial solar conditions. The 30° photodissociation rates reflect a global or hemispherical average, while the 50° rates emphasize the high-latitude nature of the event (and would apply for short times afterwards, when limited spreading had occurred; see below). For times ≈1 day the diurnally averaged calculations should be interpreted roughly as average values for that day (or night).

Temperature feedback effects were not included in the present calculations. Ozone reductions cause a cooling of the upper atmosphere, which tends to slow the chemical reactions that consume ozone. The net effect is perhaps a 10% smaller overall
ozone reduction. However, according to Luther et al. (1977), if one takes account of the warming due to enhanced NO$_2$ absorption, the net effect in the case of large NO$_x$-induced ozone depletions (~30%) is less than 5%. Even though Luther et al. (1977) did not properly account for hydrostatic readjustment of the atmosphere, their results roughly apply to the present calculations. Accordingly, our model may overestimate Tunguska ozone effects by 5 to 10%.

Ambient model predictions were validated against observational data. The ambient ozone profiles corresponding to different solar conditions all lie within the variability limits of the Krueger and Minzner (1976) data set. Other species concentrations are in reasonable agreement with measurements; the recent evaluation of model fidelity made by Hudson and Reed (1979) applies here. Specific sources of uncertainty in the Tunguska simulations are discussed later.

The Tunguska calculations were initialized as follows. The total amount of NO deposited at each height (Fig. 1) was averaged over a specific area of the globe (i.e., either the Northern Hemisphere or a 10°-latitude zone centered at 60°N). The injected NO was then “instantaneously” redistributed among NO, NO$_2$, NO$_3$, N$_2$O$_5$, and HNO$_2$ according to the following guidelines (HNO$_3$ was held fixed during initialization). The concentration ratio of each NO$_x$ constituent relative to NO$_2$ was assigned its value corresponding to ambient conditions (for N$_2$O$_5$, the ratio was taken with respect to the NO$_2$ concentration squared). In addition, the NO/NO$_2$ ratio was assumed to be inversely proportional to the ozone concentration, and the NO$_x$/NO$_2$ and N$_2$O$_5$/($NO_2)^2$ ratios directly proportional to the ozone concentration. Total odd-nitrogen and odd-oxygen conservation was also applied; here, NO$_2$ was taken to carry one odd-oxygen, NO$_3$ two, and N$_2$O$_5$ three. Finally, the concentration ratio of O to O$_3$ was held fixed at its ambient value. These relationships among the NO$_x$ and O$_x$ species concentrations yield a set of equations which are readily solved to obtain initial conditions for model simulations.

4.2. Chemiluminescent Reactions

The chemiluminescent emission rates for the following reactions are considered here:

$$\text{NO} + \text{O} \rightarrow \text{NO}_2 + \text{hv}, \quad (2)$$

$$\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2 + \text{hv}, \quad (3)$$

$$\text{NO} + \text{NO}_3 \rightarrow \text{NO}_2 + \text{NO}_2 + \text{hv}. \quad (4)$$

The effective rate coefficients for reactions (2)-(4), and a discussion of the relevant laboratory data, are given in Table III. Ivanov (1966) suggested that the “air afterglow” reaction (2) contributed to the “light nights” over Eurasia following the Tunguska event. Park (1978) invoked luminescent reaction (3) to explain some of these optical phenomena. We evaluate both hypotheses in Section 7.

High-altitude NO release experiments (above 90 km) were conducted by Pressman et al. (1956), Golomb et al. (1965), and Spindler (1966). The resulting airglow appeared to vary in color from yellow-red to silver-gray (Pressman et al., 1956), and was nearly 10,000 times brighter than the expected intensity based on laboratory studies of reaction (2) (Golomb et al., 1965). Del Greco et al. (1966) detected the same intense emission when NO was released into a low-density-air wind tunnel charged with atomic oxygen. This led Fontijn and Rosner (1967) to conclude that the anomalous NO + O emission was due to accelerated reactions of O with molecular clusters of NO (NO · M, NO · NO) formed in rapidly expanding jets of NO and in chemical releases of pressurized NO. Hence the atmospheric NO release data cannot be used to calibrate the Tunguska emissions. Rather, the appropriate rate coefficients for studying the Tunguska chemical airglows are those given in Table III.

In the atmosphere, air parcels of different composition are mixed together by a variety of natural dynamical processes. These
TABLE III
CHEMILUMINESCENT REACTIONS

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. NO + O → NO₂ + hv</td>
<td>$k_1 = \frac{1.1 \times 10^{-17} \left(\frac{300}{T}\right)^{0.9} e^{350/T}}{1 + 5 \times 10^{14}/M} + 3 \times 10^{-18} \left(\frac{300}{T}\right)^{3b}$</td>
</tr>
<tr>
<td>II. NO + O₃ → NO₂ + O₂ + hv</td>
<td>$k_2 = 0.059 \times 1.3 \times 10^{-12} e^{-2100/T} c$</td>
</tr>
<tr>
<td>III. NO + NO₃ → NO₂ + NO₂ + hv</td>
<td>$k_3 = 0.030 \times 1.9 \times 10^{-11} (1 + 3.7 \times 10^{-15} M)$</td>
</tr>
</tbody>
</table>

a Rate coefficients are given in cm³ sec⁻¹ units. The photon emission rate is $I = k\left[NO_x\right]\left[O_x\right]$ photons cm⁻³ sec⁻¹. $M$ is the concentration of air molecules (number cm⁻³) and $T$ is the air temperature (°K).
b The NO + O chemiluminescence has two components: a pressure-dependent emission and an irreducible component. Above about 0.3 Torr the emission rate constant for air for the 400- to 800-nm-wavelength interval is taken from Golomb and Brown (1975); their data at room temperature are in excellent agreement with the original measurements of Fontijn et al. (1964) and recent measurements by Sutoh et al. (1980), truncated for the 400- to 800-nm region. Below 0.3 Torr, the pressure effect is greater than 5% and we utilize the data of Reeves et al. (1964) to scale the pressure dependence. The emission quenching rate is consistent with the vibrational transfer mechanism for fluorescence quenching studied by Donnelly et al. (1978). The pressure-independent (irreducible) emission rate constant is taken from the review by Kaufman (1973), and is adjusted to correspond to the 400- to 800-nm spectral region, and is added to the pressure-dependent component. The two-body (irreducible) process dominates the emission at pressures below about 1 μm Hg, but represents less than 10% of the emission above 0.1 Torr.
c The NO + O₃ emission data are taken from Clyne et al. (1964) and Clough and Thrush (1967). The emission factor 0.059 applies to radiation at wavelengths less than 875 nm. The NO + O₃ chemiluminescence extends from about 600 to 3000 nm and peaks at about 1200 nm. For wavelengths below 800 nm, the emission factor is roughly 0.03. Clough and Thrush (1967) found the emission half-quenching pressure in O₂ to be 8.3 ± 0.5 μm Hg, with no significant difference in the half-quenching pressures at wavelengths of 700 and 1500 nm in Ar or NO. The quenching rate is roughly consistent with the results of NO₂ fluorescence studies (Keyser et al., 1971; Donnelly et al., 1978) and thermal emission studies (Paulsen et al., 1970). The NO + O and NO + O₃ chemiluminescent emissions have similar quenching factors, which is expected inasmuch as ²B processes cannot be properly simulated with a 1-D model, particularly in a turbulent meteor trail. Thus only horizontally averaged vertical column emission rates can be calculated; such calculations are, nevertheless, useful in placing limitations on the likely intensity of the emission. The important emission to consider for Tunguska is the twilight and nighttime emission. This can be crudely estimated by considering the expansion of a very dense plume of NO—in which most of the odd-oxygen is depleted—by slow mixing-in of ambient air rich in O and O₃. As the odd-oxygen is consumed by the NO in the plume, chemiluminescence results. It follows that the rate of emission at each height is proportional to the rate of increase in cross-sectional area ($A$) of the plume, the ambient odd-oxygen concentration ($[O_x]$), and the photon emission efficiency ($\epsilon$) of reactions (2) and (3).

$$E \approx \epsilon [O_x] \frac{dA}{dt}$$

(photons/vertical cm/sec). (5)
The chemical emission continues until the injected NO is diluted to a concentration below that of the ambient odd-oxygen; beyond this point, the remaining NO in the plume is rapidly converted at sunset into NO₂, which is not a very active chemiluminescent agent at night, and the twilight glow is quickly extinguished. Later, we will use Eq. (5) to estimate the Tunguska airglow emissions just after the fall.
4.3. Composition of Dense NO\textsubscript{x} Clouds

In a very dense cloud of NO\textsubscript{x}, a simple estimate of the NO\textsubscript{2} and O\textsubscript{3} concentrations can be made using photochemical equilibrium arguments. For daytime conditions, it is found that

\[
[\text{NO}_2] \sim 8 \times 10^{-9} \frac{M}{T}
\]

\[
[P_{ox} + 1.5 \times 10^{-3} M [\text{NO}]^2]^{1/2}
\]

(6)

and

\[
[\text{O}_3] \sim 4 \times 10^9 e^{1450/T} \frac{[\text{NO}_2]}{[\text{NO}]},
\]

(7)

where brackets [ ] indicate species concentrations (number cm\textsuperscript{-3}), \(T\) is the air temperature, \(M\) is the concentration of air molecules, and \(P_{ox}\) is the background odd-oxygen production rate (cm\textsuperscript{-3} sec\textsuperscript{-1}), assumed to be constant. Equations (6) and (7) apply below 50 km when NO concentrations exceed 10\textsuperscript{13} cm\textsuperscript{-3}. The second "odd-oxygen" production term in Eq. (6) arises from the slow reaction

\[
\text{NO} + \text{NO} + \text{O}_2 \rightarrow \text{NO}_2 + \text{NO}_2,
\]

(8)

which has a rate constant of \(3.3 \times 10^{-39} e^{530/T} \text{ cm}^6 \text{ sec}^{-1}\).

Note that the NO\textsubscript{2} and O\textsubscript{3} concentrations in the cloud are limited principally by the total odd-oxygen production rate. Normally, odd-oxygen production below 50 km occurs by ultraviolet photolysis of O\textsubscript{2}, limited by ozone absorption at wavelengths shorter than 250 nm. NO\textsubscript{2} also absorbs at these wavelengths, but much more weakly than O\textsubscript{3}. Accordingly, as O\textsubscript{3} is depleted, more ultraviolet light can leak to lower altitudes and \(P_{ox}\) can increase. Nevertheless, O\textsubscript{2} photodissociation is limited by O\textsubscript{2} self-absorption below 30 km. The odd-oxygen production rate due to reaction (8) is, of course, not similarly limited.

As an example of the application of Eqs. (6) and (7), when the Tunguska NO cloud had spread over an area of 10\textsuperscript{6} km\textsuperscript{2} at 30 km where \(P_{ox} \sim 10^6 \text{ cm}^3 \text{ sec}^{-1}\), \([\text{NO}]\) was \(\sim 10^{13} \text{ cm}^3\), \([\text{NO}_2]\) \(\sim 10^{10} \text{ cm}^3\), and \([\text{O}_3]\) \(\sim 10^9 \text{ cm}^3\). Thus, only about 0.1% of the total NO\textsubscript{x} was present as NO\textsubscript{2}; the NO\textsubscript{2} opacity of the cloud was restricted accordingly. At somewhat higher NO concentrations—such that reaction (8) becomes the dominant odd-oxygen source—Eq. (6) becomes

\[
[\text{NO}_2]/[\text{NO}] \sim 1 \times 10^{-27} \frac{M^{3/2}}{T^{-1}},
\]

(9)

which gives a limit of about 0.1% of NO\textsubscript{x} as NO\textsubscript{2} at 30 km, and 1% at 20 km.

5. TUNGUSKA STRATOSPHERIC PERTURBATIONS

Figure 2 illustrates the time-dependent stratospheric ozone perturbations calculated for the Tunguska meteor fall. Most of the predictions correspond to uniform spreading of the injected NO (and H\textsubscript{2}O) over the Northern Hemisphere. Some results are also shown for the 10°-latitude zone case. In the 50°-equinox hemispherical model, the total stratospheric ozone reduction reaches 45% the first year, with large ozone reductions persisting for at least 3 years. Only a small difference was found between the hemispherical ozone reductions predicted for equinoctial and solstitial conditions both at 30 and 50° latitude. However, in the 30°-equinox model, the maximum ozone reduction is \(\sim 35\%\). (Note that the lower boundary of the model is fixed at 10 km, and the calculated "total" ozone column is essentially the stratospheric ozone column. Tropospheric ozone contributes less than 10% to the total global O\textsubscript{3} abundance. The behavior of tropospheric ozone for large stratospheric NO\textsubscript{x} injections is not well understood. Accordingly, we have neglected the low-altitude ozone component. The predicted stratospheric ozone reductions may be readily adjusted to account for any fixed amount of ozone below 10 km.)

At 40 km, ozone is quickly depleted by photochemical reactions, and remains depleted for a month or so (Fig. 2). At 20 km, the ozone reduction becomes significant only after several weeks. This is due to the relatively slow chemical response of ozone in the lower stratosphere; the ambient pho-
tochemical lifetime of ozone at 20 km is several months. The ozone response at 30 km is intermediate between the responses at higher and lower altitudes (at 40–50 km the ozone lifetime is ~1 day). The structure in the 30-km ozone depletion curve in Fig. 2 is due, in large part, to the nonuniform height profile of the NO injection (Fig. 1). Thus some of the NO deposited at 50 km diffuses downward to, and enhances the NO concentration at, the 30-km level after a delay of several months.

During the first month or two following the Tunguska fall, zonal averaging yields a more realistic estimate of the local ozone depletion. In this case, ozone above 10 km is found to be depleted by ~85% for several months. After one month, the ozone reductions at 20, 30, 40, and 50 km are 91, 93, 96, and 78%, respectively. In other words, the stratospheric ozone layer was essentially removed (locally) during this period. The ozone column shows a more prompt onset of recovery in the zonal case than in the hemispherical case, apparently due to the enhanced leakage of ultraviolet radiation through the depleted ozone shield, which increases the rate of production of ozone from O₂.

In Fig. 3, the post-Tunguska time variations of the major NOₓ constituents are shown. At times ≤1 day, there is a substantial photochemical readjustment in the NOₓ partition due to the rapid depletion of ozone above 30 km. In part, enhanced ultraviolet light levels increase the O₃ and N₂O₅ photolysis rates. The large injection of NOₓ also suppresses OH concentrations through
The reactions

$$\text{OH} + \text{NO}_2 + \text{M} \rightarrow \text{HNO}_3 + \text{M},$$

$$\text{HNO}_3 + \text{OH} \rightarrow \text{H}_2\text{O} + \text{NO}_3. \quad (10)$$

The reduction in OH affects all of the stratospheric chemical cycles, including odd-oxygen, nitrogen, carbon, chlorine, and so on. Nevertheless, the nitric acid level in the lower stratosphere does not rise significantly for several weeks. Beyond this time, however, an increasing fraction of the injected NO and NO$_2$, which catalytically destroy ozone, is stored as HNO$_3$, which is inert toward ozone. Consequently, ozone recovery is accelerated.

The odd-nitrogen produced by the Tunguska meteor has two major sinks. The most important sink is diffusion from the stratosphere to the troposphere, followed by efficient washout in rainfall, primarily in the form of HNO$_3$. However, a photochemical sink for NO$_x$ also exists above 50 km. Here, the photolysis of NO creates N atoms which react with NO to form N$_2$.

This odd-nitrogen recombination process consumes roughly 20% of the injected NO.

Fig. 3. Post-Tunguska variations in NO, NO$_2$, N$_2$O$_5$, and HNO$_3$ concentrations at several altitudes assuming hemispherical spreading of the injected NO. Average daytime concentrations are shown.
Figure 4 illustrates the evolution of the ozone and total odd-nitrogen height distributions following Tunguska. Ozone is rapidly depleted above 40 km, but recovers quickly, and is slowly depleted below 30 km, where the effects persist for several years (also see Fig. 2). As expected, the injected NO\textsubscript{x} distribution tends toward a uniformly mixed state. In Section 8, predicted ozone profiles such as those in Fig. 4 are used to calculate the impact of the Tunguska meteor on atmospheric temperatures; ozone absorption of ultraviolet sunlight is the major heat source for the stratosphere.

To facilitate an evaluation of the NO\textsubscript{x} opacity perturbations attending the Tunguska meteor fall, Fig. 5 shows the overhead column abundances of those NO\textsubscript{x} species which are optically active in the near-ultraviolet through near-infrared wavelength region. The model predictions are discussed in relation to atmospheric opacity measurements in the next section.
The \( \text{H}_2\text{O} \) deposited in the upper atmosphere by the Tunguska meteor caused no particular long-lasting or widespread photochemical effects worth mentioning. Accordingly, except for a possible role in the formation of unusual noctilucent clouds, the \( \text{H}_2\text{O} \) injection is ignored.

A number of sources of uncertainty exist in the photochemical model calculations. The uncertainties in the quantity of NO injected by the Tunguska meteor were mentioned in Section 3. The uncertainties associated with state-of-the-art one-dimensional modeling are thoroughly discussed in a recent survey report on stratospheric science (Hudson and Reed, 1979). We feel that our predicted ozone reductions for the assumed NO injection are accurate to within a factor of 2 after about 1 year. They are more uncertain for the first one-half year, when the horizontal extent of the spreading is unknown, and beyond 2 years, when removal and interhemispheric mixing rates and hydroxyl chemistry dominate the ozone perturbation (e.g., see Whitten et al., 1981). For extremely large NO injections, the basic \( \text{NO}_x-\text{O}_x \) reaction cycle appears to be well established. However, the accepted theory has never been satisfactorily tested by the outcome of natural events. The Tunguska meteor fall could provide such a test (Turco et al., 1981).

6. ATMOSPHERIC TRANSMISSION MEASUREMENTS

Observations of the transmission of sunlight through the atmosphere may be analyzed for absorption in the ozone Chappuis bands at wavelengths from 0.5 to 0.7 \( \mu\text{m} \) and in the strong \( \text{NO}_2 \) band between 0.4 and 0.7 \( \mu\text{m} \), and for the turbidity caused by upper-atmospheric dust and haze. Accord-
ingly, evidence for Tunguska perturbations may be found in archived solar transmission data.

6.1. The Smithsonian Data Base

During the early 1900s when the Tunguska meteor fell over Siberia, the Smithsonian Astrophysical Observatory (APO) was carrying out a long-term program to determine the variability of the solar “constant” (Abbot and Fowle, 1908; Abbot et al., 1913). At Mount Wilson, California, a spectrobolometer was used to determine the solar intensity at 10 wavelengths from 0.35 to 1.6 μm (before 1909, data were not recorded at 0.35 μm; during and after 1909, 0.35 μm was added and 0.9 μm was dropped). Measurements were also made with pyrheliometers to calibrate the spectrobolometer data.

The Smithsonian investigators determined the effective vertical transmission of the atmosphere at each selected wavelength by inverting observations of the solar intensity at several solar elevations. The measurements were extrapolated to the zenith using the theoretically expected dependence of intensity on the exponential of the secant of the solar zenith angle times the vertical optical depth. A “quality” grade was assigned to each set of observations based on the agreement between the observed and theoretical dependences on solar zenith angle for angles less than 70°. There were essentially four grades—excellent, very good, good, and poor—and a grade was subjectively associated with each set of bolometric (spectral) transmission measurements. The higher-quality grades suggest a more accurate extrapolation to the zenith, and imply that all of the observations that day gave roughly the same transmission value. Conversely, the poorer grades imply a more uncertain extrapolation, and hint that significant changes in atmospheric transparency occurred during the time of observation, which often extended over 4 hr. We will refer to the APO grading system in the subsequent data analysis.

The statistical properties of the APO data collected between 1905 and 1911 at Mount Wilson are summarized in Table IV. Several features of the data are worth mentioning. The data base is quite extensive, consisting of thousands of individual measurements. The data are also fairly consistent with regard to the instrumentation, sampling techniques, and data reduction schemes employed. Although data were collected before and after the Tunguska event, the 1905 and 1906 observations are less reliable than the later measurements, and the 0.35-μm data must be neglected (e.g., Hoyt, 1979). Very little data was taken in 1907, as work on new instruments and siting of apparatus occupied the research team (Abbot et al., 1913). As it happens, there was a large volcanic eruption in Russia on March 28, 1907 (Shtyubelya Sopka; 52°N, 157°E) which produced a significant dust veil over the Northern Hemisphere for more than a year (Lamb, 1972). This eruption will be discussed later in relation to the analysis of the APO data.

The Mount Wilson experiments were far from perfect. Abbot later referred to the years 1905–1908 as the “ancient” period, and 1909–1920 as the “medieval” period, of the APO solar constant program (Hoyt, 1979). The major problems, however, centered on the conversion of the raw spectral data into total incident solar intensities accurate to within a few percent. This involved an extrapolation of the radiant energy spectrum measured in the visible and near-infrared wavelength regions to longer and shorter wavelengths. At the ultraviolet end of the spectrum, complications arose from strong molecular absorption and scattering. In the infrared, large variability in the water vapor bands posed a serious problem. Despite these shortcomings, however, the APO observations can still provide an excellent basis for studying the Tunguska phenomenon.

The statistical characteristics of the APO
TABLE IV
ATMOSPHERIC TRANSMISSION DATA FROM THE SMITHSONIAN ASTROPHYSICAL OBSERVATORY OUTPOST AT MOUNT WILSON, CALIFORNIA

<table>
<thead>
<tr>
<th>Year</th>
<th>1905</th>
<th>1906</th>
<th>1908</th>
<th>1909</th>
<th>1910</th>
<th>1911</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of measurements</td>
<td>55</td>
<td>62</td>
<td>114</td>
<td>95</td>
<td>115</td>
<td>113</td>
</tr>
<tr>
<td>0.35μm</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.637 ± 0.040</td>
<td>0.628 ± 0.040</td>
<td>0.626 ± 0.032</td>
</tr>
<tr>
<td>0.40μm</td>
<td>0.735 ± 0.039</td>
<td>0.744 ± 0.026</td>
<td>0.705 ± 0.031</td>
<td>0.734 ± 0.029</td>
<td>0.732 ± 0.029</td>
<td>0.738 ± 0.028</td>
</tr>
<tr>
<td>0.45μm</td>
<td>0.808 ± 0.026</td>
<td>0.812 ± 0.024</td>
<td>0.789 ± 0.032</td>
<td>0.812 ± 0.019</td>
<td>0.814 ± 0.019</td>
<td>0.816 ± 0.024</td>
</tr>
<tr>
<td>0.50μm</td>
<td>0.852 ± 0.025</td>
<td>0.853 ± 0.022</td>
<td>0.836 ± 0.029</td>
<td>0.860 ± 0.021</td>
<td>0.869 ± 0.019</td>
<td>0.871 ± 0.021</td>
</tr>
<tr>
<td>0.60μm</td>
<td>0.903 ± 0.017</td>
<td>0.903 ± 0.018</td>
<td>0.870 ± 0.027</td>
<td>0.890 ± 0.018</td>
<td>0.900 ± 0.016</td>
<td>0.899 ± 0.020</td>
</tr>
<tr>
<td>0.70μm</td>
<td>0.938 ± 0.014</td>
<td>0.935 ± 0.016</td>
<td>0.920 ± 0.024</td>
<td>0.940 ± 0.017</td>
<td>0.947 ± 0.016</td>
<td>0.952 ± 0.014</td>
</tr>
<tr>
<td>0.80μm</td>
<td>0.957 ± 0.012</td>
<td>0.952 ± 0.014</td>
<td>0.941 ± 0.021</td>
<td>0.959 ± 0.015</td>
<td>0.968 ± 0.013</td>
<td>0.970 ± 0.013</td>
</tr>
<tr>
<td>0.90μm</td>
<td>0.967 ± 0.011</td>
<td>0.961 ± 0.013</td>
<td>0.951 ± 0.019</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1.00μm</td>
<td>0.972 ± 0.010</td>
<td>0.966 ± 0.012</td>
<td>0.953 ± 0.018</td>
<td>0.968 ± 0.015</td>
<td>0.978 ± 0.013</td>
<td>0.978 ± 0.011</td>
</tr>
<tr>
<td>1.20μm</td>
<td>0.977 ± 0.010</td>
<td>0.971 ± 0.012</td>
<td>0.955 ± 0.017</td>
<td>0.966 ± 0.017</td>
<td>0.976 ± 0.014</td>
<td>0.976 ± 0.014</td>
</tr>
<tr>
<td>1.60μm</td>
<td>0.981 ± 0.010</td>
<td>0.976 ± 0.012</td>
<td>0.961 ± 0.016</td>
<td>0.973 ± 0.014</td>
<td>0.977 ± 0.016</td>
<td>0.979 ± 0.015</td>
</tr>
<tr>
<td>Average atmospheric transmission</td>
<td>0.821 ± 0.022</td>
<td>0.816 ± 0.030</td>
<td>0.798 ± 0.030</td>
<td>0.820 ± 0.027</td>
<td>0.814 ± 0.026</td>
<td>0.821 ± 0.020</td>
</tr>
</tbody>
</table>

a Vertical transmissions are given. The data are taken from Abbot and Fowle (1908), Table 14, for 1905 and 1906, and from Abbot et al. (1913), Tables 33–36, for 1908 to 1911, respectively. All of the data used here were collected at Mount Wilson, California (34°N, 118°W), during a 6-month period of each year from mid-May to mid-November. Much of the data was obtained under exceptionally clear observational conditions. Measurements were usually made in the morning, but on some occasions were made either in the afternoon or in both the morning and afternoon.

b No significant data were collected at Mt. Wilson in 1907. On March 28, 1907, the massive eruption of the volcano Shlyublya Sopka (52°N, 157°E) occurred. The eruption was estimated to have injected 3 km² of material into the atmosphere, and to have created a dust veil with an opacity one-half of that caused by the Krakatoa eruption (Lamb, 1972). The atmospheric turbidity was enhanced throughout 1907, and brilliant sunsets were reported during that year.

c This is also approximately the number of days sampled.

d Prior to 1909, data were not recorded at 0.35 μm. Later, this wavelength was added and 0.90 μm was dropped.

e The first number is the average vertical transmission for that year, and the second number is the standard deviation (σ) of the transmission data. The standard deviation of the average transmission is simply estimated by dividing the standard deviation shown by the square root of the number of measurements made that year.

The average transmission for each observation was derived by the Smithsonian investigators using both spectrobolometer and pyrheliometer data. For a description of the data reduction scheme see Abbot and Fowle (1908) and Abbot et al. (1913).

data (summarized in Table IV) clearly indicate that the average vertical transmission in 1908 was significantly lower than the transmission recorded in the other years (by several standard deviations). In Fig. 6, the 1908–1911 transmission data are plotted for each wavelength. Because the 1905 and 1906 measurements do not significantly alter the interpretation of the data, they have been omitted for clarity. In the figure, it can be seen that the transparency of the upper atmosphere in 1908 fell well below that of the other years. There is also a noticeable “absorption” event which commenced over California about 2 weeks after the Tunguska meteor fall over Siberia, and which lasted for a month. Fesenkov (1949) first associated this reduction in atmospheric transmission with dust from the Tunguska meteor. The magnitude of the transmission anomaly is well outside the 1σ interval of the data. Moreover, it appears from Fig. 6 that, for the entire year of 1908, the atmosphere was in a highly disturbed state. Another significant increase in atmospheric opacity occurred over Mount Wilson 2 weeks prior to the Tunguska fall, but this may have been associated with a dust cloud remnant from the Russian volcano of 1907 (see below).

6.2. Derived Atmospheric Opacities

The optical depth of the atmosphere at a given wavelength, or over a small wavelength interval, is defined here as

$$\tau = -\ln T = \tau_0 + \tau_r + \tau_w + \tau_d + \tau_{O_3} + \tau_{NO_2},$$

(11)

where τ is the overhead (unit-airmass, or
Fig. 6. Atmospheric transmission fractions measured by Smithsonian Astrophysical Observatory researchers at Mount Wilson, California, from 1908 to 1911. The transmissions are referred to the zenith. Data for each day of observation are plotted, with data points for the same year and wavelength of observation interconnected by straight line segments. The transmission records at each wavelength over the 4-year period are clustered together for easy comparison (note the staggered transmission scale). The 1908 (08) data are easily distinguishable from the 1909–1911 (09–11) data.
zenith) optical depth, $T$ is the vertical atmospheric transmission fraction, $\tau_0$ is the opacity due to $O_2$ and $CO_2$ vibrational bands, $\tau_r$ is the molecular Rayleigh scattering optical depth, $\tau_d$ is the opacity due to water vapor, $\tau_{d}$ is the dust and aerosol extinction (or turbidity), and $\tau_{O_3}$ and $\tau_{NO_2}$ are, respectively, the $O_3$ and $NO_2$ absorption optical depths. Henceforth, only the vertical optical properties of the atmosphere are considered, unless otherwise stated.

To calculate the average optical depth corresponding to any subset of the APO transmission measurements, two simple formulations are possible:

$$\bar{\tau} = \frac{1}{n} \sum_{i=1}^{n} -\ln[T^{(i)}]$$

and

$$\bar{\tau} = -\ln \left[ \frac{1}{n} \sum_{i=1}^{n} T^{(i)} \right],$$

where $n$ is the number of data points in the subset. Equation (12) is adopted here for calculations, but Eq. (13) gives the same optical depths to within $\pm 0.001$ for all of the subsets tested.

It is most informative to study the differences in optical depths from average background values, owing to the fact that the invariant opacity terms will cancel revealing any perturbations. Thus, assuming that $\tau_0$ and $\tau_r$ are constant,

$$\Delta \tau = \tau - \bar{\tau} = \Delta \tau_w + \Delta \tau_d + \Delta \tau_{O_3} + \Delta \tau_{NO_2}.$$  

The water vapor molecular opacity is normally very small. Thus the term $\Delta \tau_w$ in Eq. (14) can be neglected. However, as noted below, water vapor fluctuations can contribute to the term $\Delta \tau_d$ by affecting the size of aqueous aerosols.

6.3. Analysis of the June and July/August 1908 Anomalies

Volz (1974) suggested that the large absorption event of July/August 1908, apparent in the APO data of Fig. 6, may have been due to the high water vapor content of the atmosphere over Mount Wilson at that time; high humidity enhances the opacity of background tropospheric aerosol haze. From 1908 to 1911, the APO investigators measured the $H_2O$ partial pressure at the time of each solar observation at Mount Wilson. We studied the water vapor data and found that the average July and August humidities were virtually identical in each of these years. Considering the specific period from about mid-July to mid-August, water vapor was roughly 10 to 30% higher in 1908 than in 1909–1911. However, there was no apparent correlation between periods of enhanced humidity and significant transmission anomalies in any other year. The June 1908 absorption event, moreover, occurred during a period of low absolute humidity. Roosen and Angione (1977) found a distinct positive correlation between precipitable water vapor and the extinction coefficient at each wavelength of the APO data. According to their results, the extinction coefficient at 0.4 $\mu$m increases from about 0.30 to 0.34 as precipitable water increases from 0 to 10 mm (the widest range of water vapor recorded). It follows that water vapor variations would have had only a secondary role in the transmission anomaly of July/August 1908.

Another reason to believe that the July/August event at Mount Wilson was not due to local meteorological conditions alone is that Kimball (1909) recorded a similar decrease in average atmospheric transmissions over Mount Weather, Virginia, in the early summer of 1908.

In Fig. 7, the increases in the average opacities attending the June and July/August 1908 transmission anomalies (in the APO data) are plotted. Here, $\Delta \tau$ [Eq. (14)] has been averaged over the days of the anomaly (noted in the figure). The average reference opacities (\bar{\tau}) were calculated on a month-to-month basis using the data from 1909 to 1911.

Deirmendjian (1973) and Volz (1975) studied the dust layer produced by the 1912
eruption of the Katmai volcano. Both workers determined a dust opacity spectrum roughly consistent with an inverse wavelength ($\lambda^{-1}$) dependence. This dependence should also apply to the Shtyubelya Sopka dust and the Tunguska meteor dust.

The June and July/August anomalies, when compared in Fig. 7, show quite different wavelength dependences. The June anomaly exhibits a strongly decreasing optical depth in the near-ultraviolet region. This behavior is difficult to explain if a highly (size) dispersed dust cloud is responsible. Thus, while the June anomaly might have been caused by a remnant of the Shtyubelya Sopka eruption cloud formed 15 months earlier, it more likely had another origin. By contrast, the July/August turbidity spectrum closely corresponds to that seen shortly after the Katmai eruption (Volz, 1975). This suggests a relatively fresh dust cloud that might be associated with the Tunguska meteor.

If the 1908 July/August opacity increase
is attributed to dust and scaled to the optical depth enhancement observed following the Katmai eruption (Deirmendjian, 1973), a dust column density of about $4 \times 10^{-6}$ g cm$^{-2}$ is estimated. During the 2 weeks between the meteor fall over Siberia and the observation of the dust layer over Mount Wilson, a cloud of fine particles could have dispersed over an area $\sim 10^7$ km$^2$ (Bauer, 1974). Thus we deduce from Fig. 7 that if the cloud observed over California was due to Tunguska, then the meteor deposited $\sim 10^6$ tons of dust in the stratosphere. This dust mass is consistent with existing estimates of the initial mass of the meteor, its probable composition, and its disintegration in the upper atmosphere (Sections 3 and 4). Fesenkov (1949) deduced a similar dust mass from the APO data. After a month or two, of course, the Tunguska dust cloud would have disappeared because of continuing horizontal spreading and gravitational removal of the particles. In Fig. 6, some possible residual dust effects are apparent until the end of 1908.

6.4. Ozone and NO$_2$ Absorption in 1908

In Fig. 7, the atmospheric opacities associated with ambient ozone and enhanced NO$_2$ concentrations are also illustrated. In the case of an absorbing gas, the optical depth at a fixed wavelength is defined as

$$\tau = N\sigma,$$  \hspace{1cm} (15)

where $N$ is the gas column concentration (molecules cm$^{-2}$) along the line-of-sight and $\sigma$ (cm$^2$) is the gas absorption cross section. The O$_3$ and NO$_2$ absorption cross sections are given in Table V. A change in the gas opacity is obviously proportional to a change in the column abundance of the gas (in this simplified treatment, which neglects small pressure and temperature dependences of atmospheric O$_3$ and NO$_2$ absorption). Thus, if $\Delta \tau$ has been measured at a particular wavelength, one can compute

$$\Delta N = \Delta \tau / \sigma,$$  \hspace{1cm} (16)

Likewise, for a given gas concentration $N$, the difference in absorption at two specific wavelengths can be used to calculate $N$.

$$N = \Delta \tau / \Delta \sigma,$$  \hspace{1cm} (17)

where $\Delta \sigma$ is the difference in the cross section between the wavelengths.

The July/August absorption event shown in Fig. 7, which might be related to the Tunguska meteor fall, exhibits an increasing extinction above $\lambda^{-1}$ between 0.5 and 0.4 $\mu$m that may be associated with NO$_2$. The difference between the total opacity in Fig. 7 and the $\lambda^{-1}$ opacity implies NO$_2$ concentrations of $2-3 \times 10^{16}$ molecules cm$^{-2}$. It is striking that this is roughly the same

<table>
<thead>
<tr>
<th>Wavelength ($\mu$m)</th>
<th>NO$_2^a$</th>
<th>O$_3^a$</th>
<th>NO$_3^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>5.5($-19$)</td>
<td>2.5($-22$)</td>
<td>3.0($-20$)</td>
</tr>
<tr>
<td>0.45</td>
<td>4.6($-19$)</td>
<td>1.0($-21$)</td>
<td>3.0($-19$)</td>
</tr>
<tr>
<td>0.50</td>
<td>2.2($-19$)</td>
<td>4.8($-21$)</td>
<td>1.0($-18$)</td>
</tr>
<tr>
<td>0.60</td>
<td>4.0($-20$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
<tr>
<td>0.70</td>
<td>4.6($-21$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
<tr>
<td>0.80</td>
<td>4.6($-21$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
<tr>
<td>0.90</td>
<td>4.6($-21$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
<tr>
<td>1.00</td>
<td>4.6($-21$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
<tr>
<td>1.20</td>
<td>4.6($-21$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
<tr>
<td>1.60</td>
<td>4.6($-21$)</td>
<td>9.0($-22$)</td>
<td>1.0($-19$)</td>
</tr>
</tbody>
</table>

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
Wavelength & NO$_2$ & O$_3$ & NO$_3$ \\
(\mu m) & (cm$^2$) & (cm$^2$) & (cm$^2$) \\
\hline
0.40 & 5.5($-19$) & 2.5($-22$) & 3.0($-20$) \\
0.45 & 4.6($-19$) & 2.5($-22$) & 3.0($-19$) \\
0.50 & 4.6($-21$) & 9.0($-22$) & 1.0($-18$) \\
0.60 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
0.70 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
0.80 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
0.90 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
1.00 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
1.20 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
1.60 & 4.6($-21$) & 9.0($-22$) & 1.0($-19$) \\
\hline
\end{tabular}
\caption{Absorption Coefficients for O$_3$, NO$_2$, and NO$_3$.}
\end{table}

\textsuperscript{a} The visible and near-infrared absorption coefficients of other NO$_2$ species are omitted. A review of the visible absorption spectra of NO$_2$ gases is given by Johnston and Graham (1974). HNO$_3$, N$_2$O$_4$, and N$_2$O$_5$ are essentially clear gases, while N$_2$O$_3$ is blue tinted. Bibart and Ewing (1974a,b) studied the vibrational spectra of N$_2$O$_3$ and N$_2$O$_4$ in equilibrium with NO and NO$_2$, and found only very weak near-infrared absorption. HNO$_3$ absorbs strongly below 0.4 $\mu$m (Johnston and Graham, 1974) and in the infrared region above 3 $\mu$m (Baldeschwieler and Pimentel, 1960).

\textsuperscript{b} Cross sections are averaged over small (\textasciitilde 0.01 $\mu$m) spectral intervals centered on the wavelengths of interest.

\textsuperscript{c} The cross-section data for NO$_2$ and O$_3$ are taken from a review by Turco (1975).

\textsuperscript{d} The cross sections for NO$_3$ are based on measurements made by R. A. Graham and reported in Hudson (1977).
amount of NO₂ predicted for the first few months in the hemispherical model calculations of Section 5.

With regard to ozone, the data in Fig. 7 indicate little net change between July/August 1908 and the same period in the years 1909–1911. If indeed a cloud of Tunguska NOₓ and dust had drifted over Mount Wilson in July 1908, one would expect ozone to have been depressed, and the opacity at 0.6 µm to have been reduced relative to the λ⁻¹ curve. However, note that the average (ozone) opacity for the years 1909–1911 was subtracted from the average opacity for the July/August anomaly. In Fig. 2 it is obvious that ozone would have been severely depleted from early 1909 (about one-half year after the fall) through the end of 1911. Thus an ozone reduction would not stand out clearly in the data of Fig. 7 (this point is expanded below). In addition, the relatively diluted quantities of NOₓ which mixed into the air layers over Mount Wilson, California, may not have had time to deplete total ozone, the bulk of which lies below 30 km. According to Fig. 2, it takes several weeks for ozone at the 20-km level to be reduced following an NOₓ intrusion of the magnitude proposed.

While the opacity anomalies illustrated in Fig. 7 are statistically significant, the likely O₃ and NOₓ components (about 0.04 at 0.6 µm for ambient ozone, and 0.05 at 0.4 µm for 1 × 10¹⁷ NOₓ molecules cm⁻²) lie within the statistical uncertainty of the data. If, in a month’s time, the NOₓ cloud had spread over an area of only 10⁶ km², the column concentration of NOₓ would be about 10¹⁹ cm⁻² (assuming that all of the air layers moved in perfect coordination, which is certainly an exaggeration). Recalling Eq. (6), however, the NOₓ column abundance can be estimated as about 10¹⁷ cm⁻² at most. It follows that the NOₓ opacity of the cloud was probably limited to a value less than 0.05, and is therefore undetectable with statistical confidence.

Other gaseous NOₓ constituents could have contributed to the cloud absorption. Candidate species include NO₃, HNO₂, N₂O₃, N₂O₄, HNO₃, and N₂O₅; relevant cross sections and optical data are reviewed in Table V. The first four of these gases are produced in very small quantities in an NOₓ cloud (e.g., see Fig. 5, which displays the predicted NO₃ column abundance). HNO₂ and N₂O₄ also have extremely weak absorption between 0.5 and 2.0 µm. HNO₃ and N₂O₅ are produced in large quantities in the cloud (Fig. 5), but do not absorb significantly in the visible or near-infrared regions. Accordingly, none of the NOₓ compounds mentioned affect the overall cloud opacity.

6.5. Analysis for Long-Term Ozone Trends

To test more explicitly for the ozone effects of the Tunguska meteor fall, the atmospheric opacity at Mount Wilson was analyzed on particularly clear days from 1909 to 1911. By 1909, most of the dust from the Shtyubelya Sopka volcano, and any dust from the Tunguska meteor, would have been completely dissipated, eliminating an important source of variability. In addition, the NOₓ injected by the meteor would have been widely distributed over the Northern Hemisphere, allowing horizontally averaged model predictions of ozone change to be compared. For each year of interest, the clearest observational days were selected by requiring the average atmospheric transmission (specified in the APO records) to be greater than 83% (the transmission rarely exceeded 85%). Days for which the quality of the observations was judged to be less than “excellent” or “very good” (as determined by Abbot and co-workers) were ignored. The average atmospheric opacities, and the standard deviations of the opacities, were calculated for the identified clear days of each year. The average Rayleigh extinction at Mount Wilson was subtracted from these opacities (Deirmendjian, 1973). The residual optical depths (including the effects of ozone, dust, and aerosols) corresponding to the ensemble of clear, optimum-viewing days of each year are shown
in Fig. 8. Note that the total residual opacity at 0.6 μm in 1909 is larger than those in 1910 and 1911 although, as will be shown later, the ozone contribution is smaller.

The ozone Chappuis bands are quite prominent in the atmospheric opacity spectrum. Angione et al. (1976) exploited this fact to determine from the APO data base the historical ozone record extending from 1912 to 1950, accurate on a daily basis to within 7%.

In a similar manner, we calculated the ozone column concentration on any particular day using Eq. (17) with

$$\Delta \tau = \tau_{0.6} - (\tau_{0.5} + \tau_{0.7})/2,$$  \hspace{1cm} (18)

$$\Delta \sigma = \sigma_{0.6} - (\sigma_{0.5} + \sigma_{0.7})/2,$$  \hspace{1cm} (19)

where the subscripts of $\tau$ and $\sigma$ refer to the wavelength of observation in microns. The $\tau$'s in Eq. (18) are residual opacities after subtraction of the average Rayleigh extinc-
tion. The aerosol and dust turbidity between 0.5 and 0.7 μm is slowly varying (≈t−1). Thus the use of Eq. (18) effectively eliminates the dust extinction from the ozone determination; the effect of humidity on turbidity, likewise, is canceled. In averaging a large number of residual opacities, the contributions due to fluctuations in the Rayleigh optical depth about the mean value also tend to cancel at each wavelength. Average ozone column abundances, and related statistical parameters, can be computed over any time interval using the daily ozone amounts obtained from the APO observations through Eqs. (17)–(19).

In Table VI, measured and calculated average ozone column concentrations for the years 1909 to 1911 are compared. The absolute ozone abundances determined from the APO data are in general accord with the amounts measured by modern-day instruments (Angione et al., 1976). More importantly, the relative amounts of ozone observed in the atmosphere from 1909 to 1911 are in very close agreement with the model prediction for Tunguska. Note particularly that if the ozone calculations are corrected for temperature feedback effects (≈−2 to −5% less ozone depletion in 1909, −1 to −3% less in 1910, and −1% less in 1911; see Section 4), the agreement between theory and observation would be even better. This comparison, therefore, suggests that the Tunguska event may provide the first direct observational evidence for large total ozone depletions following immense NOx injections.

The correspondence between the measured and calculated time-dependent ozone variations is brought out more clearly in Fig. 9. Here the individual “clear-day” ozone concentrations are graphed together with a model prediction of the ozone change following Tunguska, which has been

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed O₃b</th>
<th>Observed O₃/O₃(1911)</th>
<th>Calculated O₃/O₃(1911)c</th>
<th>Range of observed O₃ valuesd (molecules cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1909</td>
<td>6.65 × 10¹⁸ (± 15%)</td>
<td>0.81</td>
<td>0.73</td>
<td>4.6–8.3 × 10¹⁸</td>
</tr>
<tr>
<td>1910</td>
<td>7.00 × 10¹⁸ (± 4%)</td>
<td>0.85</td>
<td>0.85</td>
<td>5.6–8.4 × 10¹⁸</td>
</tr>
<tr>
<td>1911</td>
<td>8.20 × 10¹⁸ (± 4%)</td>
<td>1.00</td>
<td>1.00</td>
<td>6.2–10.2 × 10¹⁸</td>
</tr>
</tbody>
</table>

a High-quality clear-day observations were used: i.e., the average transmission was ≥83% and the grade of the measurement was either “very good” or “excellent.”

b The vertical ozone column abundance (molecules cm⁻²) is given. The computed average ozone abundances correspond to: 17 days in 1909 (between Days 188 and 306), 30 days in 1910 (between Days 138 and 312), and 29 days in 1911 (between Days 185 and 325). The standard deviation of the mean ozone concentration (in percent) for the selected data set is indicated in brackets. Note that 1 × 10¹⁸ molecules cm⁻² equals 0.37 atm-cm STP.

c Based on the model calculation in Fig. 2, adjusted to correspond to the appropriate observational time interval of each year. The calculated ozone columns were increased by a small, fixed amount of ozone (5 × 10¹⁷ molecules cm⁻²) assumed to reside between the top of Mount Wilson (1.74 km) and 10 km, the lower boundary of the model.

d The overall ranges were determined by analyzing all of the APO data subsets defined by the following observational constraints: average transmissions exceeding levels between 80 and 90% in 1% increments, and minimum grades exceeding any one of four possibilities between “poor” and “excellent.” Resultant subsets with less than 10 data points were discarded. The total ozone concentration range shown encompasses the maximum and minimum ozone levels calculated using the acceptable subsets, and includes one standard deviation.

e Day 287 of 1909 was omitted from this analysis because it showed an anomalously high 0.6-μm transmission, and when considered individually, yielded a negative ozone abundance. Several other days were eliminated on similar grounds (Days 178 and 268 of 1910 and Day 168 of 1911).
Fig. 9. Ozone column concentrations for the period 1909 to 1911 deduced from the APO Mount Wilson transmission data in the O$_3$ Chappuis bands. Each dot gives the ozone overburden on a day of exceptional observational quality, as dictated by an average transmission fraction exceeding 83% and a high degree of measurement consistency. For each year, the mean ozone concentration and the standard deviation of the mean concentration are shown. Also plotted is the predicted total ozone variation from Fig. 2, after normalization to the observed 1910 ozone concentration (a small downward adjustment of less than 5% in the globally averaged ozone predictions for equinoctial conditions brings the measured and calculated amounts in 1910 into agreement). A correction to the predictions for the ozone content below 10 km, the lower boundary of the model, has been applied (see Table 6, footnote c).

normalized to the 1910 observations. For each year of data, the corresponding average ozone concentration is also given in Fig. 9, together with the standard deviation of the average concentration. The latter value is calculated by dividing the standard deviation, or scatter, of the individual data points by the square root of the number of observations. The substantial scatter in the ozone data arises mainly in the natural day-to-day variability of ozone, which can be attributed to the horizontal patchiness of the ozone overburden. Such variability is seen in all high-resolution measurements of the ozone column abundance (e.g., Angione et al., 1976). Nevertheless, the standard deviation of the mean of the data samples analyzed is relatively small, due to the large size of the samples available.

The observed trend in the ozone abundance from 1909 to 1911 is in close agreement with the predicted trend in the aftermath of Tunguska. The fit of the calculations to the observations falls within the 1σ statistical bounds. Note again that temperature feedback effects would improve the overall quality of the fit. Although the average 1911 ozone abundance is statistically greater than the 1909 and 1910 abundances, the 1909 ozone level can-
not be placed statistically below the 1910 level, based on the current analysis.

The interhemispheric mixing of injected $\text{NO}_x$ would accelerate the ozone recovery following the Tunguska event. The interhemispheric transfer time at stratospheric altitudes is in the range of 1–3 years (Grobecker et al., 1974). If instantaneous interhemispheric mixing occurred, the predicted ozone depletions would be approximately one-half of those calculated with hemispherical mixing. The actual ozone recovery (after ~6 months) would fall between the extreme calculations for hemispherical and global spreading. An estimate of the concomitant adjustment in the ozone column ratios given in Table VI can be made if negligible interhemispheric mixing is presumed in 1909, half mixing in 1910, and complete mixing in 1911. Then the predicted ratios 0.73, 0.85, and 1.00 in column 4 of Table VI become 0.69, 0.86, and 1.00, respectively. In other words, the adjustment is about as large, and of the opposite sign, as the estimated temperature feedback adjustment.

Obviously, a wide variety of ozone abundance curves would be consistent with the data in Table VI and Fig. 9. At the 1σ uncertainty level, an ozone recovery of only about 10–15% between 1909 and 1911 could be accepted. Such a recovery curve would imply an initial Tunguska $\text{NO}_x$ injection about one-third of that deduced in Section 3. It is also conceivable that an ozone variation this large might have had another natural origin. However, the calculated ozone trend following Tunguska, and the trend deduced from the APO data—each analyzed independently—agree remarkably well.

To test further for an ozone trend, a linear regression analysis of the data in Fig. 9 was made (Turco et al., 1981). The results are shown in Fig. 10, along with the 30°N-equinox model calculation for Tunguska. For

![Fig. 10. Linear regression analysis of the ozone data in Fig. 9. For comparison, the hemispherically averaged 30°N-equinox one-dimensional model calculation of the ozone recovery following Tunguska is shown without any adjustments.](image-url)
the 1000 days covered in the illustration the linear regression gives an absolute ozone increase of \( \sim 2.1 \times 10^{18} \) molecules cm\(^{-2}\), while the simulation gives an increase of \( \sim 2.8 \times 10^{18} \) cm\(^{-2}\). By reasonable extrapolation of the computed regression line to an ambient ozone column abundance of \( \sim 9 \times 10^{18} \) cm\(^{-2}\), the analysis is compatible with an overall ozone reduction following Tunguska of 30 ± 15% at the 95% confidence level. Thus, based on the results in Fig. 10, the APO ozone data appear to imply a somewhat smaller ozone depletion and a slower (average) rate of recovery than are given by the model calculations.

Notice in Fig. 10 that the ozone calculation for 30°N equinox, if adjusted downward slightly in absolute concentration, would essentially fit within the uncertainty limits of the regression analysis. In Fig. 9, a small (~5%) adjustment to the calculation has already been made. Ozone column concentrations vary with latitude, with more ozone generally lying at high latitudes than at low latitudes. Thus it is not unreasonable, in comparing observed local trends in ozone abundance to hemispherically averaged calculations of ozone change, to make small systematic alterations in the predicted ozone concentrations. A difference between the observational results in Figs. 9 and 10 is that the linear regression line in Fig. 10 is based on all of the APO data between 1909 and 1911, while the average ozone concentrations in Fig. 9 are based on the data from individual years.

The ozone data analysis was repeated using a wide range of subsets of the APO measurements selected on the basis of the average transmission fraction and grade of observation. When higher-quality data was employed, the sample size decreased and the statistics degenerated, but the ozone trend in Fig. 9 was retained. When poorer quality data was included, the derived ozone abundances were biased toward larger concentrations. Column 5 in Table VI summarizes the overall ranges in total ozone concentrations found, including a 1σ interval. Even the smallest subsets of data (which exhibited large mean standard deviations) suggested an increasing trend in ozone between 1909 and 1911.

The contribution of known cyclic ozone variations to the ozone trend indicated in Figs. 9 and 10 and Table VI was evaluated. Of course, the random day-to-day ozone variability is smoothed substantially by the selection of a suitably large subset of the available data. Diurnal variability does not enter because the APO transmission data (used to calculate ozone concentrations) were (almost) always collected at the same time of day; the diurnal variation in total ozone is small in any case. Inasmuch as the APO measurements were made during the same period of each year, the (small) seasonal bias in ozone abundances is also roughly compensated for.

On a global scale, ozone exhibits a weak quasi-biennial oscillation of 1–2% (Angell and Korshover, 1973). By comparison, the ozone variation under scrutiny here is 20–30%. The phase of the quasi-biennial wave, moreover, may not have matched the increasing trend in the APO measurements. Unfortunately, it is not possible to extrapolate backward the quasi-biennial oscillations observed in the 1950s and 1960s because the cycles are irregular and occasionally suffer major phase shifts (Angell and Korshover, 1976). Parenthetically, the ozone data of Angione et al. (1976) are not accurate enough to reveal the quasi-biennial variation.

Ozone displays a larger 11-year solar cycle variation of 3–6%; the 3% variation applies to low and midlatitudes, the 6% figure to high latitudes. The ozone maximum lags the sunspot maximum by about 3 years (Angell and Korshover, 1973). In the Tunguska time frame, sunspot maxima occurred in 1906 and 1917 (Lamb, 1972). The ozone maximum would have occurred during 1909–1910. Thus, from mid-1909 to mid-1911, a small (~<2%) ozone decrease would be expected due to the solar cycle variation. In summary, the identified natu-
eral ozone cycles do not markedly affect the interpretation of the APO data presented here.

It might be proposed that the large Shytubelya Sopka volcanic eruption of 1907 caused an ozone depletion that required 4 years to recover. The ozone depletion could have resulted, for example, from the injection of chlorine into the stratosphere (Cadle et al., 1979). Interestingly, a recent study of the 1974 eruption of Volcan de Fuego revealed that little HCl was deposited in the stratosphere compared to sulfur (which has no important direct effect on ozone), because the soluble HCl was apparently washed out of the eruption cloud (Lazrus et al., 1979). The injected sulfur dioxide gas could reduce OH concentrations, while injected water vapor could enhance them. OH, in turn, controls many of the ozone chemical cycles in the stratosphere. However, the OH perturbation would not last for more than a year. Angione et al. (1976), using APO data, calculated ozone concentrations following the 1912 Katmai eruption. Their results indicate an unusual (~20%) ozone increase above the mean concentration in 1913, which is probably a result of noise in the data caused by the volcanic dust. We conclude, therefore, that the Shytubelya Sopka eruption had no substantial role in the ozone recovery trend of 1909−1911.

6.6. NO2 Absorption Trend

Returning to Fig. 8, there appears to be a suggestion of NO2-band absorption at 0.4 and 0.45 μm. Note, however, that, in comparison to the total opacities in Fig. 8, the NO2 band strengths, which correspond to the NO2 calculations in Section 5, are quite weak. Moreover, at these short wavelengths, the Rayleigh extinction correction is critical. The Rayleigh optical depth is 10–20 times larger than the opacities shown in Fig. 8 at 0.4 μm. Because a fixed Rayleigh extinction factor was applied here (Deirmendjian, 1973), the short-wavelength data in Fig. 8 are subject to errors introduced by air density fluctuations. (The significance of the data at 0.4 μm in Fig. 7 is also affected, but to a lesser degree.) Obviously, a more thorough data analysis utilizing the entire spectrum of the APO observations could be used to deduce the Rayleigh, dust, ozone, and any residual extinction (Angione et al., 1976; Roosen and Angione, 1977). Until such a procedure is carried out, firm conclusions about possible NO2 enhancements during 1909−1911 cannot be reached.

7. THE “LIGHT NIGHTS” OF JUNE AND JULY, 1908

Following the Tunguska meteor fall, a vast region of Eurasia experienced unusual optical disturbances on several consecutive evenings. Eyewitness accounts of these events, as reported in the contemporary scientific literature, have been reviewed by deRoy (1908), Stentzel (1908), Zotkin (1961, 1969), Vasilev et al. (1965), and Krinov (1966). In Table VII, the observed characteristics of the anomalous light emissions are summarized. The glowing night skies, silvery clouds, and other optical phenomena may have had their origin in aurorae, dust veils, noctilucent clouds, and chemiluminescent emissions. Based on descriptions set forth by trained observers, however, it seems unlikely that aurora borealis had a significant role. The glowing skies did not display the scintillation and structure characteristic of aurorae, nor were the distinct auroral emission lines detected. Thus we are left to consider the optical aspects of cometary dust, noctilucent clouds, and chemiluminescent emissions generated by the Tunguska event.

7.1. Sunlight Scattering by Dust

The dust hypothesis has been examined at length by Fesenkov (1962, 1966, 1969). He proposed that the “tail” of the Tunguska “comet” created a thin, short-lived dust layer high in the thermosphere (above 150 km), which was responsible for the twilight anomalies. Actually, deRoy (1908), one of the first chroniclers of the light night phenomena in Europe—who was
TABLE VII

PHYSICAL MANIFESTATIONS OF THE OPTICAL DISTURBANCES OF JUNE 30–JULY 2, 1908

a. Brightness: The maximum brightness was $-10^{-4}$ of direct sunlight, one hundred times brighter than the normal airglow. At the zenith in Bordeaux, France, the brightness approached that of 100 stars of 5th magnitude per square degree. In many places, photographs could be taken with long exposures ($\sim 15–30$ min) and small print could be read unaided by artificial light. The brightness diminished by at least a factor of 10 in many places by the second night (July 1–July 2). In the northern sky, only the brightest stars (e.g., Capella) were visible.

b. Color: Typically, red, orange, and yellow hues were reported. Shining white clouds and brilliant golden glows were also noted. Occasionally, green, pink, and purple colorations were visible. Colored cloudscapes were frequently described.

c. Spectrum: The characteristic auroral line emissions (red 6300 $\AA$ and green 5577 $\AA$) were not detected in the anomalous glows. The emissions had a broad "twilight" spectrum.

d. Duration: The brightest glows occurred on the night of June 30–July 1, and diminished rapidly thereafter. Some effects were noted over the next two nights. In Central Russia, the emission peaked at 10:30 PM the first night. In many places the glow lasted all night, hence the so-called "light nights." In some places the light diminished after midnight.

e. Extent: The anomalous emissions were noticed at various times and locations between latitudes 45 and 60° north and from 95° east longitude westward to the Atlantic Ocean. No anomalies were observed over North America or Australia. It is not known whether the area of anomalous light extended over the North Atlantic. The northern extent of the glow also would have been masked by the endless twilight at the Arctic Circle near summer solstice.

f. Structure: The emissions were generally diffuse in nature—like the extended twilights which follow volcanic eruptions—without flickering or scintillation. Glows extended from the north to the zenith, and to the south and southeast as well. Bright glowing bands and columns were seen, as were glowing diffuse clouds. The illuminated clouds and skies often seemed to undulate. The light was usually brightest at the northern horizon, spreading westward and eastward. Twilight segments extending over one-fourth of the horizon were noted in Germany. The brightest spot on the horizon appeared to move from east to west in unison with the Sun (lying below the horizon).

g. Geography: No optical effects were noticed in the night-time sector of Eurasia at the time of the Tunguska fall (0:17 UT). In the Caucasus near 45° latitude, the glow was very bright the next night. In Germany, the anomalous emissions disappeared after 1:00 AM on July 1. In France, the intensity of the glow decayed by a factor of 20 the second night.

h. Sky polarization: Daytime polarization measurements by Busch at Arnsberg, Germany, indicated that on June 29 and July 22 the neutral points Babinet and Arago were normal, but on July 1 Babinet altered position from 6.2 to 4.5° by the height of the Sun.

i. Halos: A vivid rusty-orange solar halo was first noted by C. O. Stevens (Nature 78, 221, 1908) at 12:35 PM June 30 at Oxford, England. The halo lasted all afternoon and reappeared, much dissipated, on the two following days. As the halo dispersed, colored mock suns materialized. On July 2, C. J. P. Cave (Nature 78, 247, 1908) observed a bright solar halo over Torbay, England, which lasted all day. Besides the common 22° Bishop's ring, an elliptical ring spreading out to 25° was seen, and fragments of a halo could be seen out to 44° from the sun. Finch (Observatory 31, 325, 1908) also reported solar halos at the Greenwich Observatory in the forenoon and afternoon of June 30 and July 1.

unaware of the Tunguska fall—first suggested that the Earth had collided with a comet or cometary debris. The light nights occurred during the early summer season, when meteor showers are common. By coincidence, in the journal article following deRoy's, Birkenstock (1908) reported that a large number of bolides, some of exceptional brightness, had been seen that June and July. Fesenkov argued that the apparent optical effects due to dust lent credibility to the cometary encounter theory. Zotkin (1969) and Kresak (1978) pointed out that Comet Encke has celestial orbital parameters close to those deduced for the Tunguska meteor, and may have been the source of the Tunguska object.

The Tunguska event occurred at high lati-
tude (60°55' N) just 9 days after summer solstice when the Sun's declination is 23.2°. Hence conditions were ideal for a prolongation of twilight over a wide geographical area by scattering of sunlight from elevated dust layers. Volz and Goody (1962), in their search for high-altitude dust, made extensive measurements of the normal twilight intensity and found rapid attenuation of the glow for solar depressions (sd) exceeding 9°. The close of astronomical twilight occurs at about 16° sd. Other analyses by Volz and Goody imply that the sky brightness at large solar depressions is very sensitive to atmospheric dust.

In Fig. 11, the area affected by anomalous optical emissions following the Tunguska meteor fall is outlined. Obviously, because the region is quite extensive, an explanation based on a widespread dust veil seems appropriate. The visual descriptions of the anomalies compiled in Table VII strongly suggest a prolonged twilight phenomena. Additional evidence for a dust intrusion is found both in the observations of solar halos and in a change of sky polarization (Table VII). Interestingly, the first observation of a solar halo over England before noon on June 30 fixes the maximum time for the dust to reach this region as roughly 12 hr after the fall. The dust obviously could not have originated at the fall site some 6000 km away. Hence this observation supports Fesenkov's contention that the comet's dust 'tail' was directed southwest from the fall site and did not enter the atmosphere over Europe at the time of the event, but was blown there later by the pre-
vailing easterly winds (we adopt the convention that an easterly wind blows toward the west).

There are several problems with Fesenkov's dust theory, however. According to Fesenkov (1962), the dust layer would have had to extend to 700 km altitude to explain the bright sky glows at the lowest latitudes (solar depressions of 16° or more). The typical fall velocities of 0.1-μm-radius particles above 100 km are >5 m sec⁻¹, or >500 km day⁻¹. Moreover, the dust could not have been stopped by viscous forces above ~100 km, and so would probably be approaching the Earth at meteoric velocities of ~40 km sec⁻¹. It is therefore difficult to imagine any optically active dust particles (of 0.1-μm radius or greater) remaining above 100 km for a period of several days. Yet, the dust apparently entered the upper atmosphere at the time of the meteor fall and resided there a full day before causing the first twilight anomalies. By the second evening after the fall, the optical effects of the dust were greatly attenuated. Fesenkov (1966) suggests that the dust cloud was widely dispersed by horizontal winds, inasmuch as the particles would not have completely fallen out of the atmosphere in 2 days where they had remained suspended for one.

Fesenkov's arguments for a thermospheric dust layer are not compelling. It is much more likely that any fine dust accompanying the Tunguska meteor stopped in the upper mesosphere, where noctilucent clouds often appear. This possibility is explored below.

It has recently been pointed out that, in order to have a "tail," the Tunguska object would have had to be an active comet (Kresak, 1978). The Tunguska trajectory, additionally, would have corresponded to that of a short-period comet. Yet no active comets with the appropriate orbital parameters were observed prior to 1908. That leaves open, however, the possibility of a virgin comet, or a juvenile fragment of comet Encke, for example.

7.2. Noctilucent Clouds

Rather than meteoric dust, the glowing skies could have been caused by widespread noctilucent (night-luminous) clouds (NLCs). NLCs are often observed at high latitudes during the summer months when the mesopause is extremely cold (Theon et al., 1967; Donahue et al., 1972). Meteoric dust has been suggested as a nucleus for NLC formation (Hesstvedt, 1962). The influx of dust nuclei associated with the Tunguska meteor might have heightened the noctilucent cloud displays normally seen at that time of the year (Vasilev et al., 1965). Any fine cometary dust associated with the meteor would have settled to the Earth's mesopause (~80 km) and remained there for several days. However, noctilucent cloud genesis is probably limited more by the amount of water vapor present in the mesosphere—assuming very cold mesopause temperatures—than by the number of nucleation sites available for water vapor condensation (Turco et al., 1982). Accordingly, we propose that the water vapor deposited at high altitude by the cometary Tunguska meteor might have contributed to enhanced cloudiness.

The data in Fig. 1 indicate that almost 10³² H₂O molecules may have been injected by the Tunguska meteor near the mesopause. Horizontal dispersion of this water vapor could have been quite rapid (see the following section). If spread over an area of 10⁶ km², a 10-fold enhancement in the mesospheric H₂O concentration would result. Based on detailed model simulations of noctilucent cloud formation (Turco et al., 1982), it appears that perturbed cloud optical depths (at 550 nm) could approach ~10⁻³ under such conditions, where normally they are ~10⁻⁴–10⁻⁵. The meteor clouds would be much brighter than typical NLCs, and might extend to lower latitudes. The presence of extraterrestrial dust intermixed with the injected water vapor should have guaranteed the generation of unusually bright noctilucent clouds.
7.3. Chemical Airglow Emissions

Chemiluminescent air emissions could account for some of the observed optical phenomena connected with Tunguska, including the color, intensity, distribution, and temporal behavior of the anomalous glows. In Fig. 12, predicted chemiluminescent emission intensities are given for the Tunguska event. The model calculations are based on hemispherical or zonal averaging of the Tunguska NO injection and the reaction rates in Table III. The resultant average night-time intensities are quite weak, and are dominated by the NO + O airglow, with a smaller contribution from the NO + O$_3$ chemiluminescence.

The night-time NO + O emission originates at altitudes above 80–90 km, because at night free oxygen atoms do not exist in large numbers below these heights. Also shown in Fig. 12 is the total NO + O emis-

![Figure 12](image-url)

**Fig. 12.** Estimated sky brightness due to chemiluminescence following the Tunguska fall. All zenith emission intensities are increased by a factor of 10 to allow for the apparent increase in intensity when viewing an emitting layer near the horizon. A kiloRayleigh (kR) is $10^9$ photons cm$^{-2}$ sec$^{-1}$ column$^{-1}$. For each emission intensity calculated with the photochemical model, the height above which half the emission originates during the first 3 days is indicated in brackets. The daytime and night-time emissions correspond to average values for each period, although a smooth curve has been drawn from day to day. Also shown are two rough estimates of the emission intensities expected from localized clouds of NO; the basis for making these estimates is discussed in the text.
sion above 90 km in the hemispherical case, scaled to an area of $4 \times 10^6$ km$^2$ (roughly the area over which anomalous light was seen). A simple scaling procedure is acceptable because the emission consumes only a small fraction of the atomic oxygen above 90 km. Altogether, there are enough oxygen atoms above 90 km to produce an NO + O illumination of at least 10 megaRayleighs ($1$ MR = $10^{12}$ photons cm$^{-2}$ sec$^{-1}$ column$^{-1}$) for the entire night. Each NO + O reaction consumes two oxygen atoms, due to the rapid NO recycling reaction.

$$\text{NO}_2 + \text{O} \rightarrow \text{NO} + \text{O}_2,$$  \hspace{1cm} (20)

which has a rate coefficient of $9 \times 10^{-12}$ cm$^3$ sec$^{-1}$. Reaction (20) is not fast enough, however, to quench the emission.

Note in Fig. 12 that the local NO + O luminescence can be quite intense. The duration of the emission is governed by two factors: the rate of horizontal dispersion of the NO above 90 km, and the efficiency of photochemical destruction of NO. A discussion of the horizontal dispersion rate of the NO cloud will be taken up shortly. The photochemical lifetime of NO above 90 km is controlled by solar ultraviolet photolysis; accordingly, the perturbed NO + O nighttime emission can only endure, at the outside, for about 5 days (Frederick and Hudson, 1979).

The model prediction for the NO + O$_3$ chemiluminescent intensity in Fig. 12 crudely represents the average emission for each night. Actually, the emission would occur primarily at sunset—as the O$_3$ and NO combined to form NO$_2$—and would therefore be masked by normal twilight. The NO + O$_3$ emission originates above 50 km, but the efficiency of the emission is very small—in the range of one visible photon for every 100–1000 reactions. This is due to three factors: the low efficiency for emission of visible photons (~6%, see Table III), quenching of the emission (also see Table III), and competition between the light-emitting channel and the “dark” channel,

$$\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2,$$ \hspace{1cm} (21)

which has a rate coefficient of $2.3 \times 10^{-12}$ e$^{-1450/\tau}$ cm$^3$ sec$^{-1}$.

The NO + O$_3$ emission of an “expanding cloud” was calculated using Eq. (5), which was integrated between 50 and 85 km to obtain the total photon emission rate. The cross-sectional area of the cloud at each height was obtained from an empirical relation (Bauer, 1974),

$$A = (\pi/4)d^2 = (\pi/2)K_h t,$$ \hspace{1cm} (22)

where $d$ is the cloud diameter (cm) and $K_h$ is the effective horizontal diffusion coefficient (cm$^2$ sec$^{-1}$). According to the data summarized by Bauer (1974), mesospheric values of $K_h$ lie between $10^8$ and $10^{10}$ cm$^2$ sec$^{-1}$ at times of 1 hr to several days after cloud injection. Adopting a value of $10^{10}$ cm$^2$ sec$^{-1}$ for all heights and times, the cloud would expand to a diameter of about 400 km after 1 day. This estimate neglects a small contribution to cloud expansion due to the initial size of the stabilized meteor plume. The cloud would also be elongated by wind shears.

To estimate crudely the equivalent emission intensity for an observer to the side of an idealized elongated cylindrical cloud, one can calculate the total emission integrated along the axis of the cloud, divide by the cloud volume, and multiply by the cloud diameter. In this case, a slant-path magnification factor is not applied as for an emitting layer, because a cylindrically symmetric cloud has a constant apparent intensity for a fixed viewing angle with respect to the axis of symmetry. The resulting NO + O$_3$ emission intensity is given in Fig. 12. Interestingly, it has a lower magnitude than the predicted hemispherical twilight NO + O$_3$ emission (implying that mixing-in of ambient air is not an efficient means of producing chemiluminescence beyond several hours).

Figure 13 shows a full-diurnal simulation of the NO$_2$–O$_x$ emission intensities during the first 24 hr after the Tunguska fall, as-
suming zonal spreading of the injected NO. These results roughly confirm the diurnally averaged calculations of Fig. 12. Note that the NO + O and NO + O₃ emissions are quickly extinguished at sunset, and maintain low intensities throughout the night.

The spatial characteristics of the NO₂–O₃ airglow emission depends critically on the upper atmospheric wind fields. According to Webb (1966) and Belmont et al. (1975a,b), at 60°N latitude in early summer a strong easterly jet dominates the zonal circulation between 40 and 90 km altitude. The jet has winds of 80 m sec⁻¹ at 70 km, 60 m sec⁻¹ at 60 and 80 km, and 40 m sec⁻¹ at 50 km. The winds are very steady and tend to follow lines of constant latitude. Long waves (numbers 1 and 2) often propagate along the jet, causing it to meander to other latitudes. The intense polar vortex driving the winds also precesses about the pole, causing the wind streamlines to intersect circles of constant latitude. Above 80 km, the organized easterly wind pattern exists with weakened intensity (i.e., less than 40 m sec⁻¹). A strong semidiurnal tide is prominent in this region, being associated with the solar heating cycle (Webb, 1966).

In general, vertical motions in the atmosphere are strongly inhibited. Hence, it is

![Graph](image_url)

**Fig. 13.** The predicted diurnal variations of the NO + O and NO + O₃ chemiluminescent emission intensities on June 30 and July 1, 1908. The conditions for the calculation are given in the figure. The altitude above which half the emission intensity originates is indicated in brackets for both the daytime and night-time periods.
doubtful that much of the NO deposited below 50 km by the Tunguska meteor could have contributed to the observed night-time airglow effects; NO emissions are effectively quenched below 50 km. However, the hydrodynamics of the early meteor trail was not treated here, and might have led to some unusual effects.

In Fig. 11, the distance west of the Tunguska fall site that a cloud might have traveled before the first sunset after the event is indicated. Also shown are the effective ground ranges for viewing these high-altitude clouds. Several features are noteworthy. After 1 day, the Tunguska NO plume could have been stretched over a broad zonal region. Although this is consistent with the widespread occurrence of optical anomalies, it also implies a substantial dilution of the emission intensity at each location. This factor was taken into account earlier for the NO + O₃ emission, but not for the NO + O emission. Inasmuch as the maximum NO + O airglow intensity in Fig. 12 is barely equivalent to an IBC III aurora, very little dilution could be accommodated if the glow was to have a widespread impact.

In Fig. 11, note that the NOₓ-Oₓ airglow cannot explain the anomalous optical effects eastward of 70° longitude nor southward of 50° latitude, unless unusual wind patterns existed above 50 km. The NO injected above 90 km could have meandered southward on June 30. However, the NO + O emitting layer is quite limited in height extent (~90 to 100 km), and could not have spread over the entire region of disturbances outlined in Fig. 11.

It is difficult to synthesize the visual appearance of immense NOₓ chemiluminescent clouds, since none have been observed before. Substantial structure on various scales would almost certainly exist, owing to the complex dynamical mixing and transport processes at work. Such structure was not generally seen during the “light nights” following Tunguska, although “undulating, glowing clouds” were described (Table VII). Some past thermonuclear explosions produced large buoyant clouds rich in NO that stabilized in the stratosphere. However, bright visible emissions were not observed from these clouds (Glasstone, 1962).

7.4. Origins of the Glowing Skies

We can now summarize our findings on the anomalous optical displays which occurred after the Tunguska meteor fall. Most of the observational evidence supports the hypothesis of a prolonged twilight glow caused by a layer of dust and ice particles formed in the upper mesosphere where meteoric ablation debris and noctilucent clouds normally reside (e.g., Hunten et al., 1980; Turco et al., 1982). The NOₓ-Oₓ airglow emissions were too weak and localized to explain the far-ranging reports of spectacular glowing skies. Although the dust theory has flaws, it is more tenable than the airglow theory. Nonetheless, there almost certainly was a strong chemiluminescence accompanying the Tunguska event, which was probably manifest in the region of the fall and along the 60th parallel, but went unnoticed in the long summer twilights near the Arctic Circle.

In view of our conclusion that the chemiluminescent emissions of NOₓ did not control the Tunguska optical phenomena, it is worthwhile to review the other observational evidence which points to enhanced NOₓ concentrations following the meteor event.

1) It is irrefutable that the observed high-velocity bolide produced a large quantity of NO in the atmosphere. This is a straightforward consequence of aerodynamics and air chemistry. The absolute amount of NO produced by the Tunguska meteor, however, is uncertain by factors of 3 to 10.

2) A dark smoke trail was observed behind the Tunguska bolide, and dust clouds were seen after the fall (Krinov, 1966). NO₂ formed during the flight of the meteor would have contributed to the dark appearance of the trail and the terminal cloud.

3) The APO atmospheric transmission
data give some suggestion of increased NO₂ absorption between 0.4 and 0.5 μm, both in the early "Tunguska" cloud of July/August 1908, and in the background atmosphere from 1909-1911.

(4) The optical anomalies of June 30–July 2, 1908, exhibited some of the properties that might be associated with a strong NO₂–O₂ chemiluminescent emission, including: a red- to green-shaded emission spectrum, a substantial geographical extent, a rapidly decaying intensity over several days, and the distinctive appearance of glowing, undulating clouds and skies.

The optical evidence pointing to a large atmospheric NO₂ injection by the Tunguska meteor is highly circumstantial. Accordingly, the optical data can not be used to calibrate accurately the aerodynamical production of NO during the event.

8. CLIMATOLOGICAL, ENVIRONMENTAL, AND HISTORICAL IMPLICATIONS OF THE TUNGUSKA METEOR FALL

If the Tunguska meteor caused massive ozone reductions that persisted for several years, then related disturbances in global weather patterns might have occurred. Hampson (1974) first suggested that a full-scale nuclear war might severely deplete the ozone shield, possibly flooding the Earth with ultraviolet radiation and triggering a major climatic change. As noted earlier, Tunguska can be roughly equated with a 6000-megaton "nuclear war" regarding the NO₂ production. Accordingly, Tunguska may provide a test of the ozone–weather coupling hypothesis, of potential climate-triggering mechanisms, and of possible biological consequences of prolonged dosages of enhanced ultraviolet radiation.

8.1. Weather/Climate Impacts

When large NO₂ injections cause large ozone depletions in the stratosphere and mesosphere, the heating rate in these regions may be reduced, inasmuch as ozone is the predominant absorber of ultraviolet solar radiation between 15 and 80 km [the Chappuis bands also contribute to the heating; Strobel (1978)]. However, large NOₓ injections also lead to an increase in NO₂, which is an efficient absorber of visible radiation (Luther, 1976). This compensates part of the ozone heating deficiency and, in the case of very large NOₓ injections, actually results in a net heating gain (Reid et al., 1978). More importantly, the heating pattern of the entire atmosphere is dramatically modified, and coupled changes in temperature, winds, and weather may ensue.

No reliable calculations are presently available giving the changes in wind patterns following large ozone depletions. Researchers, however, have begun to study the problem of coupled ozone–temperature–dynamics perturbations with two-dimensional models (e.g., Haigh and Pyle, 1979; Ramanathan and Dickinson, 1979). The preliminary results tend to confirm the predictions made with simpler radiative transfer models. Nevertheless, the dynamical consequences of large ozone depletions are not yet fully understood.

An enduring stratospheric dust veil created by the Tunguska meteor could also have affected the Earth's radiation balance and possibly the climate (Lamb, 1972; Pollack et al., 1976; Mendonca et al., 1978). Evidence for a dust-related decrease in surface temperatures following the Mt. Agung eruption of 1963 has been developed by Newell and Weare (1976). On the basis of existing estimates of the amount of dust deposited by the Tunguska meteor (~10⁶ tons), an average surface temperature decrease of ≤0.05°K might be expected about a year after the fall. The meteoric dust may have acted in combination with the residual dust of the Shtyubelya Sopka eruption cloud, which was prominent in 1907. The close proximity in time of these two events, in fact, may have had additional climatic significance (see below).

The potential climate impact of the NOₓ and particulate emissions of a large, high-altitude aircraft fleet was thoroughly investigated during the Climatic Impact Assess-
ment Program (CIAP) (Grobecker et al., 1974). More recently, MacCracken et al. (1975) reviewed the climatic consequences of a large-scale nuclear exchange, and Reid et al. (1978) considered the global weather impact of intense, sustained cosmic ionization events. In each case, the likelihood of important climate changes due to large NO\textsubscript{x} injections was emphasized on theoretical grounds, but could not be established convincingly using observational data. The evidence for NO\textsubscript{x} effects after past atmospheric nuclear tests has also been disputed (Goldsmith et al., 1973). Accordingly, if the current estimates of NO\textsubscript{x} production by the Tunguska meteor are correct, then the event may provide a natural test of existing NO\textsubscript{x}-ozone-weather theories.

To this end, weather records from the early 1900s were surveyed for possible significant climate/weather changes in the Tunguska epoch (Lamb, 1972, 1977; Exner et al., 1944). We found several unusual weather conditions that appeared to commence around 1908 and persist for several years. For example, there was an increase (above a decreasing trend) in the south-to-north difference of the mean surface air temperature over North America (30 to 41° latitude) in both January and July beginning in 1909–1910. Total arctic sea ice increased rapidly between 1908 and 1911. In the years 1910 to 1915, the number of tropical cyclones of all intensities in the Atlantic and Caribbean Oceans decreased by almost 50% from normal values, and remained unusually low for two decades.

A particularly interesting trend uncovered was the change in average surface temperatures during this period. After 1908, and for almost a decade, the annual average surface temperature in the Northern Hemisphere (0 to 80°N) was decreasing, while the global and Southern Hemisphere (0 to 60°S) temperatures were increasing. In almost every other 10-year period from 1884 to 1974 all three temperatures had similar trends. The temperature data covering the last century are shown in Fig. 14. The anomalous temperature difference in Fig. 14 represents an overall cooling of about 0.2 to 0.3°K in the Northern Hemisphere. However, the cooling trend may have been initiated by the two large, high-northern-latitude volcanic eruptions of that era—Shtyubelya Sopka in 1907 and Katmai in 1912. Each of these eruptions could have lowered the average temperature of the Northern Hemisphere ~0.4 to 0.8°K for about 1 year (Lamb, 1977).

The changes in tropospheric and stratospheric air temperatures induced by the Tunguska-related ozone and NO\textsubscript{x} perturbations were estimated using the radiative transfer model of Pollack et al. (1976). If the ozone and NO\textsubscript{2} perturbations occurring 1 and 2 years after the Tunguska meteor fall had persisted long enough to overcome the response time of the Earth’s climate system, then the predicted Northern Hemisphere surface coolings would have been 0.3 and 0.2°K, respectively (the Tunguska dust could have lowered the surface temperature another 0.05°K). These temperature decreases are roughly one-half of those estimated for the two volcanic eruptions (Pollack et al., 1976; Lamb, 1977). Inasmuch as the ozone perturbations lasted only about 3 years, the actual temperature changes are expected to be about one-half to two-thirds of the steady-state changes (likewise for the volcanoes). Nonetheless, the Tunguska-induced temperature changes are comparable to the volcanic temperature perturbations, and must be considered in analyzing the temperature record.

Stratospheric temperature decreases associated with the Tunguska meteor fall were predicted to lie in the range of 1–2°K. These values are consistent with other calculations of temperature effects caused by large stratospheric ozone depletions. Unfortunately, there are no data from the early 1900s to compare against the Tunguska predictions.

While a long list of apparent weather anomalies spanning a wide range of spatial and temporal scales can be identified in the
Tunguska epoch, it is important to note that during this period most of the Earth exhibited normal weather patterns, or deviations from normal patterns, quite within the bounds of expected variability. Accordingly, an unambiguous relationship between the Tunguska meteor fall, large ozone depletions, and weather/climate changes cannot be firmly established by the present analysis.

8.2. Environmental Impacts

Large ozone reductions, such as those calculated for the Tunguska event, can have severe environmental consequences. For example, a 45% ozone depletion can result in almost a tripling of the erythemally active ultraviolet radiation intensity at the ground (30°N, noontime, spring; Cutchis, 1974). For smaller ozone reductions (i.e., ~10%), the increase in radiation dosage is roughly twice the ozone decrease (i.e., ~20%). The possible biological consequences of ultraviolet radiation enhancements are numerous, including a greater frequency of skin cancer in man, and the destruction of sensitive plants and microorganisms. The actual effects are not yet precisely quantified, and are controversial. If our ozone calculation for Tunguska is correct, however, the Northern Hemisphere may have received a sustained, intensified ultraviolet radiation dosage from 1908 through 1911. In all, the dosage could have been twice the normal value for that period. It is possible, but not likely, that horticultural, biological, and medical records from the Tunguska era would reveal telltale signs of increased radiation levels.

A unique, and perhaps environmentally favorable, side effect of the Tunguska meteor fall was the apparent production of an immense quantity of natural nitrogen fertilizer (Park, 1978). As is indicated by the present simulations, most of the NO generated by the Tunguska meteor was chemi-
cally converted into nitrate (HNO₃) in the stratosphere, and eventually reached the ground in rainfall. McElroy et al. (1976) estimate that the total global rate of natural nitrogen fixation is ~200 million tons N year⁻¹. The Tunguska meteor, by our reckoning, may have produced ~15 million tons of fixed nitrogen. This represents roughly 15% of the Northern Hemisphere natural fixed-nitrogen budget for 1908, and perhaps an even larger percentage of the budget in the vicinity of the meteor impact.

Early investigators surveying the Tunguska fall site thought they had detected extraordinary forest growth in the years following the event. A careful analysis of the nearby taiga by Russian scientists revealed that meteoric elements were not associated with the growth anomaly (Florensky, 1965). Moreover, the region of accelerated growth extended well beyond the region of tree flattening and conflagration. This morphology is consistent with a contribution to the reforestation of NOₓ generated in the meteor shock waves and swept to the ground by artificial convection (Park, 1978). The Russian investigators, unaware of the NOₓ source, suggested that the growth phenomenon was related to the natural ecology of the region (Florensky, 1965). In view of the present findings, however, their tentative conclusions should be reconsidered.

We can speculate on the possibility of detecting the Tunguska NO injection through analysis of nitrate concentrations preserved in glacial ice cores (e.g., Parker et al., 1978). According to Parker et al. (1982), nonbiogenic fixed nitrogen at polar latitudes originates mainly in auroral activity and galactic cosmic ray precipitation (Bauer, 1978). At nonpolar latitudes, glacial ice contains nitrate components derived from biogenic, natural nonbiogenic, and anthropogenic sources. A rough comparison of the global rates of odd-nitrogen fixation by several key processes is (in units of 10⁶ tons N year⁻¹): Tunguska, ~4 (deposited in the troposphere, averaged over 3 years); stratospheric N₂O decomposition, ~1; aurorae, ~4 (total), ~1 (reaching the troposphere); lightning, 1–10; combustion, ~40; fertilizer, ~40 (nitrate and ammonia); natural biogenic activity, ~180 (nitrate and ammonia). On the basis of these numbers, it would appear to be difficult to identify and quantify the Tunguska NO injection in glaciated nitrate samples (although in 1908 the combustion and fertilizer nitrate sources might have been much smaller than present-day values). Nevertheless, such a study could prove to be informative.

8.3. Historical Implications: Dinosaur Extinctions

The Tunguska meteor fall may have historical significance. According to Whipple (1978), a meteor the size of Tunguska could strike the Earth once each millennium. Based on an analysis of new observational data for visible meteors and craters (e.g., McCrosky and Ceplecha, 1969; Duennebier et al., 1975; Wetherill, 1976; Hartmann, 1977), we estimate that such an event might occur every 1000 to 20,000 years. Some of the large meteoroids would be composed of iron; these would strike the Earth releasing most of their kinetic energy upon impact. Some would be fragile carbonaceous chondrites, which could shatter into dust under mechanical stress. Encounters with small comets or cometary fragments would be relatively rare. However, these low-density objects could ablate entirely in the atmosphere, expending a large fraction of their initial kinetic energy in forming NO. Similarly, a dense swarm of high-velocity, moderate-sized meteoroids which penetrated deep into the stratosphere could also generate copious amounts of NO. Park and Meenees (1978) have shown that the mass of NO produced by such meteoroids can far exceed their original mass.

The dust veil produced by a massive meteoric influx, either due to ablation or to surface impact with lofting of ejecta, would last for less than a year (Toon et al., 1982). On the other hand, the NO generated
by an intense meteor shower could cause severe ozone depletions on a global scale for several years. Two possible consequences of such a massive photochemical disturbance are a change in climate and an increase in ultraviolet radiation at ground level.

On the basis of the ages of tektites, Urey (1973) proposed that rare collisions of Earth with large comets triggered most of the transitions between geological periods. The most well-known transition occurred 65 million years ago, at the end of the Cretaceous period of the Mesozoic era, which was marked by the widespread extinction of species, most notably the dinosaurs. Russell (1979) reviewed existing theories of the dinosaurs’ demise. The extinction could have occurred essentially “instantaneously” or over a time interval as long as 100,000 years. Although reptiles suffered the greatest losses, phytoplankton populations were also decimated. Russell favored the supernova theory, which predicts large ozone depletions, solar ultraviolet radiation enhancements, and background mutagenic radiation increases. Similar effects were predicted for geomagnetic reversals by Reid et al. (1976). Russell argued that, on the time scale of geological history, events such as large volcanic eruptions and giant meteor falls are commonplace. This allows, by selective survival, the development of species resistant to the attendant environmental changes.

Alvarez et al. (1980) uncovered new evidence pointing to a large meteoric influx at the time of the Cretaceous extinctions. Their data show a 20- to 160-fold enhancement in sedimentary iridium concentrations over a short time span at the end of the Cretaceous period. Meteoric bodies are highly enriched in iridium. Ganapathy (1980), Smit and Hertogen (1980), and Kyte et al. (1980) found similar patterns in the enrichment of other noble metals in Cretaceous–Tertiary boundary sediments, confirming the meteor hypothesis.

Alvarez et al. (1980) suggest that the Earth was hit by a large asteroid 65 million years ago which threw dust into the stratosphere and blotted out the Sun, causing a major convulsion in the reptilian food chain. Emiliani (1980), and Hsiü (1980) argue that the event generated considerable heat, which was responsible for the extinction of less adaptable species. We point out that an unusually intense influx of cometary fragments of the Tunguska type also would have led to nearly total ozone depletions worldwide.

The noble metal enhancements measured by Alvarez et al. and others appear to be ubiquitous, which is consistent with the disintegration of meteors at high altitude and widespread dispersal of the dust by winds. New cratering simulations by O’Keefe and Ahrens (1980) suggest that the observed meteoric-to-terrestrial mass ratio of the terminal Cretaceous clay, and the absence of a large impact crater 65 million years old, can be explained by a comet impact or meteor shower theory of the Cretaceous event. However, the cratering results are also consistent with an asteroid impact theory. Kyte et al. (1980) investigated the patterns of siderophilic element concentrations in Cretaceous–Tertiary boundary clays, and found evidence for a possible series of Tunguska-like events. Smit and Klaver (1981) recently discovered extraterrestrial spherules in terminal Cretaceous sediments whose composition is not entirely compatible with known meteorite compositions; they suggest that a cometary body is a plausible alternative source of the spherules. Thus, although the physical nature of the ancient extinction bolide remains unresolved, much of the data points to an unusually intense shower of small (<1 km) interplanetary objects.

Using their iridium measurements, Alvarez et al. (1980) fixed the Cretaceous meteoric mass influx at more than $10^{11}$ tons. This exceeds the estimated mass of the Tunguska meteor by a staggering factor of $10^5$. Even if only 0.01% of the initial kinetic energy of such a body were deposited by friction in the atmosphere, either by the
falling body or by the high-velocity cratering ejecta reaching the stratosphere (assuming a high entry velocity of $\sim 40$ km sec$^{-1}$), one might expect a multi-Tunguska event. The atmospheric perturbations may be crudely estimated by scaling against the Tunguska calculations. Thus a global ozone reduction in excess of 90% is projected for the first year, with reductions greater than 50% lasting for several years thereafter.

During the first year, the atmospheric dust produced by the meteor(s) would shield the Earth's surface from enhanced ultraviolet radiation. At the same time, photosynthesis would be suppressed, surface temperatures would drop 10–20°C, and many plants and animals would come under considerable stress (Toon et al., 1982). The dust would be removed from the atmosphere by coagulation and sedimentation long before the ozone layer could recover. Hence, already weakened organisms would be subjected to an intense dose of ultraviolet sunlight. Combined with the climate fluctuations that were likely to occur, any marginal species would have been hard-pressed to survive the cataclysm.

Despite the accumulating evidence pointing to a meteoric explanation for the dinosaur extinctions, other reasonable theories are available. For example, Gartner and McGuirk (1979) developed an extinction model based on epochal segregation of the Arctic Ocean. Kyte et al. (1981) recently found preliminary evidence of a large extraterrestrial mass influx during the late Pliocene era with no attendant widespread extinctions. Accordingly, all plausible extinction hypotheses should remain under active investigation at the present time.

Regarding the importance of Tunguska to modern man, it is worth emphasizing the raw destructive power of large meteors. The awesome Tunguska event ravaged 2000 km$^2$ of dense Siberian forest, snapping 30-in. trees like matchsticks. If the Tunguska meteor had fallen over a populated area of the globe, the casualties would have been enormous. Hopefully, we will be able to prevent such events in the future by tracking the courses of neighboring objects in the solar system, and diverting those which might intersect the Earth.

9. CONCLUSIONS

Based on a thorough analysis of the atmospheric phenomena associated with the Tunguska meteor fall of 1908, the following conclusions are reached.

(1) Records of the acoustic and seismic disturbances and forest destruction caused by the Tunguska meteor explosion severely constrain the intrinsic properties of the body. The meteor apparently had an initial energy of $\sim 10^{25}$ ergs, a velocity of $\sim 40$ km sec$^{-1}$, and a mass of $\sim 10^6$ tons. The absence of craters at the fall site suggests total destruction of the meteor within the atmosphere; this, in turn, implies a low-density "cometary" body, which could be stopped by air friction, or possibly a fragile carbonaceous chondrite, which could be pulverized by aerodynamic stresses. The mechanisms leading to the breakup of large cosmic bodies entering the atmosphere at high velocity are not currently well understood.

(2) The Tunguska meteor, because of its great intrinsic energy, may have generated as much as 30 million tons of nitric oxide in the Earth's stratosphere and mesosphere. This immense NO injection would have caused large ozone depletions over the Northern Hemisphere. Using a comprehensive one-dimensional photochemical model, a peak ozone depletion of 35–45% is predicted for early 1909. Ozone depletions of $\sim 30\%$ in 1910 and $\sim 15\%$ in 1911 are also estimated.

(3) Atmospheric transmission data collected by a research team of the Smithsonian Astrophysical Observatory (APO) at Mount Wilson, California, between 1905 and 1911 were examined for ozone absorption in the Chappuis bands. The measurements reveal a pattern of low ozone concentrations from 1909 to 1911, which closely matches the calculated ozone depletions. A linear regression analysis of the ozone data
implies an ozone deficit in early 1909 of about 30 ± 15% (at the 95% confidence level). Pending a more rigorous statistical evaluation of the data, Tunguska may provide the first direct observational verification of the theory that large total ozone depletions are caused by massive NO injections. The results also suggest that current photochemical models are reasonably accurate in predicting large ozone depletions.

(4) The APO transmission data from 1908 show evidence of a substantial turbidity increase over California about 2 weeks after the Tunguska event. It is demonstrated that the anomaly is consistent with an intrusion of ~10^6 tons of dust connected with the Tunguska meteor fall. There is uncertainty about the origin of the dust, however, because of a large volcanic eruption in Russia about 15 months before Tunguska (Shtyubelya Sopka, March, 1907). The APO data also suggest a possible increase in NOx concentrations following the Tunguska event, but the uncertainties in the data prevent a quantitative determination of the increase.

(5) The “light nights” which startled the populace of Eurasia on the evenings of June 30 through July 2, 1908, were probably caused principally by sunlight scattered from ice clouds formed at the cold summer mesopause (~80–90 km) by microscopic rock debris and water vapor ablated from the Tunguska meteor. The chemiluminescent reaction between meteor-generated nitric oxide and ambient atmospheric atomic oxygen (i.e., NO + O → NO_2 + hv) may have produced anomalous optical emissions equal in intensity to an IBC III aurora on a local or regional scale. Other chemiluminescent emissions—most notably the NO + O_3 airglow—are found to be very weak.

(6) Data are developed which suggest that a significant climate change may have occurred in the aftermath of the Tunguska meteor explosion. In the decade following 1908, the Northern Hemisphere cooled by ~0.3°K relative to the Southern Hemisphere. Radiation transport simulations of the temperature changes associated with the predicted Tunguska O_3, NO_2, and dust perturbations yield a cooling of ~0.1–0.3°K. However, a cause-and-effect relationship cannot be unequivocally established because of interference in the data from contemporary volcanic activity, uncertainty in the impact of large ozone reductions on surface temperatures, and the wide intrinsic variability of the weather.

(7) Ozone depletions and climate changes associated with large meteoric influxes may have had a role in past geological transitions, such as that which occurred at the Cretaceous–Tertiary boundary marked by the extinction of the dinosaurs.

Despite the difficulties encountered in making a quantitative scientific appraisal of the Tunguska phenomenon and its aftereffects, the great meteor of 1908 apparently caused one of the most extensive and persistent stratospheric disturbances of this century, and possibly of the millennium. The Tunguska event may reveal important information concerning theories of air pollution chemistry, ozone/weather coupling, and the evolutionary history of the Earth. Accordingly, continuing studies of the Tunguska meteor fall are warranted. We hope that the present study can provide a starting point for future research into this most impressive and consequential natural event.

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