27. J. Schneir, R. Sonnenfeld, P. K. Hansma, J. Tersoff, *Phys. Rev. B* 34, 4979 (1986).
28. A. L. Weisenhorn *et al.*, *Langmuir* 7, 8 (1991).
29. We gratefully acknowledge scientific advice and valuable discussions with J. H. Hoh, A. Engel, J. N. Israelachvili, A. Weisenhorn, E. Henderson, K. Kjoller, and M. Amrein. We thank P. Russell for providing us with samples of his super tips, P. Petroff for use of his ion mill, J. Cleveland for computer expertise, and C. L. Tang, W. Rees, J. Sayler, M. Q. Li, and K. Frye for technical support. Supported by NSF grants DMR89-17164 (P.K.H. and H.M.), DIR-90-18846 (H.G.H., R.L.S., G.K., and P.K.H.), and DIR-88-20732 (C.B. and J.V.), Digital Instruments, and NIH grant GM32543.

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The Schumann Resonance: A Global Tropical Thermometer

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The Schumann resonance, a global electromagnetic phenomenon, is shown to be a sensitive measure of temperature fluctuations in the tropical atmosphere. The link between Schumann resonance and temperature is lightning flash rate, which increases nonlinearly with temperature in the interaction between deep convection and ice microphysics.

Considerable interest has focused in recent years on temperature fluctuations in the earth's atmosphere. The global temperature variability, based on a century's surface (dry-bulb) temperature records, amounts to several tenths of 1°C (*1–3*). The reported global warming amounts to only a few tenths of 1% of the absolute temperature. Thus, it would be valuable to identify measurable physical parameters that are nonlinearly dependent on the fluctuations in atmospheric temperature so that some gain in the detection of these subtle temperature changes can be achieved. In this report I investigate the idea that the Schumann resonance, a global electromagnetic phenomenon driven by worldwide lightning activity, is one such measurable parameter. Lightning is linked with cloud electrification and the accumulation of ice particles in the upper troposphere. The nonlinear electrification process is controlled by buoyancy, the modest departures from hydrostatic equilibrium caused by temperature differences of the order of 1°C. Buoyancy in turn is controlled primarily by surface air temperature, the principal datum in current studies of global change.

Convection is systematically deeper and more frequent in the tropics than at higher latitudes. This behavior is essentially the result of the pole-to-equator temperature increase and the Clausius-Clapeyron relation. Lightning activity increases dramatically with the depth and vigor of convection (*4*) and is dominant in the tropics (*5, 6*) (Fig. 1). Approximately two of every three lightning flashes occur in the latitude interval ±23°.

Observations of lightning from space (*5, 6*) reveal that tropical land areas exhibit substantially more lightning than do the central oceans. Southeast Asia and Australia, Africa, and South America are three major zones of deep electrically active convection. The land-ocean lightning contrast is attributable to small (a few degrees celsius) differences in the surface temperature over land and over the sea.

Lightning activity at a large number of land stations in the tropics increases nonlinearly with surface air temperature. In the following comparisons, wet-bulb temperature rather than dry-bulb temperature will be used, because the former records simultaneously the effect of temperature and moisture, both of which are important to the thermodynamics of moist convection. Many parameters in addition to surface temperature influence the development of deep convection and lightning on any given day and place (for example, temperature inversions, dry layers, wind shear, and lateral gradients in surface temperature). Consequently, a single-parameter (wet-bulb temperature in this case) relation with lightning flash count is variable on a day-to-day basis. When monthly mean values are considered, however, a consistent association between lightning and temperature emerges and the data show reasonably well-defined seasonal variations. For example, data from within ~50 km of Darwin, Australia (12°S), show (Fig. 2) that monthly mean lightning counts (*7, 8*) increased more than two orders of magnitude as the wet-bulb temperature increased from 25° to 27°C (the monthly mean of maximum daily values). Lightning activity reached a maximum during the wet season months (November through March).

Observations from Kourou, French Guiana (5°N), South America (*9*), show a similar strong sensitivity (Fig. 3). This site, closer to the equator than Darwin, experiences a smaller annual variation in wet-bulb temperature, but a modest 1.9°C annual change was associated with a 20-fold change in lightning activity.

At latitudes more distant from the equator but still within the tropics, the annual variation of wet-bulb temperature increased while the annual variation of monthly mean lightning activity remained about the same. Consequently, the lightning sensitivity to seasonal variations in temperature decreases with increasing latitude. Data from Mexico (*10*), southern Brazil (*11*), and Botswana in Africa (*12*) show approximate doublings of lightning activity per 1°C of wet-bulb temperature change. In Orlando, Florida (28°N), which lies outside the tropical belt but is the most lightning-active region in the United States, a similar sensitivity has been observed (*13*) (Fig. 4).

The interpretation of the sensitive relation between lightning and wet-bulb temperature is based on observations of the thermodynamic structure of the tropical

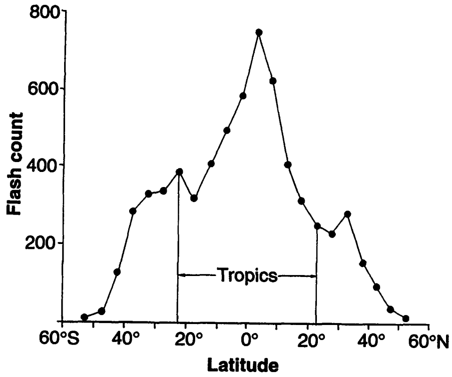

Fig. 1. Latitudinal distribution of lightning from space (*5*), showing a dominant contribution from the tropics (±23°).

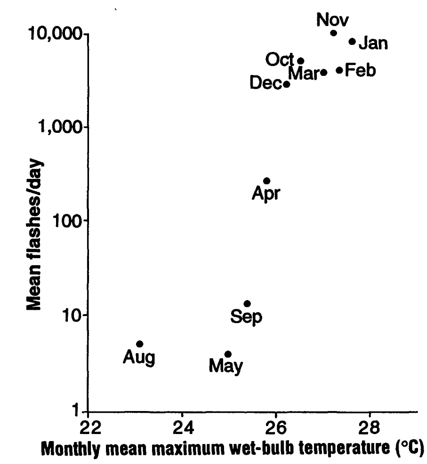

Fig. 2. Monthly lightning counts (*7*) for Darwin, Australia (12°S), versus monthly mean maximum wet-bulb temperature for 1988.

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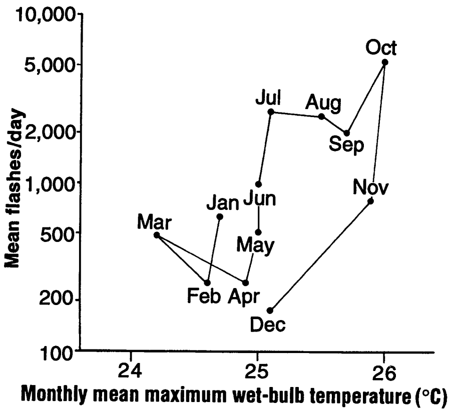

Fig. 3. Monthly lightning counts (*9*) for Kourou, French Guiana (5°N), versus monthly mean maximum wet-bulb temperature for 1989.

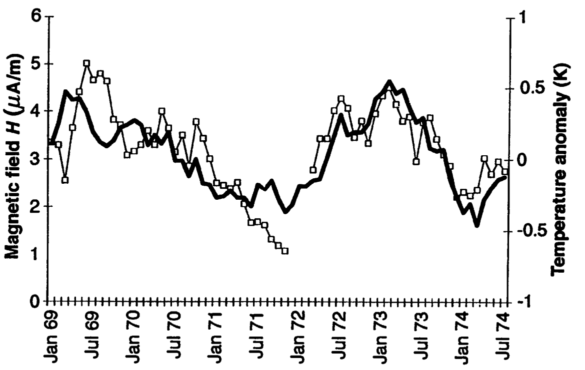

Fig. 5. Time series of the monthly tropical surface air temperature anomaly [heavy line (from (*3*)] and monthly mean magnetic field for the fundamental mode (8 Hz) of SR in Kingston, Rhode Island [light line (from (*27*)].

atmosphere (*14*) and the assumption that collisions of ice particles and charge separation by differential particle motions cause lightning. Observations at many locations in the tropics show that the energy stored in the atmosphere and made available for convection and lightning [the convective available potential energy (CAPE)] is determined largely by the wet-bulb potential temperature θ_w of boundary layer air. Changes in the shape of the temperature profile play only a secondary role in determining CAPE. In an atmosphere with a fixed temperature profile but with a variable θ_w of boundary layer air, the area on a thermodynamic diagram representing CAPE increases monotonically (and approximately linearly) with increases in the wet-bulb adiabat. Calculations of CAPE in the tropical atmosphere that allow for the presence of an ice phase (consistent with the assumption linking ice and lightning production) show that a 1°C increase in θ_w in a tropical wet season is equivalent to a CAPE of ~1000 J/kg (*14*). CAPE vanishes in the tropical

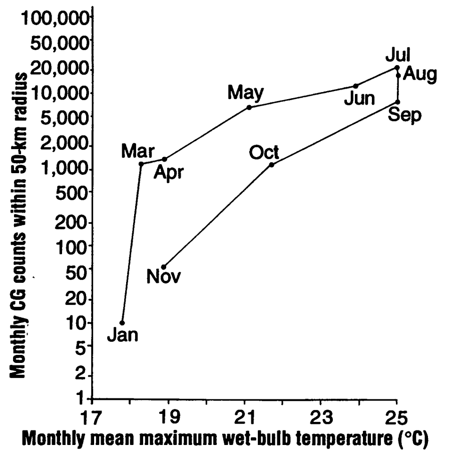

Fig. 4. Monthly lightning counts (*13*) for Orlando, Florida (28°N), versus monthly mean maximum wet-bulb temperature for 1989.

atmosphere when θ_w drops below about 23°C for tropical land stations.

According to parcel theory, the maximum achievable updraft velocity in deep convection is $(2\ \mathrm{CAPE})^{1/2}$. This dependence is not sufficient to explain the strongly nonlinear response evident in Figs. 2 to 4. Radar observations of deep tropical convection (*15, 16*) suggest that the nonlinear increase in lightning is caused by the growth of ice particles in the mixed phase region (where $0°C \geq T \geq -40°C$) of the updraft. The radar reflectivity in the mixed phase region during "break period" continental-type convection (when $\theta_w \approx 26°$ to 28°C) is two orders of magnitude greater than during monsoon convection (when $\theta_w \approx 24°$ to 25°C). The break period convection also exhibited lightning flash rates about an order of magnitude higher than monsoon convection. In (*16*) it was suggested that modest changes in updraft velocity can affect large changes in the mass of ice-phase condensate and the gravitational energy available for an ice-based charge separation process. This mechanism, the details of which are still poorly understood, may provide the amplification from temperature to lightning.

The evidence that lightning responds sensitively to temperature at many sites throughout the tropics suggests a global response. The global electrical circuit, which integrates the electrical effects of disturbed weather the world over (*17*), is expected to provide a natural global thermometer. The global circuit consists of the electrified convective clouds in the troposphere, bounded by the conductive earth and the conductive upper atmosphere and ionosphere. This global spherical capacitor is a resonant cavity for extremely low-frequency electromagnetic waves excited by global lightning, a phenomenon predicted by Schumann (*18*) and now named the Schumann resonance (SR). The theory of SR is described in (*19, 20*). The fundamental mode of the SR is a standing wave in the earth-ionosphere cavity with a wavelength equal to the circumference of the earth. Several workers (*21–26*) have drawn connections between local measurements of SR and lightning activity in tropical thunderstorms. Two complications of SR that work against the presence of a globally representative signal at a single measurement site are (i) the nodal structure inherent in resonant wave phenomena and (ii) the changes in cavity shape caused by changes in ionization in the upper atmosphere (largely a local diurnal effect). Compelling evidence that globally representative signals can be extracted from measurements at single stations is found in the recent study of diurnal variations (*26*). These investigators corrected for local ionospheric effects, summed contributions from several simultaneously recorded resonant modes, and thereby produced records at distant sites that showed considerable similarity. The corrected diurnal records showed distinct peaks that can be associated with the three major tropical zones of convection.

As a test of the idea that SR should behave as a sensitive global tropical thermometer on time scales from months to years, I examined a 5.5-year time series of SR magnetic field data (*27*). This record from Kingston, Rhode Island (71°W, 41°N), is nearly continuous, and the magnetic field measurements are well calibrated. Monthly mean values of the magnetic field H (for the fundamental ~8-Hz resonant mode) were extracted from the continuous daily records and plotted in Figs. 5 and 6 along with the monthly mean fluctuations in surface (dry-bulb) temperature ΔT for the entire tropics (*3*) for corresponding months.

The SR amplitude follows the temperature variation quite closely (Fig. 5), particularly for the long-period variation. Warmer periods are associated with enhanced magnetic field amplitude and cooler periods with suppressed amplitude. The long-period (~40-month) temperature anomalies involve a warming (or cooling) of the entire tropical belt (*3, 28*) and are associated with the El Niño–Southern Oscillation phenomenon. The annual signal in the temperature anomaly has been removed (*3*). The annual signal in SR in Fig. 5 appears to

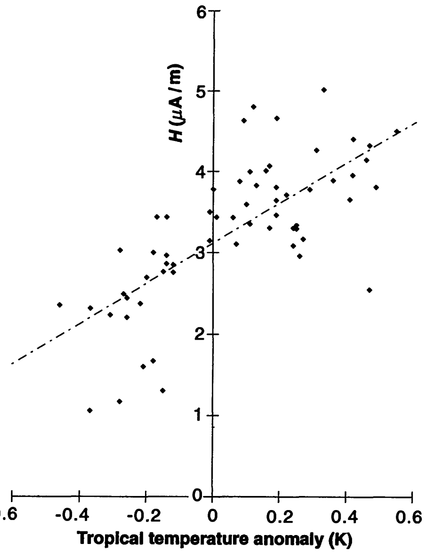

Fig. 6. Correlation plot of monthly SR amplitude and monthly tropical temperature anomaly (same data as in Fig. 5).

be significantly smaller than the long-period signal. No systematic annual cycle in earlier studies of global lightning has emerged (*5, 6, 29*), but the absence of a more pronounced annual signal in SR in Fig. 5 is puzzling in light of the climatological annual variation in tropical temperature, which is comparable to the amplitude of the long-period fluctuations in (*3*). Part of the noisiness in the comparisons of magnetic field and temperature on seasonal time scales may arise from the latitudinal migration of tropical lightning sources; such migration significantly affects the amplitude at single stations if only the fundamental resonant mode is measured (*20*).

The slope of the local linear fit to the data (Fig. 6) gives the sensitivity of the global thermometer. The data show an approximate doubling of magnetic field amplitude for a 1°C increase in temperature. According to theory (*25*), the instantaneous global lightning activity is proportional to the energy density in the resonant cavity and hence is proportional to amplitude squared. The fourfold increase in lightning per 1°C is consistent with the sensitivity determined on the basis of local measurements in Figs. 2 and 3 for tropical stations and reinforces the connection between a local and a global phenomenon. Here I have assumed that fluctuations in surface dry-bulb temperature [studied in (*3*)] are commensurate with the more physically meaningful wet-bulb temperature fluctuations.

The SR data represent the amplitude of the fundamental 8-Hz mode. The zeroth-order mode of SR is ionospheric potential, V_I, the dc voltage drop across the spherical capacitor with a nominal value of 250 kV (earth is negative, troposphere is positive). This dc mode has been the traditional measure of the global circuit (*17, 30*). It is widely believed that V_I represents an integration of electrical currents in disturbed weather worldwide, but recent studies (*31*) suggest that point discharge current rather than lightning is the main contributor to V_I. Simultaneous measurements at different locations support the idea that V_I is globally representative (*32, 33*).

The period covered by SR in Fig. 5 overlaps with a period of 65 aircraft measurements of V_I in the Bahama Islands from 11 February to 14 March 1972 (*33*). These measurements allow direct simultaneous comparisons of the zeroth order and fundamental modes of SR, valuable in establishing a global signal at time scales from days to weeks because the temperature anomaly data are not currently available for time scales less than 1 month (*3*). In the foregoing comparisons, the SR magnetic field from Kingston, Rhode Island, is read from the chart records to within ±30 min of the recorded universal time of the V_I sounding in the Bahamas. The 8-Hz data were not corrected for the local diurnal variation of ionospheric height, as in (*26*).

Simultaneous values of V_I and SR magnetic field at 8 Hz are plotted in Fig. 7. The uncertainty in V_I is estimated to be ±5% (*34*). Without more information on possible local weather disturbances in Kingston and the quality factor for the resonant cavity, the accuracy of the magnetic field measurement is difficult to estimate. The reading accuracy from the calibrated chart is estimated to be ±10%. These data show evidence for a strong association between V_I and the fundamental mode of SR (with a few outliers) (Fig. 7), thereby supporting the idea that there is a global component in both signals. The scatter in the results could be attributed to the local noise in either measurement, to local diurnal changes in ionospheric height (for the 8-Hz data), or to vagaries in the relation between global lightning activity and global point discharge current. The evidence in Fig. 7 that the extrapolated data intersect the V_I axis at a fairly large positive value is an additional indication that V_I is controlled by a process other than lightning.

SR provides a natural integration of global lightning activity, and the observations show that SR increases with temperature on a global tropical scale in a manner consistent with the observed sensitivity of lightning to temperature in local measurements. This association thereby provides a sensitive global tropical "thermometer." The relation between SR amplitude in Kingston, Rhode Island, and fluctuations in global tropical surface temperature strongly suggests that single station measurements contain globally representative signals and

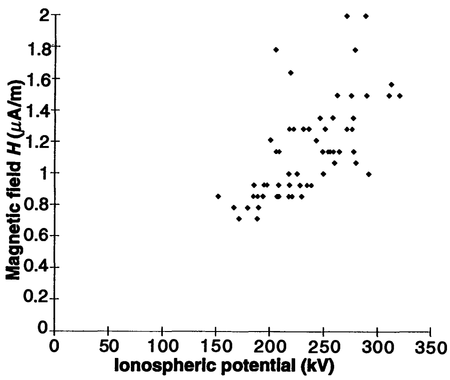

Fig. 7. Comparisons of simultaneous measurements of SR from Kingston, Rhode Island (*27*), and ionospheric potential from the Bahama Islands (*33*).

that such measurements in noise-free areas can therefore serve as a valuable real-time diagnostic of both temperature variability and deep convection in the tropical atmosphere. Improvements in achieving global signals are possible by averaging over higher order modes.

The amplification that makes SR a sensitive tropical thermometer is believed to originate in the interaction between ice microphysics and temperature-dependent buoyancy forces during deep convection. Lightning rate is a sensitive indicator of the transport of ice to upper levels of the atmosphere. The ice particles that are believed to participate in the electrification process aloft (*35*) also become the major players in the radiative feedback effects that sensitively regulate the temperature of the tropical atmosphere. SR may therefore be a useful device for understanding and quantifying these feedback effects.

The mechanism proposed for the SR thermometer depends critically on the presence of CAPE in the tropical atmosphere, and the connection between the global circuit and tropical temperature fluctuations on a wide range of time scales reinforces this result. If the tropical atmosphere continually adjusted to a state of moist neutrality (with zero CAPE), as has been assumed in a number of cumulus parameterization schemes in current general circulations models of the atmosphere, it is unlikely that the tropics would provide any contribution to SR. The closest approximation to a moist neutral condition in the real atmosphere is seen in the well-established tropical monsoon when surface temperatures are low and little or no lightning is observed (*15, 16*).

Finally, although the 5-year record in Fig. 5 is far too short to permit definitive statements about lightning's dependence on climate change, the relation among CAPE, temperature, and lightning at the longest time scales available makes it plausible that global lightning activity will increase substantially in a warmer climate.

REFERENCES AND NOTES

1. J. K. Angell, *Mon. Weather Rev.* **114**, 1922 (1986).
2. P. D. Jones *et al.*, *Nature* **322**, 430 (1986).
3. J. Hansen and S. Lebedeff, *J. Geophys. Res.* **92**, 13345 (1987).
4. E. R. Williams, *ibid.* **90**, 6013 (1985).
5. R. E. Orville and R. W. Henderson, *Mon. Weather Rev.* **114**, 2640 (1986).
6. M. Kotaki, I. Kuriki, C. Katoh, H. Sugiuchi, *J. Radio Res. Lab.* (*Tokyo*) **28**, 49 (1981).
7. The lightning counts were obtained with a CGR3-type lightning detector (*8*) and are archived by the Australian Bureau of Meteorology.
8. D. Mackerras, *J. Geophys. Res.* **90**, 6195 (1985).
9. The lightning counts were obtained with a SAFIR interferometer system (P. Richard, personal communication).
10. F. de la Rosa, personal communication.
11. R. de Araujo, personal communication.
12. R. Jayaratne, personal communication.
13. R. Orville, personal communication; these counts were for ground flashes identified with Lightning Location and Protection (LLP) equipment.
14. E. R. Williams and N. Renno, *Mon. Weather Rev.*, in press.
15. S. A. Rutledge, E. R. Williams, T. D. Keenan, *Bull. Am. Meteorol. Soc.* **73**, 3 (1992).
16. E. R. Williams *et al.*, *J. Atmos. Sci.*, in press.
17. F. J. W. Whipple, *Q. J. R. Meteorol. Soc.* **55**, 1 (1929).
18. W. O. Schumann, *Z. Naturforsch. Teil A* **7**, 149 (1952).
19. P. V. Bliokh, A. P. Nikolaenko, Yu. F. Filippov, *Schumann Resonances in the Earth-Ionosphere Cavity* (Perigrinus, London, 1980).
20. C. Polk, in *CRC Handbook of Atmospherics*, H. Volland, Ed. (CRC Press, Boca Raton, FL, 1982), vol. 1, p. 112.
21. M. Balser and C. A. Wagner, *J. Geophys. Res.* **67**, 619 (1962).
22. T. R. Madden and W. Thompson, *Rev. Geophys.* **3**, 211 (1965).
23. R. Gendrin and R. Stefant, in *Propagation of Radio Waves at Frequencies Below 30 kc/s*, W. T. Blackband, Ed. (Pergamon, New York, 1964), p. 371.
24. T. Ogawa, Y. Tanaka, M. Yasuhara, *J. Geomagn. Geoelec.* **21**, 447 (1969).
25. M. Clayton and C. Polk, in *Electrical Processes in Atmospheres*, H. Dolezalek and R. Reiter, Eds. (Steinkopff, Darmstadt, 1977), pp. 440–449.
26. D. D. Sentman and B. J. Fraser, *J. Geophys. Res.* **96**, 15973 (1991).
27. C. Polk, *Geophysics and Space Data Bulletin* [Space Physics Laboratory, Air Force Cambridge Research Laboratories, Hanscom Air Force Base, MA (1967–1974)].
28. A. H. Oort, *NOAA* (*Natl. Oceanic Atmos. Adm.*) *Prof. Pap 14* (April 1983).
29. R. E. Orville and D. W. Spencer, *Mon. Weather Rev.* **107**, 934 (1979).
30. R. Markson, *Nature* **320**, 588 (1986).
31. E. R. Williams and S. J. Heckman, *J. Geophys. Res.*, in press.
32. R. P. Muhleisen, *Pure Appl. Geophys.* **84**, 112 (1971).
33. R. Markson, *J. Geophys. Res.* **90**, 5967 (1985).
34. _____, personal communication.
35. E. R. Williams, *J. Geophys. Res.* **94**, 13151 (1989).

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An Intercomparison of Tropospheric OH Measurements at Fritz Peak Observatory, Colorado

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The hydroxyl radical (OH) controls the lifetimes and therefore the concentrations of many important chemical species in Earth's lower atmosphere including several greenhouse and ozone-depleting species. Two completely different measurement techniques were used in an informal intercomparison to determine tropospheric OH concentrations at Fritz Peak Observatory, Colorado, from 15 July to 24 August 1991. One technique determined OH concentrations by chemical analysis; the other used spectroscopic absorption on a long path. The intercomparison showed that ambient OH concentrations can now be measured with sufficient sensitivity to provide a test for photochemical models, with the derived OH concentrations agreeing well under both polluted and clean atmospheric conditions. Concentrations of OH on all days were significantly lower than model predictions, perhaps indicating the presence of an unknown scavenger. The change in OH concentration from early morning to noon on a clear day was found to be only a factor of 2.

The determination of OH concentration is fundamental to an understanding of atmospheric chemistry, but its measurement has been fraught with difficulties. Because OH noontime concentrations are thought to be extremely low [approximately 0.1 part per trillion by volume (pptv)], measurement is difficult. Initial measurements in the troposphere were based on laser-induced fluorescence of OH rotational lines in the ultraviolet (UV) part of the spectrum (*1, 2*), but many problems were discovered (*3, 4*). Modifications have been marginally successful (*5*), but not to the levels necessary to test photochemical theories (*6*). Long-path absorption of laser light in the UV has been used to measure OH concentrations near Julich, Germany (*7–9*). Although this region is industrially polluted, OH levels were measured reliably to several $\times 10^6$ mol/cm^3. Real-time chemical tracer techniques have been used without notable success; however, global tracer techniques have shown some success. Summaries of the reactions and rate constants used for theoretical calculation of tropospheric OH chemistry are given in (*10, 11*). To date, the theory is far more advanced than the measurements. In this paper we describe an intercomparison of measurements of tropospheric OH by two highly sensitive instruments operating simultaneously.

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The first technique (*12*) is an in situ ion-assisted measurement with a lower sensitivity limit of 1×10^5 mol/cm^3 in short time integrations (minutes). The calibration is difficult and dependent on chemical interpretation. The second technique (*13*) is a laser-based long-path absorption experiment with a sensitivity limit of $\sim 4 \times 10^5$ mol/cm^3, also with a time resolution of minutes. This instrument has a simple absolute calibration, but determination of the OH concentration is dependent on determination of the local spectral continuum, which is difficult to measure because of spectral interferences from other atmospheric trace species.

The Georgia Tech (GT) ion-assisted measurement of OH is performed by sampling air through a turbulence-reducing scoop and down a flow tube–reactor at a velocity of 0.6 m/s. The OH present in the center of the flow tube is titrated into $H_2{}^{34}SO_4$ by the addition of $^{34}SO_2$. The SO_2 converts OH into HSO_3, which reacts with O_2 and then H_2O to form H_2SO_4. Mixing is accomplished by the continuous injection of an SO_2-N_2 mixture perpendicular to the sampled air flow through two opposed needles. The injected mixture makes up less than 1% of the sample flow and causes turbulence primarily in the center of the flow tube. There is little to no mixing or turbulence at the walls. Because only species in the center of the flow are sampled, the lack of mixing at the walls is of little concern. To ensure that all of the OH in the sampled air has been converted