Click Here for Full Article

Direct retrieval of stratospheric CO_2 infrared cooling rate profiles from AIRS data

D. R. Feldman,[1] K. N. Liou,[2] Y. L. Yung,[1] D. C. Tobin,[3] and A. Berk[4]

[1] We expand upon methods for retrieving thermal infrared cooling rate profiles, originally developed by Liou and Xue (1988) through application to the inversion of the stratospheric cooling rate produced by carbon dioxide (CO_2) and a formal description of the associated error budget. Specifically, we infer lower- and mid-stratospheric cooling rates from the CO_2 ν_2 band on the basis of selected spectral channels and available data from the Atmospheric Infrared Sounder (AIRS). In order to establish the validity of our results, we compare our retrievals to those calculated from a forward radiative transfer program using retrieved temperature data from spectra taken by the Scanning High-Resolution Interferometer Sounder (S-HIS) on two aircraft campaigns: the Mixed-Phase Arctic Cloud Experiment (MPACE) and the Aura Validation Experiment (AVE) both in Fall, 2004. Reasonable and consistent comparisons are illustrated, revealing that spectral radiance data taken by high-resolution infrared sounders can be used to determine the vertical distribution of radiative cooling due to CO_2. **Citation:** Feldman, D. R., K. N. Liou, Y. L. Yung, D. C. Tobin, and A. Berk (2006), Direct retrieval of stratospheric CO_2 infrared cooling rate profiles from AIRS data, *Geophys. Res. Lett.*, *33*, L11803, doi:10.1029/2005GL024680.

1. Introduction

[2] Conventional clear-sky infrared cooling rates are calculated ubiquitously and the accuracy of these calculations has been shown to affect forecast and general circulation model (GCM) performance [*Iacono et al.*, 2000]. Numerical weather prediction models calculate radiative heating and cooling efficiently but are burdened by the computational requirement of estimating the atmospheric state from a suite of different instruments. In this light, novel approaches for the treatment of heating and cooling may be warranted. The largest infrared cooling takes place in the stratosphere and this atmospheric region is strongly influenced by radiative interactions. The interaction between solar heating and infrared cooling has been analyzed with satellite instrument measurements [*Mlynczak et al.*, 1999]. However, since the infrared cooling rate profile is dependent upon individual layer atmospheric state

vector values and their relationship to the broad structure of the atmospheric state, we seek to understand whether high-resolution infrared spectra can offer a better description of the infrared cooling rate profile beyond the atmospheric state standard products. The retrieval of infrared cooling rates from top-of-atmosphere (TOA) radiance data is a novel concept and may improve upon the understanding of the vertical distribution of infrared radiative cooling if successfully implemented. The approach of this retrieval will differ from atmospheric state retrievals in that we retrieve in the context of a spectral interval's description of the radiative cooling of an absorption band at a certain level as opposed to a channel's description of an atmospheric state quantity at that level.

[3] We chose to demonstrate the feasibility of a cooling rate profile retrieval with the CO_2 ν_2 band as measured by the AIRS instrument [*Aumann et al.*, 2003] for several reasons. First, this band is a major contributor to clear-sky cooling in the stratosphere and mesosphere [*Kiehl and Solomon*, 1986]. Second, CO_2 is well-mixed and the cooling rate profile varies minimally over an observation granule. Third, AIRS is a proven instrument with extensive spatial coverage, excellent signal-to-noise ratio, and well-quantified stability [*Aumann et al.*, 2005]. Finally, clouds, which greatly affect cooling rate profile values, are a minimal presence in the stratosphere so that the retrieval of CO_2 cooling rates can be greatly simplified.

[4] Calculations of the radiative cooling of CO_2 in the stratosphere are straightforward with known atmospheric state quantities, but uncertainties in some of these quantities, most notably the temperature structure, propagate into cooling rate errors in ways that have not been fully explored. A formal understanding of the cooling rate error budget through observation is therefore warranted in order to determine to what extent our method can improve cooling rate profile determination.

2. Theoretical Basis

[5] The derivation of the cooling rate profile from observed radiance data was first developed theoretically by *Liou and Xue* [1988] in order to measure the strong tropospheric cooling produced by the rotational band of water vapor in the far infrared.

[6] The spectral cooling rate profile is defined by

$$\dot{\theta}(\nu, z) = \frac{1}{\rho(z) C_p} \frac{dF^{net}(\nu, z)}{dz} \tag{1}$$

where $\dot{\theta}(\nu, z)$ is the cooling rate, $\rho(z)$ is the atmospheric density profile, C_p is the heat capacity of air at constant pressure, and $F^{net}(\nu, z)$ is the net flux at height z for

[1]Department of Environmental Science and Engineering, California Institute of Technology, Pasadena, California, USA.
[2]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA.
[3]Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison, Wisconsin, USA.
[4]Spectral Sciences, Inc., Burlington, Massachusetts, USA.
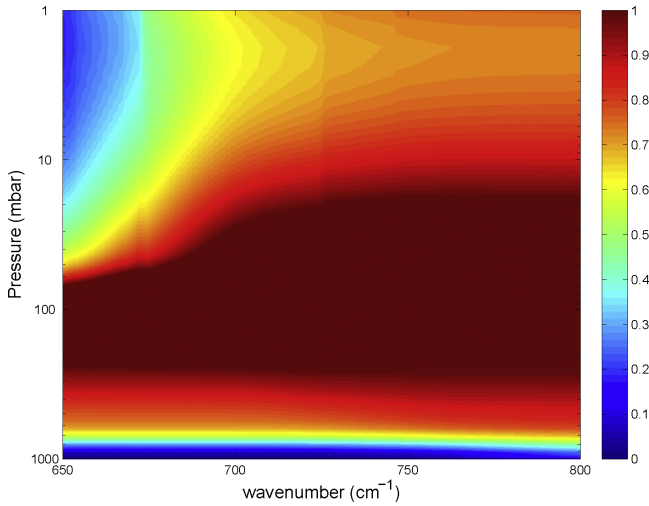
Figure 1. Spectral cumulative cooling rate contribution function for mid-latitude summer conditions. As opposed to the standard spectral cooling rate plot, this plot is useful for discerning the differential contribution of certain spectral regions to the total IR cooling rate.

wavenumber ν. Conventionally, the cooling rate profile is calculated for the entire infrared ($0-3000$ cm^{-1}) by integrating equation (1) with respect to wavenumber. The contribution to the total infrared cooling rate of a spectral region at a particular level is given by the cumulative spectral cooling rate function which is defined as

$$\dot{\Theta}(\nu,z) = \frac{\int_0^\nu \dot{\theta}(\nu,z)d\nu}{\int_0^{\nu_{max}} \dot{\theta}(\nu,z)d\nu}. \qquad (2)$$

As shown in Figure 1, a change in color at a certain level on the horizontal axis implies appreciable spectral contribution to the total cooling rate value at that level.

[7] A formal relationship between the infrared cooling rate profile and measured radiance values for a spectral band is given by *Liou and Xue* [1988]:

$$\int_0^\infty K(\nu,\mu,z)\dot{\theta}(z)dz = \alpha(\nu,\mu)\bar{I}(\bar{\mu}) + \beta(\nu,\mu)I(\nu,\mu) = y(\nu,\mu), \qquad (3)$$

where $K(\nu, \mu, z) = C_p\rho(z)T(\nu, \mu, z)$ forms the weighting function matrix, $T(\nu, \mu, z)$ is the transmittance function, $I(\nu, \mu)$ is the TOA radiance, the coefficients $\alpha(\nu, \mu)$ and $\beta(\nu, \mu)$ can be determined numerically, and $\bar{I}(\bar{\mu})$ is the mean spectral radiance as measured at a zenith angle, $\bar{\mu}$, computed from the mean value theorem (see *Liou and Xue* [1988] for derivation). In this paper, the values of $\alpha(\nu, \mu)$ and $\beta(\nu, \mu)$ are computed numerically from two executions of our radiative transfer model at slightly different atmospheric states. These terms relate radiances to spectrally-integrated and spectrally-independent TOA fluxes. Equation (3) demonstrates that the cooling rate profile cannot be measured in a forward sense with a remote spectrometer,

but it is possible to derive information about cooling from TOA radiance measurements using inverse theory based on the Fredholm equation of the first kind denoted in this equation.

[8] Assuming that the functional relationship between the measurements and the retrieval is well-behaved in the solution region, equation (3) can be analyzed using a linear Bayesian estimation technique to retrieve the cooling rate profile. With Gaussian statistics for the measurement and a priori error, the retrieved state can be expressed as a balance between the expected amount of information about the retrieval quantity as given by the measurement metric $y(\nu, \mu)$ with the knowledge that constrains the retrieval to a certain solution space. The a priori covariance matrix of the cooling rate profile which is utilized to constrain the retrieval is calculated empirically given expected state vector changes uncertainties. For the cooling rate profile a priori constraint, the long range covariances between cooling rate profile components are smoothed according to a scale-height correlation that is derived from near off-diagonal components of the empirical covariance matrix. The error covariance matrix which describes expected errors in the measurement metric is assumed to be diagonal with diagonal elements derived from the expected deviation in measurements derived from equation (3). For this type of retrieval error analysis, it can be shown [*Rodgers*, 2000] that the a posteriori covariance for the cooling rate profile can then be determined from the combination of the measurement error projected onto the data space and the prior error.

[9] In terms of computing the net flux divergence at several atmospheric levels, radiance measurements at different viewing angles provide improved information over a single spectra, but the degree and manner in which angular information can be utilized needs further exploration. We have generalized the retrieval method of *Liou and Xue* [1988] for more complicated scenarios with cross-track spatial variability where the viewing geometry does not easily lend itself to meaningful spatial resolution. Various measurements may be utilized according to the viewing geometry of instrument being considered, but for scanning instruments, radiance values taken at different viewing angles describe unique atmospheric states, thereby requiring knowledge of the atmospheric state spatial covariance. The utilization of angular radiance values represents a balance between the information that can be derived from the radiance at a single viewing angle and the lack of correlation between different atmospheric states from different viewing angles.

[10] The measurement metric through which the cooling rate profile is retrieved, **y**, must be modified to include an optimal amount of the cross-track angular scan as determined by error budget considerations described above. As such, **y**, vectorized according to wavenumber, is defined as

$$\mathbf{y} = [\mathbf{y}(\mu_o) \cdots \mathbf{y}(\mu_n)], \qquad (4a)$$

$$\mathbf{y}(\mu_i) = \int_0^\infty \left[\rho(z)C_p\mathbf{T}(\mu_i,z)\right]\dot{\theta}(z)dz, \qquad (4b)$$

where $\mathbf{T}(\mu_i, z)$ is the transmittance as a function of viewing angle and height vectorized by wavenumber, and the i
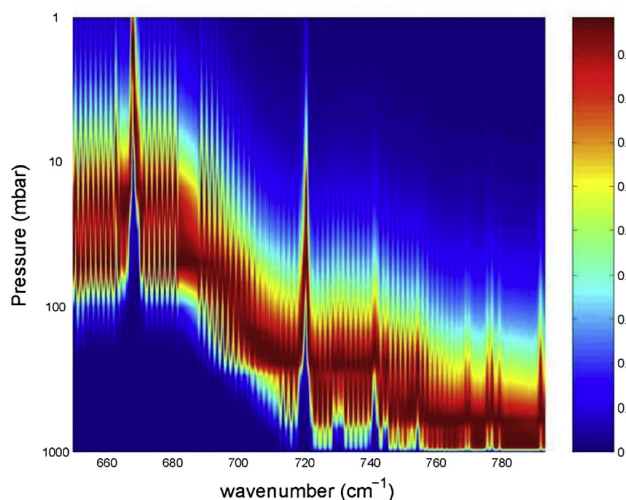
Figure 2. Normalized cooling rate weighting functions for mid-latitude summer (MLS) conditions for AIRS instrument from 649 to 800 cm^{-1}.

subscript refers to a discrete viewing angle in a cross-track scan. The metric **y** must be defined in such a way as to maximize the information content that can be derived about the integrand. We utilize new angular weighting terms to relate cross-track radiances to the left-hand side of equation (3). The formal measurement error covariance matrix then becomes the sum of two terms: The first is derived from the radiometric uncertainty multiplied by the angular weighting terms and the second term arises from an understanding of the a priori covariance of the cooling rate profile at the viewing angle μ_i with respect to the cooling rate profile of the footprint of interest at viewing angle μ_0.

3. Methods

[11] For radiance and transmittance calculations, we use Modtran™ 5, Version 2, Release 1 [*Berk et al.*, 1989], which is a pre-release product offering spectral resolution as high as 0.1 cm^{-1}. The results of this program are routinely verified using the Line-by-Line Radiative Transfer Model version 9.3 (LBLRTM) and RADSUM 2.4 calculations [*Clough and Iacono*, 1995; *Clough et al.*, 2005] and generally agree to within 0.05 K/day between 800 and 5 mbar.

[12] Forward model radiances are convolved with the pre-launch AIRS Spectral Response Function (SRF) information [*Strow et al.*, 2003] to simulate AIRS channel measurements. For Noise-effective Radiance (NeR), we use values derived from in-orbit calibration algorithms as included in the Level 1B data set [*Pagano et al.*, 2003]. We have calculated the cooling rate weighting functions for the AIRS instrument and found significant lower- and middle-stratospheric coverage from the 649 to 800 cm^{-1} region as shown in Figure 2. In this figure, the normalized cooling rate weighting functions for 453 AIRS channels with about 1 cm^{-1} FWHM per channel cover a large portion

of the CO$_2$ ν_2 band spectral interval and their cooling rate weighting functions cover from the surface to 1 mbar.

4. Cross-Comparison

[13] Direct validation of cooling rate profile retrievals requires data from *in situ* vertically ascending or descending hemispheric radiometers that span the spectral region of interest and that have the same overpass time as the remote sounder. In the absence of such a dedicated mission, only a cross-comparison between data sets is possible. We do this by analyzing other sets of coincidental spectra and deriving
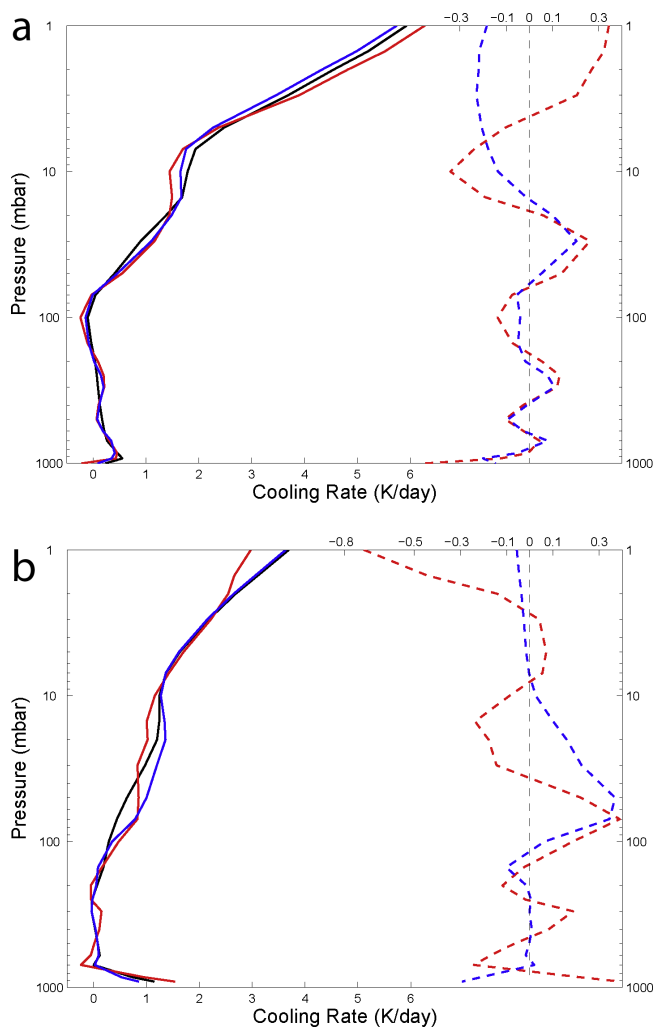
Figure 3. Deviation from a priori cooling rate profile from 649–800 cm^{-1} for AIRS retrieved and S-HIS calculated cooling rate profiles. Black solid line: a priori cooling rate profile (lower axis); black dashed line: zero line for difference from a priori; blue line: cooling rate profile deviation from a priori calculated from S-HIS zenith and nadir measurements; red line: cooling rate profile deviation from a priori retrieved with AIRS L1B spectra from coincidental footprint and at 45° in the cross-track scan. (a) AVE Flight: 10/31/2004, 24.8 N, 271.8 E. (b) MPACE flight: 10/10/2004, 62.7 N, 214.4 E.

atmospheric state information, and then inputting that data into the forward model to calculate the cooling rate profile.

[14] We utilize data from Scanning High-Resolution Interferometer Sounder (S-HIS) taken during AVE over the Gulf of Mexico and the southeastern United States during October, 2004 (AURA Validation Experiement data available at http://avdc.gsfc.nasa.gov) [*Revercomb et al.*, 1998]. These data include zenith and nadir soundings at altitudes from 10–20 km aboard a NASA WB-57 aircraft coincidental with Aqua and Aura overpasses. The instrument model for S-HIS is given by a sinc function with an FWHM of 0.96 cm^{-1}. S-HIS measurement noise is calculated using spectra of the instrument's calibration black-body.

[15] We have calculated the cooling rate profile in the 649 to 800 cm^{-1} region by using the forward model with a retrieved temperature and CO_2 profile from the S-HIS zenith and nadir spectra. The retrieved atmospheric state is calculated using a linear Bayesian update. The a priori cooling rate profile is calculated from AIRS L2 standard retrieval product data with an assumed uniform CO_2 profile of 379 ppmv. Uncertainties in the a priori and measured profiles were derived empirically from L2 estimated errors in state vector components. The calculation of the uncertainty in the retrieved cooling rate profile is described above. The error covariance matrix is calculated according to radiometric error estimation and cross-track temperature changes in the L2 granule data. A comparison of the measured, a priori, and retrieved profiles is shown in Figure 3a and suggests that our methods may be utilized for a more extensive analysis of the CO_2 cooling rate profile.

[16] Because there is greater uncertainty in stratospheric cooling processes in polar regions, we also performed a cross-comparison test using data from the MPACE mission near Fairbanks, Alaska aboard a Proteus aircraft flying at 11 km [*Harrington and Verlinde*, 2004]. As shown in Figure 3b, the agreement between retrieved and computed cooling rate profiles is insufficient in the free troposphere largely due to the difficulties associated with temperature retrievals at high latitudes and large discrepancies between skin temperature and emissivity values. In this case, the lack of appropriate a priori information seems to be quite serious.

5. Discussion

[17] The concept of a direct retrieval of radiative cooling profiles in the infrared is relatively uncharted territory and this research presents several exciting opportunities for future work. We have expanded on *Liou and Xue* [1988] so that real data are used, and two cross-comparison experiments lend confidence to the methods that we utilize. Stratospheric cooling rates caused by CO_2 are assumed to be known currently to within a few tenths of a K/day, but the uncertainty has yet to be formally quantified in light of temperature uncertainties. Our retrievals are generally precise to within 0.1 K/day in the lower and middle-stratosphere. Unfortunately, the AIRS instrument does not cover the entire CO_2 ν_2 band, and scaling between partial band and total band cooling needs to be explored further.

[18] The stratospheric temperature decrease in winter- and spring-time polar regions is of great scientific interest because of the interaction between radiative and dynamic effects in this region. The total stratospheric cooling rate profile meridional variation near the polar region has been explored briefly [*Hicke et al.*, 1999] using a cross-comparison with *in situ* data. The results of this work indicate that changes in the cooling rate profile of the lower stratosphere in polar regions will be detectable if the retrieval can be precise to around 0.1 K/day.

[19] A thorough analysis of stratospheric radiative cooling rates to measure the trends in radiative cooling due to changing stratospheric climate and CO_2 concentrations will require a robust input data set that resolves temperature profiles from the tropopause to the middle stratosphere. It will also require the development of computationally-efficient methods for calculating the angular weighting terms as discussed in the last paragraph of Section (2). Ultimately, an operational algorithm for the ingestion of radiance information into cooling rate calculations for GCMs is a monumental task and we have explored some theoretical and practical aspects for employing direct retrieval methods to this end.

References

Aumann, H. H., et al. (2003), AIRS/AMSU/HSB on the aqua mission: Design, science objectives, data products, and processing systems, *IEEE Trans. Geosci. Remote Sens.*, *41*(2), 253–264.

Aumann, H. H., D. Gregorich, and S. Gaiser (2005), AIRS hyperspectral measurements for climate research: Carbon dioxide and nitrous oxide effects, *Geophys. Res. Lett.*, *32*, L05806, doi:10.1029/2004GL021784.

Berk, A., L. S. Bernstein, and D. C. Robertson (1989), MODTRAN: A moderate resolution model for LOWTRAN 7, *Tech. Rep. GL-TR-89-0122*, 38 pp., Air Force Geophys. Lab., Hanscom AFB, Mass.

Clough, S. A., and M. J. Iacono (1995), Line-by-line calculation of atmospheric fluxes and cooling rates 2. Application to carbon dioxide, ozone, methane, nitrous oxide and the halocarbons, *J. Geophys. Res.*, *100*(D8), 16,519–16,535.

Clough, S. A., M. W. Shephard, E. Mlawer, J. S. Delamere, M. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown (2005), Atmospheric radiative transfer modeling: A summary of the AER codes, *J. Quant. Spectrosc. Radiat. Transfer*, *91*(2), 233–244.

Harrington, J., and J. Verlinde (2004), Mixed-phase arctic cloud experiment, science document, 28 pp., Pa. State Univ., Univ. Park, Pa. (Available at http://nsa.met.psu.edu/verlinde/mpace/sciencedoc.pdf)

Hicke, J., A. Tuck, and H. Vömel (1999), Lower stratospheric radiative heating rates and sensitivities calculated from Antarctic balloon observations, *J. Geophys. Res.*, *104*(D8), 9293–9308.

Iacono, M. J., E. J. Mlawer, S. A. Clough, and J. Morcrette (2000), Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3, *J. Geophys. Res.*, *105*(D11), 14,873–14,890.

Kiehl, J. T., and S. Solomon (1986), On the radiative balance of the stratosphere, *J. Atmos. Sci.*, *43*(14), 1525–1534.

Liou, K. N., and Y. K. Xue (1988), Exploration of the remote sounding of infrared cooling rates due to water-vapor, *Meteorol. Atmos. Phys.*, *38*(3), 131–139.

Mlynczak, M. G., C. J. Mertens, R. R. Garcia, and R. W. Portmann (1999), A detailed evaluation of the stratospheric heat budget 2. Global radiation

balance and diabatic circulations, *J. Geophys. Res.*, *104*(D6), 6039–6066.

Pagano, T. S., H. H. Aumann, D. E. Hagan, and K. Overoye (2003), Prelaunch and in-flight radiometric calibration of the Atmospheric Infrared Sounder (AIRS), *IEEE Trans. Geosci. Remote Sens.*, *41*(2), 265–273.

Revercomb, H. E., et al. (1998), Recent results from two new aircraft-based Fourier transform interferometers: The Scanning High-Resolution Interferometer Sounder and the NPOESS Atmospheric Sounder Testbed Interferometer, paper presented at the 8th International Workshop on Atmospheric Science from Space Using Fourier Transform Spectrometry (ASSFTS), MetoFrance, Toulouse, France, 16–18 November.

Rodgers, C. D. (2000), *Inverse Methods for Atmospheric Sounding: Theory and Practice*, 256 pp., World Sci., Hackensack, N. J.

Strow, L. L., S. E. Hannon, M. Weiler, K. Overoye, S. L. Gaiser, and H. H. Aumann (2003), Prelaunch spectral calibration of the Atmospheric Infrared Sounder (AIRS), *IEEE Trans. Geosci. Remote Sens.*, *41*(2), 274–286.

_____

A. Berk, Spectral Sciences, Inc., 4 Fourth Avenue, Burlington, MA 01803–3304, USA.

D. R. Feldman and Y. L. Yung, Department of Environmental Science and Engineering, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125–7800, USA. (feldman@caltech.edu)

K. N. Liou, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, 405 Hilgard Ave, 7127 Math Sciences Bldg., Los Angeles, CA 90095–1565, USA.

D. C. Tobin, Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, 1225 W. Dayton St., Madison, WI 53706, USA.