University of Wyoming stratospheric aerosol measurements

Principal Investigator: Terry Deshler, email: deshler@uwyo.edu
Professor Emeritus, Department of Atmospheric Science, University of Wyoming (1991-2014)
Research Scientist, Laboratory for Atmospheric and Space Physics, University of Colorado (2016-)

These data result from *in-situ* balloon-borne size resolved aerosol concentration measurements collected using University of Wyoming aerosol counters. The data files always include the total aerosol concentration, condensation nuclei (CN, r > 0.01 µm), and particles with radius ~> 0.15-0.19 µm. Measurement size channels range from 2 for the original Rosen counter (Dust), to 8-12 for the Wyoming white light optical particle counter (WOPC) to 8 for the Wyoming laser particle counter (WLPC). The continuation of this measurement record transitioned to LASP at the University of Colorado in 2019, where a new instrument has been developed by Lars Kalnajs: the LASP optical particle counter (LOPC), with upwards of 50 aerosol channels. Here is a summary table of the various instruments used.

| Instrument | Years of operation | UWv1.0 radius | UWv2.0 radius | No. of sizes | Flow rate liters/min | Sample rate (Hz) | Light source | Scattering angle degrees | Solid angle steradians |
|---|---|---|---|---|---|---|---|---|---|
| Dust | 1971-2013 | 0.15-0.25 | 0.175-0.28 | 2-4 | ~1 | 0.1 | White light | 25 | 0.15 |
| WOPC | 1989-2013 | 0.15-2/10 | 0.187-2.05/10 | 8-12 | ~10 | 0.1 | White light | 40 | 0.22 |
| WLPC | 2008-2020 | 0.075-4.5/15 | 0.092-4.5/16.6 | 8 | ~10 | 0.5 | Laser 633 nm | 90 | 3.63 |
| LOPC | 2019- | 0.15-10 | 0.15-10 | 50+ | ~20 | 0.5 | Laser 780 nm | 90 | 3.63 |

Data for the 1971-1988 Dust measurements, PI Jim Rosen, can be found on the NDACC web site: https://ndacc.larc.nasa.gov/stations/laramie-wy-united-states. Data for the 1989-2013 Dust, 1989-2013 WOPC, 2008-2020 WLPC, and 2019- LOPC can be found in the Stratospheric Aerosol Collection of WyoScholar, hosted by UW Libraries.

**Acknowledgments**: The measurements over the years have been primarily supported by the National Science Foundation and the National Aeronautics and Space Administration, with some support from the Naval Research Laboratory. They have resulted from the efforts of many individuals employed by the University of Wyoming over the years. The list of the most important contributors includes: Jim Rosen, Dave Hofmann, Lars Kalnajs; Technical people: Gary Olson, Lyle Womack, Jason Gonzales, Jim Hereford, Lou King, Stan Smith, Ben Heesen, Norm Kjome; Post docs: Bryan Johnson, Bruno Nardi, Chris Kröger, Jennifer Mercer; and graduate students: Rod Rozier, Dongliang Wang, Rigeto Zhao, Christos Mitas, Bill Bellon, Chuntao Liu, Qun Miao, Sharon Gill, Jian Yongxiao, Andrew Glen, Leslie Baran, Stephanie Luberda, Shauna Ward, Jaclyn Ritzman, Mark Hervig, David Delene, Trude Eidhammer, Mahesh Kovilakam, Patrick Campbell, Katie Foster.

If these data are useful for your work and/or publication, please offer inclusion and/or proper referencing and acknowledgment for the source of these data.

The Wyoming in situ aerosol measurements have been revised following Deshler et al. [2019]. These files are in the subfolders .../Nr_Full_Profile/ and .../SizeDist_Stratosphere/ under each of the flight locations. This is considered the UWv2.0 data, although such a subfolder is not explicitly used. All data in the primary folders are UWv2.0. The earlier version of the data is maintained in the subfolders .../UWv1.0/ within each flight location folder.

The revision primarily affects the radii assigned to each channel of the instrument, increasing the size thresholds.

Thus the canonical 0.15/0.25 um channels, from the beginning of the measurements in 1971, cannot be maintained. In fact even these sizes from the earliest measurements should perhaps be increased somewhat for the early measurements, [Deshler et al., 2019]. The number concentrations have not changed between the UWv1.0 and UWv2.0 data. The new size distributions for the UWv2.0 data, while still lognormal are fit using a revised algorithm described in Deshler et al. [2019] which incorporates the counting efficiency of each aerosol channel in the fitting algorithm. In addition unimodal fits are provided for a subset of the data indicated in the folders ...\Unimode. These were completed based upon requests. Due to the large number of aerosol channels for the LOPC, size distributions are not supplied for these measurements.

For the revised data there are, in addition to the ASCII data files for each flight, IDL.sav files for folders with a lot of measurements. The names of the IDL.sav files are indicative of the contents and the instrument included. When more than one instrument type (Dust, WOPC, WLPC) is used for a data set there are separate IDL.sav files for each instrument type. Thus, e.g., *_WOPC.sav includes only measurements from the Wyoming optical particle counter [Deshler et al., 2003], *_WLPC.sav includes only measurements from the Wyoming laser particle counter [Ward et al., 2014]. Each of the individual ASCII files contains a header containing 86(MM) - 94 (WY) lines. The header contains both general metadata for the whole data base, and specific metadata for each flight. IDL.sav files are available for the following folders: .../US_Laramie_41N_105W_1989-2020/, .../Ant_McMurdo_78S_167E_1989-2010/, .../SE_Kiruna_68N_21E_1990-2004/.

Primary references describing each of the three instrument types are:

Dust:

**Development & first use**: Rosen, J. M., The vertical distribution of dust to 30 km, J. Geophys. Res., *69*, 4673-4676, 1964.

**Description & early measurements**: Hofmann, D. J., J. M. Rosen, T. J. Pepin, and R. G. Pinnick [1975], tratospheric aerosol measurements, I, Time variations at nothern midlatitudes, *J. Atmos. Sci., 32*, 1446-1456.

**Measurements through 1990**: Hofmann, D. J. [1990] Increase in the stratospheric background sulfuric acid aerosol mass in the past 10 years, *Science, 248,* 996-1000.

WOPC:

**Development & early use**: Hofmann, D. J. and T. Deshler [1991] Stratospheric cloud observations during formation of the Antarctic ozone hole in 1989, *J. Geophys. Res., 96*, 2897-2912.

**Description & uncertainties**: Deshler, T., M. E. Hervig, D. J. Hofmann, J. M. Rosen, and J. B. Liley [2003], Thirty years of in situ stratospheric aerosol size distribution measurements from Laramie, Wyoming (41˚N), using balloon-borne instruments, *J. Geophys. Res., 108(D5)*, 4167, doi:10.1029/2002JD002514.

**Particle evaporation and calibration error**: Kovilakam, M., and T. Deshler [2015], On the accuracy of stratospheric aerosol extinction derived from in situ size distribution measurements and surface area density derived from remote SAGE II and HALOE extinction measurements, *J. Geophys. Res., 120*, 8426–8447, doi:10.1002/2015JD023303.

**Including counting efficiency in OPC data**: Deshler, T., B. Luo, M. Kovilakam, T. Peter, L. E. Kalnajs [2019], Retrieval of aerosol size distributions from in situ particle counter measurements: instrument counting efficiency and comparisons with satellite measurements, *J. Geophys. Res., 124(9)*, 5058-5087. doi.10.1029/2018JD029558

WLPC:

**Description & use for PSC measurements**: Ward, S. M., T. Deshler, and A. Hertzog [2014], Quasi-Lagrangian measurements of nitric acid trihydrate formation over Antarctica, *J. Geophys. Res., 119*, doi:10.1002/2013JD020326.

LOPC:

**Description and early use:** Kalnajs, L. E., & Deshler, T. (2022). A New Instrument for Balloon-Borne In Situ Aerosol Size Distribution Measurements, the Continuation of a 50 Year Record of Stratospheric Aerosols Measurements. *Journal of Geophysical Research: Atmospheres*, *127*(24), e2022JD037485. https://doi.org/10.1029/2022JD037485

The Wyoming aerosol data from 1989 to the present, PI Terry Deshler, can be found in the following folders grouped by rough location: mid latitude, polar, and tropical. The folder name includes the country code, location name, latitude, longitude, and range of years for the data. A dash between the years indicates a continuous record spanning those years, an underscore indicates separate years of measurements. The data are available in the data repository at the University of Wyoming Libraries (Deshler & Kalnajs, 2022). With the reference for the data to be used in a bibliography:

Deshler, T., & Kalnajs, L. E. (2022). University of Wyoming stratospheric aerosol measurements | Mid latitude [Dataset]. https://doi.org/10.15786/21534894. For references to other datasets, e.g. polar just change the DOI.

The Wyoming aerosol data from 1971-1988, PI Jim Rosen, are found on the NDACC data base at https://ndacc.larc.nasa.gov/stations/laramie-wy-united-states

Mid latitude: https://doi.org/10.15786/21534894

/Aerosol_InSitu_Meas/US_Laramie_41N_105W_1989-2020/
/Aerosol_InSitu_Meas/US_Boulder_40N_105W_2019-/
/Aerosol_InSitu_Meas/FR_Gap_45N_6E_1996_1997/
/Aerosol_InSitu_Meas/FR_AirLaDour_44N_0W_1995/
/Aerosol_InSitu_Meas/AU_Mildura_34S_142E_1972-1980/
/Aerosol_InSitu_Meas/NZ_Lauder_45S_170E_1991-2001/

Polar: https://doi.org/10.15786/21534945

/Aerosol_InSitu_Meas/SE_Andoya_69N_16E_1996_1997/
/Aerosol_InSitu_Meas/SE_Kiruna_68N_21E_1990-2004/
/Lagrangian measurements South of 60S_2010
/Aerosol_InSitu_Meas/Ant_McMurdo_78S_167E_1989-2010/

Tropical: https://doi.org/10.15786/21534951

/Aerosol_InSitu_Meas/In_Hyderabad_17N_79E_2015/
/Aerosol_InSitu_Meas/NI_Niamey_13N_2E_2006_2008/
/Aerosol_InSitu_Meas/BR_Teresina_5S_43W_2008/
/Aerosol_InSitu_Meas/AU_Darwin_13S_132E_2005_2014/
/Aerosol_InSitu_Meas/BR_Bauru_22S_49W_1997/
/Aerosol_InSitu_Meas/AU_Longreach_23S_144E_1972_1973/, UWv1.0 only
/Aerosol_InSitu_Meas/AU_AliceSprings_24S_134E_2017/, UWv1.0 only

Within each of these directories are the following subdirectories:

**/Nr_Full_Profile/** - ASCII Sounding files for aerosol size and number concentration. The file name, e.g. 20080622_WY_WOPC_ATA6m.ASC, indicates the date (yyyymmdd) and location, e.g. MM=McMurdo, WY=Laramie, the instrument name (e.g. WOPC_ATA6m). The file extension indicates the vertical resolution, .ASC, implies full data , or an average, e.g. .500m for a 500 m average. These differences in the vertical averaging are separated into separate subfolders. The files include measurements from the surface to balloon burst. All files include general and specific metadata. In the Laramie folder, where more than one instrument was used, there are separate subfolders for each instrument type.

**/SizeDist_Stratosphere/** - ASCII lognormal size distributions (either unimodal or bimodal) at the vertical resolution indicated in the file name. The file names are somewhat long and include the name of the source file for the measurements, including the vertical resolution, the altitude at which the size distributions begin (typically the tropopause), and "_Srs_ce" which indicates the fit was completed with the new fitting algorithm which accounts for the instrument counting efficiency at each channel size. All files include general and specific metadata. In the Laramie folder, where more than one instrument was used, there are separate subfolders for each instrument type. Because of the large number of channels for the instruments used in Boulder, size distributions are not provided.

The minimum concentration measurable with these instruments is given by S / F. for sample frequency, S=0.1 Hz, and flow rate, F. For example, the minimum concentration detectable is 5.7 x $10^{-4}$ $cm^{-3}$ for F = 167 $cm^3$ $s^{-1}$, and 5.7 x $10^{-3}$ $cm^{-3}$ for F = 16.7 $cm^3$ $s^{-1}$. When the aerosol concentration is below the detection threshold of the instrument the concentration is arbitrarily assigned a value of 1.01E-39. The first channel at which this occurs is arbitrarily assigned a value of 1.01 E-06 and is used to fix the large particle tail of the size distribution.

Poisson statistics define the fractional uncertainty of a counting measurement as its inverse square root, $C^{-0.5}$ for C counts in one sample, becoming important at low concentrations. The aerosol concentration, N = C S / F. Thus the

Poisson error fraction, in terms of concentration, is $(N F / S)^{-0.5}$. For these instruments: S = 0.1 Hz, F = 16.7 $cm^3 s^{-1}$ for a two channel counter and CN counter, and F = 167 $cm^3 s^{-1}$ for a counter with more than two channels. In the stratosphere these flow rates are reduced to about 80% of these values by temperature differences between outside air and pump. This leads to uncertainties of 85, 25, and 8% for concentrations of 0.01, 0.1, and 1.0 $cm^{-3}$ at the low flow rate and concentrations of 0.001, 0.01, 0.1 $cm^{-3}$ at the high flow rate. This error dominates at concentrations below 0.1 (0.01) $cm^{-3}$ for the low (high) flow rate instrument. At concentrations higher than these a concentration error of +/-10% reflects comparisons of concentration measurements from two instruments using identical aerosol in the laboratory.

**A bibligography, 1990 - 2022**, of the literature in which Wyoming Aerosol counters played a role in the analysis of mid latitude, polar, and tropical aerosol measurements follows here:

## Mid Latitude Measurements


Kalnajs, L. E., & Deshler, T. (2022). A New Instrument for Balloon-Borne In Situ Aerosol Size Distribution Measurements, the Continuation of a 50 Year Record of Stratospheric Aerosols Measurements. *Journal of Geophysical Research: Atmospheres*, *127*(24), e2022JD037485. https://doi.org/10.1029/2022JD037485

Li, Y., Dykema, J., Deshler, T., & Keutsch, F. (2021). Composition Dependence of Stratospheric Aerosol Shortwave Radiative Forcing in Northern Midlatitudes. *Geophysical Research Letters*, *48*(24), e2021GL094427. https://doi.org/10.1029/2021GL094427

Nyaku, E., Loughman, R., Bhartia, P. K., Deshler, T., Chen, Z., & Colarco, P. R. (2020). A comparison of lognormal and gamma size distributions for characterizing the stratospheric aerosol phase function from optical particle counter measurements. *Atmospheric Measurement Techniques*, *13*(3), 1071–1087. https://doi.org/10.5194/amt-13-1071-2020

Günther, A., Höpfner, M., Sinnhuber, B.-M., Griessbach, S., Deshler, T., von Clarmann, T., & Stiller, G. (2018). MIPAS observations of volcanic sulfate aerosol and sulfur dioxide in the stratosphere. *Atmospheric Chemistry and Physics*, *18*(2), 1217–1239. https://doi.org/10.5194/acp-18-1217-2018.

Campbell, P., M. Mills, *and* T. Deshler *(*2014*)*, The global extent of the mid stratospheric CN layer: A three-dimensional modeling study, *J. Geophys. Res. Atmos.*, *119*, doi:*10.1002/2013JD020503*.

Dhomse, S S, K. M. Emmerson, G. W. Mann, N. Bellouin, K. S. Carslaw, M. P. Chipperfield, R. Hommel, N. L. Abraham, P. Telford, P. Braesicke, M. Dalvi, C. E. Johnson, F. O'Connor, O. Morgenstern, J. A. Pyle, T. Deshler, J. M. Zawodny, and L. W. Thomason, (2014), Aerosol microphysics simulations of the Mt. Pinatubo eruption with the UM-UKCA composition-climate model, *Atmos. Chem. Phys.*, *14*, 11221–11246.

Ridley, D. A., S. Solomon, J. E. Barnes, V. D. Burlakov, T. Deshler, S. I. Dolgii, A. B. Herber, T. Nagai, R. R. Neely III, A. V. Nevzorov, C. Ritter, T. Sakai, B. D. Santer, M. Sato, A. Schmidt, O. Uchin, and J. P. Vernier *(*2014*)*, Total volcanic stratospheric aerosol optical depths and implications for global climate change, *Geophys. Res. Lett.*, *41*, 7763–7769*, doi: 10.1002/2014GL061541*..

Kravitz, B., A. Robock, A. Bourassa, T. Deshler, D. Wu, I. Mattis, F. Finger, A. Hoffmann, C. Ritter, L. Bitar,T. J. Duck, and J. E. Barnes, (2011), Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption, J. Geophys. Res., 116, D18211, doi:10.1029/2010JD015501.

Wurl, D., Grainger, R. G., McDonald, A. J., and Deshler, T.: Optimal estimation retrieval of aerosol microphysical properties from SAGE~II satellite observations in the volcanically unperturbed lower stratosphere, Atmos. Chem. Phys., 10, 4295-4317, doi:10.5194/acp-10-4295-2010, 2010 Deshler, T. (2008), A Review of Global Stratospheric Aerosol: Measurements, Importance, Life Cycle, and Local Stratospheric Aerosol, *Atmos. Res.*, *90*, 223-232.

Deshler, T. (2008), A Review of Global Stratospheric Aerosol: Measurements, Importance, Life Cycle, and Local Stratospheric Aerosol, *Atmos. Res.*, *90*, 223-232.

Eidhammer, T., D. C. Montague, and T. Deshler (2008), Determination of index of refraction and size of supermicrometer particles from light scattering measurements at two angles, *J. Geophys. Res.*, 113, D16206, doi:10.1029/2007JD009607.

Fromm, M., E. P. Shettle, K.H. Fricke, C. Ritter, T. Trickl, H. Giehl, M. Gerding, J. Barnes, M. O'Neill, S. T. Massie, U. Blum, I. S. McDermid, T. Leblanc, and T. Deshler (2008), The stratospheric impact of the Chisholm PyroCumulonimbus eruption: Part II, Vertical profile perspective, *J. Geophys. Res.*, *113*, D08203, doi:10.1029/2007JD009147.

Deshler, T., R. Anderson-Sprecher, J. Barnes, B. Clemesha, S. Godin-Beekmann, R. G. Grainger, D. J. Hofmann, H. Jäger, S. Marsh, M. Osborn, and D. Simonich, Non-volcanic stratospheric aerosol trends: 1971 - 2004, Chapter 5 of the *SPARC Assessment of Stratospheric Aerosol Properties* (L. W. Thomason and Th. Peter editors), WCRP-124, WMO/TD-No. 1295, SPARC Report No. 4.

Deshler, T., R. Anderson-Sprecher, H. Jäger, J. Barnes, D. J. Hofmann, B. Clemesha, D. Simonich, M. Osborn, R. G. Grainger, and S. Godin-Beekmann (2006), Trends in the nonvolcanic component of stratospheric aerosol over the period 1971–2004, J. Geophys. Res, 111, D01201, doi:10.1029/2005JD006089.

Deshler, T., M. E. Hervig, D. J. Hofmann, J. M. Rosen, and J. B. Liley, Thirty years of in situ stratospheric aerosol size distribution measurements from Laramie, Wyoming (41°N), using balloon-borne instruments, *J. Geophys. Res.*, *108(D5)*, 4167, doi:10.1029/2002JD002514, 2003.

Jäger, H., and T. Deshler, Correction to Lidar backscatter to extinction, mass and area conversions for stratospheric aerosols based on midlatitude balloonborne size distribution measurements, Geophys. Res. Lett., 30(7), 1382, doi:10.1029/2003GL017189, 2003.

Hofmann, D., J. Barnes, E. Dutton, T. Deshler, H. Jäger, R. Keen, and M. Osborn, Surface-based observations of volcanic emissions to the stratosphere, in *Volcanism and the Earth's Atmosphere, Geophys. Monogr 139*, edited by A. Robock and

C. Oppenheimer, pp. 57-73, AGU, Washington, D.C., 2003.
Jäger, H., and T. Deshler, Lidar backscatter to extinction, mass and area conversions for stratospheric aerosols based on midlatitude balloonborne size distribution measurements, *Geophys. Res. Lett.*, *29(19*), 1929, doi:10.1029/2002GL015609, 2002.
Hervig, M. E., and T. Deshler, Evaluation of aerosol measurements from SAGE II, HALOE, and balloonborne optical particle counters, *J. Geophys. Res., 107(D3)*, 10.1029/2001JD000703, 2002.
Hervig, M. E., and T. Deshler, Stratospheric aerosol surface area and volume inferred from HALOE, CLAES, and ILAS measurements, *J. Geophys. Res., 103*, 25345-25352, 1998.
Hofmann, D. J., R. Stone, M. Wood, T. Deshler and J. Harris, An analysis of 25 years of balloonborne aerosol data in search of a signature of the subsonic commercial aircraft fleet. *Geophys. Res. Lett*., *13*, 2433-2436, 1998.
Arnold, F., J. Curtius, S. Spreng, and T. Deshler, Stratospheric aerosol sulfuric acid: First direct in situ measurements using a novel balloon-based mass spectrometer apparatus, *J. Atmos. Chem., 30*, 3-10, 1998.
Hervig, M. E., T. Deshler, and J. M. Russell III, Aerosol size distributions obtained from HALOE spectral extinction measurements, *J. Geophys. Res., 103*, 1573-1583, 1998.
Deshler, T., J. B. Liley, G. Bodeker, W. A. Matthews, and D. J. Hofmann, Stratospheric aerosol following Pinatubo, comparison of the north and south mid latitudes using in situ measurements, *Adv. Space Res.*, *20*, 2057-2061, 1997.
Ansmann, A., I. Mattis, U. Wandinger, F. Wagner, J. Reichardt, and T. Deshler, Evolution of the Pinatubo Aerosol: Raman lidar observations of particle optical depth, effective radius, mass, and surface area over central Europe at 53.4°N, *J. Atmos. Sci., 54,* 2630-2641, 1997.
Post, M. J., C. J. Grund, D. Wang, and T. Deshler, Evolution of Mt. Pinatubo's aerosol size distributions over the continental United States: Two wavelength lidar retrievals and in situ measurements, *J. Geophys. Res., 102*, 13,535 -13,542, 1997.
Thomason, L. W., L. R. Poole, and T. Deshler, A global climatology of stratospheric aerosol surface area density deduced from stratospheric aerosol and gas experiment II measurements: 1984-1994, *J. Geophys. Res*.,*102*, 8967-8976, 1997.
Poole, L., S. Godin, S. Bekki, T. Deshler, N. Larsen, and T. Peter, Global distributions and changes in stratospheric particles, Chapter 3 in WMO, *Scientific Assessment of Ozone Depletion: 1998,* World Meteorological Organization, Global Ozone Research and Monitoring Project Report 44, Geneva, Switzerland, 1999.
Jäger, H., T. Deshler, F. Homburg, and V. Freudenthaler, Five years of lidar observations of the Pinatubo eruption cloud, in *Advances in Atmospheric Remote Sensing with Lidar*, Ansmann, Neuber, Rairous, Wandinger (Eds.), Springer, 485-488, 1996
Massie, S. T., T. Deshler, G. E. Thomas, J. L. Mergenthaler, J. M. Russell, Evolution of the infrared properties of the Mt. Pinatubo aerosol cloud over Laramie, Wyoming, *J. Geophys. Res., 101,* 23007-23020, 1996.
Russell, P. B., J. M. Livingston, R. F. Pueschel, J. B. Pollack, S. Brooks, P. Hamill, J. Hughes, L. Thomason, L. Stowe, T. Deshler, E. Dutton, Global to microscale evolution of the Pinatubo volcanic aerosol, derived from diverse measurements and analyses, *J. Geophys. Res*., *101*, 18745-18763, 1996.
Hervig, M.E., J.M. Russell III, L. L. Gordley, J. H. Park, S. R. Drayson, and T. Deshler Validation of aerosol measurements made by the Halogen Occultation Experiment, *J. Geophys. Res., 101*, 10267-10276, 1996.
Lambert, A., R. G. Grainger, J. J. Remedios, W. J. Reburn, C. D. Rodgers, F. W. Taylor, A. E. Roche, J. B. Kumer, S. J. Massie, and T. Deshler, Validation of aerosol measurements from the improved stratospheric and mesospheric sounder, *J. Geophys. Res*., *101*, 9811-9830, 1996.
Massie, S. T., et (21 authors) al, Validation studies using multiwavelength Cryogenic Limb Array Etalon Spectrometer (CLAES) observations of stratospheric aerosol, *J. Geophys. Res*., *101*, 9757-9774, 1996.
Wandinger, U., A. Ansmann, J. Reichardt, and T. Deshler, Determination of stratospheric-aerosol microphysical properties from independent extinction and backscattering measurements with a Raman lidar, *Applied Optics 34*, 8315-8329, 1995.
Grainger, R. G., A. Lambert, C. D. Rodgers, F. W. Taylor, and T. Deshler, Stratospheric aerosol effective radius, surface area, and volume estimated from infrared measurements, *J. Geophys. Res., 100*, 16507-16518, 1995.
Jäger, H., T. Deshler, and D. J. Hofmann, Midlatitude lidar backscatter conversions based on balloonborne aerosol measurements, *Geophys. Res. Lett., 22*, 1729-1732, 1995.
Hofmann, D. J., S. J. Oltmans, J. M. Harris, J. A. Lathrop, G. L. Koenig, W. D. Komhyr, R. D. Evans, D. M. Quincy, T. Deshler and B. J. Johnson, Recovery of stratospheric ozone over the United States in the winter of 1993-1994, *Geophys. Res. Lett., 21*, 1779-1782, 1994.
Deshler, T., In situ measurements of the size distribution of the Pinatubo aerosol over Kiruna on four days between 18 January and 13 February 1992, *Geophys. Res. Lett., 21*, 1323-1326, 1994.
Hofmann, D. J., S. J. Oltmans, W. D. Komhyr, J. M. Harris, J. A. Lathrop, A. O. Langford, T. Deshler, B. J. Johnson, A. Torres, and W. A. Matthews, Ozone loss in the lower stratosphere over the United Stated in 1992-1993: Evidence for heterogeneous chemistry on the Pinatubo aerosol, *Geophys. Res. Lett., 21*, 65-68, 1994.
Deshler, T., B. J. Johnson, and W. R. Rozier, Balloonborne measurements of Pinatubo aerosol during 1991 and 1992 at 41$^{o}$N, vertical profiles, size distribution, and volatility, *Geophys. Res. Lett., 20*, 1435-1438, 1993.
Sheridan, P. J., R. C. Schnell, D. J. Hofmann, and T. Deshler, Electron microscope studies of aerosol layers with likely Kuwaiti origins over Laramie, Wyoming, during spring 1991, *Geophys. Res. Lett., 19*, 389-392,1992.
Deshler, T., and D. J. Hofmann, Measurements of unusual aerosol layers in the upper troposphere over Laramie, Wyoming, in the spring of 1991: Evidence for long range transport from the oil fires in Kuwait, *Geophys. Res. Lett., 19*, 385-388, 1992.
Sheridan, P. J., R. C. Schnell, D. J. Hofmann, and T. Deshler, Electron microscope studies of Mt. Pinatubo aerosol layers over Laramie, Wyoming, during summer 1991, *Geophys. Res. Lett., 19*, 203-206, 1992.
Deshler, T., D. J. Hofmann, B. J. Johnson, and W. R. Rozier, Balloonborne measurements of the Pinatubo aerosol size distribution and volatility at Laramie, Wyoming during the summer of 1991. *Geophys. Res. Lett., 19*, 199-202, 1992.

## Polar stratospheric cloud measurements

Snels, M., Cairo, F., Di Liberto, L., Scoccione, A., Bracaglia, M., & Deshler, T. (2021). Comparison of Coincident Optical Particle Counter and Lidar Measurements of Polar Stratospheric Clouds Above McMurdo (77.85°S, 166.67°E) From 1994 to 1999. *Journal of Geophysical Research: Atmospheres*, *126*(6), e2020JD033572. https://doi.org/10.1029/2020JD033572

Höpfner, M., Deshler, T., Pitts, M., Poole, L., Spang, R., Stiller, G., & Clarmann, T. von. (2018). The MIPAS/Envisat climatology (2002–2012) of polar stratospheric cloud volume density profiles. *Atmospheric Measurement Techniques*, *11*(10), 5901–5923. https://doi.org/10.5194/amt-11-5901-2018

Di Liberto, L., R. Lehmann, I. Tritscher, F. Fierli, J. L. Mercer, M. Snels, G. Di Donfrancesco, T. Deshler, B. P. Luo, J-U. Grooß, E. Arnone, B. M. Dinelli, and F. Cairo (2015), Lagrangian analysis of microphysical and chemical processes in the Antarctic stratosphere: a case study, *Atmos. Chem. Phys.*, *15*, 6651–6665.

Ward, S. M., T. Deshler, and A. Hertzog (2014*)*, Quasi-Lagrangian measurements of nitric acid trihydrate formation over Antarctica, *J. Geophys. Res. Atmos.*, *119*, doi:*10.1002/2013JD020326*.

Campbell, P., *and* T. Deshler *(*2014*)*, Condensation nuclei measurements in the midlatitude (1982–2012) and Antarctic (1986–2010) stratosphere between 20 and 35 km, *J. Geophys. Res. Atmos*., 119, *doi:10.1002/2013JD019710.*

Weisser, C., K. Mauersberger, J. Schreiner, N. Larsen, F. Cairo, A. Adriani, J. Ovarlez, and T. Deshler Composition analysis of liquid particles in the Arctic stratosphere under synoptic conditions, *Atmos. Chem. Physics*, *6*, 689-696, 1-3-2006.

Scarchilli, C., A. Adriani, F. Cairo, G. Di Donfrancesco, C. Buontempor, M. Snels, M. L. Moriconei. T. Deshler, N. Larsen, B. Luo, K. Mauersberger, J. Ovarlez, J. Rosen, and J. Schreiner, Determination of PSC particle refractive indices using in situ optical measurements and T-Matrix calculation. *Appl. Optics*, *16*, 3302-, 2005.

Eidhammer, T., and T. Deshler, Evaporation of polar stratospheric particles in situ in a heated inlet, *Atmos. Chem. Physics*., *5*, 97-106, 21-1-2005

Larsen, N., B. M. Knudsen, S. H. Svendsen, T. Deshler, J. M. Rosen, R. Kivi, C. Weisser, J. Schreiner, K. Mauersberger, F. Cairo, J. Ovarlez, H. Oelhaf, and A. Schmidt, Formation of solid particles in synoptic-scale Arctic PSCs in early winter 2002/2003. *Atmos. Chem. Physics*., 4, 2001-2013, 2004

Vogel, B., R. Müller, T. Deshler, J.-U. Groob, J. Karhu, D. S. McKenna, M. Müller, D. Toohey, G. C. Toon, and F. Stroh, Vertical profiles of activated ClO and ozone loss in the Arctic vortex in January and March 2000: In situ observations and model simulations, *J. Geophys. Res.*, *108(D22)*, 8334, doi:10.1029/2002JD002564, 2003.

Deshler, T., N. Larsen, C. Weisser, J. Schreiner, K. Mauersberger, F. Cairo, A. Adriani, G. Di Donfrancesco, J. Ovarlez H. Ovarlez, U. Blum, K.H. Fricke, and A. Dörnbrack, Large nitric acid particles at the top of an Arctic stratospheric cloud, *J. Geophys. Res*., 108(D16), 4517, doi:10.1029/2003JD003479, 2003.

Voigt, C., N. Larsen, T. Deshler, C. Kröger, J. Schreiner; K. Mauersberger, B. Luo, A. Adriani, F. Cairo, G. Di Donfrancesco, J. Ovarlez, H. Ovarlez, A. Dörnbrack, B. Knudsen, J. Rosen, In situ mountain-wave polar stratospheric cloud measurements: Implications for nitric acid trihydrate formation *J. Geophys. Res.*, *108* (D5) 10.1029/2001JD001185, 2003.

Schreiner, J., C. Voigt, C. Weisser, A. Kohlmann, K. Mauersberger, T. Deshler, C. Kröger, J. Rosen, N. Kjome, N. Larsen, A. Adriani, F. Cairo, G. Di Donfrancesco, J. Ovarlez, H. Ovarlez, A. Dörnbrack, Chemical, microphysical, and optical properties of polar stratospheric clouds, *J. Geophys. Res.*, *108*, D5, 8313, doi:10.1029/2001JD000825, 2003.

Renard, J., G. Berthet, C. Robert, M. Chartier, M. Pirre, C. Brogniez, M. Herman, C. Verwaerde, J. Balois, J. Ovarlez, H. Ovarlez, J. Crespin, and T. Deshler, Optical and physical properties of stratospheric aerosols from balloon measurements in the visible and near-infrared domains. II. Comparison of extinction, reflectance, polarization, and counting measurements, *Appl. Optics*, *41*, 7540-7549, 2002.

Larsen, N., S. Hoyer, Svendsen, B. M. Knudsen, I. S. Mikkelsen, C. Voigt, A. Kohlmann, J. Schreiner, K. Mauersberger, T. Deshler, C. Kröger, J. M. Rosen, N. T. Kjome, A. Adriani, F. Cairo, G. Di Donfrancesco, J. Ovarlez, H. Ovarlez, A. Dörnbrack, T. Birner, Microphysical mesoscale simulations of polar stratospheric cloud formation constrained by in situ measurements of chemical and optical cloud properties, *J. Geophys. Res.*, *107*(D20), 8301, doi:10.1029/2001JD000999, 2002.

Höpfner, M., H. Oelhaf, G. Wetzel, F. Friedl-Vallon, A. Kleinert, A. Lengel, G. Maucher, H. Nordmeyer, N. Glatthor, G. Stiller, T. v. Clarmann, H. Fischer, C. Kröger, T. Deshler, Evidence of scattering of tropospheric radiation by PSCs in mid-IR limb emission spectra: MIPAS-B observations and KOPRA simulations, *Geophys. Res. Lett., 29*, 10.1029/2001GL014443, 2002.

Schiller, C., T. Deshler, and T. Peter, Contamination-induced particle production during balloon flights: Origin for unexpected ice particle observations in the Arctic?, *Geophys. Res. Lett*., *28*, 3247-3250, 2001

Voigt, C., J. Schreiner, A. Kohlmann, K. Mauersberger, N. Larsen, T. Deshler, C. Kröger, J. Rosen, A. Adriani, F. Cairo, G. Di Donfrancesco, M. Viterbini, J. Orvalez and H. Orvalez, C. David, and A. Dörnbrack, Nitric acid trihydrate (NAT) in polar stratospheric cloud particles, *Science*, *290*, 1756-1758, 2000.

Borrmann, S., A. Thomas, V. Rudakov, V. Yushkov, B. Lepuchov, T. Deshler, N. Vinnichenko, V. Khattatov, and L. Stefanutti, Stratospheric aerosol measurements in the Arctic winter of 1996/1997 with the M-55 Geophysika high-altitude research aircraft, *Tellus*, *52B*, 1088-1103, 2000.

Riviere, E. D., N. Huret, F. G.-Taupin, J.-B. Renard, M. Pirre, S. D. Eckermann, N. Larsen, T. Deshler, F. Lefevre, S. Payan, C. Camy-Peyret, Role of lee waves in the formation of solid polar stratospheric clouds: Cases studies from February 1997, *J. Geophys. Res.*, *105*, 6845-6853, 2000.

Deshler, T. B. Nardi, A. Adriani, F. Cairo, G. Hansen, F. Fierli, A. Hauchercorne, and L. Pulvirenti, Determining the index of refraction of polar stratospheric clouds above Andoya (69°N) by combining size-resolved concentration and optical scattering measurements, *J. Geophys. Res.*, *105*, 3943-3953, 2000.

Sugita, T., Y. Kondo, M. Koike, M. Kanada, N. Toriyama, and H. Nakajima, T. Deshler, and R. Imasu, Balloon-borne optical counter for in situ aerosol measurement, *J. Atmos. Chem*, *32*, 183-204, 1999.

Mehrtens, H., U. von Zahn, F. Fierli, B. Nardi, and T. Deshler, Type I PSC-particle properties: Measurements at ALOMAR 1995 to 1997, *Geophys. Res. Lett.*, *26*, 603-606, 1999.

Deshler, T., and S. J. Oltmans, Vertical profiles of volcanic aerosol and polar stratospheric clouds above Kiruna, Sweden:

Winters 1993 and 1995, *J. Atmos. Chem*, *30*, 11-23, 1998.
Kondo, Y., T. Sugita, R. J. Salawitch, M. Koike, and T. Deshler, Effect of Pinatubo aerosols on stratospheric NO, *J. Geophys. Res.*, *102*, 1205-1213, 1997.
Deshler, T., B. J. Johnson, D. J. Hofmann, and B. Nardi, Correlations between ozone loss and volcanic aerosol at altitudes below 14 km over McMurdo Station, Antarctica, *Geophys. Res. Lett.*, *21*, 2931-2934, 1996.
Kondo, Y., S. R. Kawa, D. Lary, T. Sugita, A. R. Douglass, E. Lutman, M. Koike, and T. Deshler, Interpretation of nitric oxide profile observed in January 1992 over Kiruna, *J. Geophys. Res.*, *101*, 12555-12566, 1996.
Adriani, A., T. Deshler, G. Di Donfrancesco, and G. P. Gobbi, Polar stratospheric clouds and volcanic aerosol during 1992 spring over McMurdo Station, Antarctica: Lidar and particle counter comparisons, *J. Geophys. Res.*, *100*, 25877-25898, 1995.
Deshler, T., Th. Peter, R. Müller, and P. J. Crutzen, The lifetime of leewave-induced ice particles in the Arctic stratosphere: I. Balloonborne measurements, *Geophys. Res. Lett.*, *21*, 1327-1330, 1994.
Peter, Th, P. J. Crutzen, R. Müller, and T. Deshler, The lifetime of leewave-induced ice particles in the Arctic stratosphere: II. Stabilization due to NAT-coating. *Geophys. Res. Lett.*, *21*, 1331-1334, 1994.
Deshler, T., B. J. Johnson, and W. R. Rozier, Changes in the character of polar stratospheric clouds over Antarctica in 1992 due to the Pinatubo volcanic aerosol, *Geophys. Res. Lett.*, *21*, 273-276, 1994.
Adriani, A., T. Deshler, G.P. Gobbi, B.J. Johnson, and G.Di Donfrancesco, Polar stratospheric clouds over McMurdo Station, Antarctica, during the 1991 spring: lidar and particle counter measurements, *Geophys. Res. Lett.*, *19*, 1755-1758, 1992.
Deshler, T., A. Adriani, D. J. Hofmann, and G. P. Gobbi, Evidence for denitrification in the 1990 Antarctic spring stratosphere: II Lidar and aerosol measurements, *Geophys. Res. Lett.*, *18*, 1999-2002, 1991.
Gobbi, G. P., T. Deshler, A. Adriani, and D. J. Hofmann, Evidence for denitrification in the 1990 Antarctic spring stratosphere: I Lidar and temperature measurements, *Geophys. Res. Lett.*, *18*, 1995-1998, 1991.
Hofmann, D. J. and T. Deshler, Stratospheric cloud observations during formation of the Antarctic ozone hole in 1989, *J. Geophys. Res.*, *96*, 2897-2912, 1991.
Hofmann, D. J. and T. Deshler, Balloonborne measurements of polar stratospheric clouds and ozone at -93$^{o}$C in the Arctic in February 1990, *Geophys. Res. Lett.*, *17*, 2185-2188, 1990.
Hofmann, D. J., T. Deshler, F. Arnold, and H. Schlager, Balloon observations of nitric acid aerosol formation in the arctic stratosphere: II. Aerosol., *Geophys. Res. Lett.*, *17*, 1279-1282, 1990.
Schlager, H., F. Arnold, D. Hofmann, and T. Deshler, Balloon observations of nitric acid aerosol formation in the arctic stratosphere: I. Gaseous nitric acid, *Geophys. Res. Lett.*, *17*, 1275-1278, 1990.

## Tropical measurements

Tidiga, M.; Berthet, G.; Jégou, F.; Kloss, C.; Bègue, N.; Vernier, J.-P.; Renard, J.-B.; Bossolasco, A.; Clarisse, L.; Taha, G.; Portafaix, T.; Deshler, T.; Wienhold, F.G.; Godin-Beekmann, S.; Payen, G.; Metzger, J.-M.; Duflot, V.; Marquestaut, N. Variability of the Aerosol Content in the Tropical Lower Stratosphere from 2013 to 2019: Evidence of Volcanic Eruption Impacts. *Atmosphere* **2022**, *13*, 250. https://www.mdpi.com/2073-4433/13/2/250
Mahnke, C., Weigel, R., Cairo, F., Vernier, J.-P., Afchine, A., Krämer, M., Mitev, V., Matthey, R., Viciani, S., D'Amato, F., Ploeger, F., Deshler, T., & Borrmann, S. (2021). The Asian tropopause aerosol layer within the 2017 monsoon anticyclone: Microphysical properties derived from aircraft-borne in situ measurements. *Atmospheric Chemistry and Physics*, *21*(19), 15259–15282. https://doi.org/10.5194/acp-21-15259-2021
Vernier, J.-P., Fairlie, T. D., Deshler, T., Venkat Ratnam, M., Gadhavi, H., Kumar, B. S., … Renard, J.-B. (2017). BATAL: The Balloon Measurement Campaigns of the Asian Tropopause Aerosol Layer. *Bulletin of the American Meteorological Society*, *99*(5), 955–973. https://doi.org/10.1175/BAMS-D-17-0014.1
Vernier, J.-P., T. D. Fairlie, T. Deshler, M. Natarajan, T. Knepp, K. Foster, F. G. Wienhold, K. M. Bedka, L. Thomason, *and* C. Trepte *(*2016*)*, In situ and space-based observations of the Kelud volcanic plume: The persistence of ash in the lower stratosphere, *J. Geophys. Res. Atmos.*, *121*, 11,104–11,118, *doi:10.1002/2016JD025344*.
Bourassa, A. E., A. Robock, W. J. Randel, T. Deshler, L. A. Rieger, N. D. Lloyd, E. J. Llewellyn, and D. A. Degenstein (2013) Response to Comments on "Large Volcanic Aerosol Load in the Stratosphere Linked to Asian Monsoon Transport", *Science*, 339, 647, 2013. *DOI: 10.1126/science.1227961*
Bourassa, A. E., A. Robock, W. J. Randel, T. Deshler, L. A. Rieger, N. D. Lloyd, E. J. Llewellyn, and D. A. Degenstein (2012), Large volcanic aerosol load in the stratosphere linked to Asian monsoon transport, *Science*, 337, 78-81.
Vernier, J.-P., Pommereau, J.-P., Thomason, L. W., Pelon, J., Garnier, A., Deshler, T., Jumelet, J., and Nielsen, J. K.: Overshooting of clean tropospheric air in the tropical lower stratosphere as seen by the CALIPSO lidar, Atmos. Chem. Phys., 11, 9683-9696, doi:10.5194/acp-11-9683-2011, 2011.
Borrmann, S., Kunkel, D., Weigel, R., Minikin, A., Deshler, T., Wilson, J. C., Curtius, J., Volk, C. M., Homan, C. D., Ulanovsky, A., Ravegnani, F., Viciani, S., Shur, G. N., Belyaev, G. V., Law, K. S., and Cairo, F.: Aerosols in the tropical and subtropical UT/LS: in-situ measurements of submicron particle abundance and volatility, Atmos. Chem. Phys., 10, 5573-5592, doi:10.5194/acp-10-5573-2010, 2010.