WHERE IS THE TROPOPAUSE?

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ABSTRACT

Much of the earth science that is being proposed for the Stratospheric Observatory for Infrared Astronomy (SOFIA) Upper-Deck Research Facility (SURF) deals with issues related to the tropopause, which will be near SOFIA's flight level at mid-latitudes. Interpreting *in situ* or remote aerosol, hydrometeor, and trace gas measurements will require accurate knowledge of the tropopause location. Examples of such measurements are presented, and a brief discussion is given on the Microwave Temperature Profiler (MTP), which the earth science community has used in the past to determine the tropopause height.

WHY THE TROPOPAUSE HEIGHT MATTERS

To interpret *in situ* and remote aerosol, hydrometer and trace gas measurement when flying close to the tropopause (as SOFIA will be at when flying at mid-latitudes), it is essential that the tropopause height be accurately known. This is particularly important when flying near the sub-tropical jet, where stratosphere-troposphere exchange (STE) can occur (Pan et al., 2004). STE is a key factor in controlling the ozone budget in the upper troposphere and the water vapor variability in the lower stratosphere.

Aerosol Measurements

The importance of an accurate tropopause height for aerosol measurements is best illustrated by data obtained using the NOAA PALMS chemical ionization mass spectrometer during the NASA WB-57 Aerosol Mission (WAM). Particles containing mercury were present about half of the time when the WB-57 was flying above the tropopause (Murphy, Thompson, and Mahoney, 1998). **Figure 1** shows the vertical profile of the percentage of mercury ions as derived from ^{202}Hg, the most abundant isotope. This peak is nearly unique for mercury in the spectra of all observed aerosol particles. (Each point is an average of ~600 spectra.) The altitudes in **Figure 1** are referenced to the tropopause height measured by the Microwave Temperature Profiler (MTP). It is clear that there is a strong mercury gradient, which peaks ~600 meters above the tropopause. Without accurate knowledge of the tropopause height this gradient would not have been seen.

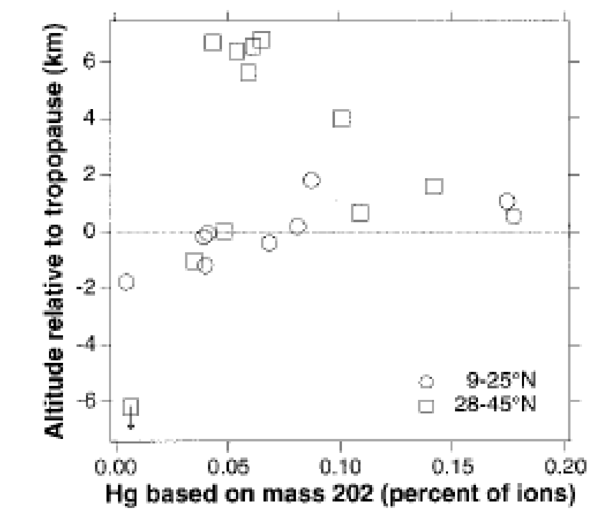

Figure 1. The mercury gradient in particles measured by the PALMS mass spectrometer relative to the MTP tropopause height (Murphy, Thompson and Mahoney, 1998).

A second aerosol (and trace gas) example concerns the impact of mid-latitude forest fire plumes that penetrate into the stratosphere, and deposit carbonaceous particles that can affect stratospheric chemistry and temperature (Jost et al., 2004). These measurements, also taken during CRYSTAL-FACE, required knowledge of the tropopause height in order to show that carbon monoxide, ozone, volatile organic compounds, and aerosols from a Canadian forest fire were present ~2 km above the tropopause in Florida, and that aircraft are not the only source of stratospheric soot.

Many other examples of the importance of an accurate tropopause height to the interpretation of aerosol measurements are available (e.g., Kojima et al., 2004, Irie et al., 2003, Popp et al., 2004, Pfister et al., 2000).

Trace Gas Measurements

As for aerosols, many examples are also available that illustrate the importance of knowing the tropopause location to interpret trace gas measurements (e.g., Pfister et al., 2003, Tuck et al., 2003, 2004, Ridley et al., 2003, 2004). A recent paper (Marcy et al., 2004) introduced a new technique for quantifying stratospheric ozone in the upper troposphere by taking advantage of the compact relationship between HCl and ozone in the stratosphere. Knowing the tropopause location was very important for interpreting these HCl, ozone and other *in situ* measurements, and making the case for the transport of stratospheric ozone into the upper troposphere.

Atmospheric Dynamics

When MTP data is used to trace isentrope surfaces -- the streamlines on which air parcel transport occurs -- atmospheric wave phenomena are easily detected. In the past MTP observations have identified Kelvin-Helmholtz waves near the sub-tropical jet (Cho et al., 1999), and many examples of gravity and mountain lee waves (Doernbrack et al., 2002; Alexander et al., 2004).

Figure 2 shows a color-coded temperature cross-section (CTC) for the last few hours of a SONEX flight returning to Shannon, Ireland. While the NASA DC-8 was flying at 39 kft with the tropopause 5,000 ft above (white trace), the tropopause abruptly jumped 6,000 ft as the aircraft came out of a cutoff low at ~1725 UT. For some time before and after this event, stratospheric tracer levels were being measured by *in situ* sensors, even though the tropopause was well above the aircraft. Indeed, the LaRC/DIAL lidar had begun to see a stratospheric intrusion of O_3 beginning at about 1710 UT and extending as low as 20,000 ft. Knowledge of the tropopause height in this example, helps considerably in interpreting the data.

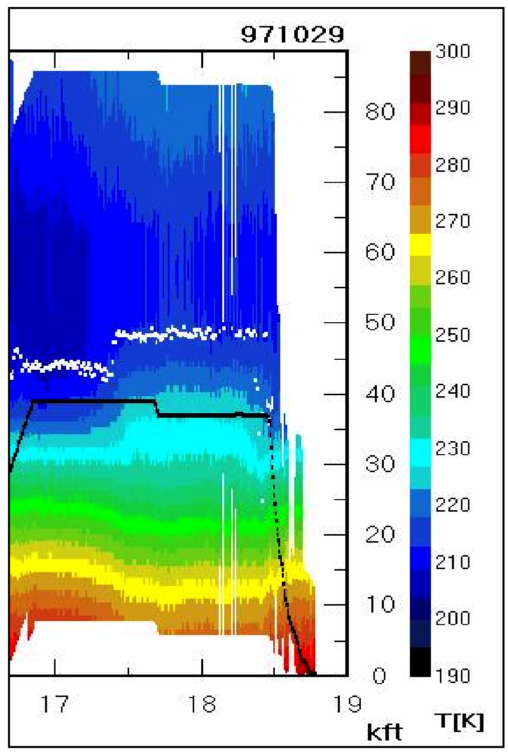

Figure 2 A CTC for the last portion of a DC8 SONEX flight on October 29, 1997.

Clear Air Turbulence

It is interesting that one of the first MTPs ever built flew more than two decades ago on the Kuiper Airborne Observatory (KAO), the predecessor to SOFIA. It's purpose then was to study clear air turbulence (CAT). MTP measurements showed that CAT is most common near the tropopause, and in the troposphere downwind of mountain ranges (Gary, 1984). This capability may be beneficial to SOFIA, and in any event, would be useful for accumulating clear air turbulence statistics.

How to Measure the Tropopause Height

For the benefit of those who are not familiar with the MTP (Denning et al., 1989), this section provides a brief description. The NASA DC-8 MTP is shown in **Figure 3**. The scan mechanism/mirror and a calibration target are located outside the aircraft behind a protective fairing that has a microwave-transparent window. The mirror scans from near-zenith to near-nadir in the flight direction making measurements at three frequencies between 55 and 59 GHz. All of the radio frequency and digital electronics are mounted on the back of the window blank, and the instrument is controlled by a flat-panel computer which can be mounted anywhere in the cabin -- even the back of window that the instrument is on.

Figure 3. The NASA DC-8 Microwave Temperature Profiler (MTP) is located on a window behind the Mission Manager's Console. A mirror behind a microwave-transparent window scans from near-zenith to near-nadir in the flight direction.

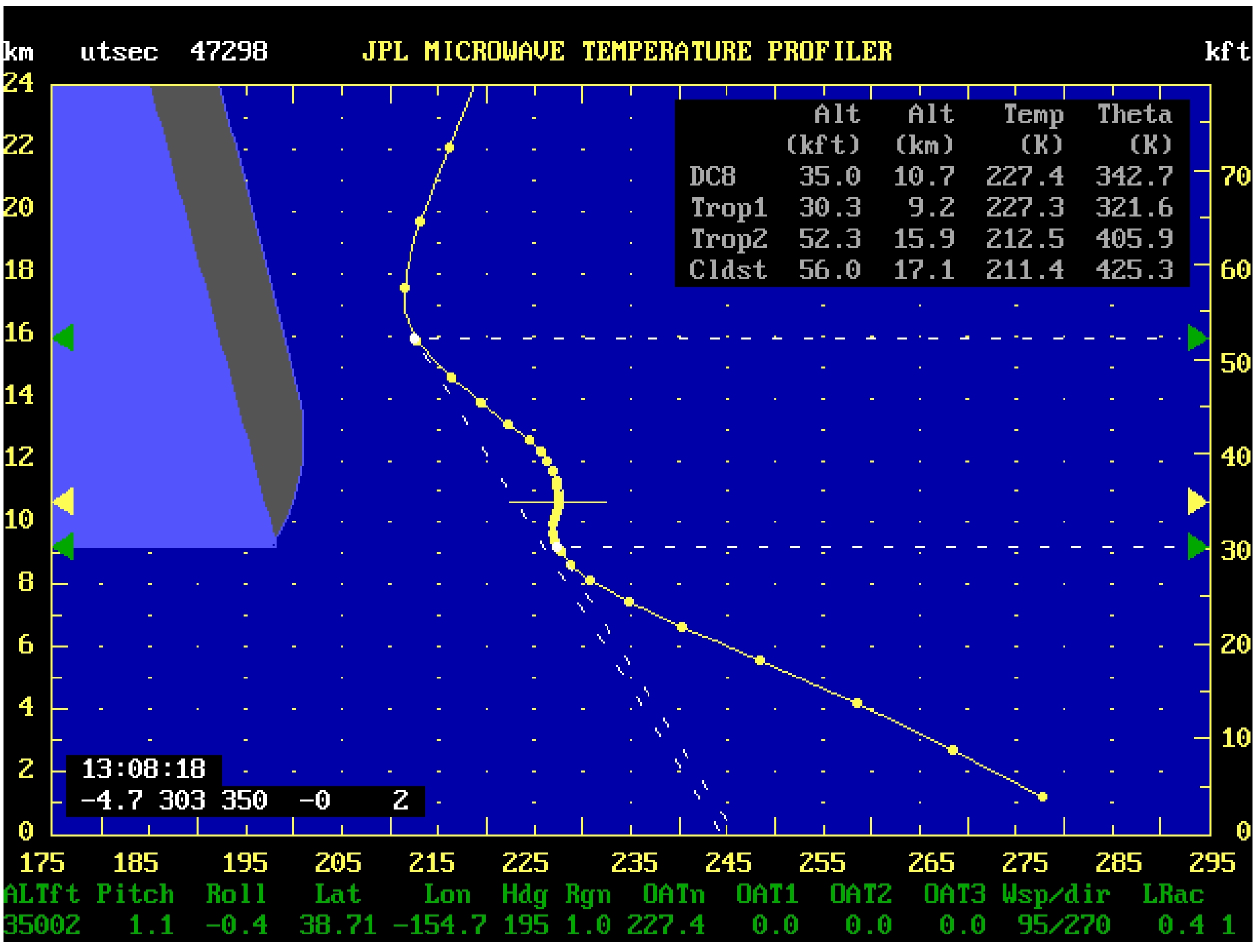

Figure 4. An example of the MTP real-time display of a temperature profile. This mid-latitude profile, which has two tropopauses locations (horizontal white dashed lines), is typical of what might be seen when flying out of Ames Research Center when the sub-tropical jet is nearby. The horizontal yellow line and pointers indicate the NASA DC-8 flight altitude when this profile was measured.

MTPs passively sense the natural thermal emission from oxygen molecules in the Earth's atmosphere, and use this information to retrieve a temperature profile, which can be displayed in real-time (see **Figure 4**). Based on past experience aboard many aircraft, the Microwave Temperature Profiler (MTP) has been an essential instrument for determining the tropopause height, and thereby providing meteorological context for *in situ* and remote aerosol, hydrometeor and trace gas measurements.

As on the NASA DC-8, the MTP can be mounted on a window blank, it can run unattended, and it makes measurements at microwave frequencies which are little affected by the presence of clouds. More importantly, MTPs have an enviable performance record on 686 flights (totaling 3863 flight hours) over two-decade's of airborne atmospheric research.

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REFERENCES

Alexander, M. J., S. Sherwood, M. J. Mahoney, and T.P. Bui, Gravity Waves in ER-2 Observations During CRYSTAL-FACE: Propagation Characteristics and Potential Role in Cirrus Cloud Formation, *AGU Chapman Conference on Gravity Wave Processes and Parameterization*, Waikoloa, Hawaii, USA, January 2004.

Cho, John Y. N., Reginald E. Newell, T. Paul Bui, Edward V. Browell, Marta A, Fenn, Michael J. Mahoney, Gerald L. Gregory, Glen W. Sachse, Stephanie A. Vay, Tom L. Kucsera, and Anne M. Thompson, Observations of convective and dynamical instabilities in tropopause folds and their contribution to stratosphere-troposphere exchange, *Geophysical Research Letters* , **104**, D17, 21,549-21,568, 1999.

Denning, R. F., S. L. Guidero, G. S. Parks and B. L. Gary, Instrument Description of the Airborne Microwave Temperature Profiler, *J. Geophys. Res.,* **94**, 16,757-16,765, 1989.

Dörnbrack, A., T. Birner, A Fix, H. Flentje, A. Meister, H. Schmid, E. Browell, M. J. Mahoney, Evidence for inertia-gravity waves forming polar stratospheric clouds over Scandinavia, *J. Geophys. Res.,* **107**(D20), 8287, doi:10.1029/2001JD000452, 2002.

Gary, B. L., Clear Air Turbulence Avoidance Using an Airborne Microwave Radiometer, AIAA Paper, *AIAA-84-0273,* 1984.

Irie, H., Y. Kondo, M. Koike, N. Takegawa, A. Tabazadeh, J. M. Reeves, G.W. Sachse, S. A. Vay, B. E. Anderson, and M. J. Mahoney, Liquid ternary aerosols of HNO3/H2SO4/H2O in the Arctic tropopause region, *Geophys. Res. Lett,* **31**, L01105, doi:10.1029/2003GL018678, 2004.

Jost, Hans-Jurg, Katja Drdla, Andreas Stohl, Leonhard Pfister, Max Loewenstein, Jimena Lopez, Paula Hudson, Daniel Murphy, Daniel Cziczo, Michael Fromm, T. Paul Bui, M.J. Mahoney, Erik C. Richard, Nicole Spichtinger, Jasna Vellovic Pittmanm, Elliot M. Weinstock, James C. Wilson, and Steven C. Wofsy, Observations of mid-latitude forest fire plumes in the stratosphere, *Geophys. Res. Lett.*, **31**, L05110, doi:10.1029 /2003GL018430, 2004.

Kojima, Tomoko, Peter R. Buseck, James C. Wilson, J. Michael Reeves, and Michael J. Mahoney, Aerosol particles from tropical convective systems: 1. Cloud tops and cirrus anvils, *Journal of Geophysical Research – Atmospheres,* accepted April 15, 2004.

Marcy, T. P., D.W. Fahey, R. S. Gao, P.J. Popp, E. C. Richard, T. L. Thompson, K. H. Rosenlof, E. A. Ray, R. J. Salawitch, B. A. Ridley, M. Lowenstein, J. C. Wilson, E. M. Weinstock, M. J. Mahoney, R. L. Herman, Quantifying Stratospheric Ozone in the Upper Troposphere Using in situ Measurements of HCl, *Science,* **304** 261-265, 2004.

Murphy, D. M., D. S. Thomson, and M. J. Mahoney, *In Situ Measurement of Organics, Meteoritic Material, Mercury, and Other Elements in Aerosols at 5 to 19 Kilometers*, *Science*, **282**, 1664-1669, 1998.

Pan, L. L., W. J. Randel, E. Browell, B. G. Gary, M. J. Mahoney, and E. J. Hintsa*, Definitions and Sharpness of the Extratropical Tropopause: A Trace Gas Perspective*, submitted to *GRL* April 2004.

Pfister, Leonhard, Henry B. Selkirk, Eric J. Jensen, Mark R. Schoeberl, Owen B. Toon, Edward V. Browell, William B. Grant, Bruce Gary, Michael J. Mahoney, Thaopaul V. Bui, Eric Hintsa, Aircraft Observations of Thin Cirrus Clouds near the Tropical Tropopause, *J. Geophys. Res.*, **106** (D9), 9765-9786, 2000.

Pfister, Leonhard, Henry B. Selkirk, Eric J. Jensen, James Podolske, Glen Sachse, Melody Avery, Mark R. Shoeberl, Michael J. Mahoney, and Erik Richard, Processes controlling water vapor in the winter Arctic tropopause region, *J. Geophys. Res.*, **107**, 8314, doi: 10.1029/2001JD001067, 2002. [printed **108**(D5), 2003].

Popp, P. J., R. S. Gao, T. P. Marcy, D. W. Fahey, P. K. Hudson, T. L. Thompson, B. Karcher, B. A. Ridley, A. J. Weinheimer, D. J. Knapp, D. D. Montzka, D. Baumgardner, T. J. Garrett, E. M. Weinstock, S. Dhaniyala, T. P. Bui, M. J. Mahoney, Nitric Acid Uptake, on Subtropical Cirrus Cloud Particles, *J. Geophys. Res.,* **109**, D06302, doi:10.1029/2003JD004255, 2003.

Ridley, B., E. Atlas, H. Selkirk, L. Pfister, D. Montzka, S. Donnelly, V. Stroud, E. Richard, K. Kelly, A. Tuck, T. Thompson, C. Brock, C. Wilson, D. Baumgardner, M. Mahoney, R. Herman, R. Freidl, J. Elkins, F. Moore, M. Ross, D. Anderson, Convective Transport of Reactive Constituents to the Tropical and Mid-Latitude Tropopause Region: I. Observations, Submitted to *Atmos. Environ*., Nov 2003.

Ridley, B., L.Ott, K. Pickering, L. Emmons, D.Montzka, A. Weinheimer, D. Knapp, F. Grahek, L. Li, G. Heymsfield, M. McGill, P. Kuecera, M. J. Mahoney, G. Brasseur, Florida Thunderstorms: A Faucet of Reactive Nitrogen to the Upper Troposphere, submitted to *J. Geophys. Res.*, February 2004.

Tuck, A. F., S. J. Hovde, K. K. Kelly, M. J. Mahoney, M. H. Proffitt, E. C. Richard, and T. L. Thompson, Exchange Between the Upper Tropical Tropopause and the Lower Stratosphere Studied with Aircraft Observations, *J. Geophys. Res*., **108**(D23), 4734,doi:10.1029/ 2003JD003399, 2003.

Tuck, Adrian, Susan Hovde, Kenneth Kelly, Stephen Reid, Erik Richard, Elliot Atlas, Stephen Donnelly, Verity Stroud, Daniel Cziczo, Daniel Murphy, David Thomson, James Elkins, Fred L. Moore, Eric Ray, Michael Mahoney, R. Friedl, Horizontal Variability 1-2 km Below the Tropical Tropopause, *J. Geophys. Res*., **109**, D05310,doi:10.1029/2003JD003942, 2004.

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