Investigating the Tropical Tropopause Layer and Lower Stratosphere with Lagrangian long-duration Balloon Borne Platforms During Stratéole 2

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Stratéole 2, a long duration scientific ballooning campaign to study the Tropical Tropopause Layer (TTL) and lower stratosphere, organized by CNES and LMD in France, is planned for 2017 – 2019. This campaign presents a rare opportunity for US scientists to make long duration physical and chemical measurements of the TTL from nearly Lagrangian balloon platforms. Measurements of water vapor, meteorological profiles, aerosol size distributions and ozone are both highly relevant and possible using instrumentation developed at several US institutions for long duration ballooning. This suite of instrumentation and the unique nature of the balloon platforms would advance scientific inquiries into the TTL concerning the role of gravity and equatorial wave dynamics, the flux of trace gases, clouds and aerosols, stratospheric hydration, and the validation of satellite retrievals and model simulations.

1. Introduction

The TTL is the layer between the rapid timescales of moist tropical convection below and multi-year timescales of the Brewer Dobson circulation above [Randel and Jensen, 2013]. Characterized by extremely cold temperatures, and frequent occurrence of thin subvisible cirrus, processes occurring in the TTL control the hydration of the stratosphere [Jensen et al., 2013]. Horizontal air motion in the TTL is relatively rapid, while vertically there is slow ascent by a zonal-mean seasonally varying flow, punctuated by waves with scales ranging from minutes to days, and from meso-scale to planetary scale. The TTL, the 'gateway to the stratosphere' [Fueglistaler et al., 2009], sets the chemical boundary conditions for the global stratosphere. Poorly understood decadal scale variations in stratospheric water vapor originate in the TTL, and have wide-ranging effects from decadal scale surface temperature variations [Solomon et al., 2012] to mid-latitude ozone loss [Dvortsov and Solomon 2001]. TTL temperature and composition also exhibit significant inter-annual variability related to the quasi-biennial oscillation (QBO) and El Niño Southern Oscillation (ENSO) [Liang et al., 2011; Davis et al., 2013]. Strong vertical gradients in ozone in the TTL and Lower Stratosphere (LS), coupled to slow chemistry time-scales, make ozone a unique dynamical tracer for waves, and for vertical and horizontal mixing processes[Thompson et al., 2011].

Dynamics in the tropical lower stratosphere also have global implications for stratospheric composition and chemical transport [Randel et al., 1998]. Despite being the dominant mode of inter-annual variability, the QBO remains absent or crudely represented in most coupled climate models [Butchart et al 2010]. Dissipation of tropical wave momentum fluxes drive the QBO [Lindzen and Holton, 1968; Holton and Lindzen, 1972], but difficulties remain in representing the spectrum of waves and their sources in global models [Kawatani et al., 2010; Evan et al., 2012]. Radiosondes indicate that in the TTL and lower stratosphere the spectrum of wave energy peaks at short vertical wavelengths near 2 km [Tsuda et al., 1994] which cannot be properly represented in reanalysis datasets [Kim and Alexander, 2013] or resolved in satellite observations [Alexander and Barnet, 2007; Wright et al., 2011] due to their relatively coarse vertical and horizontal resolution.

Given the critical importance of the TTL in the Earth system, there is a pressing need to fill the gaps in our observations and understanding of the dynamical, physical, chemical and radiative processes that regulate the TTL. Existing TTL measurements are not at sufficiently high temporal or spatial resolution to fill these observational gaps. There are few research aircraft capable of reaching the tropical stratosphere to make in situ measurements, and these aircraft give but brief glimpses of the TTL during each flight. Satellites have greatly increased our ability to observe the TTL globally, yet the coarse vertical resolution of satellite borne sounders (typically ~2 km) is insufficient to observe many of the critical processes described above. Furthermore, passive infrared sounders have difficulty observing a thin dry layer above the moist dense atmosphere below.

In situ measurements from long duration balloons can fill the observational gap between extensive low spatial resolution satellite measurements with global coverage, and high-resolution aircraft measurements with restricted coverage. Super-pressure long duration balloons provide a unique observational platform to carry high precision instrumentation for months at the upper limits of research aircraft altitudes and permit extremely long integration times for high precision measurements. The stability of the platform allows for measurements sensitive to extremely fine vertical scales and limits sampling artifacts for in situ and remote sensing measurements. By moving with the air along a quasi-Lagrangian trajectory, the platform provides unique observations of chemical and microphysical processes evolving over time in a given air mass. The platform can host a driftsonde system carrying ~50 dropsondes to make high-quality and high vertical resolution thermodynamic and kinematic measurement profiles from flight level to the surface, to connect the stratosphere with the troposphere [Cohn et al. 2013]. The relatively low per-unit cost of the super-pressure balloon system (as compared to research aircraft and satellites), allows for multiple balloons to be flown in parallel for wide geographical coverage, and in series for long duration temporal and spatial measurements.

2. The Stratéole 2 Tropical Long Duration Balloon Campaign

The Stratéole 2 super pressure balloon campaign is currently under development by Centre National d'Etudes Spatiales (CNES Balloon System PI – Philippe Cocquerez), Laboratoire de Météorologie Dynamique (LMD Science PI – Albert Hertzog) and several other partner organizations in Europe. US scientists have been involved in the planning and discussion phase of this project up to now. Stratéole 2 builds upon the highly successful joint European/US Concordiasi long duration super-pressure balloon campaign in the Antarctic in 2010, which demonstrated the scientific capabilities of the super pressure balloon system for stratospheric measurements, as seen in Figure 1 [Rabier et al., 2013]. Much as the

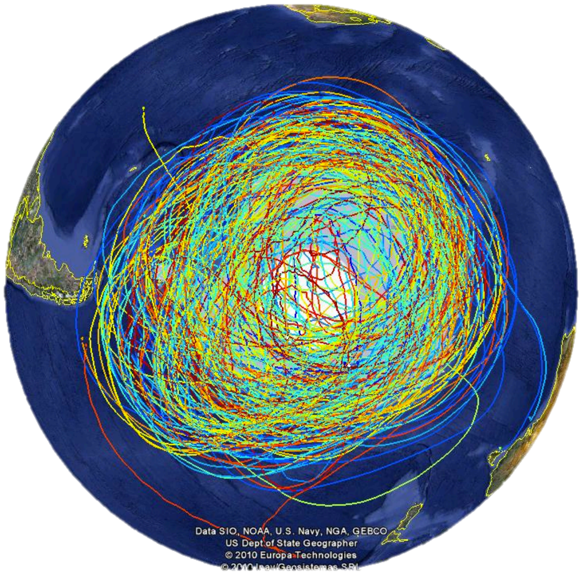

Figure 1: Trajectories of the 19 Concordiasi super pressure balloons from September 2010 to January 2011

Concordiasi campaign produced groundbreaking measurements in the Antarctic [e.g. Cohn et al., 2013; Wang et al., 2013; Ward et al., 2014], Stratéole 2 will produce the first measurements of this type at the Equator.

The Stratéole super pressure balloons have several characteristics that distinguish them from conventional means of observation, and information gathered during their flights are to a large extent complementary to both aircraft and satellite measurements:

- The Stratéole balloons will be designed for flight durations of several months, thus providing trajectories covering the entire tropical band, flying over any terrain and all kinds of weather, and sampling the entire diurnal cycle.
- GPS will provide precise positioning of the balloon at all times, and Iridium will allow transmission of large data sets between the instruments and ground stations in near real time. Measurements can be made at frequencies better than 1 sample/minute, which ensures excellent resolution of important dynamic processes. Figure 1 illustrates the sampling achieved during the Concordiasi experiment in 2010 with a fleet of 19 super pressure balloons launched from McMurdo Station, Antarctica, between early September and mid October.
- These balloons are excellent tracers of horizontal wind [Vial et al., 2001]. The virtually Lagrangian trajectories document changes in physical or chemical characteristics of the air mass *in relation to* dynamical processes and transport. By adjusting the size of the balloon and the weight of the payload, a number of flight levels are available (typically between 50 and 75 hPa or 17 – 19km). Two flight configurations are planned - Flights at the lower end of the altitude range, near the cold point, making in situ measurements of clouds and aerosols, water vapor, waves, temperature variability, and tracer transport in the TTL. Flights at the higher end of the altitude range, in the lower stratosphere, for measurements characterizing small to global scale waves, with remote observations of cirrus and wave vertical structure, and dropsondes to provide the vertical structure of the atmosphere between the platform and the surface.
- The balloon control system provides power, telemetry and temperature regulation in a standard format for the integration of an instrument suite. Dependent on power and weight requirements, each balloon is capable of carrying between one and four separate instruments.

The main Stratéole 2 field campaign is scheduled for 2018 and 2019, with approximately 20 balloons launched per year. A smaller test campaign will be conducted in 2017. The three years will allow sampling of both phases of the QBO. Due to the modular nature of the balloon payloads, sub-sets of balloons can be configured to address specific scientific questions and observational goals. The instrumentation for Stratéole 2 will be provided by partnering institutes, and at a minimum will include precise positioning, meteorological measurements, and, with instrumentation already committed from European research institutes, in situ measurements of water vapor and carbon dioxide, and remote observation of cirrus clouds with a micro-lidar. This scientific payload would be significantly broadened with the inclusion of instrumentation from US partners to include measurements of aerosol size distributions, GPS radio occultation, ozone concentrations, dropsonde meteorological profiles, and fiber optic temperature profiles (see section 4). The inclusion of these additional instruments would allow for targeted observations addressing specific science goals proposed by investigators at US institutions.

3. Scientific Objectives of US investigators:

The scientific goals of the Stratéole 2 campaign are to improve the observational basis for understanding the dynamics, chemistry, and physics of the TTL, and have been discussed at several science planning meetings in Europe and the US. Investigators from the US have identified a subset of this observational basis that could be addressed specifically through the addition of the instrumentation developed at their institutions.

3.1 Ozone and TTL transport

Ozone is an important component of the radiative and dynamic balance in the TTL, yet large uncertainties remain regarding the drivers of seasonal to inter-annual ozone variability. Long-term changes in TTL ozone concentrations contribute to stratospheric cooling, and have implications for radiative forcing estimates and for the interpretation of the tropospheric warming seen in broad-layer satellite measurements [Fu et al., 2004; Solomon et al., 2012].

The chemical composition and moisture content of air entering the stratosphere is largely determined by transport and dehydration processes in the TTL. Transport in the TTL spans tropospheric and stratospheric processes covering a range of spatial and temporal scales, from individual convective cells to planetary scale Rossby waves. The seasonal cycle of ozone in the TTL remains a topic of active investigation, with conflicting results. Both vertical upwelling and quasi-horizontal mixing of air are cited as important contributors to ozone concentration [Abalos et al., 2012; Ploeger et al., 2012; Abalos et al., 2013]. In both cases zonally asymmetric features such as the Asian monsoon, or localized upwelling regions (e.g., the Tropical Western Pacific), have significant effects on the ozone budget. Verification of TTL modeling results, especially of zonally asymmetric features, is difficult due to the the sparse nature of the ozonesonde network and the low vertical resolution of satellite measurements. Stratéole 2 ozone and water vapor measurements will help span the gap between ozonesonde and satellite measurements by providing extensive spatial sampling at high vertical resolution, although within a limited vertical layer [Kalnajs and Avallone, 2010; Haase et al., 2012]. The zonally resolved ozone measurements could help improve our understanding of the ozone seasonal cycle in the TTL as well as the effects of zonally asymmetric transport on the TTL distributions of other trace gases.

3.2 Clouds and aerosols in the TTL

Cirrus clouds are one avenue for water vapor transport in the TTL. In situ [Peter et al., 2003] and satellite observations [Dessler and Yang, 2003] reveal the presence of sub-visible cirrus near the tropical tropopause. The main regions for cloud formation and thus for setting the stratospheric water content are under study [Reverdy et al., 2012].

Observations of these clouds and their properties are important to understand the mechanisms regulating water vapor at the troposphere/stratosphere interface [Immler et al., 2007]. Geographic differences in large-scale transport and convective processes could result in rapid changes in the spatio-temporal distribution of optical thicknesses or ice content of tropical ice clouds. The impact of stratospheric chemical species on the formation of these clouds and therefore on tropospheric dehydration also remains to be determined [Chepfer et al., 2007]. The relationship between these clouds and dehydration processes are highly dependent on thermodynamic variables and atmospheric conditions which are not well constrained [Fueglistaler and Baker, 2006]. The impact of short timescale disturbances, caused by gravity waves on cirrus cloud formation and the subsequent drying, are still poorly understood. Remote and in situ observations of the tropical tropopause layer will improve this situation. The European micro-lidar measurements will document the extinction, ice content and vertical distribution and structure of clouds below the balloons. In situ observations of temperature [Hertzog et al., 2007], relative humidity, and particles [Ward et al., 2014] will address the impact of water vapor saturation on the formation of clouds, the relationship between particle size distribution and cloud nucleation and vertical extent, and the importance of gravity waves on cloud formation and dehydration. The measurements from Stratéole 2 may for the first time track the time history of transport, temperature, and composition of air parcels through the dehydration process across the TTL.

Tropical deep convection and associated tropopause Penetrating Convective Clouds (PCCs) transport moisture from the lower troposphere to the TTL and above. However, it is still not clear whether the net global effect of PCCs moisten or dry the region [e.g., Rossow and Pearl, 2007], which is partially attributed to lack of observations of anvil ice particles. Various operational satellite imagers and data from both passive and active sensors with the help of Strateole 2 in-situ temperature, particle measurements and dropsonde profiles will be used to identify PCC events, and dropsondes will be released both inside and outside PCCs. The size distribution of the ice within PCCs or within air detrained from PCCs has not been measured and would be of great interest. In-situ and dropsonde measurements over several months would permit the sampling of sufficient PCC events to constrain processes controlling water vapor in the TTL and lower stratosphere.

3.3 Dynamics of the TTL

While large-scale upwelling in the TTL above 15km is the primary mechanism for the transport of air across the tropopause, it is extremely difficult to directly measure this upwelling due to the low vertical velocities involved [Randel and Jensen, 2013]. The strong gradient in ozone and water vapor in the TTL coupled with measurements of these tracers from the isopycnal balloon trajectories can be used to infer small vertical velocities over long integration times. Wave dissipation drives the tropical upwelling, and an important component of upwelling within the TTL is tropical wave-driven [Ortland and Alexander, 2014]. The balloon measurements will clarify the types of waves responsible and provide benchmarks for validating tropical waves in reanalysis products [Vial et al., 2001].

The QBO is the dominant mode of variability in the circulation of the tropical lower stratosphere, yet most global models do not generate a QBO because they lack the broad spectrum of small-scale gravity waves that drive the QBO. Models that do generate a QBO rely on parameterizations for these small-scale waves [Lott et al 2012], but we lack observations to constrain the parameters that are chosen. This is arguably the most important and most uncertain of the model parameterizations. The Stratéole 2 Lagrangian platform with the addition of vertical structure measurements from dropsondes and from a fiber-optic temperature profiler would permit direct calculation of the gravity wave phase speed spectrum globally for the first time [Jewtoukoff et al 2013]. The fiber-optic temperature profiler will provide continuous in situ measurements of the temperature profile and thus the wave structure up to 4 km below the gondola.

3.4 Modeling and satellite validation

Stratéole 2, and in particular the dropsonde system, will provide a unique data set to validate satellite retrievals and meteorological reanalysis products. In the tropics, in-situ data are scarce because of large areas of ocean. Thus, satellite data and reanalysis products play an important role in weather and climate studies even though the scarcity of in-situ data leaves the satellite data in the tropics, on which the reanalysis products heavily rely, not well calibrated and validated. Wang et al. [2010, 2013] used the NCAR dropsonde system date from the T-PARC and Concordiasi field campaigns to validate satellite and reanalysis products, showing the value of the driftsonde data. The Strateole 2 dropsonde, flight-level, and temperature profiler data would provide an unprecedented and large number of tropical observations from 50 hPa to the surface, and will be used to validate both the satellite and reanalysis products. The dropsonde wind profiles may also be used to validate future US wind lidar satellite missions.

In addition to the validation of remote sensing products, the unprecedented temporal and spatial resolution of the Stratéole 2 data set will provide an entirely new avenue for validating the microphysical schemes used to simulate TTL aerosol particles in computer models. Vertical transport of aerosol precursors associated with convection leads to significant new particle formation in the tropical tropopause regions. These particles subside and provide an important source of cloud condensation nuclei in the tropical lower troposphere that impact clouds, precipitation, and climate. In addition, some of these TTL secondary particles may get transported into the stratosphere and contribute to the overall budget of stratospheric aerosols. There are large uncertainties in the formation mechanisms and size distributions of TTL particles. Different nucleation schemes predict quite different concentrations and sizes of TTL particles [Yu et al., 2010]. The fate of TTL particles, their interactions with sub-visible cirrus, and their dependence, as well as impact, on tropical convection are poorly understood and represented in global climate models. Measurements of aerosol size distributions along with other key parameters from Stratéole 2 would provide a test bed for various recent climate models (including NCAR Community Atmosphere Model) that consider increasingly detailed aerosol processes, not only in the troposphere [e.g., Yu et al., 2013] but also in the stratosphere [e.g. Campbell et al., 2014]. The long-duration high frequency quasi-Lagrangian aerosol measurements will provide an unprecedented opportunity to develop new insights, and to improve the representation of TTL/LS aerosols and their interactions with chemical, physical, and dynamical processes in global models.

4. Instrument contributions to Stratéole 2

CNES is currently designing and manufacturing the balloon gondolas for the Stratéole 2 campaign. At this stage of campaign planning the payload configuration is under discussion and CNES has welcomed instrument contributions from international collaborators. The balloon gondola provides a standardized interface for a modular instrument payload, which includes telemetry (via Iridium satellite modems), power, and limited temperature regulation as well as integrated in situ meteorological measurements. This modular approach allows for each balloon payload to be configured with a suite of instruments to address specific observational needs. Generally, between 2 and 4 instruments (limited by power and weight) are flown on each gondola, which over the course of the campaign would allow for up to a dozen different instrument types to be flown. While several European institutes are actively developing instruments for Stratéole 2, including several techniques for measuring water vapor, carbon dioxide, and cloud extinction with micro lidar, there is also opportunity for investigators from US institutions to utilize the balloon platform for observations. Examples of instrumentation that is currently in development, or has previously flown during the Concordiasi campaign and would be valuable to Stratéole 2 are shown in Table 1. Due to the unique engineering requirements for long-term autonomous measurements in the stratosphere, each of these instruments has to be specifically designed for this application, and has been chosen to address a specific science goal. The majority of the instrumentation described here has sufficiently low power and weight demands to allow for at least two instruments per flight. In combination with the instrumentation provided by the European partners, this will allow for many flight configurations to address a wide variety of scientific goals.

Instrument	**Measured quantities**	**Technique**	**Science Goals**	**PI/Institution**
ROC – GPS Radio Occultation	Water Vapor, Temperature, Space Weather	Radio occultation limb sounding from GPS signals	3.1, 3.3, 3.4	Jennifer Haase, Scripps.
Aerosol Sizing Spectrometer	Ice and particles, 0.2-30 µm, N > 0.001 cm-3	Optical particle detection	3.2, 3.3	Terry Deshler, U. Wyoming
Ozone	Ozone Mixing ratio	UV absorption	3.1, 3.3	Lars Kalnajs, U. Colorado
Driftsonde system	Pressure, temperature, humidity, wind speed and direction profiles	Dropsondes	3.1, 3.2 3.3, 3.4	Steve Cohn and June Wang, NCAR
Fiber Optic Temperature Profiler	Continuous temperature profiling 2 – 4km below balloon.	Raman scattering along suspended fiber.	3.1, 3.3, 3.4	Lars Kalnajs, U. Colorado

Table 1: Instruments in development by US investigators for Stratéole 2

5. Conclusion

The Stratéole 2 project will provide a unique international opportunity to study one of the most influential regions of our atmosphere. While the campaign is not contingent on US involvement to proceed, such a contribution would significantly increase the breadth of the scientific enterprise and be mutually beneficial to both US and European investigators. By inviting US participation, the European Stratéole 2 team has presented us with the opportunity to perform first of its kind science for a relatively small investment. There is a resounding interest in Stratéole 2 amongst US atmospheric scientists spanning a broad range of sub-specialties both to contribute instruments to the project and to analyze the anticipated data.

6. References

Abalos, M., W. Randel, D. Kinnison, and E. Serrano (2013), Quantifying tracer transport in the tropical lower stratosphere using WACCM, Atmospheric Chemistry and Physics Discussions, 13(5), 13245-13283.

Abalos, M., W. Randel, and E. Serrano (2012), Variability in upwelling across the tropical tropopause and correlations with tracers in the lower stratosphere, Atmospheric Chemistry and Physics, 12(23), 11505-11517.

Alexander, M. J. and C. Barnet (2007), Using satellite observations to constrain parameterizations of gravity wave effects for global models, J. Atmos. Sci., 64(5), 1652-1665.

Butchart, N., et al (2010), Chemistry-climate model simulations of twenty-first century stratospheric climate and circulation changes, Journal of Climate, 23, 5349-5374.

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.

Chepfer, H., P. Minnis, P. Dubuisson, M. Chiriaco, S. Sun-Mack, and E. Riviere (2007), Nitric acid particles in cold thick ice clouds observed at global scale: Link with lightning, temperature, and upper tropospheric water vapor, Journal of Geophysical Research: Atmospheres (1984–2012), 112(D5).

Cohn, S. A., T. Hock, P. Cocquerez, J. Wang and others, 2013: Driftsondes: Providing In-Situ Long-Duration Dropsonde Observations Over Remote Regions. Bull. Amer. Meteor. Soc., 10.1175/BAMS-D-12-00075.1.

Davis, S. M., C. K. Liang, and K. H. Rosenlof (2013), Interannual variability of tropical tropopause layer clouds, Geophys. Res. Lett., 40, 2862–2866.

Dessler, A. and P. Yang (2003), The distribution of tropical thin cirrus clouds inferred from Terra MODIS data, J. Clim., 16(8), 1241-1247.

Dvortsov, V. L., and S. Solomon (2001), Response of the stratospheric temperatures and ozone to past and future increases in stratospheric humidity, J. Geophys. Res., 106(D7), 7505–7514.

Evan, S., M. J. Alexander, and J. Dudhia (2012), Model study of intermediate-scale tropical inertia-gravity waves and comparison to TWP-ICE campaign observations, J. Atmos. Sci., 69(2), 591-610.

Fu, Q., C. M. Johanson, S. G. Warren, and D. J. Seidel (2004), Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends, Nature, 429(6987), 55-58.

Fueglistaler, S. and M. Baker (2006), A modelling study of the impact of cirrus clouds on the moisture budget of the upper troposphere, Atmospheric Chemistry and Physics, 6(5), 1425-1434.

Fueglistaler, S., A. Dessler, T. Dunkerton, I. Folkins, Q. Fu, and P. W. Mote (2009), Tropical tropopause layer, Rev. Geophys., 47(1).

Haase, J., J. Maldonado-Vargas, F. Rabier, P. Cocquerez, M. Minois, V. Guidard, P. Wyss, and A. Johnson (2012), A proof-of-concept balloon-borne Global Positioning System radio occultation profiling instrument for polar studies, Geophys. Res. Lett., 39(2).

Hertzog, A., P. Cocquerez, R. Guilbon, J. Valdivia, S. Venel, C. Basdevant, G. Boccara, J. Bordereau, B. Brioit, and F. Vial (2007), Stratéole/vorcore-long-duration, superpressure balloons to study the Antarctic lower stratosphere during the 2005 winter, J. Atmos. Ocean. Technol., 24(12), 2048-2061.

Holton, J. R. and R. S. Lindzen (1972), An updated theory for the quasi-biennial cycle of the tropical stratosphere, J. Atmos. Sci., 29(6), 1076-1080.

Immler, F., K. Krüger, S. Tegtmeier, M. Fujiwara, P. Fortuin, G. Verver, and O. Schrems (2007), Cirrus clouds, humidity, and dehydration in the tropical tropopause layer observed at Paramaribo, Suriname (5.8 N, 55.2 W), Journal of Geophysical Research: Atmospheres (1984–2012), 112(D3).

Jensen, E. J., G. Diskin, R. P. Lawson, S. Lance, T. P. Bui, D. Hlavka, M. McGill, L. Pfister, O. B. Toon, and R. Gao (2013), Ice nucleation and dehydration in the Tropical Tropopause Layer, Proceedings of the National Academy of Sciences, 110(6), 2041-2046.

Jewtoukoff, V., R. Plougonven, and A. Hertzog (2013), Gravity waves generated by deep tropical convection: Estimates from balloon observations and mesoscale simulations, J. Geophys. Res. Atmos., 118, 9690–9707

Kalnajs, L. E. and L. M. Avallone (2010), A Novel Lightweight Low-Power Dual-Beam Ozone Photometer Utilizing Solid-State Optoelectronics, J. Atmos. Ocean. Technol., 27(5), 869-880.

Kawatani, Y., S. Watanabe, K. Sato, T. J. Dunkerton, S. Miyahara, and M. Takahashi (2010), The roles of equatorial trapped waves and internal inertia-gravity waves in driving the quasi-biennial oscillation. Part I: zonal mean wave forcing, J. Atmos. Sci., 67(4), 963-980.

Kim, J. and M. Joan Alexander (2013), A new wave scheme for trajectory simulations of stratospheric water vapor, Geophys. Res. Lett., 40(19), 5286-5290.

Liang, C., A. Eldering, A. Gettelman, B. Tian, S. Wong, E. Fetzer, and K. Liou (2011), Record of tropical interannual variability of temperature and water vapor from a combined AIRS-MLS data set, Journal of Geophysical Research: Atmospheres (1984–2012), 116(D6).

Lindzen, R. S. and J. R. Holton (1968), A theory of the quasi-biennial oscillation, J. Atmos. Sci., 25(6), 1095-1107.

Lott, F., L. Guez and P. Maury (2012), A stochastic parameterization of non-orographic gravity waves: Formalism and impact on the equatorial stratosphere, Geophysical Res. Lett., 39, L06807

Ortland, D.A., and M.J. Alexander (2014), The residual-mean circulation in the tropical tropopause layer driven by tropical waves, J. Atmos. Sci., 71, DOI:10.1175/JAS-D-13-0100.1.

Peter, T., B. Luo, M. Wirth, C. Kiemle, H. Flentje, V. A. Yushkov, V. Khattatov, V. Rudakov, A. Thomas, and S. Borrmann (2003), Ultrathin tropical tropopause clouds (UTTCs): I. Cloud morphology and occurrence, Atmospheric Chemistry and Physics, 3(4), 1083-1091.

Ploeger, F., P. Konopka, R. Müller, S. Fueglistaler, T. Schmidt, J. Manners, J. Grooß, G. Günther, P. Forster, and M. Riese (2012), Horizontal transport affecting trace gas seasonality in the Tropical Tropopause Layer (TTL), Journal of Geophysical Research: Atmospheres (1984–2012), 117(D9).

Rabier, F., S. Cohn, P. Cocquerez, A. Hertzog, L. Avallone, T. Deshler, J. Haase, T. Hock, A. Doerenbecher, and J. Wang (2013), The Concordiasi Field Experiment over Antarctica: First Results from Innovative Atmospheric Measurements, Bull. Am. Meteorol. Soc., 94(3), ES17-ES20.

Randel, W. J. and E. J. Jensen (2013), Physical processes in the tropical tropopause layer and their roles in a changing climate, Nature Geoscience, 6(3), 169-176.

Randel, W. J., F. Wu, J. M. Russell III, A. Roche, and J. W. Waters (1998), Seasonal cycles and QBO variations in stratospheric CH4 and H2O observed in UARS HALOE data, J. Atmos. Sci., 55(2), 163-185.

Reverdy, M., V. Noel, H. Chepfer, and B. Legras (2012), On the origin of subvisible cirrus clouds in the tropical upper troposphere, Atmospheric Chemistry and Physics, 12(24), 12081-12101.

Rossow, W. B., and C. Pearl (2007), 22-Year survey of tropical convection penetrating into the lower stratosphere, Geophys. Res. Lett., 34, L04803, doi:10.1029/2006GL028635.

Solomon, S., P. J. Young, and B. Hassler (2012), Uncertainties in the evolution of stratospheric ozone and implications for recent temperature changes in the tropical lower stratosphere, Geophys. Res. Lett., 39(17).

Thompson, A. M., A. L. Allen, S. Lee, S. K. Miller, and J. C. Witte (2011), Gravity and Rossby wave signatures in the tropical troposphere and lower stratosphere based on Southern Hemisphere Additional Ozonesondes (SHADOZ), 1998–2007, Journal of Geophysical Research: Atmospheres (1984–2012), 116(D5).

Tsuda, T., Y. Murayama, H. Wiryosumarto, S. W. B. Harijono, and S. Kato (1994), Radiosonde observations of equatorial atmosphere dynamics over Indonesia: 1. Equatorial waves and diurnal tides, Journal of Geophysical Research: Atmospheres (1984–2012), 99(D5), 10491-10505.

Vial, F., A. Hertzog, C. Mechoso, C. Basdevant, P. Cocquerez, V. Dubourg, and F. Nouel (2001), A study of the dynamics of the equatorial lower stratosphere by use of ultra-long-duration balloons: 1. Planetary scales, Journal of Geophysical Research: Atmospheres (1984–2012), 106(D19), 22725-22743.

Wang, J., J. Bian, W. O. Brown, H. Cole, V. Grubišic, and K. Young (2009), Vertical air motion from T-REX radiosonde and dropsonde data, J. Atmos. Ocean. Technol., 26(5), 928-942.

Wang, J., T. Hock, S. A. Cohn, C. Martin, N. Potts, T. Reale, B. Sun and F. Tilley, 2013: Unprecedented upper air dropsonde observations over Antarctica from the 2010 Concordiasi Experiment: Validation of satellite-retrieved temperature profiles. Geophys. Res. Lett.,

Wang, J., L. Zhang, P.-H. Lin, Mark Bradford, Harold Cole, Jack Fox, Terry Hock, Dean Lauritsen, Scot Loehrer, Charlie Martin, Joseph VanAndel, Chun-Hsiung Weng and Kathryn Young, 2010: Water vapor variability and comparisons in subtropical Pacific from T-PARC Driftsonde, COSMIC and reanalyses. J. Geophys. Res., 115, D21108, Ward, S. M., T. Deshler, and A. Hertzog (2014), Quasi-Lagrangian measurements of nitric acid trihydrate formation over Antarctica, J. Geophys. Res. Atmos., 119

Wright, C., M. Belmonte Rivas, and J. Gille (2011), Intercomparisons of HIRDLS, COSMIC and SABER for the detection of stratospheric gravity waves, Atmospheric Measurement Techniques Discussions, 4(1), 737-764.

Yu, F., G. Luo, T. S. Bates, B. Anderson, A. Clarke, V. Kapustin, R. M. Yantosca, Y. Wang, and S. Wu (2010), Spatial distributions of particle number concentrations in the global troposphere: Simulations, observations, and implications for nucleation mechanisms, Journal of Geophysical Research, 115(D17), D17205.

Yu, F., Luo, G., Liu, X., Easter, R. C., Ma, X., and Ghan, S. J.: (2012), Indirect radiative forcing by ion-mediated nucleation of aerosol, Atmos. Chem. Phys., 12, 11451-11463