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

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Stratéole-2 is a new initiative to study the Tropical Tropopause Layer (TTL) and lower stratosphere using long-duration balloon platforms drifting near and within the TTL. The balloons and scientific gondolas have been developed and organized by CNES and LMD in France. Three ballooning campaigns are planned between 2018 and 2024 and present unique opportunities to make physical and chemical measurements of the TTL from nearly Lagrangian platforms in the TTL. *In situ* measurements of temperature, water vapor and cirrus profiles across the TTL and aerosol size distributions, ozone, and three dimensional winds in the lower stratosphere, just above the TTL, are all highly relevant to advance scientific inquiries into the TTL concerning the role of gravity and equatorial wave dynamics, clouds and aerosols, stratospheric hydration, and the validation of satellite retrievals and model simulations.

1. Introduction

The TTL is the layer between the troposphere dominated by rapid timescales of moist tropical convection and efficient vertical mixing and the stratosphere dominated by the multi-year timescales of the Brewer Dobson circulation [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 vertical motion is slow but 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 polar ozone loss. 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].

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 limited 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 made 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 vertical resolution of satellite borne sounders (typically ~2 km) is insufficient to observe many of the critical processes described above. Furthermore, remote sensors 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 satellite measurements with limited resolution, and restricted high resolution aircraft measurements. Super-pressure long duration balloons provide a unique observational platform to carry high precision instrumentation for months at a time, at the upper limits of research aircraft altitudes. Super-pressure balloons 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* chemical and meteorological measurements, and for remote sensing of the air mass surrounding the balloon. 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 relatively low per-unit cost of the super-pressure balloon system (as compared to research aircraft and satellites), allows for multiple balloons to be flying simultaneously for long duration providing relatively extensive geographical coverage.

2. The Stratéole-2 Tropical Long Duration Balloon Campaign

The Stratéole-2 super pressure balloon campaign is supported by the Centre National d'Etudes Spatiales (CNES Balloon System PI – Philippe Cocquerez), Laboratoire de Météorologie Dynamique (LMD Science Pi – Albert Hertzog), several partner institutions in Europe and the US National Science Foundation. Instrumentation to fly in the campaign is under development at both European and US institutions. 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 Concordiasi campaign produced groundbreaking measurements in the Antarctic [Cohn et al., 2013; Wang et al., 2013; Ward et al., 2014; Haase et al., 2012; Zhang et al. 2016], Stratéole-2 will produce the first large scale measurements of this type at the Equator.

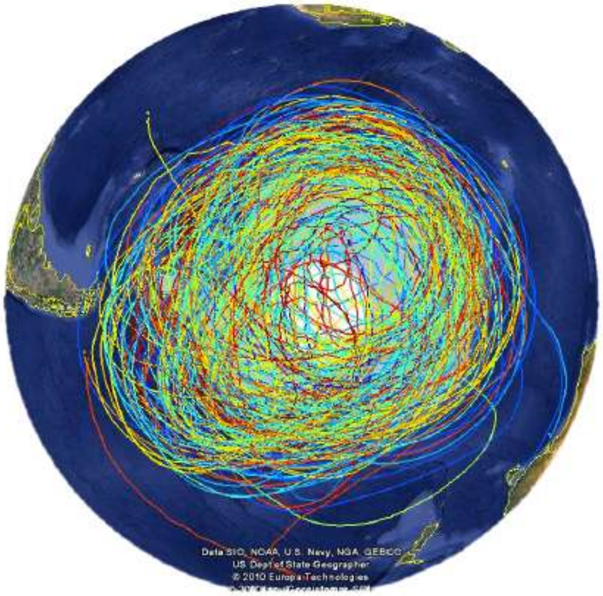

***Figure 1**. Trajectories of the 19 Concordiasi super pressure balloons from September 2010 to January 2011*

The Stratéole super pressure balloons have several characteristics that distinguish them from conventional means of observation, and information gathered during their flights are 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 higher than 1 sample/minute, which ensures excellent resolution of important dynamic processes. Figure 1 illustrates for instance 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, several flight levels are available (typically between 50 and 75 hPa or 17 – 19km). Two flight configurations are planned for Stratéole: 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.
- 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 first major Stratéole-2 field campaign is scheduled for 2020-2021, with approximately 20 balloons launched with a second major campaign in 2023 – 2024. A smaller test campaign will be conducted in late 2018. The two major campaigns are timed to 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 will be significantly broadened with the inclusion of instrumentation from US partners to include measurements of aerosol size distributions, GPS radio occultation temperature profiles, fiber optic temperature profiles and vertical profiles of water vapor, temperature, cloud and aerosol backscatter (see section 4). The inclusion of these US based instruments would allow for targeted observations addressing specific science goals proposed by investigators at US institutions.

3. Scientific Objectives:

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. Investigators from the US have identified a subset of this observational basis that could be addressed through the addition of specific instrumentation developed at US institutions.

3.1 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, a main region for cloud formation and thus for setting the stratospheric water content [Reverdy et al., 2012]. Observations of these clouds and their properties are important to understand the mechanisms regulating water vapor in the troposphere stratosphere interface [Immler et al., 2007]. Relative 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 on cirrus cloud formation, and subsequent drying, of short timescale disturbances caused by gravity waves 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 drifting at the upper level near 20 km. *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 a lack of observations of anvil ice particles. Various operational satellite images and data from both passive and active sensors, with the help of Strateole 2 in situ temperature and particle measurements and remotely sensed temperature profiles, will be used to identify PCC events. 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 measurements over several months would permit the sampling of sufficient PCC events to constrain processes controlling water vapor in the TTL and lower stratosphere.

3.2 Dynamics of the TTL

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 a fiber-optic temperature profiler, would permit direct calculation of the 2-D 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 up to 2 km below the gondola.

3.3 Modeling and satellite validation

Stratéole-2 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] demonstrates the use of *in situ* balloon data from the T-PARC and Concordiasi field campaigns to validate satellite and reanalysis products. Flight-level, remote, and fiber optic temperature profiler data would provide an unprecedented and large number of tropical observations, and will be used to validate both the satellite and reanalysis products. The balloon motion winds may also be used to validate future US and European 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 informing 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

LMD is currently designing and manufacturing the scientific balloon gondolas for the Stratéole-2 campaign, while CNES has designed the balloons and flight control systems. CNES and LMD have 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 an opportunity for investigators from US institutions to utilize the balloon platform for observations. All the instruments that are currently planned to be flown during Stratéole-2 are shown in Table 1 and the following sections describe the instruments that are currently being developed at US institutions. Due to the unique engineering requirements for long-term autonomous measurements in the stratosphere, each of these instruments has been 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 combinations of instruments to be flown to address broader science goals.

4.1 Fiber-optic Laser Operated Atmospheric Temperature Sensor (FLOATS)

The FLOATS instrument is under development at the University of Colorado and will provide high resolution profiles of atmospheric temperature using a 2km long optical fiber suspended below the balloon gondola. Using fiber optic Distributed Temperature Sensing (DTS), FLOATS can determine the temperature of the suspended fiber and thus the atmosphere with 0.5 K accuracy at 3m vertical resolution at a 1 minute intervals, spanning much of the TTL. These high-resolution temperature measurements will be the first of their kind and will dramatically increase our knowledge of the thermal structure of the TTL over what has currently been learned from in frequent radiosonde soundings and aircraft flights. The data from FLOATS will give the first direct measurements of the phase speed spectrum in the TTL and measurements of the cold point the effect of wave driven cold point depression, addressing science topics 3.1 and 3.2.

4.2 GPS Radio Occultation (ROC)

The ROC (Radio Occultation) instrument is under development by the Scripps Institution of Oceanography, UC San Diego. GPS Radio Occultation (RO) senses the atmosphere using radio signals that are Doppler shifted as they traverse the atmosphere when a transmitting GPS satellite sets behind the horizon relative to a moving receiver (Haase et al. 2012; Haase et al. 2014). The profile of refractive index of the neutral atmosphere retrieved from the observations depends on pressure, temperature, and humidity, but the sensitivity to humidity is very low near the UT/LS. Approximately 30-40 profiles per day are expected from flight level to as low as ~7 km altitude, with a vertical resolution of ~250 m. Because the sample points are as much as 450 km to the sides of the balloon trajectory, the continuous sequence of observation will essentially create triads that are closely spaced in time that can be used to derive 3-D propagation structures of atmospheric waves from the horizontal and vertical variations in temperature. Thus the observations will contribute to wave interactions that are important to science topics 3.1 and 3.2.

4.3 Reeldown Aerosol, Cloud Humidity and Temperature Sensor (RACHuTS) and LASP Particle Counter (LPC).

RACHuTS represents a combination of several proven instruments into a unique package capable of providing *in situ* profiles of temperature, water vapor, and cloud and aerosol backscatter across the TTL. While the fundamental instruments required for these measurements are available through collaborating scientific institutes or commercially, the integration and application of these instruments for deployment during the Stratéole 2 campaign will require a significant engineering effort at LASP, University of Colorado. The individual instruments for RACHuTS are a Lyman alpha hygrometer (FLASH-B), a backscattersonde (COBALD), and two temperature sensors. These will be deployed on a 2000 meter line below the balloon gondola. The instruments will be lowered and raised approximately five times per night. The reel down device will be developed in collaboration with FLOATS, but RACHuTS also requires a docking station to collect data, recharge batteries, and clear memories, an interface for remote control of each instrument, and a small gondola to carry the instruments. In addition an optical particle counter under development at LASP, the LPC, will be used at gondola level to make hourly measurements of the aerosol size distribution. The scientific challenges are to: 1) Complete water vapor, backscattersonde, and temperature profiles over a distance of 2 km across the TTL during the engineering and science campaigns. 2) Collect hourly measurements of aerosol size distribution at the top of the TTL. 3) Use the profiles of water vapor and cloud presence in the TTL to understand the transport of water into the lower stratosphere. 4) Use aerosol size distribution measurements at the top of the TTL to improve assessments of the flux of primary aerosol into the stratosphere. Insights gained into processes controlling transport of water vapor and particles across the TTL will have impacts on understanding the impact of these constituents on the chemistry of the stratosphere and ultimately on climate. There will be subsequent impacts on climate model predictions using an improved understanding of these important climate variables.

Table 1. Description of instruments to be deployed in Stratéole-2.

Instrument	Purpose	Institution	Measurement type	Altitudes	Raw measurement quantities	Geophysical quantities
GPS (Euros)	Wind (through position)	CNES	in-situ	flight level	every 30 s	3D positions horizontal winds time
TSEN	Air Pressure and Temperature	CNRS-LMD	in-situ	flight level	every 30 s every 1 s	temperature pressure
RACHuTS	Local Profiler Air Temp., Water Vap., Cloud Detection	LASP - NOAA (USA)	in-situ	flight level down to 2 km below	3/4 profiles per night	temperature H2O mixing ratio Cloud detection
FLOAT	Local Profiler Air Temperature	LASP (USA)	in-situ	flight level down to 2-3 km below	2 profile every 5-10 min	temperature
BOL-DAIR	Up-Welling Infrared Flux	CNRS-LATMOS	in-situ	flight level	every 1 min	total upwelling flux total long wave flux
SAWfPHY	Water Vapor (through dew-point)	CNRS-LMD	in-situ	flight level	every 10-15 min (only night)	H2O mixing ratio
pico-SDLA	Water Vapor and Carbon Dioxide (through light absorption)	CNRS-GSMA	in-situ	flight level		H2O mixing ratio CO2 mixing ratio
B-Bop	Ozone Photometer	CNRS-LMD	in-situ	flight level	every 10-15 min	O3 mixing ratio
LPC	LASP Particle Counter	LASP (USA)	in-situ	flight level	every 8 min	size resolved (8 bins) aerosol number concentration
LOAC	Optical Particle Counter	CNRS-LPC2E	in-situ	flight level		size resolved particle #
BeCOOL	Nadir Cloud détection trough Long Distance Lidar	LATMOS / CNR France / Italy	remote (nadir)	flight level down to ~5 km below	1 profile every 5-10 min	attenuated backscatter
ROC	Atmospheric Sounding through GPS Radio-Occultation High accuracy position through GPS	Scripps Institute (USA)	remote (limb)	flight level flight level down to z~4 km	tens of profiles per day	high-precision 3D positions temperature

5. Conclusion

The Stratéole-2 project will provide a unique international opportunity to study one of the most influential regions of our atmosphere. The US 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.

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