

# 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 set of long-duration scientific ballooning campaigns to study the Tropical Tropopause Layer (TTL) and lower stratosphere, organized by CNES and LMD in France, is planned for 2018-2024 and presents a unique opportunity for US scientists to make physical and chemical measurements of the TTL from nearly Lagrangian 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 long-duration balloon campaign 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 regions dominated by 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 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]. Strong vertical gradients in ozone in the TTL and lower stratosphere, coupled to slow chemistry time-scales there, 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 Barnett, 2007; Wright et al., 2011] due to their relatively coarse vertical and horizontal resolution.

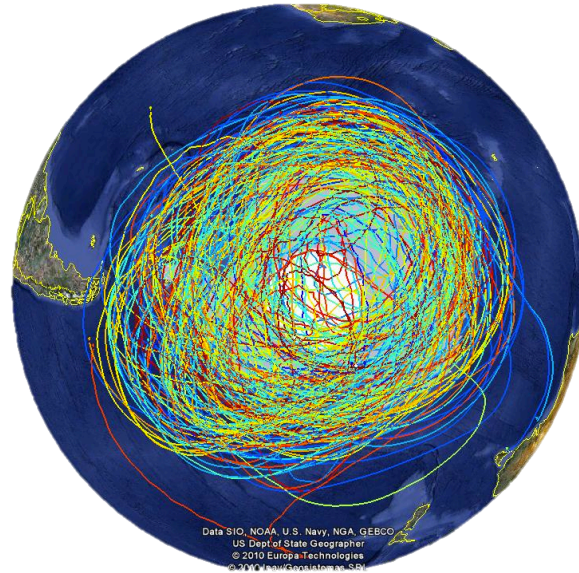
Given the critical importance of the TTL in the Earth system, there is a pressing need to fill the gaps in our observations and understanding of the dynamical, physical, chemical and radiative processes that regulate the TTL. Existing TTL measurements are not made at sufficiently high temporal or spatial 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 low spatial resolution satellite measurements, and restricted high resolution aircraft measurements. 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. 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 platform has the capability to 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], although such instruments are not currently planned within Stratéole-2. 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 and relatively extensive geographical coverage.

## **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 are involved in developing instrumentation to fly in the campaign as well. 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 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 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 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, 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.
- 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. A smaller test campaign will be conducted by late

2018. A second major campaign is planned for 2023-2024. The two campaigns will allow some 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 reel-down 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 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 interannual 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 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 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 limitations of the sparse horizontal measurement of ozone profiles and the low vertical resolution of satellite measurements. Stratéole-2 ozone and water vapor measurements will help span the gap between ozone profile and satellite measurements by providing high spatial sampling with high vertical resolution, although within a limited vertical layer. 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 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 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 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.

### **3.3 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 the tracers of 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 a fiber-optic temperature profiler, that 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.

### **3.4 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] used the NCAR dropsonde system data from the T-PARC and Concordiasi field campaigns to validate satellite and reanalysis products, showing the value of the dropsonde data. The Stratéole-2 balloons will not carry dropsondes this time, however flight-level, and 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**

CNES is currently designing and manufacturing the balloon gondolas for the Stratéole-2 campaign. 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 an opportunity for investigators from US institutions to utilize the balloon platform for observations. Examples of instrumentation that are currently in development, or have 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 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.

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
SAWPHY	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

Table 1 Description of instruments to be deployed in 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. 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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