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Stratéole-2 - Around the world in 84 days

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1 Introduction

Jules Verne's adventure novels *Five Weeks in a Balloon* and *Around the World in 80 Days* highlighted some of the great technological advances of the late 19th century that revolutionized travel and captured the imagination of the public (Verne 1863, 1873). Nellie Bly, American journalist for the New York World, was inspired to complete a journey following Verne's imagined path around the world in a record 72 days (Bly 1890). (See Figure 1.) These accounts demonstrated how new technology such as the trans-country railroads in the US and India, and the Suez Canal brought exotic destinations within reach. The revolutionary development of submarine cables and the electric telegraph allowed Nellie Bly to keep her editors and the connected world aware of her progress in near real time.

In that pioneering spirit and following in the footsteps of these fictional and factual adventurers, the France-US collaborative Stratéole-2 project will explore the equatorial tropopause region with technology that would make Jules Verne proud, and perhaps inspire new insights into this poorly sampled region of the atmosphere. Stratéole-2 will release super-pressure balloons, designed to drift in the lower stratosphere, from the Seychelles Islands in the Indian Ocean. (See Figure 2.) Each balloon (See Figure 3) will carry up to four instruments, measuring with high accuracy meteorological variables, chemical tracers and clouds/aerosols, and travel along a trajectory essentially as a parcel within the air mass (quasi-Lagrangian). These measurements will advance our knowledge and understanding of cirrus clouds, aerosols, and equatorial waves in the Tropical Tropopause Layer (TTL) and in the lower stratosphere.

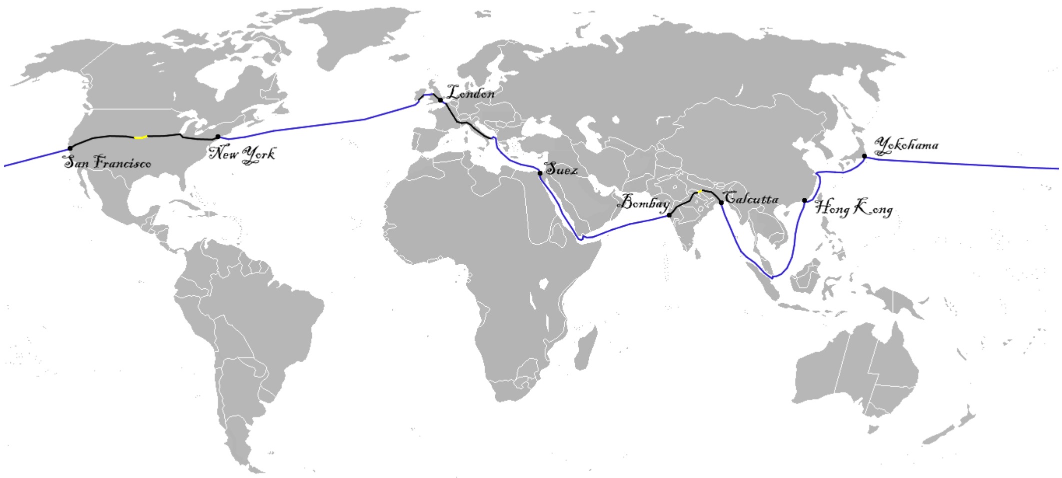

Figure 1. Jules Verne's imagined path "around the world in 80 days" that was (roughly) completed by real-life New York reporter Nellie Bly in 1890. Note: in the popular 1956 film Around the World in 80 days, Shirley MacLaine, David Niven, and Cantinflas travel by balloon on one leg of their circumnavigation of the globe. However,

the original 1873 Jules Verne novel did not actually involve any balloon travel. Nor did Nellie Bly travel by balloon when retracing the route in 1889-1890. However Jules Verne's story draws on many of the great story-telling elements of his 1863 novel Five Weeks in a Balloon, which inspired Hollywood to incorporate balloons into the film.

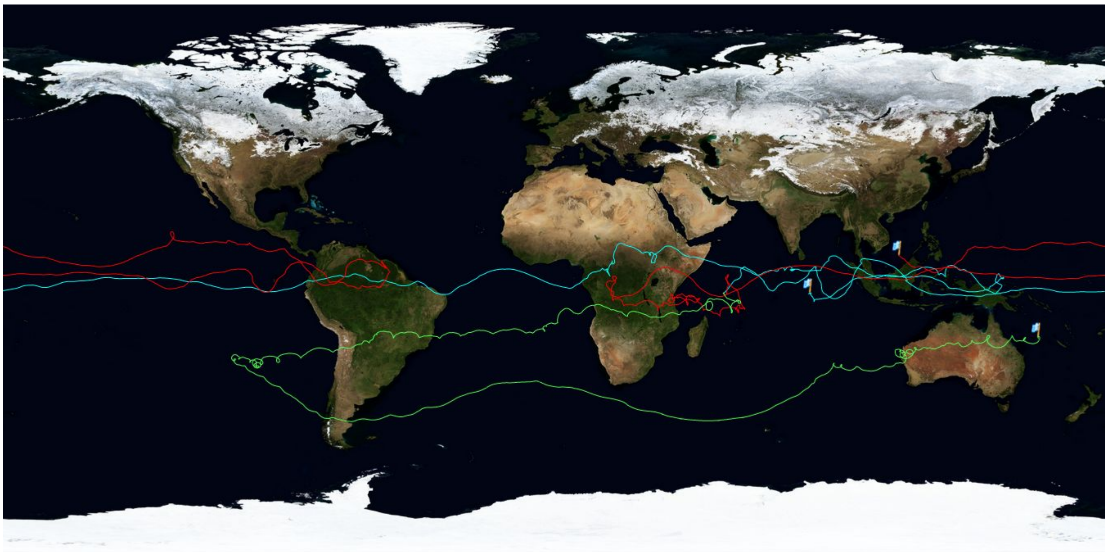

Figure 2 Early tropical test flights of the French Space Agency (CNES) super-pressure balloon system during February - May 2010. The flight durations of the three balloons were 92, 78, and (yes!) 80 days. Some wave structure is visible in the traces of the balloon paths, and the reversal of the balloon paths when the QBO changed phase is also visible (credit: A. Hertzog).

The Stratéole-2 research program will begin with a five-balloon technology validation campaign in boreal fall - winter 2018-2019, followed by 20 balloon flights in boreal fall - winter 2020-2021. In the second campaign, ten balloons will fly near 20-km altitude, just above the TTL, and another ten near 18-km altitude, within the TTL. The closed and rigid envelope of these balloons means they rise and expand to their full volume where the gas density matches the density of the surrounding air, and drift with the wind along constant density surfaces. Each balloon is expected, from past experience, to fly for more than two months. Typical durations are estimated at 84 days before chaotic motions, or interactions with Rossby waves, push the balloons outside of the deep tropics. A final 20-balloon campaign in 2023-2024 will drift in the opposite direction due to the shifting phase of the Quasi-Biennal Oscillation (QBO), a dominant periodic east-west oscillating feature in tropical lower stratospheric winds.

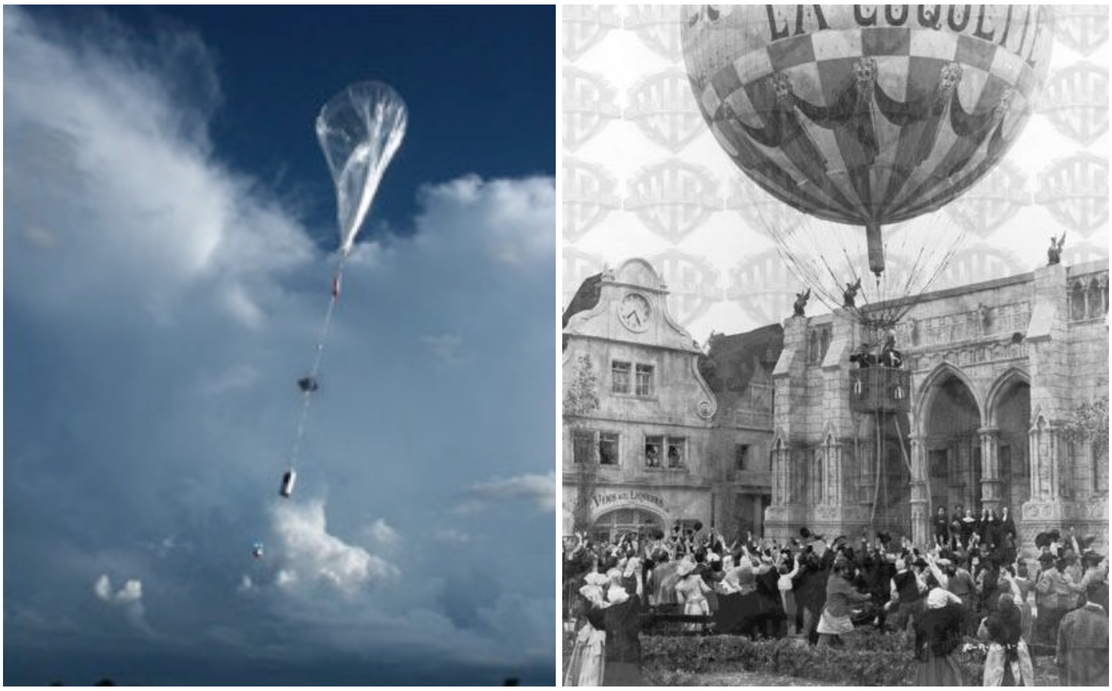

Figure 3. left) A superpressure balloon is sealed with a non-stretch envelope, and contains a fixed amount of helium to provide buoyancy. At launch, as shown here, it is not fully inflated, but as it rises the volume increases until the spherical balloon is fully inflated, giving the balloon a fixed density. Once the balloon has reached the atmospheric level where the air has the same density (95 and 125 g m^{-3} for the two sizes used), it drifts with the wind. Its horizontal motions are nearly identical to those of the surrounding air mass (parcel following or "quasi-Lagrangian"), providing a measurement of the wind with an accuracy of about 0.1 m/s. right) the typical hot air balloon is open to the atmosphere and provides buoyancy with an active heater, however as seen in this image from the 1956 movie with David Niven and Cantinflas aboard, the balloon La Coquette was always tethered to the ground, even in its original role as a training platform for the Navy in World War II.

2 Current challenges in the TTL and lower stratosphere

The Stratéole-2 campaign targets the TTL, where tropospheric air primarily enters the stratosphere and where the Cold Point Tropopause (CPT) acts as a cold trap dehydrating the air. This gives the TTL region an importance more than expected considering its geographic extent. Air slowly ascends across this layer, and the very cold temperatures encountered at the cold point regulate the humidity of the global stratosphere, resulting in the extremely low water vapor concentrations in the stratosphere. Dehydration in the TTL involves the formation of thin cirrus clouds that have a global impact on tropical radiative balance. Water vapor and cirrus feedbacks are of utmost importance in climate system models. Underlying processes controlling the formation and sublimation of these clouds remain strongly debated, involving the interplay of deep convection, microphysics, aerosols, wave-induced temperature variations with timescales ranging from minutes to weeks, and the balance of forces driving large-scale slow ascent. The superposition of wave-induced fluctuations on the mean upwelling forces the temperatures in the TTL to extreme CPT values, less than -94^{o}C at times, and well below those expected from radiative equilibrium. These same waves also drive the QBO, which plays an important role in teleconnections that affect high-latitude seasonal forecasts. The waves, generated by convection below, transport momentum vertically across the TTL and drive QBO wind variations as the momentum dissipates. While the wind reversals of the QBO are resolved in satellite and in situ observations, the QBO is not internally generated by most general circulation models due to a combination of inadequate spatial resolution and/or lack of small-scale wave drag applied at the sub-grid scale. Even when simulated, doubts remain on the contribution from different families of waves with different scales and frequencies. As a result, even models that internally generate a QBO were unable to forecast the anomalous disruption of the oscillation that occurred just last year (Osprey et al. 2016).

3 Stratéole-2 science objectives

The overarching objectives of Stratéole-2 are to explore dynamical and physical processes that control the transfer of trace gases and momentum between the equatorial Upper Troposphere and Lower Stratosphere (UTLS). The instruments will provide fine scale measurements of water vapor, temperature and aerosol/ice from the balloon gondola and also within a couple of kilometers below flight level, thus documenting air composition and investigating the formation of cirrus in the upper TTL. The balloons also provide unique measurements of equatorial waves over the full spectrum from high-frequency buoyancy waves to planetary-scale equatorial waves, providing information needed to improve their representation in climate models. Stratéole-2 balloons will sample the whole equatorial band from -20^{o}S to 15^{o}N, thus complementing in an original way the widespread (but limited resolution) spaceborne observations and the high-resolution (but geographically restricted) airborne and ground-based measurements from previous field missions. Past balloon campaign measurements sampling the Antarctic stratospheric vortex (see Hertzog et al. 2008) have been notably used to make accurate estimates of wave momentum fluxes as well as to diagnose springtime stratospheric ozone loss rates.

Other Stratéole-2 science objectives include contributions to operational meteorology and satellite validation. Wind analyses and forecasts have notably large errors in the tropics associated with the lack of balance between tropical winds and temperatures and sparse wind measurements. Stratéole-2 balloon flights will provide unprecedented, accurate wind observations in the equatorial UTLS, in particular over oceanic areas that are otherwise devoid of any wind measurements. These meteorological measurements will be disseminated in real time for operational use by all operational centers and for research aimed at reducing tropical analysis errors in future forecast systems. They will furthermore contribute to the validation of ADM-Aeolus wind products. ADM-Aeolus, due to be launched by late 2017, is an innovative ESA mission, designed to perform the first spaceborne wind lidar measurements providing unprecedented global coverage.

The ensemble of Stratéole-2 instrumentation now supported includes in situ measurements of pressure, temperature and winds every 30s, ozone, aerosols, water vapor and carbon dioxide, plus remotely sensed cloud structure from microlidar and directional radiative fluxes. Instruments providing profiles will include GPS radio-occultation temperatures, and novel reel-down devices suspended as much as two kilometers below the balloon that are designed to explore the fine-scale distribution of temperature, aerosol/ice and humidity. A complete list of instrumentation is given at the link http://www.lmd.polytechnique.fr/VORCORE/st2_instruments.htm. Capturing temperature variations in high-resolution profiles, in particular from the unique Lagrangian balloon platform, is an approach that will provide new insight into equatorial wave processes. The measurement of ozone in combination with water vapor and carbon dioxide enables tracer-tracer correlations that describe transport processes at the top of the TTL such as convective overshoots that rapidly transport air from the surface.

Broad science questions addressable from such instrumented quasi-Lagrangian balloon flights in the TTL were discussed in a community workshop partially supported by the US National Science Foundation on 18-19 March 2015 in Paris, France. The workshop drew 45 participants from 5 countries including the US, France, Italy, Germany, and Australia. It was aimed at maximizing the science return of Stratéole-2 by bringing together instrument developers and modelers.

4 Data Dissemination

The Stratéole-2 data policy is in compliance with the World Meteorological Organization (WMO) Resolution 40 (WMO Cg-XII) on the policy and practice for the exchange of meteorological and related data and products. Within 12-months of the end of each balloon campaign, the Stratéole-2 dataset will be freely available to the scientific community through the Stratéole-2 Data Archive Center (S2DAC). S2DAC will collect and make available the balloon observations and associated ground-based or satellite data, reanalyses, and model outputs. The S2DAC includes a primary, full repository at the Laboratory of Dynamical Meteorology (LMD), France, and a secondary mirror site at Laboratory for Atmospheric and Space Physics (LASP) in Boulder, CO, USA. In addition, during the balloon campaigns, a subset of the Stratéole-2 dataset, specifically flight level winds, will be disseminated on the Global Telecommunication System (GTS) for their assimilation in Numerical Weather Prediction systems. The use of Stratéole-2 data by the broader scientific community is strongly encouraged and potential users can watch for future campaign updates at URL: http://strateole2.org. Major funding for the Strateole-2 campaign is provided by the French Space Agency (CNES) and National Center for Scientific Research (CNRS), and the US National Science Foundation (NSF).

5 References

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