<u>Ba</u>lloonsonde <u>T</u>ropical Tropopause <u>Ex</u>periment (BATTREX) Science Plan

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Summary

The Pacific warm pool is the dominant region for entry of tropospheric air into the global stratosphere. Despite important theoretical advances in recent years and a growing abundance of satellite data, important science questions related to the control the humidity and chemical composition of air entering the stratosphere remain unanswered. These include the relative roles of large-scale ascent, waves and cloud microphysical processes. Answering these questions will continue to require high resolution *in situ* measurements, particularly in the vertical, as satellite observations of tracer and dynamical fields cannot yet resolve important structures at the tropical tropopause layer (TTL). At the same time, important phenomena are organized on the large-scale, placing a premium on coordinating ground-based and airborne measurements with satellite observations.

This document describes the Balloonsonde Tropical Tropopause Experiment (BATTREX), a proposed program of coordinated balloon soundings to provide high-resolution profile measurements in the context of the large-scale phenomena that modulate stratosphere-troposphere exchange and dehydration in the western Pacific warm pool. BATTREX will launch balloon sondes to measure water vapor, ozone and aerosol backscatter (referred to below simply as "balloon sondes") at several locations in the equatorial western Pacific warm pool, supplementing these with an augmentation of existing radiosonde observations in the region to yield high-resolution profiles of water vapor, ozone and very small ice particles together with temperature and winds from the lower troposphere to 30 km. These measurements will not only enable characterization of the vertical structure of the tropical tropopause layer (TTL) in this key region, but will also define coherent modes of spatial and temporal variability in the TTL driven by equatorial waves.

The BATTREX observations will take place during three campaigns of ~7 weeks duration during the winters of 2013 and 2014 and the summer of 2014. This timing will allow BATTREX to exploit synergies afforded by coordinating balloon sonde launches with airborne measurements in the NASA Airborne Tropical Tropopause Experiment (ATTREX). Approximately 25 balloon sondes will be launched at each BATTREX site in each campaign. Whenever possible, launches will be timed to coincide with overpasses of the NPOESS Preparatory Project (NPP) satellite with its CrIS/ATMS instrument as well as the A-Train satellites Aqua and Aura. Similarly, launches will be coordinated with ATTREX flights to provide match opportunities. Together these efforts will enable a

more complete characterization of the four-dimensional TTL variability than possible with stand-alone observations and will also enable cross-validation of balloon-borne, airborne and satellite-based tracer, dynamical and particle measurements.

To achieve the science goals of BATTREX, the balloon sonde payloads will consist of a frost point hygrometer[1] in tandem with an electrochemical concentration cell (ECC) ozonesonde. Second, the water vapor-ozone balloon launches will be augmented with high-frequency (four times daily or more) radiosondes in the warm pool region to facilitate diagnosis of waves in the upper troposphere and lower stratosphere in the deep tropics. The third component of the balloon sonde payloads will be a lightweight aerosol backscatter sonde such as COBALD[2], permitting the detection and characterization of ice particles in an environment that is often well above ice supersaturation.

In this document we discuss current collaborations and plans, among them existing tropical sounding projects from NOAA, NASA, and the Japanese Soundings of Ozone and Water in the Equatorial Region/Pacific Mission (SOWER/Pacific) project. We anticipate collaboration with ETH in Switzerland as well and with the Co-Ordinated Airborne Studies in the Tropics (CAST) mission, an airborne and ground-based mission that has been proposed to the UK National Environmental Research Council by researchers at the Universities of Cambridge and Manchester. Additional desired collaborations and plans are described to supplement existing efforts, and the required resources defined.

Section A below describes the motivation for BATTREX and its science goals and places these in context with the goals of the NASA ATTREX mission as well as those of CAST. Section B describes the methodology of BATTREX and its science goals. Section C describes the payload requirements for the balloon sondes to measure water vapor and ozone and the radiosondes for BATTREX, and Section D describes the augmentation of the balloon sonde payloads with the COBALD aerosol backscatter sonde. Section E discusses the observational approach and potential siting for both the balloon sondes and augmented radiosonde observations. Section F provides details plans for a nominal campaign and lists the personnel and resources required. The document concludes with a summary in Section G .

A. Background, Scientific Questions and Collaborative Opportunities for BATTREX

A.1 Background

The Tropical Tropopause Layer (TTL) plays important roles in the Earth's climate system, the stratospheric ozone budget and overall atmospheric composition (see *Fueglistaler et al.,* 2009 and references therein). Air in the TTL ascends slowly as part of the Brewer-Dobson circulation, which is driven largely by the upward propagation of mid-latitude wave energy and its deposition at higher altitudes. Within this environment

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[1] Either the Cryogenic Frostpoint Hygrometer [*Vömel et al.,*2007] or the NOAA Frostpoint Hygrometer [*Hurst et al.*, 2010].

[2] http://www.iac.ethz.ch/groups/peter/research/Balloon_soundings/COBALD_sensor

of large-scale ascent, vertical motions induced by equatorial waves as well as convective detrainment drive the formation of optically thin cirrus clouds. These cirrus clouds regulate the humidity of the TTL and consequently the dryness of the air entering the global stratosphere for which there are important radiative implications [*Solomon et al.,* 2010]. In addition, since the tropical tropopause is the predominant location where air enters the stratosphere, TTL composition becomes the chemical boundary condition for the stratosphere, and physical processes affecting the concentrations of gases that ultimately determine production and loss rates of stratospheric ozone. As the climate system continues to change in response to anthropogenic perturbation, the balance among TTL physical processes such as convection, large-scale uplift and microphysics is likely to change as well. Improved representation of TTL processes in models will allow us to better predict feedbacks associated with responses to TTL cloud radiative forcing and chemical composition.

In comparison to other climatically important parts of the atmosphere, the TTL is poorly observed due to its high altitude (>14 km), which prohibits sampling by most aircraft, and to the strong vertical gradients that limit the value of coarse-resolution satellite measurements. This makes it very difficult to assess the relative importance of the physical processes TTL such as deep convection, slow ascent and wave-driven cooling that control the dehydration of air as it is transported through the tropopause and into the stratosphere. The direct consequences of seasonal as well as interannual variations of tropical tropopause temperature include respectively the water vapor tape recorder of *Mote et al.* [1996] and the decrease of lower stratospheric middle latitude water vapor since 2001 [*Randel et al.,* 2006; *Hurst et al.,* 2011]. The record of balloon sonde *in situ* measurements of water vapor in the tropics is not long. Nevertheless, *Fujiwara et al* [2010] found that since 1993 frost point hygrometer measurements in the 68-37 hPa layer of the stratosphere followed the same pattern found by *Hurst et al* at Boulder – that is, an increasing trend in the 90s followed by a decrease after 2001 and then a resumption of an upward trend in 2006.

One continuing puzzle is the impact of supersaturation conditions at the tropopause. Balloon sonde measurements show that supersaturated conditions are frequently observed in the upper troposphere and TTL [*Vömel et al.,* 2002; *Selkirk et al* 2010], and airborne measurements show that significant supersaturation may occur in ice clouds near the tropical tropopause [*Peter et al.,* 2006]. Nevertheless, *Schiller et al.* [2009] have shown consistency between airborne water vapor measurements in the tropics with minimum mixing ratios obtained from back trajectories, while *Jensen and Pfister* [2004] have shown that inclusion of wave perturbations in Lagrangian cloud model calculations effectively decrease the effective cold-trap temperature (*Schiller et al.'s* 'set point').

The important effect of waves in the TTL and horizontal transport was underscored in *Schoeberl and Dessler* [2011] who used a relatively simple saturation adjustment scheme to calculate stratospheric water vapor fields in a Lagrangian 3-d model. Their results are remarkably close to Aura MLS water vapor fields. *Pfister et al* [2010] and *Selkirk et al* [2010] have shown a strong impact of coherent wave disturbances in the tropical UT/LS using high-frequency radiosonde observations from the Central American wet season. Excursions of 5 K or more in tropopause temperatures are not uncommon. These are often associated with strong anomalies in ozone, and *Thompson et al.* [2010] and *Thompson et al.* [2011] identified laminae of gravity wave origin in the UT/LS in up to 90% ozone soundings from the Southern Hemisphere Additional Ozone sondes (SHADOZ) network. Finally, the evanescence of waves in the tropical lower stratosphere acts to limit the maximum altitude at which temperature excursions lead to saturation and hence dehydration.

A.2 Scientific Questions for BATTREX

The primary goal of BATTREX is to further our understanding of how deep convection, slow large-scale ascent, waves, and cloud microphyiscs control the humidity and chemical composition of air entering the stratosphere. A second important goal is to improve global model predictions of feedbacks associated with future changes in TTL cirrus, stratospheric humidity, and stratospheric ozone as the climate continues to change.

These overarching goals require answers to the following questions:

Q1. What are the formation processes of TTL cirrus and how effectively do they dehydrate air entering the stratosphere? How are these likely to change in a changing climate?

Q2. How do gravity waves, Kelvin waves, and other equatorial waves regulate clouds and dehydration in the TTL?

Q3. What roles do tropical waves play in the maintenance of and variability in tropical upwelling within the stratospheric transport circulation?

Q4. How might the TTL thermal structure be altered in a changing climate, and what are the potential feedback effects?

A.3 Collaborative Opportunities in BATTREX

The remoteness of the Pacific warm pool and its vast scale impose additional challenges to comprehensive observation of the TTL in this most important region on the globe. This places a premium on co-ordination of observations of all kinds, from ground-based measurements to those on orbiting platforms. BATTREX will benefit form collaboration with both ongoing programs and several new observational initiatives coming together in the next three years. Collaborations with these programs will provide a unique opportunity to address the science questions above.

These programs are

- **SOWER**: BATTREX's chief partnership in balloon sounding will be with the Soundings of Ozone and Water in the Equatorial Regions (SOWER) program led by Prof. Fumio Hasebe of Hokkaido University. Since 1998 SOWER has been launching balloon sondes to measure ozone and water vapor in ozonesondes and water vapor across the Pacific Basin and in the Maritime Continent region. SOWER's plan for the BATTREX campaigns is to launch balloon sondes at Biak and possibly also at Tarawa (see site list in Table 1).

- **ATTREX:** ATTREX shares the overall science goals of BATTREX. During each of its three flight campaigns, the NASA Global Hawk, carrying a payload of *in situ* and remote sensing instrument will make extended flights in the TTL traversing the Pacific warm pool Campaigns are planned for January-February 2013 and 2014, the latter based in Guam, and a third in June-July 2014 at Darwin, Australia.

- **CAST:** A second aircraft mission presenting a collaborative opportunity is the Co-ordinated Airborne Studies in the Tropics (CAST) project. CAST is currently in reveiw by the UK National Environmental Research Council (NERC). The three scientific topics that will be addressed by CAST are (a) halogen sources, transport and chemistry, (b) cirrus formation, occurrence and impact, and (c) the tropical tropopause layer. CAST activities related to both ATTREX and BATTREX will include measurements of near-equatorial convection with the BAe-146 aircraft in Jan-Feb 2014 and deployment of CAST instruments on the Global Hawk during ATTREX. Of particular interest to BATTREX however are their plans to launch ozonesondes at a site in Micronesia, probably Chuuk (Truk), along with a Leosphere ALS300 lidar to monitor clouds, including sub-visible cirrus.

- **GRUAN/TWP:** The GCOS Reference Upper Air Network (GRUAN) is in discussion with the DOE's Atmospheric Radiation (ARM) Program to establish upper air monitoring programs at one or both of the ARM program's Tropical West Pacific (TWP) sites near the equator at Manus and Nauru. A third possibility would be the TWP site at Darwin, Australia. These programs would include regularly scheduled launch of CFH/ozonesonde payloads.

- **NPOESS Preparatory Project (NPP):** NPP will be the first of the United States's new generation of polar-orbiting satellites and is scheduled for launch in late October this year. On board NPP is the Cross-track Infrared Sounder (CrIS) which will produce high-resolution, three-dimensional temperature, pressure and moisture profiles. One potential collaboration would involve sharing of BATTREX water vapor and CrIS soundings in near-real time with the NOAA Center for Satellite Applications and Resarch (STAR; Chris Barnet, personal communication.)

- **Operational radiosondes:** The western Pacific warm pool is blessed with a line of reliable radiosounding sites in Micronesia, most of them close to 7 degrees north latitude. BATTREX would most likely work with sites operated by the National Weather Service.

- **NOAA Frost point soundings**: The Global Monitoring Division (GMD) at the NOAA Earth Sciences Research Lab in Boulder, CO is developing a launch program for FPH soundings at Hilo, Hawaii. Launches at Hilo could be coordinated with ATTREX over flights, and provide a broader perspective from the edge of the Warm Pool.

- **Dept. of Energy Darwin Raman Lidar:** Over the next couple of years DoE may be installing a Raman lidar for tropospheric water vapor profiling at TWP Darwin. This would be similar to one at the ARM Southern Great Plains (SGP) site. It is possible that ARM would support CFH launches at Darwin for cal/val of the lidar.

B. BATTREX Methodology and Science Goals

The observational approach of BATTREX is obtain two basic sets of data:

- Balloon soundings of water vapor, ozone, particle backscatter, temperature and winds from the surface to the lower-to-mid stratosphere at two to three sites in the equatorial zone of the western Pacific during three six week campaigns over 18 months
- High-frequency (4X daily or higher) radiosonde data at one or more sites off the equator in the western Pacific

Together with data from ATTREX, CAST and satellites, these will serve as a basis to address the following science goals:

1. Characterize the fine-scale vertical structure and temporal variability of the TTL at each balloon sonde site
2. Define tropical wave modes and their effect clouds, water vapor and dehydration through examination the longitudinal structure of the TTL in the equatorial zone and time series at individual stations
3. Determine TTL heating rates in different seasons and locations through detailed information on ozone, water vapor, temperature, cirrus clouds and aerosols
4. Support calibration and validation of current and new satellite instruments
5. Match balloon sounding data with aircraft and satellite observations
6. Intercomparison of balloon sonde vertical profiles with in situ profiles obtained from aircraft, in particular the Global Hawk

C. Balloon payloads

This project will make both balloon sonde measurements of water vapor and ozone and high-frequency and high-resolution radiosonde measurements to characterize the spatial and frequency structure of the equatorial waves contributing to the variability of water vapor and ozone in the TTL and above.

a. Water vapor-ozone balloon sondes:

The Cryogenic Frostpoint Hygrometer or CFH [*Vömel et al.,* 2007] is recognized as a reference *in situ* instrument for water vapor measurements from the surface up to 25 km. It was developed from the NOAA Frost Point Hygrometer or FPH [*Vömel et al.,* 2002] which is used by NOAA GMD in its long-running record of middle latitude water vapor at Boulder, CO. Both of these instruments have the accuracy and precision to provide the water vapor measurements to achieve the BATTREX Science Goals.

The electrochemical cell (ECC) ozonesonde [*Komhyr et al.,* 1995] is a standard instrument worldwide for ozone profiling, and for this reason, both CFH and FPH instrument packages incorporate an ECC ozonesonde.

For NPP cal/val (Science Goal #4) the high accuracy and precision of the CFH water vapor measurements make this instrument a critical tool for calibration and validation of moisture profiles from the CrIS (Crosstrack Infrared Sounder) instrument. Likewise the ECC ozonesonde can provide profiles for calibration and validation of the OMPS (Ozone Mapping and Profiler Suite).

2. *Radiosondes:*

Programs of radiosondes launched 4-times daily (or more) at one or more sites in the ATTREX region (see *e.g, Selkirk et al.,* 2010) would address Science Goal #2. Both the Vaisala RS92 or Japanese Mesei RS06G would be preferably be used in these campaigns. Vaisala RS92 SGP radiosonde is particularly useful for this purpose as the biases and time lag of its relative humidity measurement that becomes significant in the upper troposphere can be corrected [*Miloshevich et al.*, 2009].

3. Enhancement of CFH/ECC payloads with the Vaisala RS92 radiosonde

The CrIS cal/val utility of the CFH would be further enhanced by piggybacking a Vaisala RS92 or Meisei RS06G to the CFH/ECC payloads. These radiosondes are recognized as world leaders among operational radiosondes, and by mounting one to the CFH instrument package, the ascent would provide not only two streams of RH data but also a well-characterized temperature measurement for CrIS cal/val.

D. Augementation of balloon sonde payloads with the COBALD backscatter sonde

Water vapor measurements in the tropics by balloon borne frost point hygrometers and airborne in situ sensors have shown a high frequency of ice supersaturation in the TTL. As an example, Figure 1 taken *Selkirk et al.* [2010] shows a 4-km deep layer below the tropopause over Costa Rica during July 2005 that was on average close to saturation and with campaign maximum saturations to more than 160%. Likewise, satellite limb-sounding measurements from space and more recently nadir-viewing lidar observations by CALIPSO have shown a very high incidence of thin cirrus in the TTL. However co-located *in situ* particle and water vapor measurements in the TTL have been largely been limited to aircraft platforms. Recently Thomas Peter and colleagues at the Swiss Federal Institute of Technology (ETH) have developed the dual-wavelength COBALD lightweight aerosol backscatter sonde which can detect and characterize aerosols and ice particles in densities typical of thin cirrus. Figure 2 shows profiles obtained in launches from Lauder, New Zealand.

COBALD has been successfully interfaced with the CFH and FPH instruments and flown in various campaigns in this configuration (T. Peter, personal communication) Incorporation of COBALD into ATTREX balloon soundings would provide important information about the relationship between ice supersaturation and the presence (or lack thereof) of clouds at very cold TTL temperatures.

ETH also has a Lagrangian model for forecasting of both balloon and air parcel trajectories. The same model scheme has been applied successfully during the RECONCILE Arctic winter campaign in order to obtain matches from balloon soundings from NyAlesund, Spitzbergen or Sodankylä, Finland, with either the CALIPSO satellite orbit or the Geophysica aircraft flight track. The model is available for the planned project. It has recently been enhanced by a rigorous physical treatment of the vertical balloon motion through the atmosphere (including thermal heat diffusion and the dependence of the drag coefficient on the Reynolds number for the given turbulent atmospheric state). One aim of this approach is to deduce the vertical air motion directly from the sounding data, which is of potential value addressing question Q1b.

E. Observational Approach

The first component of the observational program would consist of water vapor/ozone/backscatter sonde launches at least two locations in the warm pool region during each BATTREX observational period with a minimum frequency of one every two days, and if possible targeted around ATTREX Global Hawk flights. Given the prominence of the Madden-Julian Oscillation (MJO) in the western equatorial Pacific region and its profound effects on large-scale convection, the sounding program should be 7-8 weeks in length. Thus we are recommending a program of ~25 water vapor/ozone/backscatter balloonsondes at each sounding location in each campaign.

The second component of the observational program would be a set of high-frequency radiosondes (minimum 4x daily) over the same time periods as the balloon sondes at two or more sites in the region. The radiosondes would be to characterize the temporal and longitudinal structure of equatorial waves affecting the tropopause in the region. At four times per day, these soundings should be able to resolve inertio-gravity modes as well as equatorial waves at periods of up to several weeks. Of the latter, both Kelvin and Rossby-gravity are likely to be particularly important in modulating tropopause temperatures so an optimal location to observe both types of waves would be off-equator, preferably near 5° latitude.

A multi-week series of balloon sondes would provide important insight into temporal variability in the lower stratosphere, including the advective effects of wave disturbances. For example, the time-height cross-sections in Figure 3 are based on temperature and ozone data from a sounding campaign at Biak in 2006 led by Holger Vömel. 19 sondes were launched over 18 days, and the cross-sections resolve not only Kelvin waves with periods of ~7 days, but hint at shorter-period waves as well. Longer lags between soundings would under-sample important temporal variability in the water vapor and ozone fields driven by waves and horizontal transport.

To some extent this under-sampling can be mitigated by complementing water vapor/ozonesonde launches with 4-times daily radiosonde launches. During all four of the Ticosonde CFH/ECC campaigns near San José, Costa Rica [10°N, 84.2°W], launches were complemented by a parallel program of 4-times daily radiosondes (see *Selkirk et al.,* 2010). The radiosondes were able to characterize the dynamical variability of the TTL from the inertial range out to synoptic scales.

A potential "match" type experiment: With programs of water vapor/ozone soundings at both Guam and Biak there would be an opportunity to do a 'Match' type experiment. In this scenario, the aircraft would fly a Lagrangian path that passed over both Biak and Guam. The aircraft would not only sample at each launch site, but the TTL along the path between the two locations.

E.1. Sites for balloon sonde observations

The water vapor and ozone soundings should be launched at sites with the following characteristics:

- within the longitudes spanned by the western Pacific warm pool
- within ~5° of the Equator – this maximizes effects of equatorial waves (either Kelvin waves or mixed Rossby-gravity waves depending on latitude)
- within or immediately downstream of climatological regions of deep convection

Four sites (Biak, Manus, Nauru, and Tarawa) satisfy this requirement and are listed in Table 1 in longitudinal order west-to-east. Two have been used by the SOWER program in the past while the remaining two are Tropical Western Pacific (TWP) sites in the US Department of Energy Atmospheric Radiation Measurements (ARM) program.

Site	**Location**	**Comments**
Biak, New Guinea (Indonesia)	1°S, 136°E	SOWER site
Manus Island, Admiralty Islands (Papua New Guinea)	2°S, 147°E	ARM TWP site
Nauru (Republic of Nauru)	0.5°S, 167°E	ARM TWP site
Tarawa, Gilbert Islands (Kiribati)	1.4° N, 173.2° E	SOWER site

Table 1. Preferred BATTREX water vapor/ozone sounding locations

ATTREX flights in all three science campaigns will probe the western Pacific warm pool region, though flight operations will take place at different locations – NASA Dryden in California (winter 2013), Guam (winter 2014) and Darwin, Australia (summer 2014.) In each instance, launches at the sites listed in Table 1 will be able to take advantage of match observations with the ATTREX airborne measurements.

An additional five sites outside of the warm pool region are listed in Table 2. Two of these (Guam and Darwin) are planned as deployment sites for ATTREX Global Hawk sorties and thus will afford opportunities for inter-comparison with ATTREX instruments on final descent. NOAA GMD now routinely launches FPH at the Hilo site.

For sampling the Asian monsoon anticyclone in a region near where the Global Hawk can fly, Hanoi [20°N, 105°E] would be reachable from Guam. Hanoi will be in and out of the Asian monsoon anti-cyclone (mostly within) at TTL levels during the summer season, and the Global Hawk should be able to fly off-shore of Hanoi.

While not critical to the central science goals of BATTREX, launches at all of these sites could be incorporated into a BATTREX Match campaign.

Site	**Location**	**Comments**
Hanoi (Viet Nam)	21°N, 106°E	SOWER/SHADOZ site
Watukosek (Indonesia)	7.5°S, 114°E	SOWER/SHADOZ site
Darwin (Australia)	12.5°N, 130.8°E	ATTREX flight ops, summer 2014
Guam (Mariana Islands)	13.5°N, 144.5° E	ATTREX flight ops, winter 2014
Nandi (Fiji)	17.8°S, 177.4°E	SHADOZ site
Pago Pago (American Samoa)	14.3°S, 170.7°W	SHADOZ site
Hilo, Hawaii	19°N, 157°W	NOAA GMD FPH/ECC site

Table 2. Additional water vapor and/or ozone sounding locations

All of the sites in Tables 1 and 2 have at least minimum scientific infrastructure, and successful sonde campaigns have been conducted at each in the past. In particular, the SOWER project has significant infrastructure at Biak, with local trained personnel that may be able to assist the project.

E.2 Sites for augmented radiosonde observations

The western Pacific warm pool region has a number of active sounding stations that generally launch radiosondes twice daily (00Z and 12Z) which would be excellent candidates for augmenting soundings to four times daily during the BATTREX campaigns. These stations are listed in Table 3. The list includes three of the four sites in Table 1, Biak, Manus, and Nauru. Another four are located roughly along 7°N in the Line Islands of Micronesia, and as these are located off the equator, they would be particularly well suited to diagnosing both symmetric and anti-symmetric equatorial wave modes.

Site	**Location**	**WMO/ICAO**	**Operated by**
Biak, New Guinea (Indonesia)	1°S, 136°E	97560/WABB	USNT
Momote AP, Admiralty Islands (Papua New Guinea)	2°S, 147°E	94044/AYMO	Australian BOM
Nauru (Republic of Nauru)	0.5°S, 167°E	91552	Australian BOM
Tarawa, Gilbert Islands (Kiribati)	1.4° N, 173.2° E	91610/NGTA	USNT
Tarawa/Bonriki (Kiribati)	1.2°N, 158.2°E	91348/PTPN	USNT
Yap (Micronesia)	9.5°N, 138.1°E	91413/PTYA	NWS
Koror (Micronesia)	7.5°N, 134.5°E	91408/PTRO	USNT
Truk (Micronesia)	7.5°N, 151.9°E	91334/PTKK	NWS
Ponape (Micronesia)	7.0°N, 158.2°E	91348/PTPN	USNT

Majuro (Marshall Islands)	7.1°N, 171.4°E	91376/PKMJ	NWS

Table 3. Radiosonde locations in the western Pacific warm pool region

Finally, during test flights, it is likely that the Global Hawk will be flying in the vicinity of Hawaii. A NOAA sounding station for frostpoint soundings is likely to be in operation near Hilo, and it may be possible to perform a TTL dive in conjunction with a balloon launch.

F. Nominal sounding campaign details

As discussed in Section B, each of the three BATTREX observational periods will have balloon sondes launched every other day from equatorial sites for a period of 7 weeks plus a program to augment Micronesian twice-daily radiosondes to 4 per day or more. To provide a sense of the personnel and resources required, we describe here a scenario for one sounding campaign in which balloon soundings were made at each of the two TWP sites and at Biak, with enhanced radiosondes at Ponape and Chuuk/Truk.

In such a scenario, the Biak site will be the responsibility of SOWER. We also assume that an ongoing GRUAN/TWP sounding program will have been established by the time of the observations so that a sounding ground station will already be on site along with a ozonesonde prep facilities.

Resources:

The additional resources required for balloon sounding at each of the two TWP sites would then consist of

- 25 water vapor/ozone sondes
- 30 sets of 1200-g balloons, parachutes, and dereelers
- 20 cylinders of helium
- 1 cylinder of cryogen

We would recommend two students at each TWP site in support of TWP staff to assist in the sonde prep, launches and data handling. Adding the COBALD instrument to the payload will require an additional person from ETH. Finally, the payload with a Vaisala RS92 radiosonde will require a Vaisala ground station

Augmenting radiosoundings at each of the NWS Micronesia sites will require

- 100 Vaisala RS92 radiosondes
- 100 sets of 300-g balloons, parachutes, and dereelers
- 20 cylinders of helium

G.. Summary

A coordinated balloonsonde campaign in the tropical Western Pacific warm pool region would provide a rich data set to understand key processes in the Tropical Tropopause Layer. Balloonsondes are now capable of high accuracy and high vertical resolution measurements of TTL water vapor, ozone, temperature and cloud/aerosol particles. A small campaign focused at a 2 sites with possible supplementary radiosondes would provide a valuable in-situ data set for detailed process studies of the TTL. The campaign would leverage (a) existing infrastructure and (b) coordinate with other balloon (SOWER, NOAA), ground based (DOE-TWP) and aircraft (ATTREX, CAST) programs planned in the region. Balloon measurements would complement other projects and provide additional data. The benefits of such a campaign would be large to all the projects concerned, and for satellite validation efforts. In return, these other projects would provide a rich data set surrounding a BATTREX campaign that can result in advancing our understanding of stratospheric chemistry and tropospheric climate on a changing planet. The project would also significantly involve students and young scientists.

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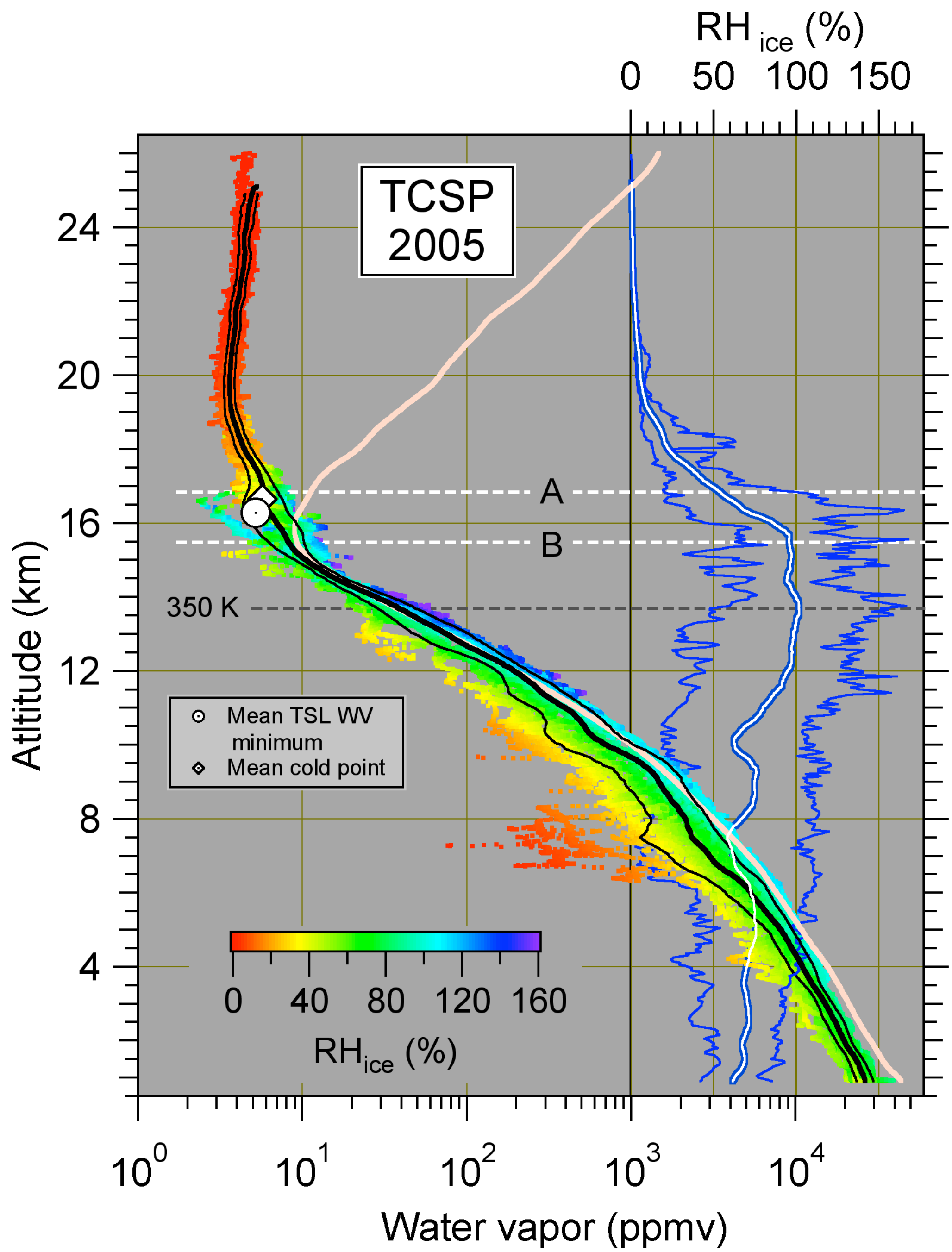

Figure 1: Water vapor and RHi profiles from the Ticosonde CFH/ECC campaign, Alajuela, Costa Rica, July 2005. At left, water vapor volume mixing ratio data from each ascent color-coded by RHi; mean profile, heavy line; envelope of ± 1 standard deviation, thin lines; mean saturation mixing ratio, heavy pink line; mean water vapor minimum in the TSL, white circle; and mean cold point, white diamond; mean altitude of the 350 K surface, horizontal dashed gray line, and upper and lower bounds of tropopause saturation layer, dashed white lines A and B. At right, the mean profile of RHi, blue/white line; envelope of RHi maxima and minima, thin blue lines. [Taken from *Selkirk et al.,* 2010]

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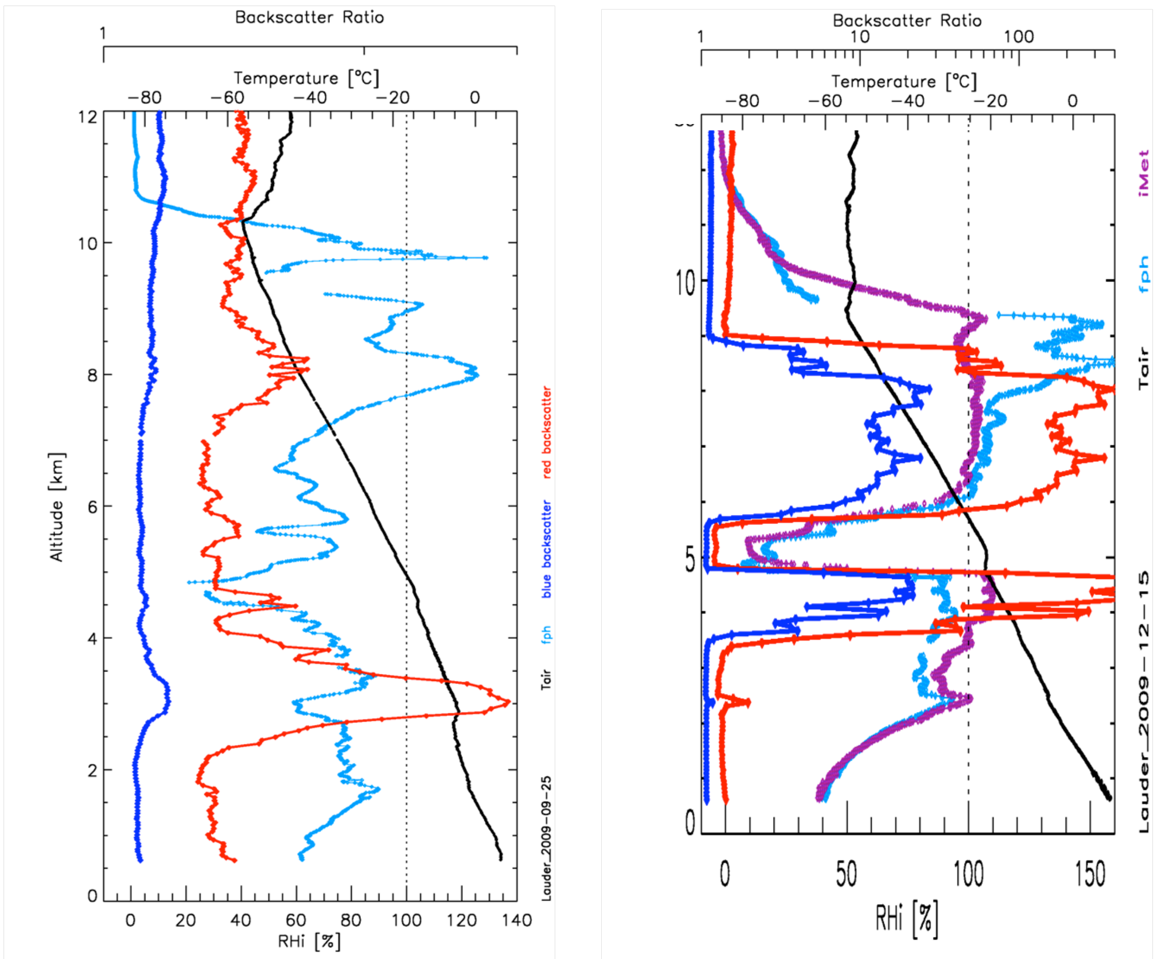

Figure 2: Two examples of FPH/COBALD sounding profiles taken in Lauder, New Zealand, 2009. Colors indicate temperature (black), 455 nm & 870 nm backscatter ratio (blue & red), FPH RHi (light blue) and iMet RHi (magenta). Note the different scales for the backscatter ratio. Left panel, 3 km altitude: enhanced backscatter with reduced relative humidity is attributed by trajectory calculation to a dust storm event in south-eastern Australia. Left panel, 8 km altitude: the supersaturation is reflected in optical backscatter at a signal level indicating aerosol growth but yet excluding ice particle formation. Right panel, 6 to 9 km altitude: Thick – both optically and vertically - cirrus cloud with saturated conditions inside. Right panel, 8 to 10 km altitude: The cloud top is clearly identified by the backscatter signals. In contrast to the FPH the iMet capacitive water vapor sensor is incapable to detect supersaturation at the cloud top. The topmost 500 m of the cloud is characterized by high supersaturation with the backscatter signal indicating newly formed and growing particles. Moderate supersaturation extends abobe the cloud top (as identified by the backscatter) – a feature commonly observed for clouds forming in upwelling air motion.

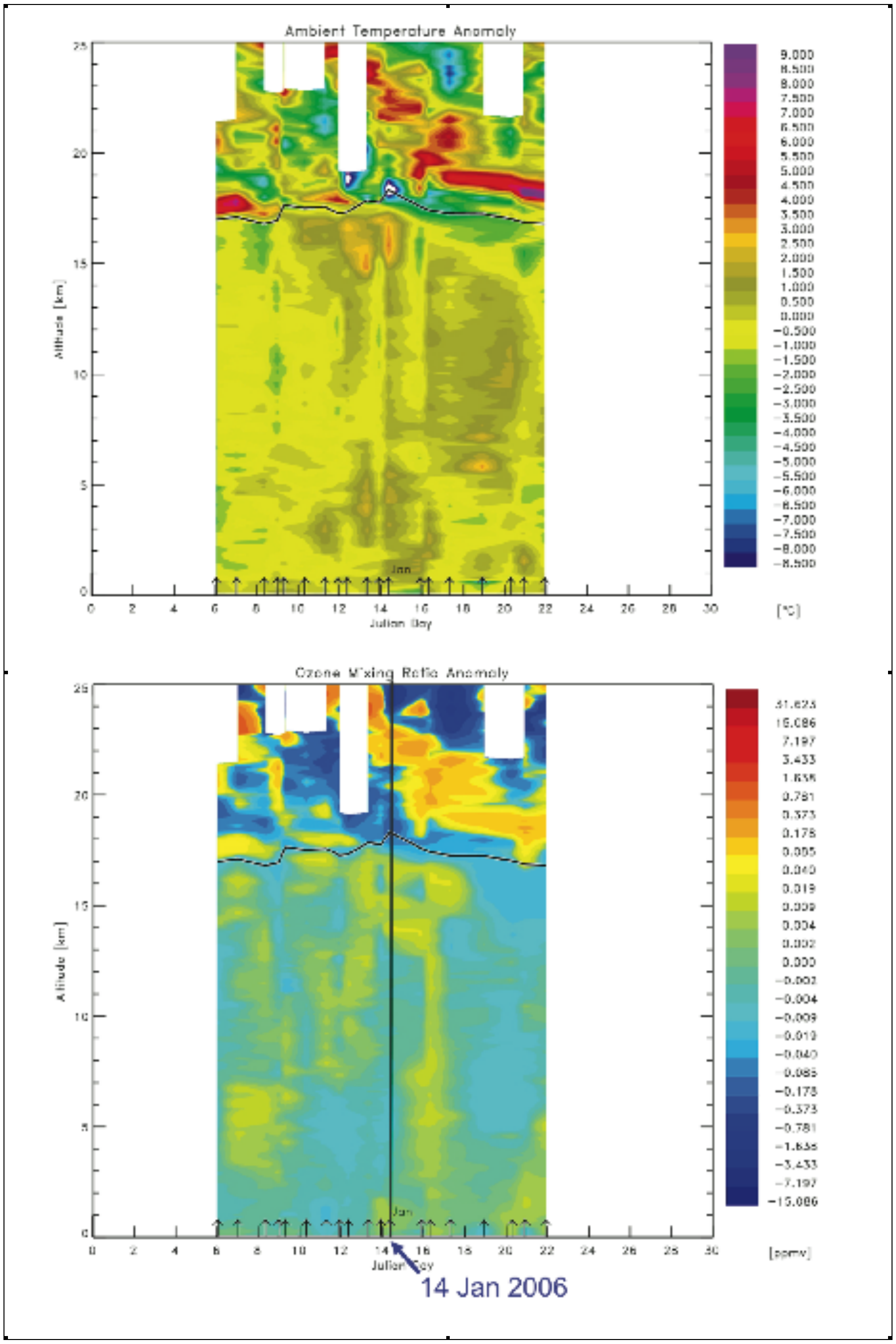

Figure 3. Anomaly cross-sections of temperature (top) and ozone mixing ratio (bottom) from CFH/ECC launches at Biak, Indonesia, January 2006. The campaign's lowest water vapor mixing ratio occurred along with the largest negative temperature anomaly in the period on January 14. Wind data (not shown) and the downward phase propagation in temperature are consistent with a Kelvin wave, and the strong correlation between the temperature and ozone anomalies indicate the positive (negative) ozone anomalies are due to descent (ascent) induced by the Kelvin wave. [From a presentation by H. Vömel to the Aura Science Team, Boulder, CO, September 2006]

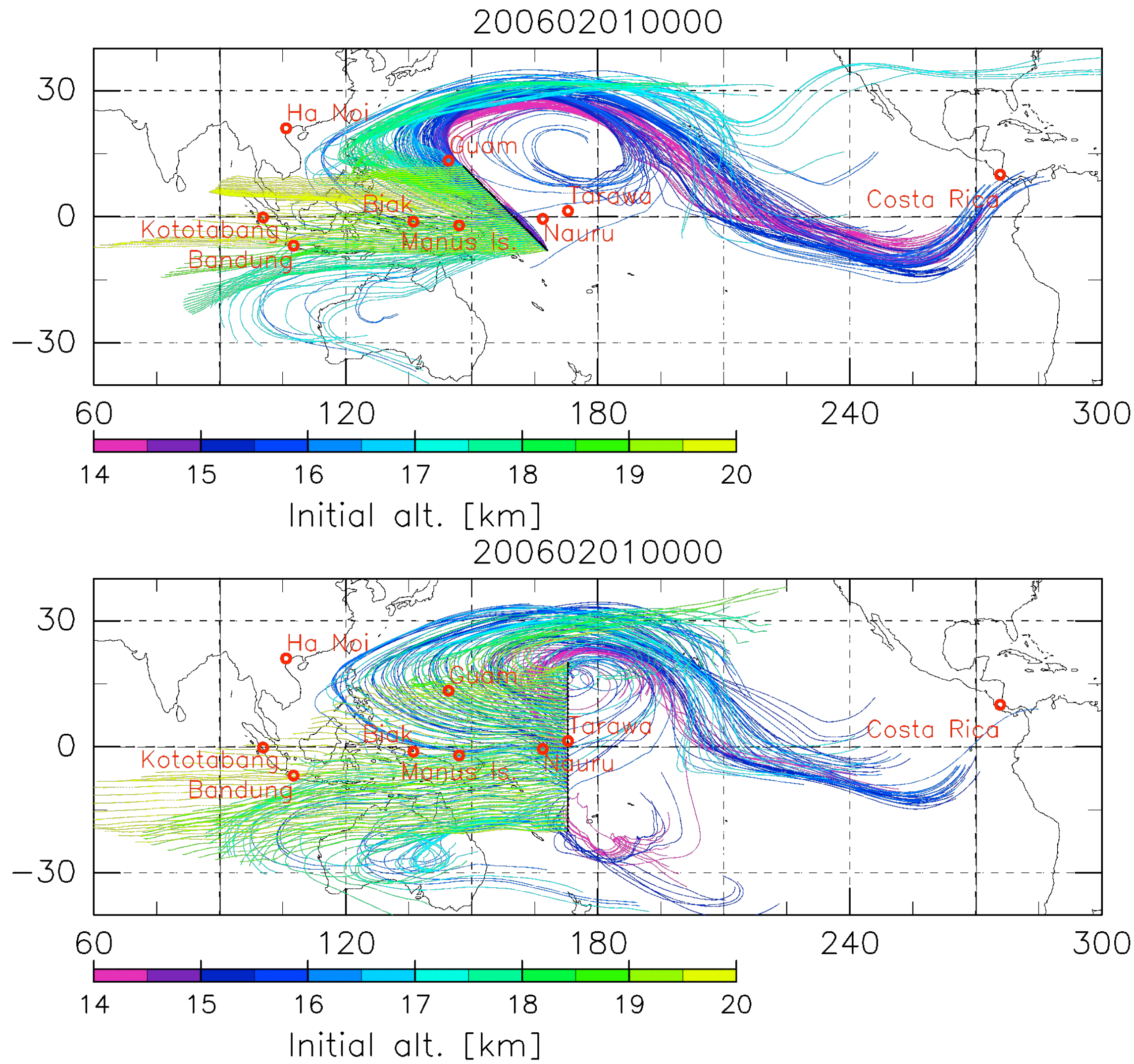

Figure 4. Two examples of the "match" measurements between aircraft flight paths and balloon sites over the tropical western Pacific. Black lines show assumed aircraft paths. Color coded curves are 7-day isentropic forward trajectories starting from the aircraft paths on February 1st, 2006 at 00 UTC. Different colors show different starting levels between 14 km and 20 km by 1 km (see the color code). ERA-Interim reanalysis data are used for the calculations.