

Composition and Transport in the Tropical Troposphere and Lower Stratosphere Meeting
20 - 23 June 2015
Boulder, Colorado, USA

Monday, July 20, 2015

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Composition and physical properties of the Asian Tropopause Aerosol Layer and the North American Tropospheric Aerosol Layer

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Abstract

Recent studies revealed layers of enhanced aerosol scattering in the upper troposphere and lower stratosphere over Asia (Asian Tropopause Aerosol Layer (ATAL)) and North America (North American Tropospheric Aerosol Layer (NATAL)). We use a sectional aerosol model (Community Aerosol and Radiation Model for Atmospheres (CARMA)) coupled with the Community Earth System Model version 1 (CESM1) to explore the composition and optical properties of these aerosol layers. The observed aerosol extinction enhancement is reproduced by CESM1/CARMA. Both model and observations indicate a strong gradient of the sulfur-to-carbon ratio from Europe to the Asia on constant pressure surfaces. We found that the ATAL is mostly composed of sulfates, surface-emitted organics, and secondary organics; the NATAL is mostly composed of sulfates and secondary organics. The model also suggests that emission increases in Asia between 2000 and 2010 led to an increase of aerosol optical depth of the ATAL by 0.002 on average which is consistent with observations.

Aerosol Composition and Volatility in TTL - In situ Balloon Borne Measurements and sampling over Biak Indonesia -

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Abstract

Cloud process is one of key process of dehydration at tropical tropopause layer (TTL). Super saturations were detected frequently around TTL, and it is not understood until now. What is the ice nuclei in TTL? What kind of nucleation process is most important to form TTL cirrus? In order to understand TTL cirrus processes, balloon borne aerosol observations were conducted as one part of SOWER campaign, observation for water vapor, ozone, cloud and aerosol using many kinds of balloon borne instruments and a Lidar.

Thermo Denuding tandem Optical Particle Counters (TD-OPC) and aerosol samplers (AS) were launched by 3 kg rubber balloon from Biak Indonesia. Seven TD-OPCs were launched during January of 2011, 2012 and 2013. One TD-OPC and two AS were launched in February/March 2015. One AS, launched on 26 February, was separated from balloon at 23km after collecting 10 samples and another AS, launched on 1 March, separated at 25km after collecting 14 samples.

TD-OPC has two OPCs. One OPC measure aerosol size distribution, diameter of 0.3-10 μm , in ambient condition and the other measures those at high temperature through after heated. On the basis of knowledge about aerosol composition and origin, volatility of 4 kinds of test particle were examined in the laboratory. They show that temperature of 100 to 300 $^{\circ}\text{C}$ is suitable to examine the TTL aerosol.

The ratio un-volatile to ambient concentrations, for 0.3-0.8 μm in every 200 m, is low in stratosphere and high in troposphere. Those in TTL show middle value, but are little higher than those at just below TTL, suggesting possibility of direct injection from troposphere. Concentrations of un-volatile particles are around mixing ratio of 100 #/g, corresponding to volume concentration of 10 #/liter. It is similar to cloud particle concentration in sub-visible cirrus, suggesting importance of un-volatile constituent for cloud activation. Temperature dependency in residual ratio was compared with test particle examination. Residual ratios between 100 to 300 $^{\circ}\text{C}$ are similar in stratosphere and TTL suggesting major constituent is sulfuric acid, with some % of non-volatile matter. There is some slope below 200m in lower TTL, similar to the feature of ammonium sulfate.

Analyses of morphology and elemental composition of aerosols recovered from TTL are now under processing.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 22241004 and 26220101.

Correcting the record of volcanic stratospheric aerosol impact: Nabro and Sarychev Peak

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Since 2010 several papers have been published that reveal a pattern of discrepancies between stratospheric aerosol data from the Optical Spectrograph and InfraRed Imaging System (OSIRIS) instrument and comparable measurements or model simulations of volcanic plumes from Kasatochi (2008), Sarychev Peak (2009), and Nabro (2011). The OSIRIS discrepancies are two-fold: a post-eruption lag in aerosol onset/increase and low bias in maximum stratospheric aerosol optical depth. Assumed robustness of the OSIRIS data drove various conclusions, some controversial. For example, one conclusion was that the June 2011 Nabro (northeast Africa) plume was strictly tropospheric, and entered the stratosphere indirectly via Asian monsoon convection. In that case the conclusions were driven by OSIRIS data and a volcano activity report by the Smithsonian Institution that indicated strictly tropospheric injection heights. We address the specific issue of Nabro's eruption chronology and injection height, and the reasons for the OSIRIS aerosol discrepancies that impacted these several case studies.

First we lay out the time line of Nabro injection height with geostationary nadir image data, and stratospheric plume evolution for 4 days after eruption onset using nadir and limb-view retrievals of sulfur dioxide and sulfate aerosol. Satellite- and ground-based observations show that Nabro injected sulfur directly into the lowermost stratosphere (up to heights of 18 km) upon the initial eruption on 12/13 June, and again on 16 June 2011. Next, OSIRIS data are examined for non-volcanic and volcanically perturbed (Nabro and Sarychev Peak) conditions. In non-volcanic conditions OSIRIS profiles systematically terminate 1-4 km above the tropopause; the balance of the lowermost stratosphere is thus unresolved and potentially unaccounted for. Additionally, our analysis reveals that OSIRIS profiles terminate when 750 nm aerosol extinction exceeds $\sim 0.0025/\text{km}$; optically denser stratospheric plumes—which we show to be common after volcanic and pyroconvective injections—are not sampled. Care must therefore be taken when using OSIRIS data in order to account for significant biases in aerosol loading following a strong volcanic eruption.

Our findings largely resolve the unexplained discrepancies in published works involving OSIRIS aerosol data and invite a new interpretation of previous conclusions. They also offer a correction to the Smithsonian report of the Nabro injection-height and eruption chronology.

Composition and sources of aerosol in the upper troposphere/lowermost stratosphere

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Satellite derived time-series of lower stratospheric aerosol extinction showed an increase by ~7%/year starting from about 2000. This increase has been attributed mostly to a series of relatively small tropical volcanic eruptions. The detection of a region of enhanced aerosol extinction over Asia during the monsoon period (Asian tropopause aerosol layer, or ATAL), however, suggests that convective lifting of tropospheric aerosol can also be an important source of aerosols in the lower stratosphere.

We present an assessment of the composition and sources of aerosols in the lower stratosphere from model results by the Goddard Earth Observing System Chemistry Climate Model (GEOSCCM), coupled to the GOCART aerosol model. To ensure the highest similarity to the observed meteorology, we run GEOSCCM in replay mode, i.e. using the MERRA reanalysis meteorology. Our simulation span the period from 2000 to present, and includes natural and anthropogenic emissions of precursor gases and tropospheric aerosols (sulfate, black carbon, organic carbon, dust, and sea salt), volcanic sulfate emissions, and stratospheric sulfate aerosol resulting from the photolysis and oxidation of carbonyl sulfide (OCS). By separately tracking aerosol sources, we calculate the partitioning of stratospheric aerosol between anthropogenic and natural sources, and the contribution to the stratospheric sulfate loading of volcanic eruptions, transport of tropospheric sulfate, and OCS chemistry.

Trace gas sources and distributions in the tropical troposphere and TTL

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The recent CONTRAST, ATTREX, and CAST missions have provided a unique data set to examine the vertical distributions and transport of trace gases in the tropical West Pacific atmosphere. Trace gas measurements from the marine boundary layer to near 19 km are being used to characterize how the chemical composition of the tropical atmosphere varied due to emissions, convective redistribution, and longer scale vertical and horizontal transport processes. In addition to profiling the troposphere, we obtained multiple profiles of trace gas composition across the tropical tropopause layer (TTL). Prior to these missions, a relatively few in-situ trace gas profiles in the TTL had been made, with none in the tropical West Pacific region during boreal winter season. These profiles are impacted by transport and mixing, air mass source region, recent convection, and chemical loss. A variety of tracers of different lifetimes and sources were measured that provide insight into these various processes. The trace gases that we measured included non-methane hydrocarbons, organic nitrates, sulfur compounds, and a range of organic halogenated hydrocarbons from both biogenic (mainly marine) and anthropogenic sources. Importantly, the measurement of halogenated compounds in TTL define the input of reactive halogen into the lowermost stratosphere, with subsequent impact on ozone production and loss rates. The presentation will examine some of the details of the correlations and vertical distribution and variations of trace gases during the recent missions.

Science questions and measurement strategies within the European research project StratoClim

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The overall goals of StratoClim are to quantitatively assess the role of the Upper Troposphere and Stratosphere (UTS) in climate change, and to improve climate projections by developing and including within Earth System Models (ESMs) new, interactive modules for stratospheric ozone and aerosol and by improving our understanding of UTS water vapour variations and the representation of upper tropospheric clouds in ESMs.

In NH summer, the Asian Monsoon plays a key role for the composition of the UTS and will be a focus point of field activities within StratoClim. In summer 2016 a large scale campaign with the high altitude research aircraft Geophysica will be carried out to analyse the composition of air that is transported by the monsoon system to the upper troposphere and into the stratosphere, as well as to study in detail the processes that affect the composition of air in the Asian Monsoon Anticyclone (AMA), with a focus on aerosol properties in the AMA.

In NH winter, the tropical West Pacific is the major source of air that ascends into the stratosphere. The composition of the troposphere and the TTL in this region is a second focus of field activities in StratoClim. A new measurement station will be set up on Palau Island and will initially operate during 2015 – 2018 with a potential longer term operation depending on additional funding.

The measurements will be combined with satellite data analysis including development of new satellite data products, process and regional modelling and global modelling with Chemical Climate Models and ESMs. The presentation will give an overview of the StratoClim science questions and tropical field activities.

Stratéole 2: A Unique Super Pressure Balloon Campaign For Long Duration, Quasi-Lagrangian, Chemical And Dynamical Measurements In The Tropical Tropopause Layer.

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Stratéole 2, is a long duration scientific ballooning campaign to study the Tropical Tropopause Layer (TTL) and lower stratosphere, organized by CNES and LMD in France and planned for 2017 – 2019. This campaign presents a rare opportunity to make long duration physical and chemical measurements of the TTL and lower stratosphere from nearly Lagrangian balloon platforms. This experiment builds on the super pressure balloon platform that was successfully used during the VORCORE and Concordiasi missions in the Antarctic and Pre-Concordiasi mission at the equator. The balloon constellation will follow constant density surfaces, with two flight levels planned at pressure levels near 50 and 75 hPa. The project will consist of two intense field campaigns during consecutive years, with approximately 20 balloon launches per campaign. Flight durations in excess of 3 months are expected, providing extensive zonal sampling over latitude band of 10°N to 15°S. The instrument payload will include measurements of water vapor, ozone, particle size distributions, vertical temperature profiles, μ LIDAR cloud measurements and GPS radio occultation measurements of water vapor and temperature profiles.

The scientific goals of Stratéole 2 include topics related to the chemistry, dynamics and transport in the TTL. Examples include dehydration processes and the thermal structure of the TTL, which will be investigated using flight level measurement of water vapor, high-resolution temperature profiles through the TTL, and microphysical measurements of cloud particles with a μ LIDAR. The dynamics of the equatorial stratosphere, in particular the relationship between the QBO and generation and propagation of gravity waves in TTL are also a focus of the campaign. Flight level measurements of meteorology and the balloon displacement, in combination with temperature profile measurements will deliver an unprecedented view of wave frequency and phase spectra, and the zonal coverage of the observations will highlight geographical asymmetry in wave activity. In situ measurements of aerosol size distributions, ozone and methane will be useful for investigating transport, particularly in relation to the Asian Monsoon, and for satellite and model validation. Stratéole 2 is in the advanced planning stages, and we are exploring synergies with other equatorial observational, theoretical and modeling studies.

Changes in Stratospheric Thermal Structure and Chemical Composition during a Major Stratwarm Event of 2013

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Ozone mass mixing ratio obtained from both European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis (ERA)-Interim and Sounding of Atmosphere by Broadband Emission Radiometry (SABER) instrument onboard Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite shows large values in the equatorial upper stratosphere during the occurrence of a major sudden stratospheric warming (SSW) in January 2013 preceded by a large reduction of planetary wave activity. However surprisingly equatorial temperature is found to decrease at pressure levels where the ozone mixing ratio is larger. The computed radiative heating rate using SBDART model also shows positive heating rate indicating that the temperature should increase in response to the ozone accumulation over equator. In addition to radiative heating due to ozone, heating rate due to the other dominant factors, namely, ascending motion and convergence of meridional heat flux which could influence the thermal structure of the equatorial stratosphere, are estimated. It is found that the observed low temperature during the SSW is mainly due to large upward motions. The estimated heating rates agree reasonably well with the observed heating rates at 10-8 hPa indicating the dominance of transport at lower stratosphere. The large discrepancy between the estimated and observed heating rates in the upper stratosphere may be due to the dominance of photochemistry. To study the variations of chemical constituents during the SSW, we investigated the volume mixing ratios (VMR) of different chemical components obtained from Microwave Limb Sounder onboard Aura satellite which show distinct variations at high and low latitudes in the upper stratosphere (30-50 km) during the occurrence of SSW in January 2013. In this study, it is being observed that zonally averaged H₂O VMR (WVMR) is decreasing over equatorial region with the onset of the warming event. Oxidation of methane (CH₄) is the primary source of upper stratospheric water vapour, so probably this change in WVMR is due to change in methane concentration during the SSW. The cause of this HVMR decrease is still under investigation; Further results will be presented during the meeting.

Ozone in the Tropical Tropopause Layer (TTL) over the Western Pacific

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The tropopause over the western tropical Pacific is one of the primary entry points of air from the troposphere into the stratosphere. Temperatures there are low enough in the TTL (~14-18.5 km) to dehydrate air to the low values observed in the stratosphere. The NASA Airborne Tropical Tropopause Experiment (ATTREX) mission included flights of the Global Hawk unmanned aircraft system (UAS) over the western tropical Pacific from Guam in January-March 2014 (ATTREX-3), with flights to the central and eastern tropical Pacific in previous years. During ATTREX-3, the Global Hawk was joined in Guam by the NSF/NCAR GV and British BAe-146 research aircraft on complementary missions, providing coverage of the atmosphere from the boundary layer to 19 km. Coincident balloon measurements of ozone and water vapor were also obtained for the February Global Hawk flights. The Global Hawk flew more than 100 vertical profiles in the TTL over the western tropical Pacific, as well as long sections at constant altitude. Ozone was consistently low (10-40 ppb) in the lower part of the TTL, with low values extending up to the thermal (cold point) tropopause, particularly in March 2014. While ozone as low as 20 ppb was occasionally observed over the central and eastern Pacific in February-March 2013 during ATTREX-2, it more often averaged 40-50 ppb, and typically increased slowly with height from about 14 km to the tropopause. In ATTREX-3, long-lived tracers such as N₂O were very close to their tropospheric values over the western tropical Pacific. Sulfur hexafluoride (SF₆) data suggested that sampled air masses had very recently originated at the surface, with negligible in-mixing of stratospheric air from midlatitudes. Methane and CO often peaked just below or near the local tropopause. These results indicate frequent deep convection, bringing air from the marine boundary layer (with low ozone and high values of long-lived trace species) directly to the upper troposphere. The origins and transport of air in the TTL during ATTREX-3 will be discussed, as well as the implications of the low ozone observed.

Vertical and quasi-isentropic transport pathways through the Asian monsoon anticyclonic circulation into the lowermost stratosphere

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The Asian summer monsoon region is characterised by strong convective activity causing substantial upward transport of boundary layer air to high altitudes. This boundary layer air will carry with it strong signatures of tropospheric air (e.g. enhanced HCN, CO, and water vapour; low ozone). It has been suggested that the monsoon circulation thus provides an effective pathway for pollution from Asia, India, and Indonesia deep into the global stratosphere. Here we will discuss vertical transport in the Asian monsoon circulation based on simulations of the Chemical Lagrangian Model of the Stratosphere (CLaMS) driven by ERA-Interim meteorological fields. The model results indicate that the tropical tropopause in the monsoon region constitutes a clear barrier to upward transport of tropospheric air, with only a minor fraction of the uplifted tropospheric air entering the stratosphere vertically. However, horizontal, quasi-isentropic transport into the lowermost mid-latitude stratosphere is very efficient. Air masses in the core of the monsoon anticyclone are separated from stratospheric air by a horizontal transport barrier, but the anticyclonic circulation also extends to air masses outside the core of the Asian summer monsoon region. We show a case, where air masses originating from the boundary layer in the Southeast Asia/West Pacific are rapidly lifted (within 1–2 days) in a typhoon up the outer edge of the Asian monsoon anticyclone, circulate around the monsoon core and are then transported (within 8–14 days) to the lowermost stratosphere in northern Europe. The chemical signature of air masses affected by the Asian monsoon anticyclone were measured in situ in the lowermost stratosphere over northern Europe on 26 September 2012 during the TACTS aircraft campaign. We suggest that the combination of rapid uplift by a typhoon and eastward eddy shedding from the Asian monsoon anticyclone is a novel fast transport pathway that may carry the chemical signature of boundary emissions from Southeast Asia/West Pacific within approximately 5 weeks to the lowermost stratosphere in northern Europe.

Trajectory dispersion due to uncertainties in analysis wind fields and the inherent limitations of transport calculations in the upper tropical troposphere

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Lagrangian trajectory calculations, in which air-parcel paths are determined from wind fields from operational analysis and reanalysis data, are standard tools for diagnosing dynamical interactions and chemical concentrations in the upper troposphere and lower stratosphere. However, due to poor observational sampling, these calculations suffer from uncertainties that are difficult to account for. We examine trajectory dispersion from two sources. The first arises from the uncertainty of resolved fluctuations in the analysis wind fields. This uncertainty is investigated via ensembles of trajectories calculated using wind fields from different analysis data sets. The second is the uncertainty that arises from small-scale wind fluctuations that are unresolved by analyzed fields. This uncertainty is investigated by simulating, with random perturbations, small-scale wind fluctuations. This work is aided by the fact that, while actual wind fluctuations are not known, their statistical properties are constrained by high-resolution observations from aircraft. These two methods agree that the uncertainty of air-parcel location in the upper tropical troposphere grows at a rate of 1 degree per day in the horizontal and 5 mb per day in the vertical.

Transport Rates and Age of Air in the TTL during Boreal Winter

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The tropics serve as the main gateway for surface air to enter into the stratosphere. Pollutants and ozone-depleting substances (ODS) reaching the stratosphere via the tropics have shown to have an adverse effect on the chemical and radiative properties of this layer of the atmosphere and hence Earth's climate. Within the tropics, the Western Pacific has been previously identified as the dominant region for stratospheric entry. This study focuses on data collected in the Tropical Tropopause Layer (TTL) aboard the NASA Global Hawk aircraft during the ATTREX campaign. This campaign achieved extensive sampling between 14 and 19 km in altitude over the Central and Eastern Tropical Pacific in Feb – Mar 2013 and over the Western Tropical Pacific in Feb – Mar 2014. The goals of this study are twofold: (i) to quantify transport rates in the TTL and (ii) to evaluate age spectra and mean age of air derived from aircraft observations and models in the TTL. Aircraft data, complemented by NOAA's surface measurements, show comparable ascent rates above the 380 K isentrope, but different mean ages at the top of the TTL over the Eastern and Western Pacific regions. Within the Western Pacific, we also find comparable ascent rates, but different sources of air feeding the Northern and Southern Hemispheres. While vertical ascent dominates, there are other transport pathways that can affect the chemical composition and radiative properties of the TTL. During the deployment to the Western Pacific for instance, we encountered isolated events such as an early season typhoon and convectively injected air over Africa as evidenced by distinct signatures in CO₂, CH₄, CO, H₂O, and O₃. We also expanded our latitudinal coverage by crossing the Northern Hemisphere subtropical jet over both the Western and Eastern Pacific in order to assess the extent of horizontal mixing between tropics and subtropics during boreal winter. These special cases allow us to explore the effect of these transport pathways on transport rates in the TTL. Under all conditions, we also investigate age spectra and mean age of air using aircraft measurements, trajectory analysis driven by ERA-interim circulation and simulations from the NASA GEOS-5 atmospheric global climate model. Several general circulation models predict an acceleration of the Brewer-Dobson circulation under scenarios of increased concentrations of greenhouse gases in the troposphere. A consequence of this acceleration is a shorter residence time, hence a decrease in the mean age of air in the stratosphere. This study provides an opportunity to test models at the shortest transport time scales and at the start of the stratospheric journey over the tropics.

Evaluating and Diagnosing the Transport of Trace Gases to the Upper Troposphere / Lower Stratosphere in the CAM-Chem Model using Aura Microwave Limb Sounder Measurements

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We present an evaluation of the climatology and spatial, seasonal, and interannual variability of a range of trace gas species over the tropical continental convection regions (South America / Africa / Indonesia) and in the Asian summer monsoon anticyclone in the Specified Dynamics version of the NCAR Community Atmosphere Model with Chemistry (CAM-Chem-SD) against more than 10 years of observations from the Aura Microwave Limb sounder (MLS) satellite instrument. We examine whether the model correctly reproduces the observed trace gas distributions and variations, as well as whether it captures the observed relationships of these trace gases to meteorological variations such as deep convective intensity and tropospheric jet position and strength. We also use the model to aid in interpretation of the trace gas measurements and help understand what they can tell us about variations in transport processes and source strength and location. Our results indicate, for example, that the model does not accurately reproduce observed trace gas ratios that assess the relative strength of vertical transport over the tropical convection regions and does not fully capture the observed isolation of trace gases within the Asian monsoon anticyclone.

A Modeling Study of STE Near Tropical Cyclones Talas and Ita

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Abstract. The relationship among convection, inertial stability, dipoles of potential vorticity (PV), and stratosphere / troposphere exchange (STE) in the upper troposphere / lower stratosphere (UTLS) above typhoons Talas and Ita is investigated with the University of Wisconsin Nonhydrostatic Modeling System (UWNMS). Both were category 5 tropical cyclones that caused extensive damage in the high-tropopause environment of the western Pacific. Talas reached minimum central pressure south of Japan on September 2-3, 2011, while Ita formed over the Coral Sea and reached maximum strength off Australia on April 11, 2014. Turbulent kinetic energy, Richardson number, angular momentum, divergence, streamfunction, equivalent potential vorticity (EPV), absolute vorticity, and trajectories are used to diagnose STE and dynamical processes. Two primary modes of STE are found: 1) at the scale of the cyclone itself, inertially unstable-to-neutral anticyclonic outflow overrides surrounding stratospheric air in a “medusa” configuration, while 2) at the scale of embedded convective complexes, PV dipoles are generated with inertial instability and tropopause folding. In the absence of strong shear, vertical PV dipoles are produced in the UTLS near the tops of convection. The level between the dipole center is the level at which the flow turns from cyclonic to anticyclonic (and from inertially stable to inertially unstable). In the presence of strong shear, horizontal dipoles are produced with associated inertial instability features and gravity wave radiation, similar to recent findings in the warm upglide sector of midlatitude cyclones (Rowe and Hitchman, 2015).

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Vertical and Horizontal Mixing in the Tropical Tropopause Layer

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Nearly all air enters the stratosphere through a single layer in the tropics. The tropical tropopause layer (TTL) is a transition region between the troposphere and stratosphere and its roles include regulating stratospheric chemistry and surface climate. Multiscale dynamics existing in the TTL range from transient convection to the hemispheric wave-driven circulation and the relative influences of these processes still remain unclear. This study pays special attention to vertical and horizontal mixing which are associated with breaking gravity waves and Rossby waves, respectively. We quantify the roles of these dynamics by taking advantage of the conservative nature of water vapor in the lower stratosphere. Unable to change concentration in the lowermost stratosphere after passing through the cold point, water vapor becomes a tracer for total transport and its signal is known as the tape recorder. This tape recorder is studied using observations, reanalysis data, a chemistry-climate model (CCM), and simple idealized modeling. Modifying past methods, we are able to capture the seasonal cycle of effective transport in the TTL and we introduce seasonally-dependent dynamics to a one-dimensional model and perform a parameter-sweep to test all possible dynamical combinations. Simulating with annual mean transports results in bimodality where either vertical advection or vertical mixing dominate. The solutions that depend on unrealistically large vertical advection disappear when seasonally-dependent transports are used. Overall, all datasets show that vertical mixing is as important to TTL transport as vertical advection itself even during boreal winter when advection peaks. The reanalysis and CCM have increased effective transport compared to observations, however, they rely on different dynamics. The reanalysis has amplified vertical mixing while the CCM has amplified vertical advection. This hints at the possible influence of spurious diffusion from data assimilation and its role in amplifying TTL transport.

Research Collaborations on Stratosphere-Troposphere Dynamical Coupling in the Tropics in Association with the Project of Years of the Maritime Continent (YMC) for 2017-2019

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Stratosphere-troposphere (S-T) dynamical coupling has been studied over decades, mostly focusing in mid- and high- latitudes (e.g., annular mode variability in both hemispheres, impacts of the ozone hole on surface climate, and so on). However, there are not so many studies on S-T dynamical coupling (i.e., two-way interactions) in the tropics, even though influence of the troposphere on the stratosphere by upward propagating tropical waves is quite clear and has been studied extensively.

S-T dynamical coupling in the tropics is a scientifically interesting and challenging subject, because the dynamics of the coupling processes is largely different from those in the extratropics. In the tropics, Coriolis parameter is so small that quasi-geostrophic constraint is not very strong. Small-scale moist convection is the predominant source to drive the atmospheric motions in contrast to synoptic-scale baroclinic instability in the extratropics. Multiscale interactions of moist convections produce a wide variety of coherent motions and structures of the tropical atmosphere. However, the scale separation is not very straightforward because the moist convection and larger scales are so tightly coupled, and it is hard to extract causality in the interactions. On the other hand, the stratospheric influence on the tropospheric variations is weak, but it is clearly external. S-T coupling process in each time scale could be studied to know how large-scale stratospheric variations influence on moist convection, and thus to understand how stratospheric variations influence on the tropospheric variations in weather and climate continuum.

There are some recent observational studies on such downward influence in association with stratospheric sudden warming (e.g., Kodera et al. 2011), quasi-biennial oscillation (e.g., Camargo and Sobel 2010, Liess and Geller 2012), and anthropogenic cooling trend (e.g., Emanuel et al. 2013, Vecchi et al. 2013). Numerical model studies with idealized experimental framework also made to study such a possible downward influence, including influence of QBO-like oscillation on convective organizations (Yoden et al. 2014) and that of the tropopause temperature trend on the intensity of tropical cyclones (Wang et al. 2014).

Stratosphere-troposphere interaction is one of the five main themes of the international research project “Years of the Maritime Continent” (YMC) planned for a two-year period from 2017 to 2019. Its objective is to improve understanding of processes governing the dynamical coupling of the stratosphere and troposphere and their mass exchanges over the MC. Possible SPARC-related activity on the S-T dynamical coupling in the tropics associated with the YMC project is proposed.

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QBO dynamics in a 7-km global climate simulation

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The quasi-biennial oscillation (QBO) in equatorial stratospheric zonal wind is a fairly predictable component of interannual climate variability, with documented effects on tropical cyclone activity and tropical-extratropical teleconnections. Model experiments suggest the QBO frequency may change with changing climate, however the sign and magnitude of predicted future changes are sensitive to highly uncertain model details. Our understanding of the QBO has evolved considerably over the last half century, but there is still much to learn. For example, there are uncertainties about the relative contribution from different wave populations to the zonal force driving the QBO. Furthermore, generating a QBO in atmospheric general circulation models (GCMs) is not a simple task. There is no singular method for obtaining a QBO in GCMs, and the QBO is extremely sensitive to many model parameters, such as horizontal and vertical resolution. A few models have been able to spontaneously generate a QBO without the use of parameterized gravity waves, but most models still need to rely heavily on them to get a QBO. We have investigated the dynamics of the QBO in the global 7-km GEOS-5 Nature Run. Even with very high horizontal resolution, parameterized gravity wave drag is still necessary to obtain a QBO. The results offer clues about the importance of vertical resolution, and choice of diffusion scheme and dynamical core for producing a QBO in GCMs.

Characteristics of Waves in the Tropical Tropopause Layer

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Resolving waves in the tropical tropopause layer (TTL) in climate models is beneficial in many ways. Waves in the TTL play an important role in regulating the water vapor transport into the stratosphere by modulating temperature and subsequent cirrus cloud formation. Also, wave-driven wind perturbations affect the distribution of atmospheric constituents and enable effective mixing of air. Furthermore, waves propagating into the stratosphere contribute to driving the mean tropical upwelling and quasi-biennial oscillation (QBO) of stratospheric wind. To properly represent waves in the stratosphere in global models, good representations of waves in the TTL is necessary since stratospheric waves mainly originate in the troposphere.

We will present basic properties of TTL waves such as geographic and seasonal variability, frequencies, and vertical wave scales from various observations including radiosondes, aircraft measurements, and COSMIC GPS temperatures. Results from reanalysis data will be compared to observations to identify missing components of wave properties. We will especially highlight the properties of fine vertical scale waves. Our comparisons between observations and reanalysis data will show that coarse vertical resolutions in current analysis systems and climate models hamper proper representations of wave-induced processes in the TTL and stratosphere.

Cirrus and Wave-induced Temperature Anomaly Relationships in ATTREX Measurements

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Wave-induced temperature changes are known to influence formation of cirrus clouds in the tropical tropopause layer (TTL). Formation and sedimentation of thin cirrus are a primary process affecting dehydration of air entering the stratosphere through the tropical tropopause. Previous studies have identified Kelvin wave influences on cirrus formation above 15-km altitude, and model studies have shown that higher frequency gravity wave temperature changes can increase cirrus cloud occurrence frequency and efficiency of dehydration in the TTL. Radiosonde observations indicate that wave induced temperature anomalies in the TTL typically have short vertical scales, with wavelengths commonly shorter than 4 km. These waves are generally poorly represented in global models due to limitations on vertical and horizontal resolution, and due to associated difficulties in representing the spatial and temporal scales of latent heating in precipitating cloud that are wave sources. We investigate relationships between fine-vertical-scale temperature structure and cirrus layers in ATTREX measurements.

Flight paths of the Global Hawk during ATTREX included frequent dive maneuvers through the TTL with insitu measurements of fine-scale structure in both temperature and ice particles. Measurements near radiosonde sites indicate layers due to very low-frequency gravity waves with periods of 2-3 days and vertical wavelengths of 1-2 km that have large horizontal extent, and are associated with thin cirrus layers. Overflight measurements with the down-looking cloud lidar give further indication of the horizontal extent of the cirrus layers. We also investigate statistical relationships between layered temperatures, winds, and ice particle occurrence in ATTREX data to support interpretation of layers as wave-induced.

An upper tropospheric cloud-convection (UTCC) process study

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The WCRP clouds grand challenge (GC) calls out for a focus on the role of convection on cloud feedbacks (Bony et al., 2015). Some of the questions posed in this GC concern the role of convection on cloud feedback and thus climate sensitivity. In particular there is a focus on feedbacks involving convection and UT clouds. There is some evidence that UT clouds (and cirrus in particular) assert a control on convection itself and thus on precipitation, an influence perhaps more important than on climate sensitivity. Critical to these feedbacks is the radiative heating in the upper troposphere and it has been hypothesized that high clouds regulate convection. The initial goal of this UTCC PROES, is to: understand the relation between convection and the heating introduced by the UT clouds produced by convection and provide observational based metrics that can be used to evaluate this process in models. This heating will be affected by at least 3 main factors:

- 1) Areal coverage of high clouds
- 2) Cloud emissivity
- 3) Temperature difference between the UTC and clouds underneath

Data are being assembled to address the question and to examine the factors that influence this heating. The data collected and initial results obtained will be presented. The hypothesis that it is the lower emissivity parts of anvils that produce the greatest UT heating and not those parts of anvils adjacent to the convection is being tested. The study is to be extended to examine relative roles of convectively generated UT clouds versus synoptically forced UT clouds and work toward these goals will be described.

Tropical tropopause layer variability associated with the Madden-Julian Oscillation during DYNAMO

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Observations show time variations in the TTL across multiple scales, including the intraseasonal variability of the Madden-Julian oscillation (MJO). In this study, we investigate the evolution of TTL properties and their vertical structure during the Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign from October-December 2011. This time period is particularly interesting in that two prominent MJO passages were seen over the tropical Indian Ocean. High vertical resolution radiosonde observations from the MJO initiation region (Gan Island; 0.7 S, 73.2 E) are contrasted with those from the decay region (Manus Island; 2.1 S, 147.4 E). CALIPSO satellite data is additionally used in determining the presence of thin cirrus clouds. Characteristics of the broad-scale structure of the MJO are analyzed, as well as higher-frequency variations. Spectral filtering is used to isolate low-frequency variability, Kelvin wave activity, and higher-frequency gravity wave perturbations. In particular, a 7-20 day bandpass of the temperature and zonal wind fields reveals strong TTL Kelvin wave signals in late October and early December. Its descending cold phase between 100-150 hPa coincides with a lowering of the cold point tropopause and an increase in cirrus cloud frequency preceding the active phase of the MJO. Another strong Kelvin wave signal appears in the lowermost stratosphere during the October MJO event, but which seems unrelated to the MJO below. Our analysis also shows that lower stratospheric gravity wave activity does not appear to be modulated by the MJO, but is generally stronger at Manus Island due to its proximity to the west Pacific warm pool.

Transport across the TTL and convective sources

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Transit properties across the TTL are studied using extensive forward and backward Lagrangian trajectories between cloud tops and the reference surface 380K. The tropical domain being subdivided into 11 sub-regions according to the distribution of land and convection, we estimate the contribution of each region to the mass flux across the 380K surface, the vertical distribution of convective sources and of transit times over the period 2005-2008. The excellent agreement between forward and backward statistics shows the robustness of the results presented here.

It is found that about 80% of the tropical parcels at 380K originate from convective sources all along the year. From November to April, the sources are dominated by the warm pool which accounts for up to 70% of the flux. During summer, Asian monsoon region is the largest contributor with similar contributions from oceanic regions and Asian man land, although the signature in vertical distribution and transit time is very different, Asian main land displaying higher sources and smaller transit times. The Tibetan plateau, although a minor overall contributor, is found to be the region with the highest proportion of convective parcels reaching 380K due to its central location beneath the Asian upper level anticyclone.

A simple 1D model ignoring horizontal transport is shown to reproduce very well the vertical regional source distribution but not the transit times. The reason is that the source distribution depends on local detrainment and transport near the zero level of heating rate while the transit depends a lot of the recirculation by horizontal transport. This 1-D model is used to perform a comparison of source distributions using several reanalysis, finding good agreement between ERA-Interim and JRA-55, that differ both from MERRA.

Convective transport of NMHCs and VSLS from the surface to the upper troposphere and lower stratosphere

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Deep convection is the primary mechanism that delivers important chemical constituents, e.g. nonmethane hydrocarbons (NMHCs) and very-short-lived halogen species (VSLS), into the upper troposphere and the lower stratosphere (UT/LS), where they exert significant impact on atmospheric O₃ and OH. Western Pacific has traditionally been viewed as the primary convective lofting region for air to enter the tropical tropopause layer (TTL). We will analyze aircraft measurements of CO₂, NMHCs (CO, ethyne, ethane, HCHO), and very-short-lived bromocarbons from both the ATTREX and CONTRAST missions to examine the transport timescale and transport efficiency of these chemical compounds from the surface to the UT/LS in the western Pacific. Using a newly developed model CO₂ capability as an accurate transport clock tracer, we will compare modeled CO₂, NMHCs and VSLS from the NASA Goddard GEOS-5 simulations with these observations to assess model transport and to diagnose potential model biases in these trace constituents, whether it is due to biases associated with photochemistry and emissions or due to transport errors. The results from the CONTRAST/ATTREX missions will be compared with our earlier results from the NASA SEAC⁴RS mission to address regional differences in convective lofting into the TTL and the impacts on UT/LS atmospheric composition.

Convective impacts on trace gases in the Tropical Tropopause Layer during Boreal Winter as seen during ATTREX

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In the Tropical Tropopause Layer, deep convective injection competes with slow, wave forced ascent and advection from midlatitudes in determining the distribution of trace gases (CO and water vapor) and clouds. Past studies have clearly shown that such convective injection is essential to understanding TTL satellite observations. In this paper, we: (1) briefly describe a high time/spatial resolution method based on satellite observations to incorporate convective injection into trajectory models, as well as its validation; and (2) apply this method to understanding aircraft observations of trace gases made during ATTREX.

Results for ATTREX3 indicate an evolution in the origin of convectively influenced air from the early flights during February (Africa and Indian Ocean) to the later flights during March (western and southwestern Pacific). This is due to the interaction of convection with the placement of the northern hemisphere western Pacific monsoon anticyclone. During ATTREX2, aircraft observations in the eastern Pacific were further from convective sources, but showed convective origins from both the southwestern and northwestern Pacific. The relationship between subseasonal variations of convective influence and TTL temperature (significant for in situ cloud formation processes) will be explored.

Efforts Toward Development Of A High Resolution Global Climatology Of Overshooting Cloud Top Detections Using MODIS and Geostationary Satellite Imager Data

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Researchers at NASA Langley Research Center have been developing an automated pattern recognition algorithm to identify overshooting convective cloud tops (OTs) in support of the GOES-R satellite program. This algorithm identifies regions of overshooting at the individual 1-4 km geostationary satellite pixel scale using visible (during daytime only) and infrared channel imagery and numerical weather analysis data. The algorithm has been developed based upon analysis of 0.25-1 km spatial resolution Aqua MODIS imagery, using a database of over 2000 manually identified OT features throughout the world in storms with varying intensity and morphology. The OT database includes storms ranging from small, warm topped storm cells over Alaska and Mongolia, tornadic supercells over the U.S. Central Plains and Europe, large tropical mesoscale convective systems, and overshooting in the eyewalls and spiral bands of intense tropical cyclones. The algorithm is designed to operate on data from any current and historical satellite imager, allowing for development of a highly accurate global OT detection climatology that extends back into the 1990's at up to a 15-30 min temporal resolution throughout the diurnal cycle. As members of the McIDAS Users Group, NASA LaRC has immediate access to the full global archive of geostationary imager data which would allow rapid development of OT climatologies and short-term databases. This type of capability has never been available within the weather and climate research community.

Regional geostationary OT databases have been already developed over periods ranging from 5-20 years over tropical regions such as Australia, Southeast Asia, and East Africa, and the eastern Caribbean Sea among many other non-tropical regions. Some of these datasets are being used by climate researchers and private industry to examine UTLS-penetrating storm spatial distributions and their temporal variability, in addition to weather hazards associated with these storms at unprecedented spatial detail. This presentation will describe the OT pattern recognition algorithm and highlight recent product applications.

Impact of Overshooting Deep Convection on the Stratospheric Water Vapor: an A-Train Satellite View

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The effect of overshooting deep convection (ODC) on the lower stratospheric humidity has been an unsettled subject. While the detrainment of extremely cold and dry air from convective cores may dehydrate the Tropical Tropopause layer (TTL), the convectively lofted ice crystals may moisten the TTL and the lower stratosphere. We seek to quantify the impact of ODC on the stratospheric water vapor by analyzing combined A-Train observations from Aura MLS, CloudSat/CALIPSO, Aqua AIRS and MODIS. CloudSat and CALIPSO reveal internal vertical structure of ODC while AIRS and MODIS provide a wide coverage of ODC in horizontal space. By matching ODC measurements from the active and passive sensors and identify statistical relationships between convective detrainment height and infrared bright temperature, we will establish a 3-dimensional ODC database with sufficient spatial and temporal coverage. The Aura MLS observed water vapor, temperature, ice water content and relative humidity profiles in the upper troposphere and lower stratosphere (UTLS) will be examined in relation to the ODC occurrence with the aid of Lagrangian trajectory calculations driven by reanalysis meteorological fields. We will compare the properties of stratospheric air parcels with and without ODC influence. Our preliminary results show that tropical ODC acts as an “express way” to moisten the lower stratosphere, although the rarity of ODC makes its impact on the annual mean stratospheric water vapor concentration rather small.

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Survey of global distribution of convection overshooting tropopause using first year GPM observations

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About a decade ago, the Tropical Rainfall Measuring Mission (TRMM) precipitation radar has observed the deep convection reaching above tropical tropopause dominantly over land, especially over central Africa (Liu and Zipser 2005). Since the launched in February 2014, the Global Precipitation Mission (GPM) satellite, the successor of TRMM, has provided more than one year space borne radar observations covering 65°S-65°N. Using the similar methodology of Liu and Zipser (2015), the global distribution of the convection reaching tropopause is surveyed again with one year GPM data. In addition to the confirmation of what TRMM has observed, significant differences in the occurrence of overshooting convection are found at mid to high latitudes in summer between Northern and Southern hemisphere. Several hotspot regions with frequent overshooting convection are present at mid and high latitudes in Northern land. They could have significant influences in the water vapor budget in the stratosphere there.

The OMPS Limb Profiler Stratospheric Aerosol Products and Comparisons to the GEOS-5 Chemistry-Climate Model

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The Ozone Mapping and Profiler Suite (OMPS) on board the Suomi National Polar-orbiting Partnership (S-NPP) spacecraft was launched on October 28, 2011. The Limb Profiler instrument on OMPS (OMPS LP) is designed to provide high vertical resolution ozone and aerosol profiles from measurements of the scattered solar radiation in the 290 – 1000 nm spectral range. OMPS LP collected its first Earth limb measurements on January 10, 2012, and continues to provide daily, global measurements from cloud top to altitudes of 60 km for ozone and 40 km for aerosols. Although the instrument was designed primarily for vertical ozone profile measurement, it has a high sensitivity to stratospheric aerosols, cirrus clouds in the upper troposphere, and stratospheric and mesospheric clouds. The relatively high vertical and spatial sampling allow detection and tracking of periodic events when aerosol particles are injected into the stratosphere, including volcanic eruptions and meteor explosions. Here we review the OMPS LP aerosol products and present highlights of its recent measurements. We will also compare OMPS stratospheric aerosol products to model results from the NASA Goddard Earth Observing System (GEOS-5) chemistry-climate model, which has been updated to include a sectional aerosol microphysical module for simulating stratospheric aerosol lifecycle.

An assessment of upper-troposphere and lower-stratosphere water vapor in GEOS5, MERRA, and ECMWF analysis and reanalyses using Aura MLS observations

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Abstract

Global water vapor (H₂O) measurements from the Microwave Limb Sounder (MLS) are used to evaluate upper troposphere (UT) and lower stratosphere (LS) H₂O produced by Goddard Earth Observation System assimilation system, version 5 (GEOS5), Modern-Era Retrospective Analysis for Research and Applications (MERRA) and European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalyses. Focusing on quantifying the H₂O amount and the transport from UT to LS, we show that all analyses/reanalyses overestimate UT H₂O by ~200% compared to MLS observations. Both observation and analyses show that boreal summer monsoon convection has a dominant influence on UTLS H₂O, resulting in moister air in the northern hemisphere (NH) than in the southern hemisphere (SH). However, substantial differences in H₂O transports are found in different datasets. Vertically, H₂O transport across the tropical tropopause simulated by GEOS5, MERRA and ECMWF are faster by ~200%, 130% and 300% respectively, compared to the MLS observations; in the LS (20-30 km), ECMWF simulated vertical transport is twice as fast as implied by MLS observations, while GEOS5 and MERRA have vertical transport velocities similar to the MLS values. Horizontally, both observation and analyses show faster poleward transport in the NH than in the SH; In the NH, the simulated 100 hPa H₂O “effective horizontal transport velocities” are 180%, 210%, and 130% of the MLS observed value for GEOS5, MERRA, and ECMWF respectively; In SH, these simulated “effective horizontal transport velocities” are slower (50%) for GEOS5 and MERRA, but faster for ECMWF (120%), compared to the MLS observations.

An assessment of the CAM5/CARMA model's TTL cirrus cloud representation through comparisons with ATTREX 3 and CALIPSO observations

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The Tropical Tropopause Layer (TTL) over the Western Pacific is a region known to be crucial in facilitating the exchange of tropospheric and lower stratospheric air. From satellite observations we can see that large amounts of upwelling occurs in the Western Pacific that transports water vapor into the lower stratosphere. These characteristics make this region important to Earth's hydrological cycle and climate. Unfortunately, until recently there has been an overwhelming lack of in situ observations for the Western Pacific. Consequently, it is difficult to assess the performance of global climate models (GCM's) in this region. Due its importance however, it is imperative that GCM's properly represent this region when simulating Earth's climate. The completion of the ATTREX 3 campaign centered in Guam, USA has addressed this issue by providing a comprehensive and unique set of observations of the TTL over the Western Pacific. In our study we use this new data set alongside the long running CALIPSO satellite mission to perform model comparisons and assess model performance. We use the National Center for Atmospheric Research's (NCAR) CAM5 model coupled with an advanced sectional microphysics cloud model CARMA. In our investigation two separate comparisons with observational data are performed. The first evaluation assesses the model's ability to represent higher resolution features seen by aircraft observations. We study some of the unique cloud features seen during ATTREX 3 supported by CALIPSO observations. The second model comparison looks at 5-year model climatology of the Western Pacific against 5 years of CALIPSO observational data. The use of a satellite simulator, COSP, allows CAM5/CARMA output to be directly compared to CALIPSO observations by forcing the model to simulate the CALIPSO retrieval methods. For this study the model was run a 1x1 degree resolution. We present our results here.

Comparison of WRF simulated mass fluxes with those derived from radar observations for the Tropical Western Pacific

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The Australian Monsoon during Austral summer experiences vigorous convection rapidly delivering air masses from the surface to the tropical tropopause layer (TTL). The tropical western pacific is of crucial importance in determining very short lived substance delivery from the ocean and land surfaces to the stratosphere [Fueglistaler and Haynes, 2005]. In particular, the stratospheric halogen [Salawitch, 2006] and sulfur budgets, and the oxidative capacity of the tropical atmosphere are defined by these meso-scale dynamical processes. A critical examination of the mass fluxes is made using the Weather Research and Forecasting (WRF) convection resolving case studies during Stratospheric-Climatic Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-03) and Tropical Warm Pool International Cloud Experiment (TWP-ICE) campaigns (November 2005 and January - February 2006 respectively). The SCOUT-03 campaign occurred before the main monsoon period, and experienced biomass burning conditions [Frey *et al.*, 2015]. Two 5-day simulation periods during TWP-ICE are examined, during break and monsoon conditions respectively [Hassim *et al.*, 2014]. These simulated mass-fluxes are compared with observational estimates from radar and the implications for trace-gas delivery are discussed. The rate at which air-masses are replaced, an important quantity in chemistry climate modelling, is explored through the determination of detrainment rates from WRF simulations and radar observations.

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Growth in the stratospheric loading of halogenated very short-lived substances and their impact on ozone and climate

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Observations show that very short-lived substances (VSLS), with lifetimes generally <6 months, are an important source of stratospheric halogens. Bromine-containing VSLS are produced naturally by seaweed and phytoplankton, whereas chlorine-containing VSLS are primarily anthropogenic. We have used the TOMCAT/SLIMCAT chemical transport model to quantify the depletion of ozone in the lower stratosphere from VSLS, and a radiative transfer model to quantify the radiative effects of that ozone depletion.

According to our simulations, VSLS-driven ozone loss had a radiative effect nearly half that from long-lived halocarbons in 2011 and, since pre-industrial times, has contributed a total of about -0.02 W m^{-2} to global radiative forcing. We find that natural bromine-containing VSLS exert a $\times 3.6$ larger ozone radiative effect than long-lived halocarbons, normalized by halogen content, and are therefore relatively efficient at influencing climate.

We have also developed a detailed chemical mechanism describing the tropospheric degradation of chlorine-containing VSLS. The scheme was included in the CTM and used to quantify trends in the stratospheric injection of chlorine from anthropogenic VSLS, $\text{Cly}[\text{VSLS}]$, between 2005 to 2013. By constraining the model with surface measurements of chloroform (CHCl_3), dichloromethane (CH_2Cl_2), tetrachloroethene (C_2Cl_4), trichloroethene (C_2HCl_3) and 1,2-dichloroethane ($\text{CH}_2\text{ClCH}_2\text{Cl}$), we infer a 2013 stratospheric $\text{Cly}[\text{VSLS}]$ mixing ratio of 123 parts per trillion (ppt). Stratospheric injection of source gases dominates this supply, accounting for $\sim 83\%$ of the total. The remainder comes from VSLS-derived organic products, phosgene (COCl_2 , 7%) and formyl chloride (CHClO , 2%), and also hydrogen chloride (HCl , 8%). Stratospheric $\text{Cly}[\text{VSLS}]$ increased by $\sim 52\%$ between 2005-2013, with a mean growth rate of 3.7 ppt Cl/yr. This increase is due to recent and ongoing growth in anthropogenic CH_2Cl_2 – the most abundant chlorinated VSLS not controlled by the Montreal Protocol.

We conclude that potential further significant increases in the atmospheric abundance of short-lived halogen substances, through changing natural processes or continued anthropogenic emissions, could (i) be important for future climate and (ii) become relevant for understanding the future evolution and recovery of stratospheric ozone.

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Halocarbons in the TTL: the roles of oceanic emissions and atmospheric transport

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Global modelling studies of brominated and iodinated halocarbons often rely on annual mean emission scenarios following the top-down approach. One drawback of this approach is the adjustment of the emissions in order to reproduce upper-air observations without taking into account seasonal or interannual variations in either of the two factors. Recent biogeochemistry-halocarbon modelling has shown, however, that temporal variations in the oceanic production can drive a strong seasonal reversal of the emissions. Comprehensive methods combining our understanding of oceanic and atmospheric processes are required in order to derive reliable estimates of halocarbon emissions and TTL abundances.

In this study, we will use monthly mean emissions of brominated and iodinated halocarbons to derive their contribution to the global stratospheric halogen loading based on transport calculations with the Lagrangian particle dispersion model FLEXPART. We will analyze how seasonality in both processes, marine emissions and atmospheric transport, drives the seasonality of the halocarbon distribution in the TTL. Aircraft observations from the last 25 years are classified according to the temporal variability of the halocarbon distribution derived from the FLEXPART simulations. Thus, we are able to identify which aircraft observations can be considered representative for the mean halocarbon abundance and which observations are strongly tied to the seasonal variations in emissions and transport. In combination with backward trajectory runs from the aircraft locations to the surface, we will show where upper-air observations are consistent with our understanding of emissions and transport and where marine sources are missing. Based on the global Lagrangian transport calculations, the overall contributions of various oceanic regions to the TTL halogen budget are determined. In addition, the importance of halogen emissions from the open ocean versus emissions from coastal regions for the TTL budget is discussed. By combining up-to-date emission scenarios, global Lagrangian transport calculations and existing aircraft measurements our study identifies where and when future oceanic and upper-air measurements are necessary to enhance our understanding of marine halocarbons in the TTL.

Tropical tropospheric bromine and stratospheric injection of Br_y from VSL compounds inferred from CONTRAST

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The CONvective TRansport of Active Species in the Tropics (CONTRAST) field campaign was designed to quantify the abundance of very short lived (VSL) bromocarbons in the marine boundary layer (MBL) of the Tropical Western Pacific, the variation with respect to altitude of these compounds from the MBL to the base of the tropopause transition layer, and the abundance of BrO throughout the tropical troposphere. Here we examine the theoretical understanding of VSL source gases by comparing measurements of these bromocarbons provided by two instruments, AWAS and TOGA, to model values found using CAM-Chem. We examine also the bromine budget in the tropical troposphere: i.e., consistency between tropospheric loss of these compounds and the appearance of products using observations of BrO from two other instruments, CIMS and DOAS. Finally, implications for supply of bromine to the lower stratosphere via source gas and product gas injection will be examined, based largely on data collected during flights that probed the extra-tropical, lower stratosphere.

Measurements of bromine monoxide and iodine monoxide in the lower stratosphere: constraints on total inorganic bromine and iodine

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Halogens have important direct and indirect effects on atmospheric chemistry e.g. ozone destruction, oxidative balance, mercury processing, particle seeding and growth. The monoxides of bromine and iodine (BrO and IO) are important constituents of inorganic halogens that were measured by the Airborne Multi AXis Differential Optical Absorption Spectroscopy (AMAX-DOAS) instrument during the The CONvective TRansport of Active Species in the Tropics (CONTRAST) campaign. Here we examine two case studies – CONTRAST RF06 and RF15 – which sampled the tropical UTLS during a horizontal transect jet-crossing into the mid-latitude lower stratosphere. We have accomplished a first detection of IO in the lower stratosphere. We compare our observations with the global chemistry climate model CAM-Chem, and the global chemistry transport model GEOS-Chem. We further use a chemical box-model, constrained by measurements of BrO and IO as well as by AWAS, TOGA, and other measurements on the aircraft, to determine the total budgets of inorganic bromine and iodine, and investigate correlations of total Br_y and I_y with air mass indicators such as CFC-11.

Measurement and simulation of CH₄, O₃, NO₂, BrO, and major brominated source gases during the NASA-ATTREX Global Hawk deployments in 2013: Implications for the photochemistry and total amount of bromine in the TTL and stratosphere

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Bromine chemistry impacts the levels of ozone in the upper troposphere and the stratosphere. An accurate quantitative understanding of the sources, sinks, and chemical transformation of bromine species is thus important to understand the photochemistry and budget of bromine in the tropical upper troposphere, tropopause layer and lowermost stratosphere (UT/TTL/LS). These regions are also known to serve as a gateway for delivery of ozone depleting gases to the stratosphere. CH₃Br, halons, and short-lived organic bromine precursors (VSLs), such as CHBr₃, CH₂Br₂, and possibly inorganic product gases, have been identified as the main bromine gases delivered to the stratosphere. However, many important details for example how, and to what extent, VSLs and inorganic bromine compounds are transported to the TTL are not clear to date. Moreover, a number of chemical processes, including the transformation of the source gases and cycling of inorganic bromine species at low ambient temperature and on ice particles are also poorly understood.

The present talk (which complements the talk of Navarro et al. on the GWAS measurements of brominated source gases) reports on measurements of CH₄, O₃, NO₂, and BrO performed by different instruments and techniques during the 2013 NASA-ATTREX flights in the TTL and LS. The interpretation of our measurements is supported by chemical transport model (SLIMCAT) simulations. SLIMCAT results in conjunction with extensive radiative transfer calculations using the Monte Carlo model McArtim also assist in an improved concentration retrieval of O₃, NO₂, and BrO from limb scattered sunlight measurements using the well-known Differential Optical Absorption Spectroscopy (DOAS) technique. The model also allows us to attribute observed concentration variations to transport and photochemical processes. When properly accounting for the transport-related concentration variations, measured BrO is found to be mostly larger than model simulations using standard JPL-kinetic data in the model. When these kinetic data, which are mostly available for higher temperatures than those (> 188K) encountered during the NASA ATTREX mission are adjusted to match our temperature observations, this gap can be largely closed, and total bromine in the TTL is quantified to 21±1 ppt in 2013.

NAME modelling activities for ATTREX-CONTRAST VLS measurements

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The work presented shows the analysis of the Numerical Atmospheric dispersion Modelling Environment (NAME model) runs made from the ATTREX-2 flight campaign over the East Pacific in January-February, 2013, and the ATTREX-3 and CONTRAST flight tracks over the West Pacific in January-March, 2014. For each flight, particles (15,000 per single point along the flight track where Advanced Whole Air Samplers took measurements) are released from the flight altitude tracks and followed 12 days backwards to identify the origin, location and timescales of the air mass reaching the Tropical Tropopause Layer (TTL). Cases presented are for flights with evident high and low degree of convective influence. Fractions of trajectories are calculated according to particles which crossed certain levels in the low troposphere such as 5 and 1 km. Then, initial concentrations for Very Short Lived Species (VLS), in particular bromoform, methyl iodide and dibromomethane are assigned, based on (i) AWAS ATTREX/CONTRAST observations and (ii) WMO (2010) boundary layer concentrations - to particles which originated from below 5/1 km. The contributions of low altitude air masses to the high altitude samples can then be estimated. These NAME modeled results are then compared with ATTREX VLS flight measurements. Flights from the ATTREX-2 and ATTREX-3 are used to assess the spatial and temporal variability within the vertical transport in deep convection which is one of the crucial factors in redistributing chemicals within the Pacific tropical troposphere.

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Enhanced ozone loss by active inorganic bromine chemistry in the tropical troposphere

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This study represents the first simultaneous airborne measurements of BrO, BrCl, Br₂ and HOBr in the tropics using a chemical ionisation mass spectrometer (CIMS). The results suggest that inorganic halogen chemistry has a more significant impact on O₃ depletion and oxidising capacity of the troposphere than previously thought. The CIMS instrument was operated on-board the BAe-146 FAAM research aircraft across 20 flights, as part of the CAST (Coordinated Airborne Studies in the Tropics) campaign based on Guam, Micronesia and was supported by measurements of O₃ and NO_x from core instruments and bromocarbons from Whole Air Samples (WAS). The mean tropospheric BrO concentration over 20 flights was calculated to be 0.69 ppt; a factor of 4 times greater than that predicted by GEOS-Chem running with a tropospheric bromine simulation. An underestimation of HOBr, Br₂ and BrCl in the model, when compared to the CIMS data, will contribute to this discrepancy, thus increasing the availability of atomic Br through photolysis, however this does not compensate for the bias currently observed. The magnitude of this discrepancy and subsequent effect on O₃ depletion in the tropics is assessed and possible mechanisms are proposed. The measurements of these halogenated species are further used to assess their impact on the HO_x budget in the tropics via steady state estimations.

Transport of halogenated VSLS from the Indian Ocean to the stratosphere through the Asian monsoon circulation

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Halogenated very short lived substances (VSLS, e.g. bromoform) are naturally produced in the ocean and emitted to the atmosphere. When transported to the stratosphere, these compounds and their product gases increase the stratospheric halogen burden and influence ozone and climate. The Asian monsoon circulation provides an effective pathway for air masses from the atmospheric boundary layer to enter the global stratosphere during boreal summer. The role of biogenic VSLS emissions from the tropical Indian Ocean and their entrainment into the stratosphere above India and Bay of Bengal has not been investigated yet, but is crucial in understanding chemical and dynamical processes controlling ozone concentrations in the tropical tropopause layer (TTL) and the stratosphere.

During the research cruises SO234-2 and SO235 from Durban, South Africa, to Malé, Maldives, on board RV SONNE in July-August 2014 we measured oceanic VSLS in the subtropical and tropical West Indian Ocean and calculated their emission strengths. In order to analyze the transport of VSLS in the atmosphere we use the Lagrangian transport model FLEXPART with ERA-Interim meteorological fields.

First, we investigate the direct contribution of oceanic VSLS to the atmospheric halogen budget based on emissions observed during the ship cruise. FLEXPART forward trajectories were initiated with observed bromoform emissions along the cruise track, prescribing a varying atmospheric lifetime profile for bromoform between 11 and 18 days. For emission points within the influence of the Asian monsoon circulation, between 15°S and 3°S, about 2% of the emitted bromoform was entrained into the stratosphere.

Furthermore, we analyze the coupling between the oceanic source regions and the monsoon anticyclone in the TTL above the Asian continent during boreal summer. Trajectory ensembles released at the West Indian Ocean surface mainly enter the stratosphere above the Indian subcontinent and the Bay of Bengal. This is the region of where the Asian monsoon anticyclone isolates tropospheric air masses and lifts them to the lower stratosphere. We calculated FLEXPART backward trajectories, starting from different heights in this region, to investigate the major source regions for air masses reaching the stratosphere.

Bi-modal Distribution of Tropical Tropospheric Ozone over the Western Pacific from CONTRAST Observations

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Observations during the recent airborne field campaign CONTRAST revealed a bi-modal distribution of free tropospheric ozone over the remote western Pacific. A primary mode, narrowly distributed around 20 ppbv, dominates the free troposphere from the surface to 15 km in altitude (~360 K potential temperature level). A secondary mode, broadly distributed with a 60 ppbv modal value, is prominent between 315 K to 345 K potential temperature levels. These findings provide new insight on the physical interpretation of the mean ozone profiles in the tropics, including the identification of the TTL. In this paper, we present the observations, analyses and modeling, using both NCAR global model CAM-Chem and trajectory models, to characterize the bi-modal behavior of ozone and the controlling mechanisms.

A Tropical Tropospheric Source of High Ozone/Low Water Filaments in the Western Pacific

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Numerous field campaigns have noted the prevalence of filaments of high O₃ and low H₂O (HOLW) in the tropical western Pacific (TWP) troposphere. These filaments can drastically alter the chemistry, meteorology, and climate of the region through alteration of the OH budget, suppression of convection, and changes in local radiative forcing. These filaments are often cited as having a dynamical origin, caused by transport from the mid-latitude upper troposphere (mlUT) or stratosphere. Studies attributing the high O₃ to tropical tropospheric processes, namely biomass burning, frequently do not explain the low H₂O. We will show that these filaments were a dominant feature observed during the CONTRAST and CAST campaigns, conducted in the TWP during January and February 2014. Back trajectory analysis connects the observed HOLW filaments to regions of active biomass burning in the tropics. The chemical composition of the filaments confirms this biomass burning origin and suggests that mlUT and stratospheric influence is negligible. We will also show that the low H₂O observed in these filaments is consistent with large-scale subsidence in the tropics.

Modelling Manus ozone using WRF

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Ozonesondes launched as part of the CAST campaign on Manus Island, Papua New Guinea have been verified. One of the features appearing from the ozonesonde profiles was an episode of anomalously low ozone concentrations in the TTL (12 ppb), which will become the focus of a modelling exercise to ascertain the dynamics that produced these low ozone concentrations.

It is hypothesized that the low ozone was lifted from the lower troposphere to the TTL in a region of deep convection to the east of Manus Island, before advection moves the air parcel over Manus. Using WRF, we want to address the questions of whether the model can replicate the convection in the West Pacific, and how deep the convection is: has the air ascended from within the boundary layer and/or all the way from the surface?

In this presentation, the method used to address these scientific questions will be presented, along with preliminary experimental results and plans for future experiments.

Sources of Seasonal Variability in Tropical UT/LS Water Vapor and Ozone: Inferences from the Ticosonde Dataset

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We present an analysis of joint balloon sonde profiles of water vapor and ozone made at Costa Rica from 2005-2011 using compositing techniques, tracer-tracer diagrams and back-trajectory methods. Our analysis reveals important seasonal differences in structure in the upper troposphere and lower stratosphere. Water vapor amounts in boreal winter at Costa Rica are much lower than expected from local ice saturation temperatures. The boreal summer data show both higher average water vapor amounts and a much higher level of variability than the winter data. To understand this seasonal contrast we consider three sources of tracer variability: wave-induced vertical motion across strong vertical gradients ('wave variability'), differences in source air masses resulting from horizontal transport ('source variability'), and changes induced along parcel paths due to physical processes ('path variability'). The winter and summer seasons show different mixes of these three sources of variability with more air originating in the tropical western Pacific during winter.

Near-tropopause Ozone Variability at Tropical and Subtropical Ozonesonde Sites Revealed from Self-Organizing Map Clustering

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Recent efforts have been made to characterize long-term ozonesonde records with self-organizing map (SOM) clustering. Clusters of ozone (O₃) mixing ratio profiles reveal seasonal, source region, and large-scale meteorological influences on the tropospheric profile. SOM clustering of two tropical ozonesonde profile data sets by Jensen et al. (2012) revealed clusters corresponding to convection and subsidence, and biomass burning transport. Stauffer et al. (2015, submitted JGR) clustered >4500 O₃ profiles with SOM from four contiguous U.S. sites and found clusters that exhibited tropopause height anomalies of several km below monthly climatological values. Mid-tropospheric O₃ mixing ratios also deviated from climatology by up to +30% in a cluster containing polluted Wallops Island, VA O₃ profiles. We show the SOM clustering technique applied to tropical and subtropical O₃ profiles to quantify variability of O₃ in the near-tropopause region (NTR) over a range of latitudes. As in both the Jensen et al. (2012) and Stauffer et al. (2015) studies, we find O₃ profile clusters reveal features of O₃ in the NTR that would otherwise be diluted by monthly or seasonal averaging techniques.

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The impact of upper tropospheric and lower stratospheric ozone changes on global warming projections

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Trace gas concentrations in the tropical upper troposphere and lower stratosphere (UTLS) are of crucial importance for the global energy budget, firstly, because the very low temperatures make greenhouse gas changes in this region particularly effective in driving radiative forcing and, secondly, since the tropical UTLS structure plays a central role in determining the entry of trace gases and aerosols into the stratosphere.

In a recent study (Nowack *et al.*, 2015), we provided further evidence that composition changes in the UTLS can significantly affect global warming projections. Using a state-of-the-art atmosphere-ocean chemistry-climate model, we found a ~20% smaller global warming in response to an abrupt 4xCO₂ forcing if composition feedbacks were included in the calculations as compared to experiments in which composition feedbacks were not considered. We attributed this large difference in surface temperature change mainly to circulation-driven decreases in tropical UTLS ozone and related changes in stratospheric water vapor, partly counteracted by simultaneous changes in ice clouds.

Here, we extend our previously reported results by analyzing longer runs and additional experiments. Based on these modeling experiments, we show how considering different levels of complexity in composition changes can affect estimates of global clear-sky and cloud feedbacks. Finally, we explain why the impact of these processes is expected to differ among models. We highlight that improving our understanding of processes in the tropical UTLS and their representation in Earth system models remains a key challenge in climate research.

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Air mass source regions and their influence on the distribution of organic and inorganic brominated species.

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Brominated very short-lived substances (VSLS), along with their degradation products (e.g. BrO, Br_y^{inorg}), contribute significantly to the stratospheric bromine that ultimately lead to ozone depletion. However, the accurate estimation of the stratospheric bromine budget remains uncertain due to the limited understanding of their tropospheric processes, the distribution and magnitude of emissions, and the sparse observations of organic and inorganic brominated species.

Several studies have revealed that short-lived brominated gases, and/or their breakdown products, are delivered from the marine boundary layer to the lower stratosphere via rapid deep convection, but their temporal and spatial distribution vary significantly. These changes in their distribution are attributable to the several factors, including the geographical location of the source, the transport dynamics and history of air masses.

In this presentation, we examine the vertical distribution of organic brominated species (CH₃Br, Halons, and VSLS) and the VSLS degradation products (BrO and Br_y^{inorg}) measured simultaneously, and for the first time, by two instruments deployed during NASA ATTREX campaign (GWAS and Mini-DOAS). We focused on measurements taken during ascending profiles (from ~14 to 19 Km) where observations from both instruments overlapped. 10-day diabatic back trajectories (from selected points along the flight tracks) are used to investigate the impact of the air masses source regions on the distribution of organic and inorganic brominated species, and on the estimation of the total bromine in the Tropical Tropopause Layer.

AMAX-DOAS profiles of BrO and IO in the tropical UTLS: comparison of optimal estimation and parameterization methods

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Recent measurements of limb-scattered solar photons by the University of Colorado Airborne Multi-AXis DOAS instrument (CU AMAX-DOAS) aboard the NSF/NCAR GV aircraft have detected up to 3.0 pptv BrO and 0.1 to 0.25 pptv IO over the tropical Pacific Ocean (Dix et al., 2013; Volkamer et al., 2015). These observations remain currently unexplained by atmospheric models. The CU AMAX-DOAS instrument is optimized to (1) locate BrO, IO and glyoxal in the troposphere, (2) decouple stratospheric absorbers, (3) maximize sensitivity at instrument altitude, (4) facilitate altitude control and (5) enable observations over a wide range of SZA. Several techniques are available to derive vertical columns or vertical trace gas profiles from measured slant columns. The most widely used approach is based on Optimal Estimation, an inversion technique that we have applied in the past to retrieve vertical BrO and IO profiles during aircraft ascents and descents, and successfully evaluated by comparing trace gases such as NO₂ and H₂O with atmospheric models and in-situ observations (Volkamer et al., 2015). Optimal Estimation requires detailed knowledge on the atmospheric state, including aerosol load, and is computationally intensive as it requires calculation of weighting functions from radiative transfer models. We have developed a method that parametrizes radiative transfer and converts slant column densities into volume mixing ratios along the flight track based on comparison of O₂-O₂ collision complexes at tropospheric altitudes. Here we present a comparison of BrO and IO profiles calculated using Optimal Estimation and the new parametrization method using data from the Tropical Ocean Troposphere Exchange of Reactive halogen species and Oxygenated VOC (TORERO) and CONvective TRansport of Active Species in the Tropics (CONTRAST) field campaigns. We compare both methods and discuss their suitability and specific advantages for select case studies.

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COMPARATIVE STUDY OF VARIABILITY OF ORGANIC ACID IN AIR OF THE ATMOSPHERE IN THE HUMID SAVANNAH OF LAMTO IN CÔTE D'IVOIRE AND DJOUGOU IN BENIN

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From January 2005 to December 2009, a total of 457 and 444 samples were collected respectively rains in humid savannas of Djougou and Lamto. Using Henry's law, we determined the concentration in the air of the major organic monoacid (HCOOH and CH₃COOH) from their concentration in rainwater. At Lamto, annual partial pressure of organic monoacid on the five year study is very little variable. It covers a range of 0.1 ppb and 0.2 ppb to 0.4 to 0.7 ppb respectively for formic acid and acetic acid. While in Djougou, it is very variable. It varies from .01 to 0.19 ppb to formic acid and 0.04 to 0.54 ppb to acetic acid. For both stations, it is a two times higher in the dry season than the wet season factor. This difference is related to the enrichment of a monoacid organic acid content in the air by supplying various sources of these acids. However, the correlation analysis that enables the production of formic acid and acetic acid Djougou like Lamto is not related to the marine source although the latter is close to the Gulf of Guinea.

Keywords: partial pressure; organic acidity; variability, humid savanna

Water Vapor Measurement Biases in the TTL: MLS vs Frost Point Hygrometers

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Water vapor in the tropical tropopause layer (TTL) influences the Earth's radiation budget. The water vapor distribution in the TTL is established as moist tropical air masses are freeze-dried as they enter the stratosphere. Our ability to accurately quantify dehydration and the ice nucleation processes that control it is limited by the accuracy of water vapor measurements in the TTL. Frost point hygrometers have been used for several decades to measure water vapor vertical profiles from the surface through the TTL to the stratosphere, but soundings are temporally and spatially sparse, especially in the tropics.

The Aura Microwave Limb Sounder (MLS) has provided near-global measurements of upper atmospheric water vapor since August 2004. Tropical data from MLS are used to quantify the stratospheric entry mixing ratios of water vapor, to determine vertical transport rates in the tropical stratosphere through analysis of the "tape recorder", and to evaluate long-term water vapor trends that may result from climate change.

Statistically significant biases of -0.1 and -0.3 ppm (-3 and -8%) have been reported [Hurst *et al.*, 2014] between NOAA frost point hygrometer (FPH) soundings at Hilo, Hawaii (20°N), and coincident MLS water vapor retrievals in the TTL (83 and 100 hPa) during 2010-2012. Here we extend the comparison further down into the TTL and include data for 2013-2014. By the end of 2014 the Hilo FPH-MLS bias at 83 hPa had increased to -0.4 ppm (-11%) while the 100 hPa bias remained unchanged. Lower in the TTL, at 121 and 147 hPa, FPH-MLS biases during 2010-2014 were +0.5 and +1.9 ppm (+10 and +20%). A similar analysis of differences between cryogenic frost point hygrometer (CFH) soundings at San José, Costa Rica (10°N), and coincident MLS retrievals indicates similar biases in the TTL during 2005-2014, with an even larger increase in the 83 hPa bias to -0.5 ppm (-13%) by mid-2014.

Though none of these biases exceed the combined MLS and FP measurement accuracies, their magnitudes translate to significant uncertainties in the amounts and vertical distribution of water vapor in the TTL. For example, if MLS retrievals are used preferentially over FP sounding profiles, air masses are 10-20% drier in the lower TTL and 5-13% wetter in the upper TTL near the coldpoint. The large differences in TTL water vapor mixing ratios presented by these two data sets lead to considerable uncertainties when trying to understand dehydration and ice nucleation processes in the TTL.

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The relationship between tropical lower stratospheric upwelling and global temperature change in chemistry- climate models

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Climate models consistently simulate an increase in the strength of upwelling in the tropical lower stratosphere under climate change. Despite this being a ubiquitous feature in climate change projections, the mechanisms underlying this response have received relatively little attention. Data from an ensemble of chemistry-°©-climate models are analysed and show that the strengthening of tropical lower stratospheric upwelling over the 21st century is strongly correlated with the magnitude of lower tropospheric warming. However, the magnitude of the increase in upwelling for a given warming differs amongst models. This spread in 'dynamical climate sensitivity' is important for understanding simulated trends in tropical lower stratospheric ozone and water vapour, which have been highlighted as important climate feedback mechanisms. The strong relationship between tropospheric warming and the change in tropical upwelling offers insights into the possible underlying mechanisms.

Representation of the Bi-modal Distribution of Tropical Free Tropospheric Ozone over the Western Pacific and Associated Controlling Mechanisms in CAM-CHEM

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During the CONTRAST field study, *in situ* aircraft observations revealed persistent layers of enhanced ozone relative to background concentrations in the Western Tropical Pacific middle troposphere during the Northern Hemispheric winter, creating a distinct bi-modal distribution of ozone mixing ratios. These enhancements may have a measureable impact on the troposphere's oxidizing capacity in the tropics, which has a direct effect on the regional climate of the western tropical Pacific Ocean and beyond. In this work, we investigate whether the bi-modal ozone behavior is represented in the NCAR chemistry-climate model CAM-CHEM. Initial results show that the CAM-CHEM model is capable of adequately reproducing the background ozone and enhanced ozone layers that form the bi-modal ozone mixing ratio distribution. Further investigations to identify the mechanisms in the model that control the two modes will be presented.

Verification of the CAST ozonesonde measurements from Manus

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The CAST ozonesonde measurements were hindered by a contamination event, which required careful consideration to eliminate the effects of the contamination on the ozone data. The ozone measurements are highly sensitive to the background correction, especially in the tropical tropopause layer (TTL), where the background signal constitutes about half of the measured signal.

Using a combination of post-CAST laboratory experiments and comparison between the CAST ozonesondes and the Gulfstream V aircraft, an effective method for correcting the background signal for both contaminated and uncontaminated ozonesondes was devised.

It can be shown that there is no instance of near-zero ozone, which was reported in previous papers (e.g. Kley et al., 1996; Rex et al., 2014), within the CAST ozonesondes. However, the near-zero ozone can be reproduced in the CAST ozonesondes by an incorrect choice of background signal correction; it is expected that the near-zero ozone events reported are actually artefacts of the background correction.

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O₃ variability in the troposphere and the stratosphere from IASI observations in 2008-2014

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In this study, we present for the first time, geographical patterns of ozone (O₃) variability in the troposphere and the stratosphere derived from the seven first years of the Infrared Atmospheric Sounding Interferometer (IASI) observations (2008-2014). The IASI/MetOp instrument provides a unique dataset of global vertically-resolved O₃ profiles with a high temporal sampling and a fairly good vertical resolution in the troposphere and the stratosphere allowing us to monitor the year-to-year variability in these layers. The retrievals are performed using the FORLI software, a fast radiative transfer model based on the optimal estimation method, set up for near real time and large scale processing of IASI data. Multivariate regressions which include important geophysical drivers of O₃ variation (e.g. solar flux - SF, quasi biennial oscillations - QBO, El Niño/Southern Oscillation - ENSO) and a linear trend term have been performed on time series of spatially averaged O₃ on spatial grids. The resulting covariates and trend spatial structures are analyzed. In particular, direct effects of positive (or negatives) ENSO indexes measured during moderate to intense El Niño (or La Niña) episodes in 2009 and 2014 (or 2010) are observed and analyzed in the ozone columns in the tropics.

New measurements of CH₃OH in the TTL from the Aura Microwave Limb Sounder

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Methanol (CH₃OH) is one of the most abundant organic molecules in the atmosphere and has been detected in biomass burning plumes in the upper troposphere / lower stratosphere. The Microwave Limb Sounder (MLS), launched as part of NASA's Aura mission in July 2004, measures vertical profiles of temperature, cloud ice, and an extensive suite of trace gases in the middle atmosphere. With the release of the version 4 (v4) data processing algorithms in early 2015, Aura MLS now also provides daily observations of CH₃OH. Initial evaluation of the MLS CH₃OH measurements suggests that they will be scientifically useful in the tropics at 100 and 147 hPa. Here we describe the new MLS v4 CH₃OH data and present preliminary validation results, including comparisons with limited correlative measurements and output from a chemistry climate model. We will explore whether new insights can be gained about the impact of pollution transport on the composition of the TTL by analyzing the ~11-year MLS CH₃OH record in conjunction with MLS measurements of other biomass burning markers.

MLS Version 4: Improved Products for TTL Studies

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The Microwave Limb Sounder (MLS), launched as part of NASA's Aura mission in July 2004, measures vertical profiles of temperature, cloud ice, and an extensive suite of trace gases from the upper troposphere to the mesosphere. Version 4 (v4) algorithms provide improved carbon monoxide (CO), ozone (O₃), water vapor (H₂O), and nitric acid (HNO₃) products compared to those of version 3 (v3), with particular benefits in the tropical upper troposphere and tropical tropopause layer (TTL). Cloud induced artifacts in v3 products that result from convective cores in limb views, particularly problematic in v3 CO and to varying extents in the other products, have been significantly reduced, allowing simpler data screening to produce a higher yield of better quality data. Persistent vertical oscillations in v3 TTL O₃ have also been substantially reduced. V4 products are currently available for most of the Aura time period, with the completion of reprocessing of the entire record expected by early June of 2015

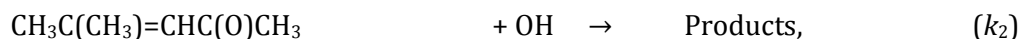
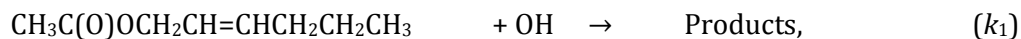
Gas phase kinetic of unsaturated carbonyl compounds with OH radicals at 298K and atmospheric pressure

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Volatile organic compounds (VOC) are emitted into the atmosphere by anthropogenic and biogenic sources. They can degrade by photolysis or reactions with atmospheric oxidants such as OH radical, Cl atoms, O₃ molecules and NO₃ radicals (Finlayson-Pitts and Pitts, 2000). The *trans*-2-hexenyl acetate and 4-methyl-3-penten-2-one are unsaturated and oxygenated VOC's emitted mainly by vegetation (Grosjean et al, 1996; Chen et al, 2012).

As part of an ongoing program in our laboratory to study the atmospheric chemistry of oxygenated species, we report relative rate coefficients for the gas-phase reactions of OH radicals with *trans*-2-hexenyl acetate (k_1) and 4-methyl-3-penten-2-one (k_2). The kinetic data were obtained using an 80 L collapsible Teflon bag employing gas chromatography with flame ionization detector (GC-FID) as detection system at 298 K in 1 atm nitrogen.



The rate coefficients obtained by averaging the values from different experiments and using different reference compounds were the following (in cm³ molecule⁻¹ s⁻¹): $k_1 = (6.85 \pm 1.17) \times 10^{-11}$ and $k_2 = (1.02 \pm 0.18) \times 10^{-10}$ respectively. Kinetic data were used to estimate the atmospheric lifetimes for the oxygenated unsaturated VOC's studied. Lifetimes of few hours were obtained for the OH-initiated degradation of these unsaturated VOC's indicating their possible importance in the photochemical smog production.

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Tropospheric Transport over south-east Asia/western Pacific region

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Tropospheric atmosphere is vertically transported from the boundary layer (BL) to the upper troposphere and lower stratosphere (UT/LS) by deep convections. In particular, south-east Asia/western Pacific are important region for global environment because it is pollutant source region as well as convectively active region. While a number of studies have addressed transport process over Asia and/or Pacific based on model and satellite observations, it is not easy to make actual transport clear from those approaches.

Carbon dioxide (CO₂) has long chemical lifetime and its sources/sinks are ununiformly distributed at the Northern Hemispheric (NH) land surface. Basing on these facts, we examine tropospheric transport processes by using trajectory calculation and spatial-temporal distribution of CO₂ which is regarded as a tracer. In this study, CO₂ concentrations measured by the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL) and those measured by ground-based observatories of the National Oceanic and Atmospheric Administration (NOAA), the Japanese Meteorological Agency (JMA), and the Commonwealth Scientific and Industrial Research Organization (CSIRO), ECMWF Era-Interim meteorological fields, and geostationary satellite infrared image are used.

From our analysis, it is suggested that strong seasonal variation in convective activity changes tropospheric transport pathway from BL to UT and that CO₂ distribution in UT is controlled by it as well as CO₂ variation in BL. To create a picture of tropospheric transport and interpret spatial-temporal CO₂ distribution in UT, we examine how CO₂ concentration changes from BL to UT along its transport pathway. From the statistical analysis, it is found that CO₂ concentrations are conserved from the original region (BL) to the arrival region (UT). This result ensures an effectiveness of our approach and supports our estimate of tropospheric transport at least in statistics.

On the Influence of the Antarctic Ozone Hole on Tropical Lower Stratospheric Temperature Trends

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Observations of temperature show that the tropical lower stratosphere has cooled over the past 30 years (Free, 2011). Understanding the drivers of the observed cooling trends in the tropical lower stratosphere is important not only for determining contributions to past changes in climate, but also for projecting future ones.

Stratospheric temperatures are influenced by changes in radiatively active species, including ozone, water vapor, long-lived greenhouse gases, and volcanic aerosols, along with dynamical changes related to the Brewer Dobson Circulation (BDC). Polvani and Solomon (2012) analyzed the roles of changes in ozone, greenhouse gases, and sea surface temperatures on tropical lower stratospheric temperature trends in integrations of the Community Atmospheric Model and concluded that the tropical lower stratospheric temperature trends were predominately controlled by radiative cooling associated with local ozone depletion. Moreover, they found that changes in polar stratospheric ozone exhibited a weak influence on annually averaged modeled tropical lower stratospheric temperature trends. The ozone specified in these CAM simulations was from the SPARC (Cionni et al., 2011) dataset. Aside from the SPARC ozone dataset, two additional ozone datasets are available, RW07 (Randel and Wu, 2007) and BDBP (Hassler et al., 2009).

In this work, we reexamine the role of polar stratosphere ozone loss, specifically the Antarctic ozone hole, on the circulation as well as temperature trends in the lower tropical stratosphere. We present results from model simulations using the specified-chemistry version of the Whole Atmosphere Community Climate Model (SC-WACCM, Smith et al., 2014) forced with each of the three different ozone datasets. To isolate the temperature trends due to local ozone depletion from those associated with changes in the BDC due to the Antarctic ozone hole, results with only the polar stratospheric ozone loss for each of the three datasets will also be presented. Furthermore, we examine the seasonality of the temperature changes in the tropical lower stratosphere in our simulations, which are distinct due to the pronounced seasonality of the Antarctic ozone hole. A caveat of this work is that the observed tropical lower stratospheric ozone depletion is most likely due to anomalous upwelling of ozone-poor air from the troposphere, likely due to changes in the BDC. Consequently, our results present a lower bound on the possible influence of the Antarctic ozone hole on tropical lower stratospheric temperature trends.

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Rapid Transport of Carbon Monoxide from Troposphere to Stratosphere via Tropical Convection During Stratospheric Sudden Warming in January 2010

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Abstract

A potential transport mechanism of various tracers from the tropical troposphere to the lower stratosphere (LS) across the tropical tropopause layer (TTL) is the overshooting convective clouds which inject air with tropospheric characteristics (high carbon monoxide (CO), high water vapor (H₂O), low ozone (O₃) into the LS over a period of a few days. Evidence of such convective intrusions is observed at the end of January and beginning of February in 2010 associated with increased convective activity over the southern African continent following the onset of stratospheric sudden warming (SSW) event. The modulation of tropical upwelling by SSW appears to force stronger and deeper tropical convection, particularly in the Southern Hemisphere (SH) tropics. The simulation analysis with fine vertical resolution also showed that deep convection especially in the SH became stronger during the SSW event because the upwelling associated with SSW destabilized the TTL [Eguchi et al., ACP, 2015].

The January 2010 SSW event induced the lowest recorded LS temperature in MLS history (2004-13), which destabilized the TTL allowing an unprecedented clear detection of stratosphere-troposphere exchange process by way of CO, H₂O and O₃ intrusions. The present study suggests that short duration, overshooting clouds can have a large impact on the zonally averaged fields of LS composition.

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Structure of the convectively-driven cold layer and its influences on moisture in the TTL

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Characteristics of the cold anomaly that is commonly observed in the tropical tropopause layer (TTL) over deep convection are examined using CloudSat and Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) GPS radio occultation measurements. Deep convective events are sampled based on the cloud top height from CloudSat 2B-CLDCLASS, and then temperature profiles from COSMIC are analyzed around the convective events. The composite temperature shows anomalously warm troposphere (up to 14 km) and a significantly cold layer near the tropopause (at 16-18 km) in the regions of deep convection. Generally in the tropics, the cold layer has a larger horizontal scale (2,000 - 6,000 km) than that of mesoscale convective cluster, and it lasts one or two weeks with minimum temperature anomaly of $\sim -2\text{K}$. In the deep tropics, the cold layer shows slight but clear eastward-tilted vertical structure with an additional warm anomaly to the west of the cold layer indicating a large-scale wave response in the tropics. Further analysis using pressure anomaly suggests that these anomalies have Kelvin wave-like structure superimposed on the hydrostatic adjustment. In the subtropics, the temperature and pressure anomalies show only a dominant hydrostatics adjustment structure. Influences of the cold layer on the moisture are also examined in the TTL using microwave limb sounder (MLS) water vapor measurements. The water vapor anomalies show a consistent structure with the temperature anomaly, which is dry in the cold region and moist in the warm region, implying a large-scale dehydration process due to the convectively driven cold layer in the upper TTL.

The Effects of Ice Crystal Shape on the Evolution of Optically Thin Cirrus Clouds in the Tropics

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Thin cirrus clouds in the tropical tropopause layer (TTL) play potentially important roles in Earth's radiation budget and in the transport of water into the stratosphere. Radiative heating of these clouds results in mesoscale circulations that maintain them against sedimentation and redistribute water vapor. In this study, the System for Atmospheric Modeling (SAM) cloud-resolving model is modified in order to calculate the fall speeds, growth rates, and radiative absorption coefficients of non-spherical ice crystals. This extended model is used in simulations that aim to constrain the effects of ice crystal shape on the time evolution of thin cirrus clouds and to identify the physical processes responsible for these effects. Model runs assuming elongated spheroids instead of spheres result in a higher center of cloud ice mass than in the control, spherical case, which is roughly 60% due to a reduction in fall speeds and 40% due to stronger updrafts caused by stronger radiative heating. Other effects of ice crystal shape on the cloud evolution include faster growth and sublimation in supersaturated and subsaturated environments, respectively, and local temperature increases caused by diabatic heating. Effects of ice crystal shape on the total and mean ice crystal masses are within about 10% but do not appear to be entirely negligible. Comparisons of modeled ice crystal size distributions with recent airborne observations of TTL cirrus show that incorporating non-spherical shape has the potential to bring the model closer to observations. It is hoped that this work will eventually lead towards a more realistic physical representation of thin tropical cirrus clouds in global climate models.

Observations of the ice water content – extinction relationship in TTL cirrus during ATTREX 2014

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Cirrus clouds occur with high frequency and large spatial extent in the tropical tropopause layer (TTL), contributing significantly to the Earth's radiation balance. In addition to relating directly to cloud radiative properties, cirrus ice water content (IWC) is an important physical parameter in global models and presents a metric for comparison with the IWC values derived from space-based lidar retrievals of cirrus cloud extinction.

The NASA Airborne Tropical Tropopause Experiment (ATTREX) deployment in January – March 2014 yielded more than 35 hours of sampling TTL cirrus in the western Pacific from the Global Hawk UAS. Cirrus clouds were encountered throughout the TTL, at temperatures from 185 to 215 K, with IWC down to the detection limit of $3 \mu\text{g m}^{-3}$ and water vapor mixing ratios as low as 1.5 ppm. Most TTL cirrus sampled had ice number concentrations (INC) of less than 100 L^{-1} , and very few had INC of more than 1000 L^{-1} . The mean value for relative humidity with respect to ice within cirrus was near 100%, but encompassed a range from < 50% to higher than 150%.

The significant number of in situ observations of IWC and cirrus cloud properties made during ATTREX provide an outstanding dataset by which to investigate the relationship of IWC to extinction with a goal of producing a robust parameterization that can be used to derive TTL cirrus IWC values from space-based lidar retrievals.

Ice nucleation in the Tropical Tropopause Layer characterized by ice cloud parameters observed by ATTREX 2011

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Stratospheric water vapor is important to the decadal variation of global surface temperature (Solomon et al. 2010). Because stratospheric water amount is strongly controlled by dehydration processes in the Tropical Tropopause Layer (TTL), extensive observational studies have been carried out. For example, detailed vertical structure of the TTL cirrus, water vapor and temperature were observed from ATTREX 2011. Jensen et al. (2013) discussed homogeneous and heterogeneous ice nucleation processes for TTL cirrus clouds observed in ATTREX 2011. These processes have been conventionally discriminated by referring to ice number concentrations ($N_{c,i}$) consisting the cirrus (Jensen et al., 2010; Krämer et al., 2009). However, the frequently observed $N_{c,i}$ values of 10^2 to 10^3 L⁻¹, intermediate between the typical homogeneous (10^3 to 10^4 L⁻¹) and heterogeneous ($< 10^2$ L⁻¹) nucleations, await careful interpretation. In the present study, some attempts are made to examine the homogeneous and heterogeneous nucleation processes in the TTL by taking the advantages of size distribution of ice particles with high vertical resolution derived from ATTREX 2011 data published on the web. The observed concentration of water vapor and size-classified $N_{c,i}$ are used to estimate the threshold of ice nucleation (RH_c) under the following assumptions: no sedimentation, mixing, diffusion and change of meteorological state in the atmosphere during ice formation to observation and spherical-shaped ice particles.

In the case of TTL cirrus with low $N_{c,i}$, the estimated RH_c s reach the threshold of heterogeneous nucleation (~ 1.4) but stay well below that of homogeneous nucleation. This is consistent with the notion that low $N_{c,i}$ TTL cirrus is formed by heterogeneous nucleation. On the other hand, there found varieties of conditions in terms of number concentration and size distribution of the particles in the layers supposed to be formed by homogeneous nucleation. Some discussions will be made by paying special attention to thin layers in which the dehydration is probably under way. In the scatter plot of RH_i and RH_c against $N_{c,i}$, there found very few cases of ice particles with high $N_{c,i}$ corresponding to the homogeneous nucleation while the estimated RH_c s often stay below the homogeneous nucleation threshold. Instead, ice particles with $N_{c,i}$ intermediate between the homogeneous and heterogeneous nucleations appear at relatively high frequency with the RH_c significantly high. In view of the importance of these ice particles in the TTL dehydration, further study is required to investigate the formation and evolution of cirrus clouds in the TTL.

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Overview of the Airborne Tropical Tropopause Experiment (ATTREX)

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The NASA Airborne Tropical Tropopause Experiment (ATTREX) is a series of airborne campaigns focused on understanding physical processes in the Tropical Tropopause Layer (TTL) and their role in atmospheric chemistry and climate. ATTREX is using the high-altitude, long-duration NASA Global Hawk Unmanned Air System to make in situ and remote-sensing measurements spanning the Pacific. A particular ATTREX emphasis is to better understand the dehydration of air as it passes through the cold tropical tropopause region. The ATTREX payload contains 12 in situ and remote sensing instruments that measure water vapor, clouds, multiple gaseous tracers (CO, CO₂, CH₄, NMHC, SF₆, CFCs, N₂O), reactive chemical compounds (O₃, BrO, NO₂), meteorological parameters, and radiative fluxes.

ATTREX flight series have been conducted in the fall of 2011 from Armstrong Flight Research Center (AFRC) in California, in the winter of 2013 from AFRC, in the winter/spring of 2014 from Guam, and in the spring of 2015 from AFRC. The first two flight series provided extensive sampling of the central and eastern Pacific, whereas the last flight series permitted sampling in the western Pacific. The sampling strategy has primarily involved repeated ascents and descents through the depth of the TTL (about 13-19 km). Over 100 TTL profiles were obtained on each flight series. The ATTREX dataset includes TTL water vapor measurements with unprecedented accuracy, ice crystal size distributions and habits. The cloud and water measurements provide unique information about TTL cloud formation, the persistence of supersaturation with respect to ice, and dehydration. The plethora of tracers measured on the Global Hawk flights are providing unique information about TTL transport pathways and time scales. The meteorological measurements are revealing dynamical phenomena controlling the TTL thermal structure, and the radiation measurements are providing information about heating rates associated with TTL clouds and water vapor.

This presentation will provide an overview of the ATTREX flights, examples of measurements from the flights, and plans for modeling/analysis of the ATTREX dataset.

Introducing a new light scattering instrument in the Small Ice Detector family: AIITS, with preliminary data from particles in the Tropical Tropopause Layer during the CAST campaign

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The new optical particle spectrometer AIITS (Aerosol Ice Interface Transition Spectrometer) is the next instrument in the Small Ice Detector (SID) family. Like SID3, it acquires two-dimensional forward scattering patterns from particles in the size range from about one to a few hundred micrometers (depending on variable settings). The patterns allow quantifying the phase, habit and fine surface features of large aerosol and ice crystals, which are frequently too small to be adequately characterised using traditional imaging techniques.

Two 2D-forward scattering patterns are recorded per particle using two high-resolution cameras. The cameras fire simultaneously, recording the scattering pattern via a beamsplitter. AIITS can be configured such that the cameras measure either perpendicular polarisations (i.e. P-polarisation with one camera, S-polarisation with the other) or to have a different gain setting on each camera to encompass a larger dynamic range. The incident beam can be either circularly or linearly polarised. Backscatter depolarisation is also measured. The camera and beam configuration must be selected pre-flight.

The probe was deployed on board the NASA Global Hawk aircraft during a recent ATTREX/CAST campaign over the tropical eastern Pacific. We present preliminary results from a case study from the 5th of March 2015 which showed the existence of a variety of particles, including rough surfaced ice crystals, some regular, hexagonal ones, as well as particles with smooth, curved surfaces (but not spherical). We compare AIITS data with co-located particle imaging from the SPEC Hawkeye probe.

The Hawkeye probe combines a 2D-Stereo optical array probe, a Cloud Particle Imager (CPI), and a Fast Cloud Droplet Probe (FCDP) to provide high resolution images (2.3 micron pixel resolution) and particle size distributions of concentration, area, and mass for particles with diameter between one micron and a few centimeters.

The TTL is known to be of importance due to the presence of subvisual cirrus, which contributes to net climate radiative feedback. Knowledge of the processes involved in the creation and persistence of such clouds is limited due to sparse observational data.

Effect of gravity wave temperature fluctuations on homogeneous ice nucleation in the tropical tropopause layer

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The impact of high-frequency fluctuations of temperature on homogeneous nucleation of ice crystals in the vicinity of the tropical tropopause is investigated using a bin microphysics scheme for air parcels. The imposed temperature fluctuations come from measurements during isopycnic balloon flights near the tropical tropopause. The balloons collected data at high frequency, guaranteeing that gravity wave signals are well resolved.

With the observed temperature time series, the numerical simulations with homogeneous freezing show a full range of ice number concentration (INC) as previously observed in the tropical upper troposphere. In particular, low INC may be obtained if the gravity wave perturbations produce a non-persistent cooling rate (even with large magnitude) such that the absolute change in temperature remains small during nucleation. This result is explained analytically by a dependence of the INC on the absolute drop in temperature (and not on the cooling rate). This work suggests that homogeneous ice nucleation is not necessarily inconsistent with observations of low INC.

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Vertical and horizontal transport of water vapour and aerosol in the tropical stratosphere from high-resolution balloon-borne observations

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We present the results of accurate balloon-borne observations of water vapor, methane and aerosol obtained during a field campaign held during March 2012 in Bauru, Brazil (22.3 S) in the frame of a French TRO-Pico project. The aim of the TRO-Pico project is to characterize the variability and frequency of convective cross-tropopause injections, their contribution at the regional wet season timescale, and to improve the understanding of their role with respect to the cold trap at a wider scale. The balloon payloads flown during the campaign included Pico-SDLA IR laser hygrometers, FLASH-B Lyman-alpha hygrometers, COBALD aerosol backscatter sondes and several other instruments for measurement of gas-phase and particle constituents. An S-band radar operating on the site provided the information on cloud tops. The water vapour profiles obtained by the two different measurement techniques are in excellent agreement, demonstrating high quality of the observations.

The signatures of long-range horizontal transport are inferred from a series of vertical profiles, which show coincident enhancements in water vapour and aerosol accompanied by methane local minima at specific levels in the lowermost stratosphere. Trajectory analysis unambiguously links these features to advection from the southern hemisphere extra-tropical stratosphere, containing more water and aerosol, as demonstrated by MLS and CALIPSO global observations. The intrusion of extratropical air is successfully reproduced by CLaMS chemistry transport model simulation, showing water-rich and methane-poor filaments extending to 20 S.

The signature of local cross-tropopause transport of water is observed during a convectively active day, revealing water vapour enhancements of up to 0.7 ppmv as high as 405 K. These are shown to originate from convective overshoots upwind detected by the local S-band radar. The relative contribution of the horizontal transport and that of local updrafts to the stratospheric humidity is discussed.

A “Match” approach to quantifying processes affecting TTL humidity based on MLS observations

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The humidity of the lower stratosphere is influenced by a combination of factors, notably the freeze-drying of air that slowly ascends in the Tropical Tropopause Layer (TTL), through the Lagrangian cold point, into the lower stratosphere, as well as the convective injection that effectively bypasses the cold point, depositing ice directly into the lowermost stratosphere. Long-term variability in both of these processes and their relative contributions has important implications for stratospheric humidity and thus Earth’s radiative balance. Here we describe a new application of observations from the Aura Microwave Limb Sounder (MLS) to the study of TTL processes. The “Match” approach uses trajectory calculations to identify cases where MLS has observed the same air mass on multiple occasions. Examination of the changes in water vapor between these observations gives insight into the extent to which overshooting convection hydrates the lower stratosphere. We investigate the suitability of this approach to quantifying such hydration, and examine the relationship between the estimated hydration and other climate variables.

Two decades of water vapor measurements with the FISH fluorescence hygrometer: A review with special emphasis on TTL water vapor

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Water vapor is one of the key species regarding troposphere stratosphere exchange in the tropical transition layer (TTL). The strong temperature minimum at the tropical tropopause reduces the water vapor concentration to very low values. Reliable water vapor measurements at these low concentrations down to mixing ratios of 1 ppmv are a challenging task for water vapor instruments.

The airborne Fast In-situ Stratospheric Hygrometer (FISH) is a Lyman-photofragment fluorescence hygrometer for accurate and precise measurement of total water mixing ratios (WMR) (gas phase + evaporated ice) in the upper troposphere and lower stratosphere (UT/LS) since almost two decades. Here, we present a comprehensive review of the measurement technique, calibration procedure, accuracy and reliability of FISH with special emphasis on TTL water vapor. A crucial part for the FISH measurement quality is the regular calibration to a water vapor reference, namely the commercial frostpoint hygrometer DP30. In the frame of this work this frostpoint hygrometer is compared to German and British traceable metrological water standards and its accuracy is found to be 2-4 %. Overall, in the range from 4-1000 ppmv, the total accuracy of FISH was found to be 6-8 % as stated also in previous publications. For lower mixing ratios down to 1 ppmv, the uncertainty reaches a lower limit of 0.3 ppmv. The performance of FISH in the field is assessed by reviewing intercomparisons of FISH water vapor data with other in-situ and remote sensing hygrometers over the last two decades. We find that the agreement of FISH with the other hygrometers has improved over that time span from overall up to 30% or more to about 5-20% @<10ppmv and to 0- 15% @>10ppmv.

We will show here that the robust and continuous calibration and operation procedures of the FISH instrument over the last two decades establish FISH as one of the core instruments for in-situ observations of water vapor in the UT/LS. In addition, an overview of all FISH measurements in the TTL region (20°S to 20°N, and 355 to 425 K) from four campaigns with the high altitude aircraft Geophysica will be presented.

WB-57 platform Upgrades and opportunities for supporting Earth Science

Charles Mallini, Timothy Propp, Brook Gerky, Andrew Roberts

Abstract:

The WB-57 is a high altitude, heavy lift R&D platform. There are many advantages to the science community in utilizing this highly flexible and adaptable platform. The platforms over the past few years have gone thru significant upgrades including regenerating a third aircraft and building a robust deployable support capability. The presentation will show some of the multi payload past missions as a starting point to generate discussions on new uses for Earth Science and especially for the UTLS researchers through maximizing opportunities to expand the use of this platform. The presentation will also open up some instrument creative options to offer opportunities with current WB57 missions. The WB57 program office is highly motivated to support the CT3LS science community and is looking forward to discussing new mission ideas with this meeting's participants.

Gulfstream-III Platform, Supporting Airborne Science

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NASA JSC, Houston, TX

Summary and Overview

NASA Johnson Space Center's (JSC) Gulfstream-III, "NASA 2", provides a reliable and flexible airborne science platform for the earth science community and other customers to support research, advanced technology development, and testing worldwide. Starting in the fall of 2011, AOD completed an engineering design and modification on the aircraft to fly a P-band radar science campaign for the NASA Airborne Science Program called AirMOSS (Airborne Microwave Observatory of Subcanopy and Subsurface), and these modifications make the aircraft a valuable asset to the airborne science community. In situ sensors can be integrated into an external pod weighing a maximum of 1,200 pounds flown on the lower fuselage centerline. Existing designs allow the cabin to be configured with equipment racks weighing up to 300 pounds each along with operator consoles as required to support payload equipment. NASA 2 provides a comfortable, shirt sleeve operating environment for science researchers and mission managers to operate experiments during the execution of airborne science missions. In addition, AOD has an engineering department, extensive manufacturing capability, and a robust internal airworthiness certification process that can implement design modifications and alterations to the airplane to address individual customers' needs, like dropsondes and cabin window probes. AOD's Gulfstream-III program is highly motivated to support the CT3LS science community and looks forward to discussing new missions with participants.

High Resolution Modeling of the Indian Summer Monsoon with the UM-UKCA Chemistry-Climate Model

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We use simulations conducted with a high resolution (~40km in the horizontal) nudged version of the UM-UKCA chemistry-climate model to study the Indian Summer Monsoon and assess its role in transport of trace gas species into the upper troposphere/lower stratosphere. Model results will be presented from a simulation of the 2005 Indian Summer Monsoon and compared to ECMWF reanalysis products and satellite observations. High temporal (3 hourly) data is used to characterize the impacts of the Indian Summer Monsoon on upper tropospheric/lower stratospheric (UT/LS) CO, O₃ and H₂O. The model simulation includes idealized tracer emissions from six regions, scaled to represent industrial CO emissions from Northern and Southern China, Northern and Southern India and biomass burning emissions from Indonesia and surrounding areas. A uniform tracer emission is also prescribed over the Bay of Bengal. We use these idealized tracers to give an indication of how air masses from the surrounding region are entrained in the Monsoon flow and transported into the UT/LS.

A Reevaluation of the Contribution of VSL Bromocarbons to Stratospheric Br_y Loading

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The Aura Ozone Monitoring Instrument (OMI) has provided global measurements of total column BrO over the past decade. Salawitch *et al.* (2010) suggested 5 to 10 ppt of inorganic bromine (Br_y) must be supplied to the lower stratosphere, from the decomposition of very short lived (VSL) bromocarbons to accurately represent the variation of total column OMI BrO with total column O₃. Here we will re-evaluate this recommendation in light of ground-based total column BrO measurements obtained over Fairbanks, Alaska using a multifunction differential optical absorption spectroscopy (MFDOAS) instrument during the spring of 2011. Additionally, we will assess how modifications to kinetics regulating the partitioning between BrO and BrONO₂ proposed by Kreytcy *et al.* (2013) affect the VSL Br_y estimate. Finally, we will evaluate the impact of our new understanding of VSL Br_y on the tropospheric residual BrO inferred from OMI BrO.

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Solar Occultation Constellation for Retrieving Aerosols and Trace Element Species (SOCRATES) Mission Concept

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The goal of SOCRATES is to resolve the critical but underexplored role of the upper troposphere/lower stratosphere (UTLS) in climate change. SOCRATES science objectives are:

- (1) Provide measurements of the key radiatively active gases and aerosols, transport tracers and temperature with sufficient precision, vertical resolution, and geographic coverage to study UTLS transport pathways, and to quantify long-wave radiative fluxes.
- (2) Constrain the relative importance of the main transport pathways that control variations in UTLS composition.
- (3) Model the effects on UTLS composition of predicted changes in the transport pathways as well as resultant impacts on radiative forcing and global circulation.
- (4) Establish a scientific foundation for a new cost effective approach for the long-term monitoring of key constituents and temperature in the UTLS and stratosphere.

The SOCRATES sensor is a 23-channel Gas Filter Correlation Radiometer (GFCR), referred to as GLO (GFCR Limb solar Occultation), with heritage from HALOE on UARS, and SOFIE on AIM. GLO measures aerosol extinction from 0.45 to 3.88 μm , important radiatively active gases in the UTLS (H_2O , O_3 , CH_4 , N_2O), key tracers of UTLS transport (HCN, CO, HDO), gases important in stratospheric O_3 chemistry (HCl and HF), and temperature from cloud top to 50 km at a vertical resolution of < 1 km. Improved pointing knowledge will provide dramatically better retrieval precision in the UTLS, even in the presence of aerosols, than possible with HALOE. In addition, the GLO form factor is only of order 10% of that of HALOE, and costs for a constellation of GLO sensors is within the cost cap of a NASA Venture mission. The SOCRATES mission concept is a 6-element constellation of autonomous small satellites, each mated with a GLO sensor, deployed from a single launch vehicle. The SOCRATES/GLO approach reaps the advantages of solar occultation: high precision and accuracy; robust calibration; and high vertical resolution, while mitigating the sparse coverage of a single solar occultation sensor. We present the SOCRATES science case, and key elements of the SOCRATES mission and GLO instrument concepts.

Reexamining the tropical stratospheric ozone response to the 11-year solar cycle

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Previous studies using long-term satellite vertical ozone measurements has suggested a double peak structure of the 11-year solar cycle response in the tropical (25°N-25°S) ozone. The first peak (~3%) is in the upper stratosphere and is a direct result of photolytic ozone formation. However, the statistically insignificant (i.e. ~0%) response in the middle stratosphere and the second peak (~4%) in the lower stratosphere cannot be explained in terms of standard photochemistry. Recent modeling work have provided strong evidence that the second peak in the lower stratosphere is a statistical aliasing with the record-high stratospheric aerosol injection due to the Pinatubo eruption in 1992, which coincided with the solar maximum in 1989-1991. The insignificant response in the middle stratosphere, on the other hand, remains unresolved. A number of hypotheses have been proposed, including the dynamical coupling with the quasibiennial oscillation (QBO), the slow-down of the Brewer-Dobson residual circulation, anomalous transport of odd-nitrogen (NO_x) species, and etc. We are not able to reproduce the insignificant ozone response using our 2-dimensional chemistry-dynamics model that has self-calculated QBO, residual circulation, and catalytic ozone chemistry. Recently, the GOZARDS merged ozone dataset using NASA's satellite measurements since 1979 has provided the longest vertically resolved ozone data for studying decadal variability. Preliminary results show that the middle stratospheric response may be due to aliasing of some unidentified short term fluctuations in the ozone data. We propose that these fluctuations should be carefully filtered before the analysis.

OH in the TWP: An In-Depth Comparison of CONTRAST and CAM-Chem OH Precursors and Implications for the Oxidative Capacity of the Troposphere

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Hydroxyl radical (OH) is the main daytime oxidant in the troposphere and determines the atmospheric lifetimes of many compounds of interest. It has been hypothesized that a region of very low OH in the tropical western Pacific Ocean allows otherwise short-lived compounds (including biogenic ozone depleting substances) to be transported intact to the UTLS by deep convection. We use the complete, updated measurements from the CONTRAST field campaign in the tropical western Pacific to constrain the box model DSMACC and estimate OH concentrations encountered in the mid- to upper-troposphere of this region. Measurements reveal a background, unpolluted state of the troposphere, with pervasive high O₃/low H₂O filamentary structures present in the mid-troposphere. We examine the impacts of these distinct air parcels on OH as well as the global model CAM-Chem's ability to reproduce these conditions. The effects of OH precursor differences between observations and CAM-Chem on the oxidative capacity of the troposphere are further investigated using the box model.

Understanding the long-term trend in stratospheric water vapor

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Chemistry-climate models predict that 1) the TTL warms during the 21st century and 2) the humidity of air entering the stratosphere increases over this same period. It seems reasonable to conclude that the former causes the latter, but to our knowledge no one has actually shown that. We test this hypothesis in two chemistry-climate models (the Goddard Earth Observing System Chemistry Climate Model, GEOSCCM, and the Whole Atmosphere Community Climate Model, WACCM). We find that the warming of the TTL explains only part of the increase in stratospheric water vapor over the 21st century. We demonstrate that the remainder of the trend can be explained by an increase in the flux of ice through the TTL. An analysis of MLS data provides some support that this is occurring in the real world.

A solar signal in lower stratospheric water vapour?

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A merged time series of stratospheric water vapour built from HALOE and MIPAS data between 60°S and 60°N and 15 to 30 km and covering the years 1992 to 2012 was analysed by multivariate linear regression including an 11-year solar cycle proxy. Lower stratospheric water vapour was found to reveal a phase-shifted anti-correlation with the solar cycle, with lowest water vapour after solar maximum. The phase shift is composed of an inherent constant time lag of about 2 years and a second component following the stratospheric age of air. The amplitudes of the water vapour response are largest close to the tropical tropopause (up to 0.35 ppmv) and decrease with altitude and latitude. Including the solar cycle proxy in the regression results in linear trends of water vapour being negative over the full altitude/latitude range, while without the solar proxy positive water vapour trends in the lowermost stratosphere were found. We conclude from these results that a solar signal generated at the tropical tropopause is imprinted on the stratospheric water vapour abundances and transported to higher altitudes and latitudes via the Brewer-Dobson circulation. Hence it is concluded that the tropical tropopause temperature at the final dehydration point of air is also governed to some degree by the solar cycle. The negative water vapour trends obtained when considering the solar cycle impact on water vapour abundances can solve the water vapour conundrum of increasing stratospheric water vapour abundances at constant or even decreasing tropopause temperatures.

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Revisiting water vapor seasonal cycle observed in tropical lower stratosphere: Role of BDC, convective activity and ozone

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In the present study, we are revisiting the issues related to the hydration of the tropical lower stratosphere (TLS) particularly over the Asian monsoon region (AMR) and dehydration occurring over the Indonesian-Australian western Pacific region (IAWPR). Low tropopause temperatures ($T_{100} \leq 191$ K) and convective activity are observed over both the regions, but hydration in the TLS is observed over AMR during NH summer monsoon and dehydration over IAWPR during NH winter (SH summer monsoon). In this study, an attempt has been made to understand these anomalies over the two tropical regions. It is observed that during NH summer monsoon, BDC is relatively weak and areas of low T_{100} occur in patches over AMR. The area of convection is observed to partially overlap the region of low T_{100} and noted to play a significant role in hydration of TLS over AMR. In contrast, during NH winter (SH summer monsoon), BDC is relatively stronger and the areas of low T_{100} are wide spread, especially over the southern tropics. In such condition, freeze drying process is likely to occur over a relatively large spatial area of IAWPR, triggering the dehydration of TLS. In addition, deep penetrating convection appears to be relatively less frequent over this region.

Impact of Sudden Stratospheric Warming Event on the TTL and Deep Convective Activity

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Abstract.

We investigate the role of deep convection and overshooting convective clouds in stratosphere–troposphere dynamical coupling in the tropics during two large major stratospheric sudden warming events in January 2009 and January 2010. During both events, convective activity and precipitation increased in the equatorial Southern Hemisphere as a result of a strengthening of the Brewer–Dobson circulation induced by enhanced stratospheric planetary wave activity. Correlation coefficients between variables related to the convective activity and the vertical velocity were calculated to identify the processes connecting stratospheric variability to the troposphere.

Convective overshooting clouds showed a direct relationship to lower stratospheric upwelling at around 70–50 hPa. As the tropospheric circulation change lags behind that of the stratosphere, outgoing longwave radiation shows almost no simultaneous correlation with the stratospheric upwelling. This result suggests that the stratospheric circulation change first penetrates into the troposphere through the modulation of deep convective activity.

Role of saturation in the water vapor diurnal cycle in the South American Tropical Tropopause Layer

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With a focus on two highly convective South American land regions, namely the equatorial Amazonia and the tropical region of Sao Paulo state in southern Brazil, we attempted to characterize and understand the mechanism controlling the water vapor (H₂O) diurnal variability in the tropical tropopause layer (TTL). This work, part of the TRO-Pico French project, is based on a decade of Microwave Limb Sounder (MLS) H₂O, temperature, relative humidity (RH_i), and cloud ice water content (IWC) observations. In both regions, deep overshooting convective systems loft adiabatically cooled air, ice crystals, and H₂O that hydrates the TTL. Observations performed at 01:30 am and pm however suggest a moister nighttime compared to daytime in the tropical region, and the opposite in the equatorial region. In this work, we show that the diurnal cycle of H₂O potentially results from different saturation conditions in the TTL of both regions. The tropical sub-saturated TTL would favor rapid sublimation of lofted ice crystals, while the equatorial super-saturated TTL would instead delay it. We further emphasize that difference in the two regimes when considering the preliminary results from the assimilation of MLS observations in the Météo-France multi-scale Chemistry and Transport Model MOCAGE which provides a refined estimation of the H₂O diurnal cycle with hourly outputs in the TTL of both regions.

The Radiative Effects of Tropical Tropopause Layer Water Vapor and Ozone on Tropical Cyclone Potential Intensity

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A sudden reduction in tropical tropopause layer (TTL) water vapor was observed in 2011, and was concurrent with reductions in TTL temperature and ozone. Termed "abrupt drops" these large variability events were previously known to be associated with radiative forcing and local radiative temperature changes. A recent study by the author and colleagues (Gilford, Solomon, and Portmann, *submitted to JOC*) used Aura Microwave Limb Sounder (MLS) water vapor and ozone observations and two radiative transfer models to examine the structure and radiative impacts of the 2011 abrupt drop. It was found that ozone and water vapor perturbations both nonlocally radiatively cooled the tropical upper troposphere, leading to a mean cooling of about 0.4K associated with the 2011 abrupt drop. Because the outflow temperatures of tropical cyclones can fall within this upper tropospheric region, abrupt drop radiative cooling could have increased tropical cyclone environmental potential intensities (PI). Notably, the largest reductions in TTL water vapor and ozone occurred over the Western Pacific basin, which recorded an above average tropical cyclone season near the end of the abrupt drop period (2013), including Typhoon Haiyan. In this study we use satellite observations of the 2011 abrupt drop along with the radiative-convective MIT single-column model (Emanuel and Zivkovic-Rothman 1999) to estimate the changes in PI associated with the 2011 abrupt drop in the Western Pacific basin. Results suggest that both dynamical and radiative changes in temperature associated with the 2011 abrupt drop were important for modifying environmental PI in the Western Pacific. We find that environmental PI is very sensitive to the level of outflow because of the substantial temperature stratification in the TTL.

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A Lagrangian Description on the Troposphere-to-Stratosphere Transport Changes Associated with the Stratospheric Water Drop Around the Year 2000

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The cause and effect of the sudden drop of stratospheric water vapor (SWV) after 2001 (e.g., Randel et al., 2006; Rosenlof and Reid, 2008) need to be fully understood since SWV is an important driver of decadal scale global climate change (Solomon et al., 2010). While some difficulty in constructing a reliable long-term SWV record is still a concern (Hegglin et al., 2014), the understanding of a possible stepwise change in SWV is quite important in assessing the age of stratospheric air with its long-term trends as well. In the light of great role of TTL dehydration in SWV, here we present a Lagrangian description on the changes in the minimum saturation mixing ratio of water (SMR_{min}) along the trajectories with its geographical location (Lagrangian Cold Point; LCP) for the air parcels advected in the Tropical Tropopause Layer (TTL) before entering the stratosphere. The backward kinematic trajectories initialized on 400 K potential temperature surface in the tropics similar to those of Fueglistaler et al. (2005) are used relying on the ERA interim meteorological fields. The calculations are started on the 5th, 15th, and 25th of every month during the period 1997 to 2002. The statistical features of the SMR_{min} and LCP are analyzed for the 90-day trajectories in which the air parcels experienced LCP in the TTL (spanning from 355 K to 400 K in the vertical and within 30 degree latitudes from the equator).

The decrease of SMR_{min} in the 2000 to 2001 period has been found most remarkable in boreal summer. The stepwise change in the ensemble mean SMR_{min} is identified for the air parcels initialized in September 2000. Thereafter, the horizontal projection of trajectories in the layer between 360 K and 370 K exhibits eastward expansion of the anticyclonic branch circulating the Tibetan high. Eastward spread of the area of maxima in the frequency distribution of LCP accompanies this expansion. The SMR_{min} averaged in each latitude-longitude bin accumulated on the occasion of LCP events shows significant decrease in the central Pacific where the LCP population increase takes place. These results do not give insights into the driving mechanism such as the eddy heat flux on TTL cooling (Fueglistaler et al., 2014). However, they may imply that the drop has resulted from a response of the TTL circulation to modulated boreal summer monsoon combined with intensified extratropical pump and thermal forcing at the bottom boundaries. It is quite interesting to investigate further how these changes have interacted between each other.

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TTL cooling and drying during the January 2013 Stratospheric Sudden Warming.

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Extremely low water vapor concentrations (as low as 1.5 ppmv) in the tropical tropopause layer (TTL) were observed by in-situ measurements during the Airborne Tropical TRopopause Experiment (ATTREX) winter 2013 deployment in February 2013. The January 2013 tropical (15°N-15°S) mean value of Microwave Limb Sounder (MLS) water vapor satellite data at 82 hPa (2.3 ppmv) was one of the lowest during the instrument record (2004-2013). The relationship between a cooling of the tropical tropopause, a Sudden Stratospheric Warming (SSW) event and convective activity in Western Pacific is investigated using satellite data and reanalysis meteorological products to elucidate the likely origin of those extremely low water vapor concentrations.

A major mid winter SSW developed on January 6, 2013. Stratospheric polar temperatures increased by ~30 K in a matter of days and temperatures in the tropical upper troposphere and lower stratosphere (UTLS) dropped at the same time. As a result of the easterly shear phase of the quasi-biennial oscillation and the SSW, the tropical tropopause in January 2013 was anomalously cold (zonal mean of 187 K) and elevated (85 hPa). The tropical cold point tropopause (CPT) temperature and water vapor concentration at 82 hPa decreased by about 2 K and 1.5 ppmv respectively within the first 15 days of January; the water vapor change was likely a result of dehydration associated with the rapid cooling of the tropical CPT during that period.

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Dynamical processes and transport influencing the water vapour budget in the upper troposphere / lower stratosphere (UTLS)

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Changes and variability of UTLS composition are major drivers of surface climate change. Even small changes of spatially highly variable concentrations of greenhouse gases such as water vapor (H₂O) have significant effects on the atmospheric radiation balance. Improved projections of chemistry-climate models (CCM) therefore rely on a realistic representation of physical and chemical processes affecting UTLS composition. This is problematic, because UTLS composition is governed by the complex interactions of various physical and chemical processes that operate at a wide range of temporal and spatial scales (local to global).

We analyze important underlying processes based on multi-annual simulations by the Chemical Lagrangian Model of the Stratosphere (CLaMS), in combination with satellite observations. Our results indicate that the Asian monsoon plays a crucial role for transporting moist air from the tropical troposphere into the extra-tropical lowermost stratosphere during boreal summer. In the tropics, transport of water vapour into the deep stratosphere, which is associated with the ascending branch of the large-scale Brewer-Dobson circulation, is significantly influenced by Major Stratospheric Warming events during boreal winter.

TTL dehydration efficiency evaluated using in-situ data and back-trajectories

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Water in the stratosphere (SW) has a significant impact on Earth's climate, and on stratospheric chemistry. The efficiency with which tropospheric air parcels are dehydrated en route to the stratosphere exerts a dominant control on stratospheric water concentrations. The uniquely cold, clean, and dynamic environment in the upper troposphere where this dehydration takes place challenges our ability to predict how the physical processes involved in this dehydration lead to the observed SW. Predictions of how SW may change in the future will hinge on an accurate, process-level understanding of what currently controls it.

Here we use measurements from the ATTREX campaign to statistically constrain dehydration efficiency in the TTL. We use measurements of water vapor, ice water content, and ice crystal number and size distributions from the upper troposphere ($350 < \theta < 375\text{K}$) to examine how various processes (nucleation, deposition, settling) contribute to incomplete dehydration. We also use measurements of water vapor from the lowermost stratosphere ($375 < \theta < 390\text{K}$) and compare these data to the minimum saturation mixing ratios calculated along back-trajectories initiated from the water vapor measurement locations. These analyses lead to the conclusion that in the Pacific TTL regions sampled by the Global Hawk, dehydration inefficiency increases with decreasing temperatures below $\sim 195\text{K}$ and is expected to result in a $>10\%$ higher entry value for WV transported into the stratosphere than would be the case if dehydration was completely efficient.

Gravity Waves Amplify Upper Tropospheric Dehydration by Clouds

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We use a 1D cloud model run along trajectories to investigate the role of gravity waves in dehydration near the tropopause, more specifically the Tropical Tropopause Layer (TTL).

We find that gravity waves play an important role in the TTL dehydration process beyond just a lowering the temperature of the air parcels. We show that the more rapid cooling associated with gravity waves significantly increases the number of ice crystals formed.

This increase causes a more rapid depletion of vapor in excess of saturation and increases the cloud dehydration efficiency. The nucleation effect on dehydration has a larger impact than the suppression of temperature by the waves. Using a spectrum of gravity waves, we generate ice particle statistics that are in good agreement with observations.

We also find that the presence of gravity waves increases cloudiness. Our results show that cloud physics and gravity wave temperature fluctuations cannot be neglected in simulating the TTL dehydration process.

Saturation at the tropical tropopause

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Profiles of water vapor and ozone between the surface and the middle stratosphere have been measured at Costa Rica since 2005 and at a number of other tropical sites since 1964. These soundings provide a unique opportunity to study transport processes across the tropical tropopause, long term changes of these trace gases and atmospheric processes such as the dehydration at the tropical tropopause and the tropical tape recorder.

The majority of observations at Costa Rica have been taken as part of the routine monitoring program outside of dedicated campaigns with the goal of monthly water vapor soundings. Therefore a good coverage of all seasons has meanwhile been achieved.

In this presentation we focus on the dehydration at the tropical tropopause. The 10 year data set at Costa Rica shows the tropical tape recorder with high vertical resolution and shows when the seasonal maximum of stratospheric water vapor detaches from the local tropopause.

This data set shows that the tropical tropopause at Costa Rica is on average saturated with respect to ice with only minimal seasonal variation. This result is not necessarily to be expected, because the data set contains observations of large supersaturation as well as low subsaturation and there is no obvious reason to assume that the number of supersaturated and subsaturated observations averages out to ice saturation; however, the observations indicate that this is the case over Central America. Campaign based observations in the Western Pacific region and at San Cristobal, Galapagos indicate that this is the case there as well.

Large scale modeling efforts of stratospheric water vapor may therefore need to accurately represent the tropical tropopause temperature, but may not need to understand the details of the dehydration process, at least for the Central American region.

Moist phase in the SH extratropical lower stratosphere: a view of transport from the tropics

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Stratospheric water vapor in the Southern Hemisphere (SH) presents a “wet phase” of the annual cycle during September to December, right after the Northern Hemispheric (NH) monsoon season. The variability of this “wet phase” is dominated by stratospheric water vapor variations over three regions – Western Pacific, South American and African regions. In this study, we use Aura MLS measurements during 2004-2014 to examine the sub-seasonal and interannual variability of water vapor in those regions and characterize their relationships to deep convection, large-scale temperatures and circulation. Results show that the interannual variations are mainly dominated by QBO and ENSO. The subseasonal variations are controlled by the cold-point temperatures over those three regions, with warmer temperatures lead to less dehydration and more water vapor entering the stratosphere, and vice versa. The transport of water vapor from those regions to the SH extratropics is further identified by a domain-filling forward trajectory model. Trajectory results show that water vapor parcels in the SH are from the above three regions in the tropics and get finally dehydrated by the cold-point temperatures, after which, parcels transport southward along with the general circulation. These results demonstrate that the moist phase in the SH is mainly due to the transport from the tropics rather than from the NH summer monsoon regions, and the water vapor variations are primarily controlled by temperatures and large-scale circulation.

A Quick Report on the LAPAN-CRYO-SOWER 2015 Biak Campaign

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To investigate dehydration processes in the tropical tropopause layer (TTL) and the stratosphere-troposphere exchange (STE) processes over the western Pacific, balloon-borne observational campaign was conducted at Biak Indonesia in February – March 2015 as a collaborative project among LAPAN, Indonesia, Cryogenic Air Sampling Group and SOWER Group of Japan. The greatest attempt of this campaign was stratospheric whole air samplings by using compact cryogenic samplers with plastic balloons. Eight atmospheric samples were collected at eight different altitudes from 17 km to 30 km. In addition, five sets of Cryogenic Frostpoint Hygrometer, ECC ozonesonde, and Cloud Particle Sensor, four sets of CO₂ sonde, two sets of aerosol sampler, one set of Optical Particle Counter, and ten sets of GPS radiosonde were launched by rubber balloons.

While detailed analyses await to be done in the future, the data have a significant benefit for understanding interannual variation of the TTL/LS because this campaign was carried out one year after the western Pacific mission of the ATTREX/CONTRAST/CAST campaigns. It means our cryogenic samplers must have collected atmospheric samples upwelling in the tropical LS previously observed by ATTREX campaign one year ago giving us an opportunity to investigate how atmospheric composition changed during this one year. Collaborative analyses of those dataset will provide novel findings and improve our understanding about dynamical and chemical process in the TTL and UT/LS. This paper will present an overview of this campaign.

Anomalous dehydration of the TTL during January 2013: evidence from balloon, aircraft and satellite observations

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The goal of this study is to comprehensively document an anomalous dehydration of the Tropical Tropopause Layer (TTL) related to a major Sudden Stratospheric Warming in early January 2013. The analysis involves the data of balloon soundings of water vapour at various tropical locations using FLASH-B, Pico-SDLA and CFH hygrometers as well as NOAA Water instrument flown onboard high-altitude Global Hawk aircraft. Simultaneous water vapour and backscatter measurements by FLASH-B and COBALD sondes provide information on tropopause clouds formation process. Satellite observations of water vapour by Aura MLS are used to derive the deviation from climatological values. Trajectory modeling is applied for locating the dehydration source spots. Spatiotemporal evolution of dehydration at different scales is characterized after combining the consistent in situ and satellite water vapour observations. All data sets provide evidence of rapid and severe dehydration of the TTL throughout the tropical belt shortly after the onset of SSW. In situ measurements around the Cold Point Tropopause (CPT) show up to 2 ppmv of negative deviation from Aura MLS 10-year climatology with record-low water mixing ratios below 1 ppmv in the Western Pacific region.

The TTL dehydration case of 2013 is compared with previous similar occurrences and the role of extra-tropical dynamics in setting the global stratospheric water budget through thermal response in the TTL is pointed out.

Microphysical Properties of TTL Cirrus

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Cirrus systems near the Tropical Tropopause Layer (TTL) were sampled during NASA Global Hawk flights from California to the tropics in 2011, 2013, and 2015, and from Guam in the western Pacific in 2014 during the Airborne Tropical Tropopause Experiment (ATTREX). In situ aircraft measurements made by a Fast Cloud Droplet Probe (FCDP) and Hawkeye probe onboard the aircraft provide particle concentrations and sizing between 1 and 1280 μm as well as particle images for ice habit identification. The Hawkeye is a combination cloud droplet probe, 2-D stereo optical array probe with 10 μm resolution channels, and a high-resolution cloud particle imager. The FCDP was present in the first three years, and the Hawkeye was a new addition to the flights in 2014 and 2015. We present the variability in ice concentrations, particle size distributions and in particle habit as a function of temperature, supersaturation with respect to ice, and cirrus type. Supporting measurements made by a NOAA instrument onboard the aircraft, which measures both water vapor and total water, as well as pressure and temperature measurements made by MMS, are used to derive estimates of the supersaturation with respect to ice, which demonstrates good correlation with cloud particle observations made by the FCDP and Hawkeye.

Comparisons of cirrus cloud properties between polluted and pristine air based on in-situ observations from the NASA ATTREX, NSF HIPPO and EU INCA campaigns

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Cirrus clouds, covering about 30% of the Earth's surface area, play an important role in the climate and weather systems. Cirrus cloud radiative forcing (cooling or warming) is influenced by their microphysical (e.g., ice crystal number concentration and size distribution) and macroscopic (e.g., spatial extent) properties. Currently it is still unclear how the formation of cirrus clouds and their microphysical properties are influenced by anthropogenic emissions.

In this work, we use in-situ observations from three flight campaigns to compare the cirrus cloud properties between polluted and pristine regions. Our dataset includes: (1) the NASA Airborne Tropical Tropopause Experiment (ATTREX) campaign (2013), (2) the NSF HIAPER Pole-to-Pole Observations (HIPPO) Global campaign (2009-2011), and (3) the European Union (EU) Interhemispheric Differences In Cirrus Properties from Anthropogenic Emissions (INCA) campaign (2000). The combination of these three campaigns provides in-situ measurements of both extratropical and tropical cirrus clouds, over the Northern and Southern Hemispheres.

We use the in-situ measured carbon monoxide (CO) mixing ratio as a pollution indicator, and compare ice microphysical properties (i.e., ice number concentration (N_c) and mean diameter) between polluted and pristine air masses. All analyses are restricted to temperatures $\leq -40^{\circ}\text{C}$ to exclude mixed-phased clouds. By analyzing the ice crystal measurements (Fast-2DC probe, 87.5-1600 μm) from the HIPPO data, we found that the mean diameter of ice crystals decreases with increasing CO concentration. In addition, analysis of INCA data shows that the number concentration of small ice particles (FSSP 3-20 μm) increases at higher CO concentrations. We filter out the particles smaller than 87.5 μm in Fast-2DC data to minimize the shattering effect, but the FSSP measurements are subject to possible shattering. The HIPPO and INCA datasets are mostly confined to cirrus clouds in the extratropical regions due to the flight ceiling. On the other hand, analysis of the ATTREX data (FCDP 1-100 μm), which mostly sampled cirrus in the tropical tropopause layer, shows that the correlation between N_c and CO is not significant. The results suggest that when extratropical cirrus clouds form in the more polluted background, they are likely to have more numerous small ice particles, yet no obvious adjustments have been observed for tropical cirrus clouds.

More work is required to investigate if the different responses of cirrus microphysical properties between the extratropical and tropical cirrus clouds sampled from these three campaigns are due to different dynamical conditions, or due to the different temperature ranges being used for the analysis (i.e., -40°C to -65°C for HIPPO and INCA versus -65°C to -75°C for ATTREX). Overall, these analyses will help to improve the estimation of the impacts from anthropogenic emissions on cirrus cloud formation.

Distribution of Cirrus Cloud Ice in the Tropical Tropopause Layer as Indicator of Regional Cloud Formation Processes and Climate Cycles

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High altitude cirrus clouds in the tropical tropopause layer (TTL) indicate where relatively cold temperatures and supersaturated air occur together. The focus of the research presented here is to characterize regional and seasonal changes in the tropical uppermost troposphere, using measurements of thin cirrus clouds as indicators of convection and gravity wave activity. The Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on the CALIPSO satellite has captured more than nine years of elastic backscatter measurements (at 532 and 1064 nm) and depolarization (at 532 nm). CALIOP measures backscatter and depolarization from TTL cirrus of all particle sizes, enabling the lidar to detect very thin TTL cirrus clouds. A critical factor in the newest CALIOP climate data record is the increased stability of the recent Version 4 CALIOP calibration, due to a higher calibration reference altitude that is not impacted significantly by volcanic aerosols. We also take advantage of the recent Airborne Tropical Tropopause Experiment (ATTREX) aircraft remote and in situ measurements of extinction and semi-direct measurements of condensed (ice) water in the TTL to evaluate our thin cirrus extinction retrievals and cirrus ice water parameterization. Preliminary comparison of the CALIOP Version 4 and NOAA water instrument measurement of ice water content (IWC) during ATTREX show good agreement (within a factor of 2) at temperatures between 188 and 203 K. Having gained confidence in the satellite data from ATTREX, we map regional distributions of TTL cirrus and IWC to highlight the difference in cloud ice amount above tropical marine and continental convection, and to show seasonal cycling in TTL condensed water amount. Finally, we examine nine years of CALIOP Version 4 Level 1 and adjusted Version 3 Level 1 data to correlate variations in TTL ice water content with ENSO, the QBO and other climate cycles.

Variability of Ice Supersaturation, Nucleation, and Cirrus in TTL Vertical Layers

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High altitude cirrus clouds strongly influence Earth's radiative balance, and thus climate. This effect is not due as much to the direct extinction of the clouds, but their ability to enhance water vapor concentrations in the stratosphere. Cirrus cloud formation is dependent on characteristics and composition of ice supersaturation (ISS) regions, or regions where the relative humidity with respect to ice exceeds 100%, as well as the availability and characteristics of cloud condensation nuclei. The Airborne Tropical Tropopause Experiment (ATTREX) was a series of campaigns focused on improving our understanding of humidity in the TTL. Jensen et al. (2013) reported two classes of cirrus observed during 2011 ATTREX deployment. One class consisted of large ISS, low ice concentrations, and large vertical extents; the other class consisted of much smaller ISS and higher ice concentrations, and was present in very thin vertical layers. We will present analysis of these classes of cirrus using data from the more recent 2013 and 2014 ATTREX deployments, including further evidence of the existence of these thin, low ISS, and high ice concentration layers, as well as evidence of their horizontal extent. We will also discuss the relative frequencies of the two classes in the TTL.

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Using ATTREX Data to Improve the Representation of TTL Cirrus in CAM5

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We use data from the Airborne Tropical Tropopause Experiment (ATTREX) to improve the representation of cirrus clouds in the tropical tropopause layer (TTL) in the Community Atmosphere Model version 5 (CAM5). We simulate all of the ATTREX flights and compare the results along the flight paths to the observations of temperature (MMS), water vapor (NOAA Water and DLH), ice water content (NOAA Water, FCDP, and Hawkeye), ice particle size distributions (FCDP and Hawkeye), and cloud fraction (NOAA Water, FCDP, Hawkeye, and CPL). We find important differences between the model and the observations in temperature, relative humidity, cloud fraction, cloud ice water content and cloud ice particle number density. Some of these differences are due to model parameterizations, and some are due to biases in the temperature fields used to drive the model. We will show how adjustments to correct the temperature biases and changes to the cloud parameterizations in CAM5 result in improved comparisons with the data and affect the simulated TTL cirrus and their heating rates.

On the Susceptibility of Cold Tropical Cirrus to Ice Nuclei Abundance

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Numerical simulations of cirrus formation in the tropical tropopause layer (TTL) are used to evaluate the impact heterogeneous ice nuclei (IN) abundance on cold cloud microphysical properties. The model includes homogeneous and heterogeneous ice nucleation, deposition growth/sublimation, and sedimentation. Reanalysis temperature and wind fields are used to force the simulations, with addition of high-frequency wave temperature variability based on in situ measurements. The model results are constrained by recent in situ observations of TTL cirrus and relative humidity, as well as satellite measurements of cirrus bulk properties and occurrence frequencies, with the caveat that the in situ observations may represent biased samples of the overall TTL properties, particularly for the occurrence of ice supersaturations. Temperature variability driven by high-frequency waves has a dominant influence on TTL cirrus microphysical properties and occurrence frequencies, and inclusion of these waves is required to produce agreement between the simulated and observed cloud properties as well as the abundance of TTL cirrus. With a composition-independent supersaturation threshold for homogeneous freezing of aqueous aerosols, the model produces excessive ice concentrations compared with in situ observations. Inclusion of relatively numerous heterogeneous nuclei ($> 100/L$) in the simulations improves the agreement with observed ice concentrations. However, when IN contribute significantly to TTL cirrus ice nucleation, the occurrence frequency of large supersaturations with respect to ice is less than indicated by in situ measurements. The simulated TTL cirrus extinction statistics agree with observations (within uncertainties) from both in situ and remote-sensing measurements. The model tends to underestimate the occurrence of TTL cirrus with relatively large ice water content compared to the observations. We find that the sensitivity of TTL cirrus extinction and ice water content statistics to heterogeneous ice nuclei abundance is relatively weak. Likewise, the simulated occurrence frequencies of TTL cirrus are insensitive to ice nuclei abundance, both in terms of cloud frequency height distribution and regional distribution throughout the tropics.

Microphysical, radiative and dynamical impacts of thin cirrus clouds on humidity in the tropical tropopause layer and lower stratosphere

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Cloud-resolving numerical simulations are carried out to study how in situ formed cirrus affect the humidity in the tropical tropopause layer and lower stratosphere. Cloud-induced impacts on the specific humidity are evaluated separately in terms of (i) the dehydration efficiency and (ii) the increase in the saturation mixing ratio associated with cloud radiatively induced temperature adjustment.

The numerical results show that the dehydration efficiency of cirrus clouds, which is measured by the domain average relative humidity, varies within $100\pm 15\%$ in all model configurations (with/without heterogeneous ice nucleation, and with/without cloud radiative heating and cloud dynamics).

A larger impact on the specific humidity comes from temperature increase (of a few Kelvins) induced by cloud heating. The latter is found to scale approximately linearly with the domain average ice mass. Resolving the cloud radiatively induced circulations approximately doubles the domain average ice mass and associated cloud-induced temperature change.

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A modeling case-study of a tropical tropopause layer cirrus : roles of dynamics and microphysics and cirrus impacts

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Cirrus clouds in the tropical tropopause layer (TTL) control dehydration of air masses entering the stratosphere and contribute to the local radiative heating. In this study, we aim at understanding, through a real case simulation, the formation and life cycle of a cirrus cloud event in the TTL. We also aim at quantifying the impacts of the cirrus in the TTL and its sensitivity to the microphysics and dynamics in the simulation.

To do this, we use the Weather Research and Forecast (WRF) model to simulate a large scale TTL cirrus event happening in January 2009 (27-29) over the Eastern Pacific, which has been previously described from satellite observations (Taylor et al., 2011). Comparisons of the simulated and observed cirrus show a fair agreement, and validate the reference simulation regarding cloud extension, location and life time. The simulations are then used to understand the cloud formation. It is confirmed that the cirrus forms due to adiabatic cooling and large-scale uplift rather than from ice lofting from convective anvils. The uplift results from the equatorial response (equatorial wave excitation) to a mid latitude Potential Vorticity intrusion. Sensitivity tests are then performed to assess the relative importance of microphysical assumptions, and of initial and boundary conditions in our simulations. In general, as much sensitivity is found on the (comparable) initial conditions than on the microphysics for the simulation of the large scale characteristics of the cloud field (area, location). On the other hand, the cloud induced sedimentation flux and water redistribution strongly depends on the microphysics scheme, and will in turn control future cloud events.

Last, the fair agreement with the observations allows to estimate the cloud impact in the TTL from the simulations. We show that the cirrus has a small but not negligible impact on the radiative budget of the local TTL. However, we do not find a strong influence of the cloud radiative heating on the simulated dynamics, and we propose possible explanations for this behavior. We also quantify the vertical redistribution of water by the cloud and emphasize the importance in our case of both re and dehydration in the vicinity of the cirrus, as well as their dependence on microphysical assumptions.

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What Controls the Low Ice Number Concentration in the Upper Tropical Troposphere?

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Cirrus clouds in the tropical tropopause play a key role in regulating the moisture entering the stratosphere through their dehydrating effect. Low ice number concentrations and high supersaturations were frequently observed in these clouds. However, low ice number concentrations are inconsistent with cirrus cloud formation based on homogeneous freezing. Different mechanisms have been proposed to explain this discrepancy, including the inhibition of homogeneous freezing by pre-existing ice crystals and/or glassy organic aerosol heterogeneous ice nuclei (IN) and limiting the formation of ice number from high frequency gravity waves. In this study, we examined the effect from three different parameterizations of in-cloud updraft velocities, the effect from pre-existing ice crystals, the effect from different water vapor deposition coefficients ($\alpha=0.1$ or 1), and the effect from 0.1% of secondary organic aerosol (SOA) acting as glassy heterogeneous ice nuclei (IN). Model simulated ice crystal numbers are compared against an aircraft observational dataset. Using grid resolved large-scale updraft velocity in the ice nucleation parameterization generates ice number concentrations in better agreement with observations for temperatures below 205K while using updraft velocities based on the model-generated turbulence kinetic energy generates ice number concentrations in better agreement with observations for temperatures above 205K. A larger water vapor deposition coefficient ($\alpha=1$) can efficiently reduce the ice number at temperatures below 205K but less so at higher temperatures. Glassy SOA IN are most effective at reducing the ice number concentrations when the effective in-cloud updraft velocities are moderate ($\sim 0.05\text{--}0.2\text{ m s}^{-1}$). Including the removal of water vapor on pre-existing ice can also effectively reduce the ice number and diminish the effects from the additional glassy SOA heterogeneous IN.