The unique role of airborne in situ observations in identifying and characterizing stratosphere-troposphere exchange (STE)

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In situ observations play a unique role in characterizing the linkage between dynamical processes of all scales and atmospheric composition. Many of these processes are not resolved by satellite observations, and their representations in global chemical climate models are yet to be examined. In this talk, I will present a set of examples using the data from some recent airborne campaigns, including those over the continental US and in the tropics. The examples focus on observations in the upper troposphere and lower stratosphere from high-flying research aircraft NCAR Gulfstream V (GV), NASA DC-8, ER-2 and the Global Hawk.

Small-scale wind fluctuations in the tropical tropopause layer from aircraft measurements : relationship with clouds and convection and impact on vertical mixing

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Turbulent vertical mixing in the tropical tropopause layer (TTL) is poorly known, although it could make a substantial contribution to the heat and tracer transport budgets in that part of the atmosphere. Past observations of small-scale turbulence in the TTL with Radar and radiosondes have been limited to a few tropical locations. Recently, during the ATTREX (Airborne Tropical TRopopause EXperiment) and POSIDON (Pacific Oxidants, Sulfur, Ice, Dehydration, and cONvection) campaigns, in situ measurements from scientific aircraft have provided extensive sampling of small-scale motions over the tropical Pacific, between 14 and 20 km.

In this presentation, high-frequency meteorological observations collected during those recent aircraft campaigns are used to characterize the occurrence of ‘‘clear air turbulence’’ in the TTL. Turbulent bursts are highly intermittent, and are more frequent and intense in the lower TTL and near deep convection. The relationship between turbulent bursts and cirrus clouds is quantified. Finally, the impact of "turbulent" bursts on vertical mixing is estimated and contrasted between convective and non convective regions. The estimated diffusivities are compared with those predicted by turbulent diffusion schemes used in operational analyses systems.

Keywords: tropical tropopause layer, turbulent mixing, aircraft measurements

Methane variations observed in the upper troposphere/lowermost stratosphere over the Eurasian Continent and their interpretation based on the carbon and hydrogen isotopic ratio

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Aircraft observation campaigns over northern high latitudes have been conducted several times to elucidate spatial and temporal variations of CH_4 concentration and their sources on the surface. However, simultaneous observations of CH_4 concentration and its isotopic ratios ($\delta^{13}C$ and δD) in the upper troposphere/lowermost stratosphere (UT/LMS) are quite limited, although such observations provide crucial information for quantifying contributions of sources/sinks of CH_4 to its atmospheric variations. In this study, we present spatiotemporal variations of CH_4, $\delta^{13}C$ and δD using monthly on-board commercial airliners in UT/LMS over the Eurasian continent from April 2012. In the LMS, CH_4 and $\delta^{13}C$, δD showed clear aniti-phase seasonal variations; seasonal maximum (minimum) of the CH_4 concentration ($\delta^{13}C$, δD) was found in November to January and seasonal minimum (maximum) was in March to May. The observed seasonal variations can be explained by effective flushing of the LMS air with the tropospheric air (high CH_4 and low $\delta^{13}C$ and δD) from summer to autumn, and by subsidence of the deeper stratospheric air (low CH_4 and high $\delta^{13}C$ and δD) from winter to spring. Backward trajectory analyses with ERA-Interim reanalysis data were conducted for all air samples. By classifying the results into four seasons, it was found in each season that the correlation of $\delta^{13}C$ or δD with potential velocity (PV) at each sampling point is improved by employing the PV values at locations where each air mass is suited 2-3 weeks before. Such an improvement is probably made, reflecting that isotopically heavier CH_4 generally originates in higher altitudes and/or latitudes, and CH_4 with lighter isotopes in lower altitudes and/or latitudes. We also examined the chemical pathways of CH_4 destruction in the extratropical UT/LMS based on correlations between CH_4 and $\delta^{13}C$. The enriched $\delta^{13}C$ values with the lower CH_4 concentrations indicate occurrence of reactions of CH_4 with Cl and $O(^1D)$, in addition to the major destruction pathway via OH.

Keywords: methane, isotopic ratio, UT/LMS region, backward trajectory analyses

Tropical Tropopause Dynamics (TTD) Campaigns under CAWSES India Phase II over Indian region: Overview and Scientific Accomplishments

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In recent years the 'Tropical Tropopause' has received immense scientific attention because of its sensitivity to anthropogenic activities leading to climate change. Several campaigns have already been conducted and also are being planned to address various issues related to it. Despite many campaigns, several scientific issues still remain unexplained. In order to address some of the issues, particularly over the Indian region, intensive observational campaigns named as the 'Tropical Tropopause Dynamics (TTD)' have been conducted between December 2010 and March 2014 at two stations namely Gadanki(13.5°N, 79.2°E) and Trivandrum(8.5°N, 76.9°E). This work is aimed at bringing out the importance of a sustained study on the tropical tropopause, using collocated instruments as well as complementary data from the satellites. In general, a prominent updraft prevails below and above the TTL, suggesting that deep convection is not essential for the transport of minor species across the tropopause. Sub-daily variations are observed at both the stations and the amplitude of this variation is small at Gadanki. The behavior of the cold point tropopause (CPT) at Gadanki and Trivandrum revealed that there are important differences in the CPT characteristics even within the monsoon region. Significant modulation in the tropical tropopause parameters by the prevailing tides and planetary waves is noticed. The vertical temperature gradient in the tropical tropopause layer (TTL) is related to the presence of tropical cirrus. Altitude structure of tropical cirrus in the upper troposphere is clearly associated with that of turbulence. This Indian Program is expected to provide important contributions to the international campaigns planned over Pacific and Asian region on the TTL.

Keywords: Tropical Tropopause Layer, STE processes, Campaigns

Stratosphere-troposphere exchange over the northern Pacific Ocean using chemical reanalysis data

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Stratosphere-troposphere exchange (STE) is one of the important factors that determine the distribution of constituents in the troposphere and stratosphere. Two-way airmass exchange between the lower stratosphere and the troposphere occurs in association with mid-latitude weather disturbances, with the net transport from the stratosphere to troposphere. Among various mid-latitude disturbances, explosive cyclones are those with very rapid surface pressure drops and cause severe weather phenomena. In this study, we investigate the role of explosive cyclones over the northern-hemisphere Pacific Ocean in the STE. We analyze ozone and carbon monoxide (CO) data from a chemical reanalysis data set called the Tropospheric Chemical Reanalysis data (TCR-1).
TCR-1 is a 10-year chemical reanalysis data set for the period from 2005 to 2014. TCR-1 assimilates satellite chemistry data from the Ozone Monitoring Instrument (OMI), Aura Microwave Limb Sounder (MLS), Tropospheric Emission Spectrometer (TES), and Measurement of Pollution In The Troposphere (MOPITT), by using a global chemical transport model CHemical AGCM for Study of atmospheric Environment and Radiative forcing (CHASER) driven with NCEP-DOE reanalysis data and the ensemble Kalman filter technique. NCEP-DOE reanalysis data are also used to calculate potential vorticity (PV) and to obtain TCR-1 ozone and CO data on isentropic surfaces. The definition of explosive cyclones used in this study is the one used by the Japan Meteorological Agency, that is, extra-tropical cyclones whose center-pressure drop rate is more than 24 hPa $\times\sin(\phi)/\sin(60^\circ)$ (where ϕ is latitude) within 24 hours. Both monthly mean and instantaneous 2-pvu PV curves on isentropic surfaces are used to define the tropopause. Indices for irreversible Stratosphere-to-Troposphere Transport (STT) and Troposphere-to-Stratosphere Transport (TST) are further defined using ozone and CO data to investigate quantitative impact of explosive and non-explosive cyclones over the northern-hemisphere Pacific Ocean. Explosive cyclones over the northern Pacific Ocean are observed in winter, with the maximum activity in January and February. It is found that about half of the explosive cyclones cause significant STE. In January, the average amount of STT per cyclone due to explosive cyclones is significantly greater than that due to other cyclones. It is also found that the amount of STT (TST) in years 2005-2009 is significantly smaller (greater) than that in years 2010-2014. In the presentation, we will discuss possible causes of this interannual change.

Keywords: Stratosphere-troposphere exchange, Ozone, Explosive cyclones

Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP)

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The climate research community uses atmospheric reanalysis data sets to understand a wide range of processes and variability in the atmosphere, yet different reanalyses may give very different results for the same diagnostics. The Stratosphere–troposphere Processes And their Role in Climate (SPARC) Reanalysis Intercomparison Project (S-RIP) is a coordinated activity to compare reanalysis data sets using a variety of key diagnostics. The objectives of this project are to identify differences among reanalyses and understand their underlying causes, to provide guidance on appropriate usage of various reanalysis products in scientific studies, particularly those of relevance to SPARC, and to contribute to future improvements in the reanalysis products by establishing collaborative links between reanalysis centres and data users. The emphasis is on diagnostics of the upper troposphere, stratosphere, and lower mesosphere. An overview of S-RIP will be presented, together with some scientific highlights.

Keywords: reanalysis, intercomparison, SPARC

The stratospheric signature of warming Arctic and its impacts on mid-latitude climate change

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Recent evidence from both observations and model simulations suggests that an Arctic sea ice reduction tends to cause a winter negative Arctic Oscillation (AO) phase, which is indicative of the Arctic warming and the severe winter weather in the mid-latitude Northern Hemisphere. The negative phase of AO is often preceded by weakening of the stratospheric polar vortex (i.e., sudden stratospheric warming, SSW). We performed a time-slice experiment using a high-top AGCM, in which only the Arctic sea ice loss is responsible to altering the climate state (Nakamura et al., 2015). The results show a negative AO-like pattern that brings more heat transport into the Arctic and cold air outbreak over the mid-latitudes (positive feedback) via dynamically induced secondary circulation in the meridional plane. The simulated responses show high similarity with observed climate change signals of the recent decades, seen in an increased SSW frequency and its downward influences (Jaiser et al., 2016) as well as dynamical properties (Hoshi et al., 2017).
Such a sea ice-AO linkage largely disappears when model's stratospheric representation is artificially deteriorated (i.e., mimicking low-top model), confirming a crucial role of the stratosphere-troposphere (S-T) coupling in the current Arctic climate changes (Nakamura et al. 2016a). Even in an extreme climate of the ice-free (Blue Arctic Ocean) simulation there appears a negative AO response but the S-T coupling process becomes absent (Nakamura et al., 2016b).
The complexity arising from positive feedback mechanism of the heat transport and non-linearity of the stratospheric response may be a cause of uncertainty of the Arctic and mid-latitude climate linkage. More extensive studies about S-T coupling process will help to understand underlying mechanisms for this complexity.
Reference: Nakamura et al. (2015), JGR, 120, 3209-3227; Nakamura et al. (2016a), GRL, 43, 3494-3501; Jaiser et al. (2016), JGR, 121, 7564-7577; Nakamura et al. (2016b), GRL, 43, 10394-10402; Hoshi et al. (2017), GRL, 44, 446-454.

Keywords: Arctic sea ice retreat, Arctic Oacillation, Polar amplification, Stratosphere-Troposphere interaction, Sudden stratospheric warming, Arctic-mid-latitude climate linkage

Lower stratospheric control of the frequency of sudden stratospheric warming events

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Simple atmospheric models are often used to investigate the dynamical coupling between the stratosphere and the troposphere. Several studies have examined, using such models, the sensitivity of stratospheric polar vortex variability to the upper-stratospheric relaxation temperatures. Although it is known that the lower stratosphere can act as a valve for the upward propagation of planetary-scale waves and thus a regulator for the occurrence of SSW events, the sensitivity of the model setup to lower-stratospheric temperatures was not thoroughly investigated.

We contrast in this work the sensitivity of stratospheric variability to the lower and upper stratospheric temperatures by performing parameter-sweep experiments. It is found that lower-stratospheric temperature is of prime importance to regulate the temporal variability of the vortex. Against the common intuition that a warm high-latitude polar stratosphere results in a weaker vortex and more frequent reversals of zonal-mean zonal wind, we find that a cold lower stratosphere at the pole is crucial for the occurrence of sudden stratospheric warming (SSW) events. We hypothesize that a stronger meridional temperature gradient helps to maintain a waveguide between the troposphere and the stratosphere.

The wave-1 and wave-2 SSW events generated in our model runs are further studied with the transformed Eulerian mean and finite amplitude wave activity frameworks. It is shown that the evolution of SSW events in the model are qualitatively similar to SSWs seen in observations. Interestingly, while the wave activity signal propagates downward in wave-1 events, it is propagating upward in wave-2 events, hinting to different wave-mean flow interactions.

Defining stratospheric sudden warming in climate models: Accounting for biases in model climatology

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A sudden stratospheric warming (SSW) is often defined as zonal-mean zonal wind reversal at 10 hPa and 60°N. This simple definition has been applied not only to the reanalysis data but also to climate model output. In the present study, it is shown that the application of this definition to models can be significantly influenced by model mean biases; i.e., more frequent SSWs appear to occur in models with a weaker climatological polar vortex. In order to overcome this deficiency, a tendency-based definition, is proposed and applied to the multi-model data sets archived for the Coupled Model Intercomparison Projection phase 5 (CMIP5). In this definition, SSW-like events are defined by sufficiently strong vortex deceleration. This approach removes a linear relationship between SSW frequency and intensity of climatological polar vortex in the CMIP5 models. Models' SSW frequency instead becomes correlated with the climatological upward wave flux at 100 hPa. Lower stratospheric wave activity and downward propagation of stratospheric anomalies to the troposphere are also reasonably well captured. However, in both definitions, the high-top models generally exhibit more frequent SSWs than the low-top models. Moreover, a hint of more frequent SSWs in a warm climate is commonly found.

Keywords: Stratospheric Sudden Warming, CMIP5 models

A mechanism to explain the variations of tropopause and tropopause inversion layer in the Arctic region during a sudden stratospheric warming in 2009

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The mechanism to explain the variations of tropopause and tropopause inversion layer (TIL) in the Arctic region during a sudden stratospheric warming (SSW) in 2009 was studied with MERRA reanalysis data and GPS/COSMIC temperature data. During the prominent SSW in 2009, the cyclonic system changed to the anticyclonic system due to the planetary wave with wavenumber 2 (wave2). The GPS/COSMIC temperature data showed that, during the SSW in 2009, the tropopause height in the Arctic decreased accompanied with the tropopause temperature increase and the TIL enhancement. The variations of the tropopause and TIL were larger in higher latitudes. A static stability analysis showed that the variations of the tropopause and TIL were associated with the variations of the residual circulation and the static stability due to the SSW. Larger static stability appeared in the upper stratosphere and moved downward to the narrow region just above the tropopause. The descent of strong downward flow was faster in higher latitudes. The static stability tendency analysis showed that the strong downward residual flow induced the static stability change in the stratosphere and around the tropopause. The strong downwelling in the stratosphere was mainly induced by wave2, which led to the tropopause height and temperature changes due to the adiabatic heating. Around the tropopause, a pair of downwelling above the tropopause and upwelling below the tropopause due to wave2 contributed to the enhancement of static stability in the TIL immediately after the SSW.

Keywords: tropopause, TIL, SSW, planetary wave, static stability, residual vertical velocity

A latitudinal dependence on the summer tropopause inversion layer and its seasonality

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The latitude-dependent structure of the summer tropopause inversion layer (TIL) and the seasonality of the mid-latitude TIL are examined using a general circulation model (GCM) with a vertical resolution of about 300m above a 10 km height and an offline column radiative transfer model (CRM). A comparison with GPS radio occultation temperature observations shows that the GCM successfully simulates the fine structure and seasonality of the TIL.
A gradient genesis analysis for the static stability at the TIL is performed. It is shown that a large negative tendency due to the stretching effect of the vertical velocity is balanced by a large positive tendency due to the radiative effect related to water vapor in the mid-latitude summer TIL. The negative stretching effect is caused by a shallow branch of the Brewer-Dobson circulation. Given that the radiative effect of water vapor is essential for the summer TIL as suggested by previous studies, this means that the stretching effect weakens the mid-latitude summer TIL. On the other hand, the polar summer TIL is balanced with a small tendency due to both the radiative and the stretching effects, suggesting that the polar TIL is not largely affected by the stretching effect. Using CRM, an idealized mid-latitude TIL without the stretching effect is estimated assuming that vertical velocities above the TIL are the same as that at the TIL height. The magnitude of the static stability of the idealized mid-latitude TIL is quite similar to that of the real polar summer TIL. This fact suggests that the latitude-dependence of the TIL structure is at least partly explained by the shallow branch of the stratospheric circulation. In contrast, it is shown that the TIL structure in the winter mid-latitude TIL is strengthened by the stretching effect. These results indicate that the stretching effect is essential to the seasonality of the mid-latitude TIL, although the TIL itself is mainly caused by the radiative effect of the water vapor.

Keywords: Tropopause Inversion Layer

The understanding of subseasonal variability of the Asian monsoon anticyclone as shallow water system

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The circulation in the upper troposphere and lower stratosphere (UTLS) over Asia in summer is characterized by the Asian Monsoon Anticyclone (hereafter referred to simply as 'the anticyclone') driven by Monsoonal convective heating. Recently much attention has been paid to the role of the anticyclone on the transport and mixing processes. Despite its importance, the detailed understanding of dynamical and physical processes around the anticyclone is still insufficient. One of the important ongoing discussion is on the mechanism of the subseasonal variability of the anticyclone. An important observed feature is frequent westward propagation with 'bimodal' structure favoring two distinct locations over the east and west Asia. Dynamical understanding of this feature is the main purpose of this study.

Previous studies have tackled this issue from two contrasting perspectives. Some considered the variability of the anticyclone simply as the response to the temporal variability of the tropical convection. Others rather focused on the nonlinear nature of the circulation (Hsu and Plumb, 2000; hereafter referred to as 'HP00'), which lead to the possibility of spontaneous periodic response to a finite amplitude steady forcing. We follow the latter perspective.

First, we revisited HP00 model to examine the validity of their result in a realistic parameter range. The model is a beta-plane shallow water system with linear damping and a localized steady mass source on the subtropics. We confirmed that, with some extension regarding the forcing amplitude range, the vortex shedding is found under the realistic forcing latitude and damping time scale. Moreover, the speed of westward propagation was found approximately 10-20m/s, which is consistent with the real atmosphere.

Next, the validity of shallow water concept is examined using the reanalysis data. We calculated composite of Ertel's potential vorticity (PV), Montgomery streamfunction (M), and thickness (sigma) on isentropic surfaces from ERA-Interim reanalysis for the summer period of 2011-2015, classifying 6-hourly snapshots by the longitudinal location of the anticyclone. On 360 and 365K surfaces, we found excellent consistency regarding the latitudinal structure of the vortex shedding with the shallow water model, in which maximum in M and sigma is located slightly north of low PV anomaly.

The resemblance between the structure of M and sigma implies the validity of the shallow water concept. We further estimate the equivalent depth as the first order coefficient of the linear regression between M and sigma from the reanalysis data. Linear relation between the two quantities is clear not all latitude regions but each of the regions in the north and south of 35N. The estimated depths are approximately 60m and 200~300m in the south and north, respectively.

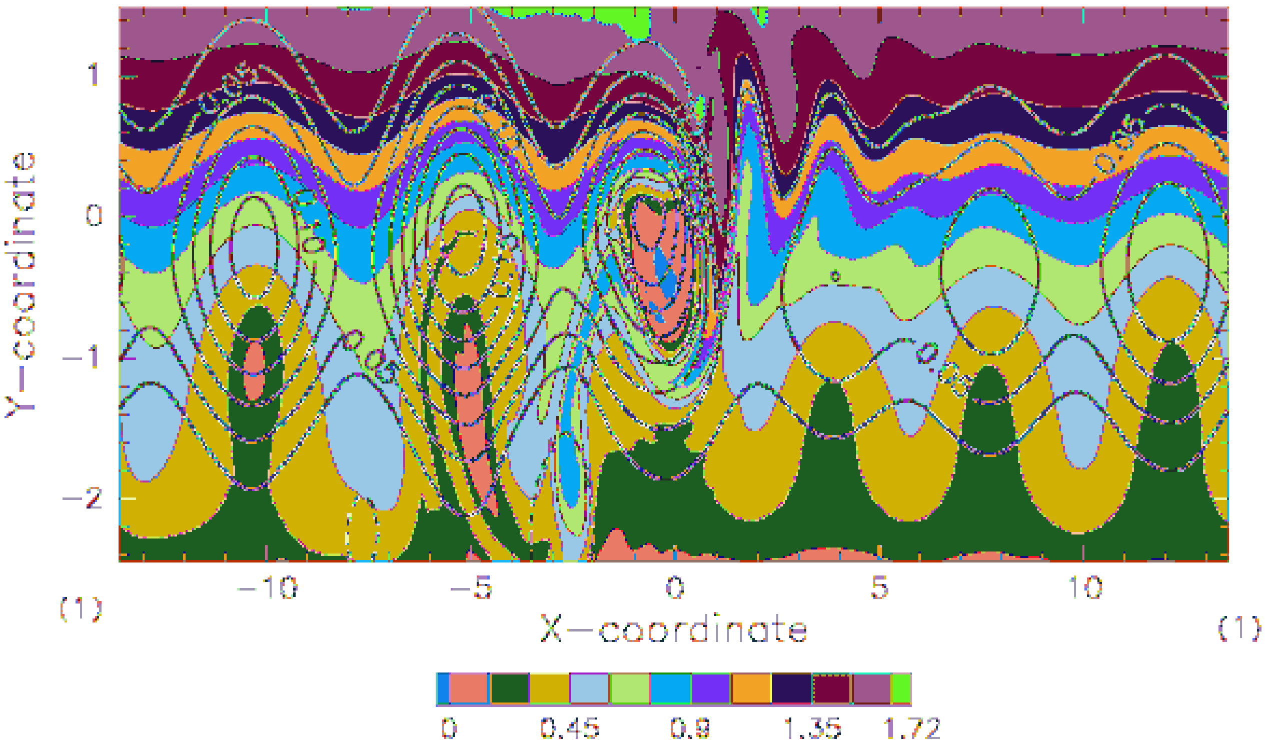
Last, taking account of the implication above, we performed additional experiments with the shallow water model with the inclusion of the latitudinally dependent mean depth. In a certain range of forcing amplitude, experiments with three times larger equivalent depth on the north produce similar periodic response but with different spatial structure, in which PV and height disturbances favor two center longitude and do not propagate westward beyond(fig. b). This structure is much more realistic than the previous case with homogeneous equivalent depth (fig. a), in terms of the westward propagation and the

'bimodal' behavior.

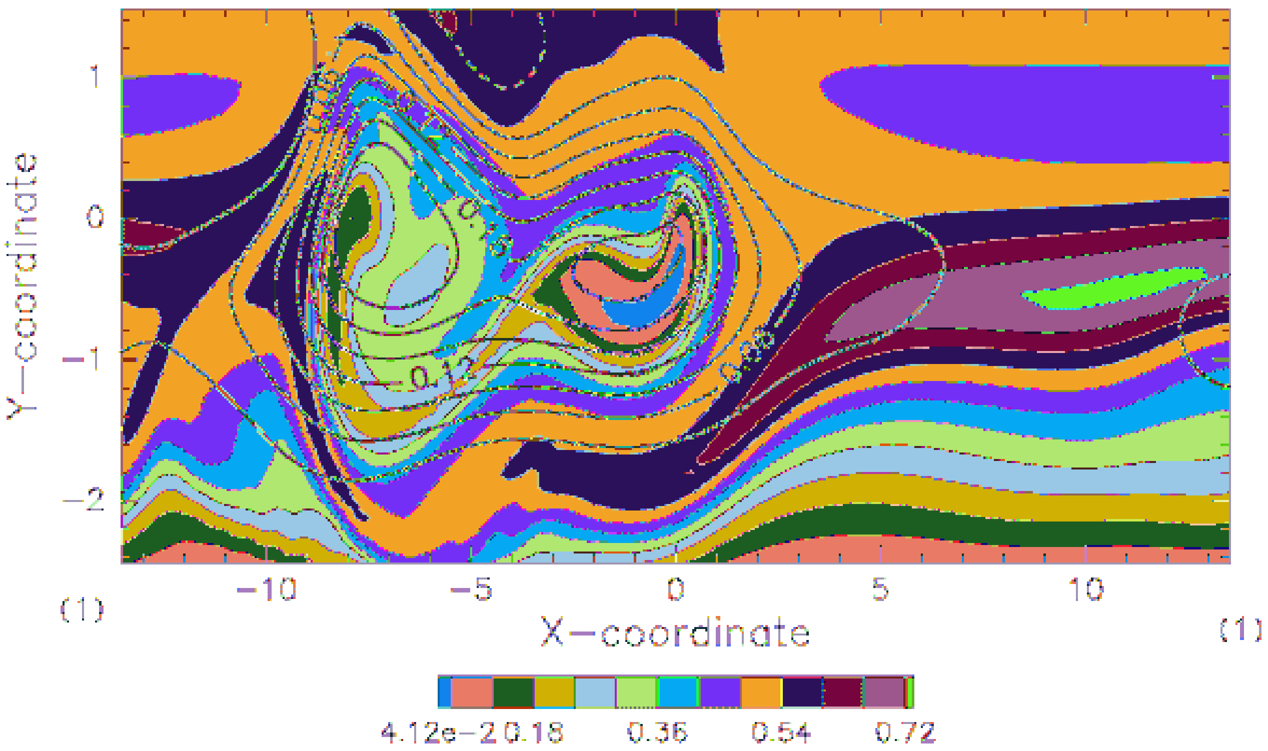
In summary, **the shallow water model with variable mean depth is found to be capable of reproducing spontaneous westward propagation of the anticyclone with realistic speed and structure**. It is worth emphasizing that this simple model includes neither periodicity in the forcing nor any external longitudinal asymmetry. This suggests that the subseasonal variability of the anticyclone is, at least qualitatively, the intrinsic behavior of the anticyclone itself, but not necessarily due to externally imposed constraints.

Keywords: Atmospheric Dynamics, Stratosphere-Troposphere Coupling, The Asian Monsoon

(a) homogeneous H_{eq}



(b) three times larger H_{eq} for y>0.5



Downward Influence of QBO-like Oscillation to Moist Convection in a Two-Dimensional Minimal Framework

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A self-sustained oscillation in zonal mean zonal winds that is analogous to the equatorial quasi-biennial oscillation (QBO) was first obtained in a radiative-convective equilibrium state of a two-dimensional model by Held et al. (1993). The robustness of the QBO-like oscillation was reconfirmed by Yoden et al. (2014; hereafter, YBN14) in a two-dimensional minimal framework. High temporal-resolution outputs from YBN14's framework were analyzed by Nishimoto et al. (2016) and revealed that there appear two types of precipitation patterns as squall line and back building, depending on the magnitude of vertical shear near the surface.

In this paper, we further investigate the influence of the QBO-like oscillation on convection using the minimal framework of YBN14 with two series of parameter sweep experiments. The first series, *Model top experiments*, change the height of model from 40 km to 15 km to examine the sensitivity of the precipitation modulation to the choice of model height. In the second series, *Low-level nudging experiments*, the zonal mean zonal wind is nudged towards zero in a certain depth from the surface to remove the effect of low-level wind shear. Two typical examples of the experiments are chosen for further composite analysis to reveal the convective structures in different conditions of precipitation.

The results show that the QBO-like oscillation modulates the convection via two mechanisms related to vertical shear of the zonal mean zonal wind. Large values of shear near the surface enhance the longevity and intensity of the convective systems in the form of squall line type. On the other hand, large values of shear near the cloud top disrupt the convective structure and leads to a smaller amount of precipitation. The first mechanism seems to be dominated as the second one only be revealed when the low-level shear is nudged to some certain levels.

Keywords: QBO-like oscillation, influence to moist convection, two-dimensional minimal framework

Role of Stratospheric Cooling on the Tropical Troposphere and the Ocean

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Large changes in circulation have occurred around the end of 1990's in the troposphere and the ocean as well as in the lower stratosphere, such as an advancement of the onset of Asian summer monsoon, cooling of the equatorial eastern Pacific connected to the hiatus of the global warming, and cooling in the tropical lower stratosphere. Whether or not a causal relationship exists among these phenomena, is an interesting yet challenging question.

We, therefore, investigate a transient phenomenon as well as long-term change or recent trend to gain insight into the relationship between changes in the stratosphere and the ocean. For this, we select sudden cooling events in the tropical lower stratosphere during the boreal summer. Stratospheric temperature decreased in association with an increased upwelling induced by an enhancement of planetary wave activity in the SH. Increased upwelling is apparent in the UTLS region of the summer hemisphere particularly around 15N-25N, where the ascending branch of the Hadley circulation is in line with the upwelling branch of the Brewer-Dobson circulation. Because this connected zone is situated poleward of the climatological center of the ascending branch of the Hadley circulation, enhancement of the upward velocity in this region shifts the Hadley circulation poleward, which leads to an increase in the cross-equatorial surface flow from the winter to summer hemisphere. This increase of the southerlies decreases the SSTs in the equatorial eastern Pacific.

Impact of the SSTs on the lower stratosphere through changes in convective activity is well known. Adding to this, the present study suggests a possibility that a change in stratospheric circulation induces anomalous SSTs in the tropics.

Keywords: stratosphere, troposphere, Convection, Hadley circulation, Brewer-Dobson circulatioon

Asymmetry and nonlinearity of the influence of ENSO on the northern winter stratosphere: Observations vs. simulations

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This study explores the nonlinearity and the asymmetry of ENSO’ s influences on the northern winter stratosphere. It is revealed that the ‘moderate El Niño’ and the ‘strong La Niña’ are more efficient than the ‘strong El Niño’ and the ‘moderate La Niña’ respectively. The tropical rainfall anomalies induced by a moderate El Niño or a strong La Niña are centered over the central equatorial Pacific region near the dateline, while the convection responses to a strong El Niño or a moderate La Niña are centered farther eastward. Accordingly, the anomalous Pacific–North America wave train pattern is modulated by ENSO in a nonlinear and asymmetric way, which leads to the large nonlinear and asymmetric components of the vertical Eliassen-Palm (E–P) flux responses to ENSO in the extra-tropics. The nonlinearity and asymmetry of ENSO-stratosphere coupling are well confirmed by the long-term simulations from the CESM-WACCM. Sensitivity experiments with WACCM further reveal that the nonlinearity and asymmetry of the stratospheric responses to moderate ENSO are dominated by the inherent properties of the atmosphere. Whereas those of the stratospheric responses to strong ENSO are mainly resulted from the asymmetry of ENSO SST forcing between strong El Niño and La Niña. Furthermore, the and the “high-top” WACCM are adopted to investigate the asymmetry and the nonlinearity. It is revealed that the dominant role of the inherent properties of the atmosphere.

Keywords: Winter Stratosphere, ENSO's influences, Nonlinearity, Asymmetry

Do stratospheric ozone measurements show large tropical width changes?

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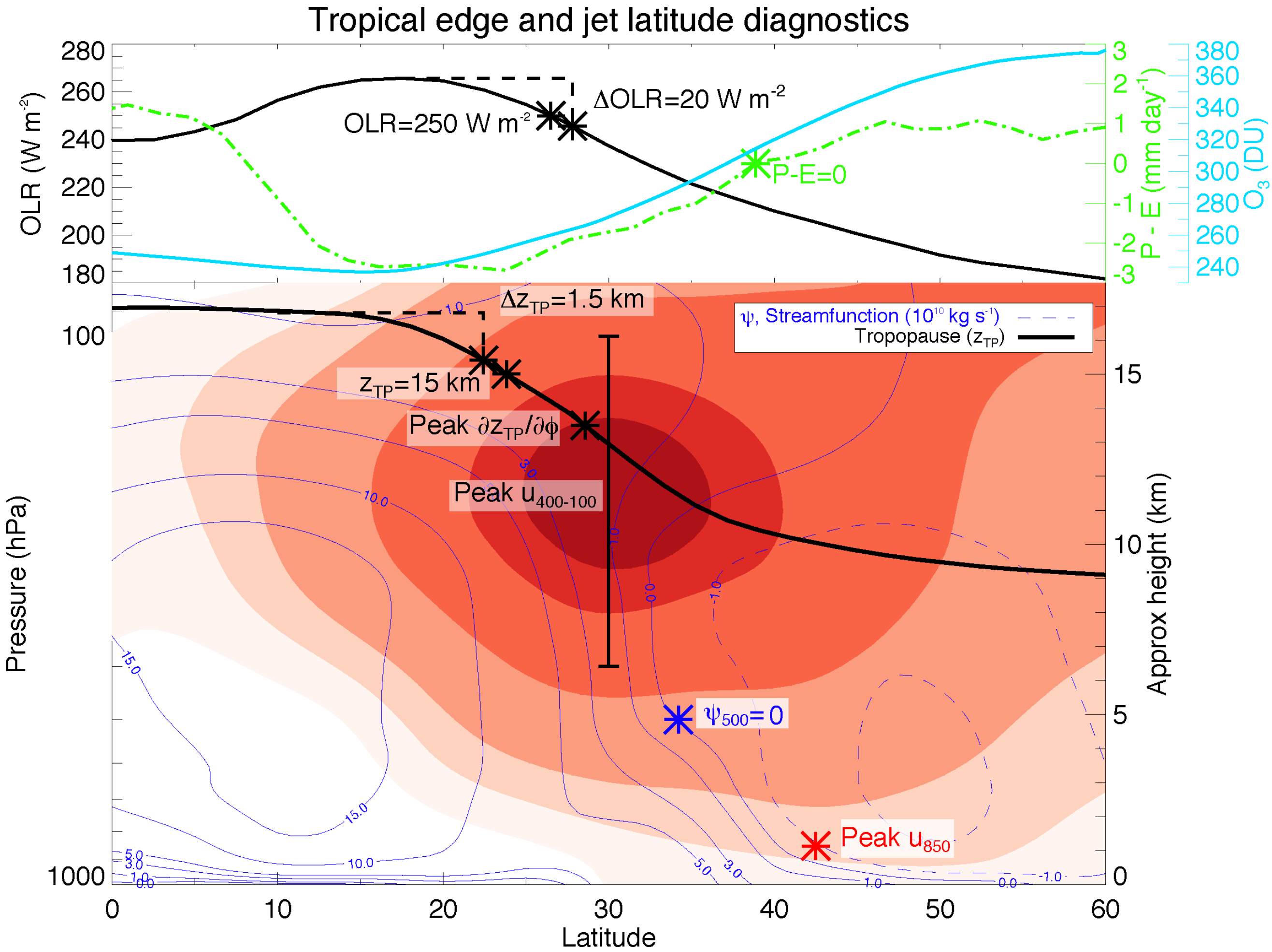
The total column ozone amount varies with latitude, in part due to the difference in tropopause height between the tropics and midlatitudes. This dependency of column ozone on latitude has been exploited by several studies to identify tropical edge latitudes and to compute their trends. The tropical widening trend over the past several decades from this method is greater than 3° latitude decade^{-1}, a rate which is significantly larger than most other tropical widening estimates.

We assess the robustness of the previously used methodology by comparing it to a new objective gradient-based method of total column ozone. The total column ozone methodologies are then compared to a diagnostic based on vertically resolved satellite ozone data from the Stratospheric Water and OzOne Satellite Homogenized (SWOOSH) data set. Our results indicate a general lack of robustness of the previous estimates, and are more in line with other tropical widening estimates indicating poleward expansion rates of < 1° latitude decade^{-1}.

Keywords: Stratosphere, Tropical width, Tropical widening, Ozone, Satellite measurements


Tropical edge and jet latitude diagnostics
OLR (W m-2)
ΔOLR=20 W m-2
OLR=250 W m-2
P-E=0
P - E (mm day-1)
O3 (DU)
ΔzTP=1.5 km
zTP=15 km
Peak ∂zTP/∂φ
Peak u400-100
ψ, Streamfunction (10^10 kg s-1)
Tropopause (zTP)
ψ500=0
Peak u850
Pressure (hPa)
Approx height (km)
Latitude

Variation in the mixing fraction of tropospheric and stratospheric air masses sharing the tropical lower stratosphere

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Stratospheric abundance of tropospheric species is largely controlled by air mass transport into the stratosphere through the tropical tropopause layer (TTL) associated with the Brewer-Dobson circulation (BDC). In addition to this transport process, quasi-horizontally mixing process between the tropical and extra-tropical lower stratospheres is also affected the abundance of such species flowing into the mid and upper stratosphere. We focus on the mixing fraction of tropospheric and stratospheric air mass sharing the tropical lower stratosphere (TLS) and its temporal variation. To estimate the origins, i.e., tropospheric or stratospheric origins, for the TLS air masses, the backward trajectories are initialized between 20°S and 20°N with 1.5° x 5.0° latitude/longitude resolution at 400 K and 440 K potential temperature surface and are calculated every month for a maximum of 180 days over the period from January 1980 to December 2015 by using Era-Interim 3-dimentional wind field. The air mass origin is determined by history information along the backward trajectory, such as potential temperature, potential vorticity, and latitude, for each air parcel. By means of statistical analyses of such air mass origins in the TLS, it is shown that (1) the mixing fraction of tropospheric and stratospheric origins is almost consistent with that estimated by Sargent et al. (2014) based on aircraft campaigns in the comparison at the same temporal-spatial region, (2) the fractions of tropospheric/stratospheric origins have seasonal variations with the maxima in boreal spring/boreal summer-autumn, and (3) their annual averages have decreasing/increasing trends from 1980 to 1999 and have increasing/decreasing trends from 2000 to 2015, respectively. We examine how such long-term variation in the mixing fraction of the TLS air masses affects stratospheric abundance of tropospheric species and the stratospheric "age of air" (AOA) (Hall and Plumb, 1994). The results qualitatively agree with long-term variation of the AOA estimated from CO_2 mixing ratios that have been observed by the cryogenic whole air samplings in mid-latitude mid-stratosphere.

Keywords: stratosphere-troposphere exchange, trajectory analysis, age of air, air mass origin, tropical lower stratosphere

Stratospheric Residence Time Inferred from Trajectory Model Driven by Modern Reanalyses

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Stratospheric mean residence time (τ) is a useful quantification of the Troposphere-Stratosphere exchange. We use Lagrangian trajectories driven by modern reanalyses (MERRA, MERRA-2, CFSR, ERA-Interim, and JRA-55) to investigate the τ and its variability in three decades. The results show systematic consistency among the MERRA, MERRA-2, and CFSR, but differ in ERAi and JRA-55. Starting from the 370-K isentrope, it takes ˜3 months for tracers to transport through the Tropical Tropopause Layer (TTL, upper boundary 425-K) when driven by MERRA, MERRA-2, and CFSR, while it only takes 2.5 and 2 months when driven by JRA-55 and ERAi, respectively. In middle to upper stratosphere (450–1500K) the accumulated differences could be up to one year. The discrepancies are mainly caused by uncertainties in total heating rates that are subject to changes by temperature, ozone, and clouds (especially cirrus) assimilated differently in reanalysis system. The residence time varies spatially and is shorter over frequent convection region and over the Asian summer monsoon where persistently strong upwelling ascends parcels faster. Despite the discrepancies, the interannual variability of τ shows common features that are linked to the stratospheric quasi-biennial oscillation (QBO) and to the El Nino–Southern Oscillation (ENSO) events. While excluding the impact from QBO and ENSO, we found a negative trend of -1–4%/decade of residence time throughout the TTL, indicating a faster transport from strengthened upwelling in the stratosphere.

Keywords: stratospheric residence time, troposphere-stratosphere exchange, trajectory model, reanalysis

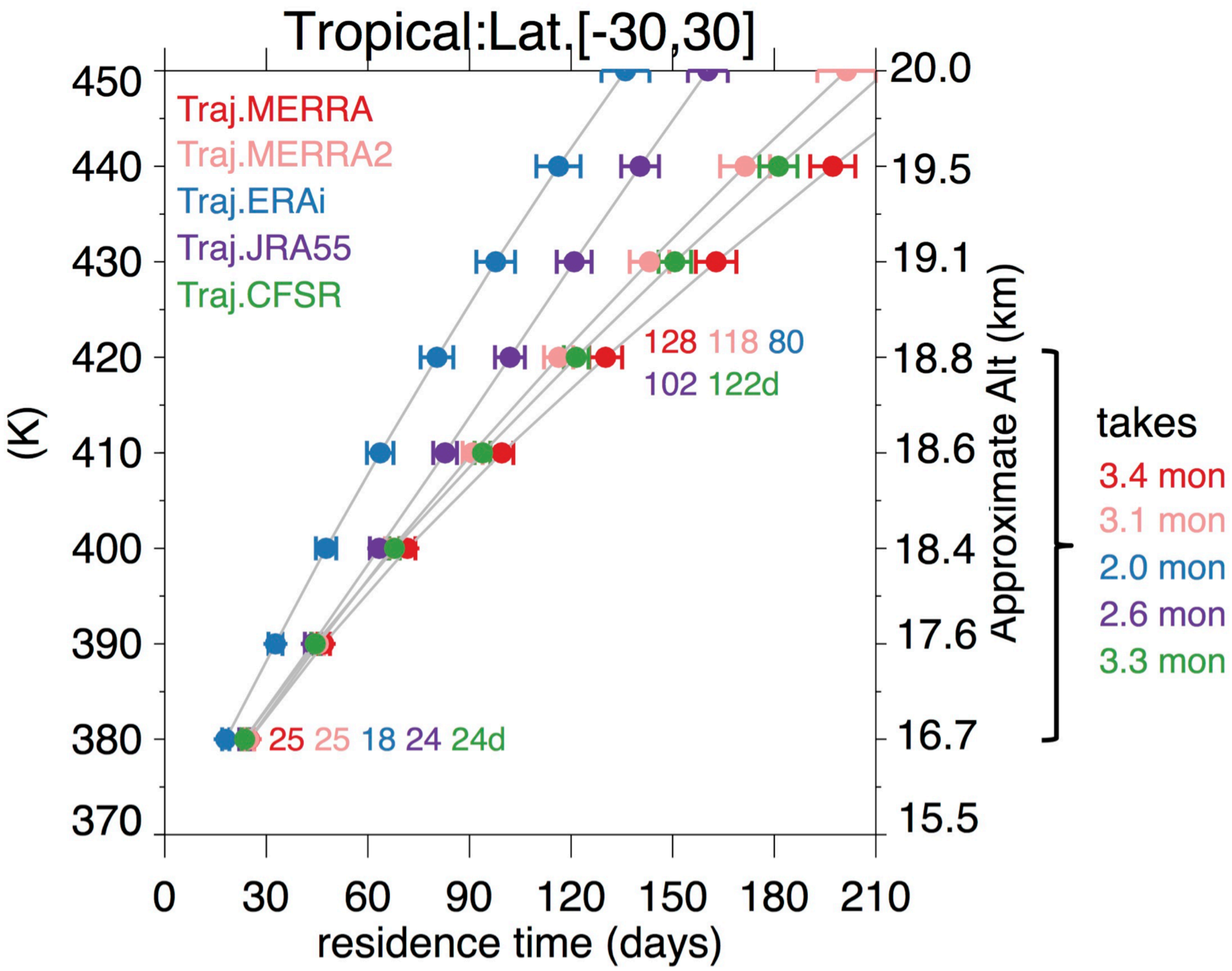

Figure 1. The residence time (days) within the lower stratosphere inferred from diabatic trajectories driven by circulations from MERRA, MERRA2, ERAi, JRA55, and CFSR. Trajectories are initiated at 370 K within 30° N-S and being advected upward by total diabatic heating rates Q_{tot} (vertical velocity $d\theta/dt = Q_{tot} \bullet (P/P_0)^{-R/Cp}$).

A warming tropical central Pacific dries the lower stratosphere

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The amount of water vapor in the tropical lower stratosphere (TLS), which has an important influence on the radiative energy budget of the climate system, is modulated by the temperature variability of the tropical tropopause layer (TTL). The TTL temperature variability is caused by a complex combination of the stratospheric quasi-biennial oscillation (QBO), tropospheric convective processes in the tropics, and the Brewer–Dobson circulation (BDC) driven by mid-latitude and subtropical atmospheric waves. In 2000, the TLS water vapor amount exhibited a stepwise transition to a dry phase, apparently caused by a change in the BDC. In this study, we present observational and modeling evidence that the epochal change of water vapor between the periods of 1992-2000 and 2001-2005 was also partly caused by a concurrent sea surface temperature (SST) warming in the tropical central Pacific. This SST warming cools the TTL above by enhancing the equatorial wave-induced upward motion near the tropopause, which consequently reduces the amount of water vapor entering the stratosphere. The QBO affects the TLS water vapor primarily on inter-annual timescales, whereas a classical El Niño southern oscillation (ENSO) event has little effect on tropical mean TLS water vapor because its responses are longitudinally out of phase. This study suggests that the tropical central Pacific SST is another driver of TLS water vapor variability on inter decadal timescales.

Keywords: tropical lower stratosphere, water vapor, central Pacific , Convection

Ice Nucleation in the Tropical Tropopause Layer: Implications for cirrus occurrence, cirrus microphysical properties, and dehydration of air entering the stratosphere

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Recent laboratory experiments have advanced our understanding of the physical properties and ice nucleating abilities of aerosol particles at low temperatures. In particular, aerosols containing organics will transition to a glassy state at low temperatures, and these glassy aerosols are moderately effective as ice nuclei. These results have implications for ice nucleation in the cold Tropical Tropopause Layer (TTL; 13-19 km). We have developed a detailed cloud microphysical model that includes heterogeneous nucleation on a variety of aerosol types and homogeneous freezing of aqueous aerosols. This model has been incorporated into one-dimensional simulations of cirrus and water vapor driven by meteorological analysis temperature and wind fields. The model includes scavenging of ice nuclei by sedimenting ice crystals. The model is evaluated by comparing the simulated cloud properties and water vapor concentrations with aircraft and satellite measurements. In this presentation, I will discuss the relative importance of homogeneous and heterogeneous ice nucleation, the impact of ice nuclei scavenging as air slowly ascends through the TTL, and the implications for the final dehydration of air parcels crossing the tropical cold-point tropopause and entering the tropical stratosphere.

Keywords: Ice nucleation, Heterogeneous nucleation, Dehydration

Is convection important for controlling stratospheric humidity?

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We investigate the role of convection on stratospheric water vapor and upper tropospheric cloud fraction using two sets of complementary transport and microphysical models driven by MERRA-2 and ERA-Interim meteorological analyses: (1) computationally efficient ensembles of forward trajectories with simplified cloud microphysics, and (2) one-dimensional simulations with detailed microphysics along back trajectories. Convective influence along the trajectories is diagnosed based on TRMM/GPM rainfall products and geostationary infrared satellite cloud-top measurements, with convective cloud-top height adjusted to match the CloudSat, CALIPSO, and CATS measurements. We evaluate and constrain the model results by comparison with satellite observations and high-altitude aircraft campaigns (e.g., ATTREX, POSIDON).

Convection moistens the lower stratosphere by approximately 0.6 ppmv (about 15% increase) and increases the cloud fraction in the upper troposphere by roughly 15%. Convection moistens the upper troposphere and lower stratospheric region mostly by saturating the convectively-influenced parcels. Including lofted ice in the microphysics has a negligible impact on lower stratospheric humidity. The highest convection has a disproportionately large impact on stratospheric water vapor enhancement. Implications of these model results on the role of convection on present and future climate will be discussed.

Keywords: tropical tropopause layer, water vapor, cirrus clouds, stratosphere, convection, climate

Tropopause cold layer and its influence on stratospheric moisture

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Characteristics of the tropopause-level cold layer associated with tropical deep convection are examined using CloudSat and Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) GPS radio occultation measurements. Deep convection is sampled based on the cloud top height (>17 km) from CloudSat 2B-CLDCLASS, and then temperature profiles from COSMIC are composited around the deep convection. Response of moisture to the cold layer is also examined in the upper troposphere and lower stratosphere using microwave limb sounder (MLS) measurements.

The composite temperature shows an anomalously warm troposphere (up to 14 km) and a significantly cold layer near the tropopause (at 16-19 km) when deep convection occurs over the western Pacific. The cold layer has a significantly large horizontal scale (˜ 6,000 km in longitude) compared to that of underlying mesoscale convective clusters (occur generally on hundred-kilometer scale), and it lasts more than two weeks with a minimum temperature anomaly of ˜ -2 K, particularly related to the Madden-Julian Oscillation. The water vapor anomalies show coherent structures with the temperature anomalies emphasizing the importance of the freeze-drying mechanism in the western Pacific region. The moisture is also affected by anomalous circulation patterns in the cold layer, and dry air further spreads in the TTL following the circulation patterns. These results suggest that convectively-driven tropopause cold layer and associated transient circulation play an important role in the large-scale dehydration process in the lower stratosphere.

Keywords: Tropopause cold layer, Stratospheric water vapor, Convection

Convective Gravity Waves during the Madden-Julian-Oscillation –results of numerical modeling

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Weather systems in the tropical Indian Ocean region are prominently influenced by the Madden-Julian-Oscillation (MJO) (Madden and Julian, 1972). Once an MJO active cycle is established, it can drive surface weather for several months, forcing heavy rainfall and droughts on the Indian Subcontinent. Although understanding of the MJO has improved over the last decade, MJO still considerably degrades forecasting skill, particularly in the Asian Monsoon region (Kim et al. 2014). This is especially true for seasonal prediction. The interaction of gravity waves (GW) from convection during MJO active phases is one of the various sources of uncertainties in MJO modeling. We developed a coupled model of convective gravity wave (CGW) forcing and propagation to evaluate the entire life-cycle of GWs from their convective excitation to their dissipation in the upper stratosphere / lower mesosphere region. CGW forcing at source level was calculated using the Song & Chun (2005) model. GW trajectories were calculated using GROGRAT (Marks & Eckermann 1995). Simulations were performed for all respective MJO phases for MJO cycles during a 30 years period using CFSR3 data for the full spectrum of CGWs. Our results show a strong correlation between momentum flux at cloud top height and 850 hPa zonal wind anomalies. Maximum momentum flux is prominently found in the inner tropics at altitudes between 20 km and 45 km. Horizontal and vertical wavelength spectra show maximum momentum flux for rather short wavelengths (~15-20 km) –a challenge for limb- and nadir-sounding satellite instruments. Maximums in GW drag are consistently found at altitudes higher than 45 km. We therefore conclude that convective GWs during MJO are an important contribution to the middle atmosphere momentum and energy balance and have significant effect on large-scale middle atmosphere circulations like the Brewer-Dobson circulation.

Keywords: Madden-Julian-Oscillation, Gravity waves, ray-tracing

Is There a Stratospheric Pacemaker Controlling the Daily Cycle of Tropical Rainfall?

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Rainfall in the tropics exhibits a large, 12-hour sun-synchronous variation with coherent phase around the globe. A long-standing, but unproved, hypothesis for this phenomenon is excitation by the prominent 12-hour atmospheric tide, which itself is significantly forced remotely by solar heating of the stratospheric ozone layer. We investigated the relative roles of large-scale tidal forcing and more local effects in accounting for the 12-hour variation of tropical rainfall. A model of the atmosphere run with the diurnal cycle of solar heating artificially suppressed below the stratosphere still simulated a strong coherent 12-hour rainfall variation (~50% of control run), demonstrating that stratospherically-forced atmospheric tide propagates downward to the troposphere and contributes to the organization of large-scale convection. The results have implications for theories of excitation of tropical atmospheric waves by moist convection, for the evaluation of climate models, and for explaining the recently-discovered lunar tidal rainfall cycle.

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