

TC4 Mission overview

The tropical tropopause transition layer (TTL) is one of the most mysterious regions of the atmosphere. Only a handful of research aircraft are able to reach the layer, which extends from about 12 km altitude to a few kilometers above the tropopause (the coldest point in the lower atmosphere), which is located at about 16-17 km altitude. Satellites have opened a new window into the TTL but they have difficulty observing it because there are often high clouds in the layer, which obscure the view, and because it has less mass than the underlying regions of the atmosphere. However, the TTL is of critical importance to the Earth's climate and atmospheric chemistry. The TTL is the gateway to the stratosphere. Deep convection sometimes penetrates the TTL to reach the stratosphere, while gentle upward motions within the TTL may also loft materials across the tropical tropopause. Hence the chemistry of the stratosphere may be affected in a significant way by processes that alter the transport across the TTL and by the chemicals in the TTL. Changes in water vapor in the stratosphere and upper troposphere can play an important role in modulating the climate since water is the most powerful greenhouse gas in the atmosphere. The TTL is the main dehydration region for air entering the stratosphere, and it is also an important reservoir for moisture lofted by tropical convection. Understanding how water behaves in the TTL is one key to better understanding the greenhouse effect, and global climate change. The TTL also contains cirrus clouds. One type of cirrus forms from anvils, the flattened tops of tropical cumulus clouds. Tropical cumulus pump vast quantities of air in just a few minutes from near the tropical surface to the TTL where they spill the air out into their anvils. The TTL also contains cirrus clouds that may be formed in situ. Many of these are so thin that they cannot be seen with the naked eye and so are called sub-visible cirrus. These clouds are easily seen by satellite however, and are now known to cover a large fraction of the tropics. Finally, the transport to and evolution of trace gases such as ozone in the TTL play an important role in determining what gases are carried into the stratosphere and upper troposphere globally. In order to learn more about the mysterious TTL NASA has designed the Tropical Composition, Clouds and Climate Coupling Experiment, TC4. Three NASA research aircraft will compliment a suite of NASA Earth observing satellites during July and August of 2007 as part of TC4. There will also be ground based observing facilities and balloon launches. Participants will come from multiple NASA centers, NOAA, NCAR, numerous universities, and Costa Rica.

The goals of TC4 are outlined in the Table below. TC4 is planned as a two-phase mission, with the first phase occurring in Costa Rica during July and August of 2007. The second phase is

planned for a later date in Guam. The first phase of the mission in Costa Rica is aimed at validating and collaborating with the new CloudSat and Calipso satellites, as well as the instruments on the Aura satellite and others in the A-Train. The A-Train is a suite of satellites that passes over in formation so that multiple types of complimentary data can be gathered. Costa Rica offers the opportunity to reach deep tropical cumulus clouds, which are very common in the Gulf of Panama during July and August. Guam offers the best location to investigate the coldest regions of the tropopause, where air is believed to preferentially enter the stratosphere.

Detailed Major questions	Primary Mission addressing ?
1. How can space-based measurements of geophysical parameters, particularly those known to possess strong variations on small spatial scales (e.g., H ₂ O, cirrus), be validated in a meaningful fashion?	Costa Rica 07 Guam
2. How do convective intensity and aerosol properties affect cirrus anvil properties?	Costa Rica 07
3. How do cirrus anvils, and tropical cirrus in general, evolve over their life cycle? How do they impact the radiation budget and ultimately the circulation?	Costa Rica 07
4. What controls the formation and distribution of thin cirrus in the TTL, and what is the influence of thin cirrus on radiative heating and cooling rates, and on vertical transport?	Costa Rica 07
5. What are the physical mechanisms that control (and cause) long-term changes in the humidity of the upper troposphere in the tropics and subtropics?	Costa Rica 07 Guam
6. What are the source regions, identities, concentrations and chemical fates of short-lived compounds transported from the tropical boundary layer into the TTL. (i.e., what is the chemical boundary condition for the stratosphere?)	Guam, Costa Rica 07
7. What are the mechanisms that control ozone within and below theTTL?	Guam, Costa Rica 07
8. What mechanisms maintain the humidity of the stratosphere? What are the relative roles of large-scale transport and convective transport and how are these processes coupled?	Guam, Costa Rica 07

In order to address the 8 questions in Table 1, NASA will employ not only its constellation of Earth sensing satellites but also a fleet of three research aircraft. Figure 1 outlines how these aircraft will be used. The ER-2 is able to fly at very high altitudes, at the top of the TTL, and will serve as a surrogate for the A-Train. Since the A-Train passes over in just a few minutes, and only twice per day, the ER-2

can be used to extend the period of time when remote sensing data are available. The WB-57 will fly in the TTL. It will sample the chemicals present there, and also investigate the properties of the clouds within the TTL. The DC-8 will operate at the base of the TTL. Its job will be to validate the A-Train with remote sensing data, and to understand the characteristics of the air entering the TTL.

In addition to satellite and aircraft TC4 will use numerous balloon borne sondes and ground based sensors. Costa Rican students and scientists will launch many of the sondes. Extensive numerical modeling and weather observations will also be employed to better understand the meteorological framework of the data.

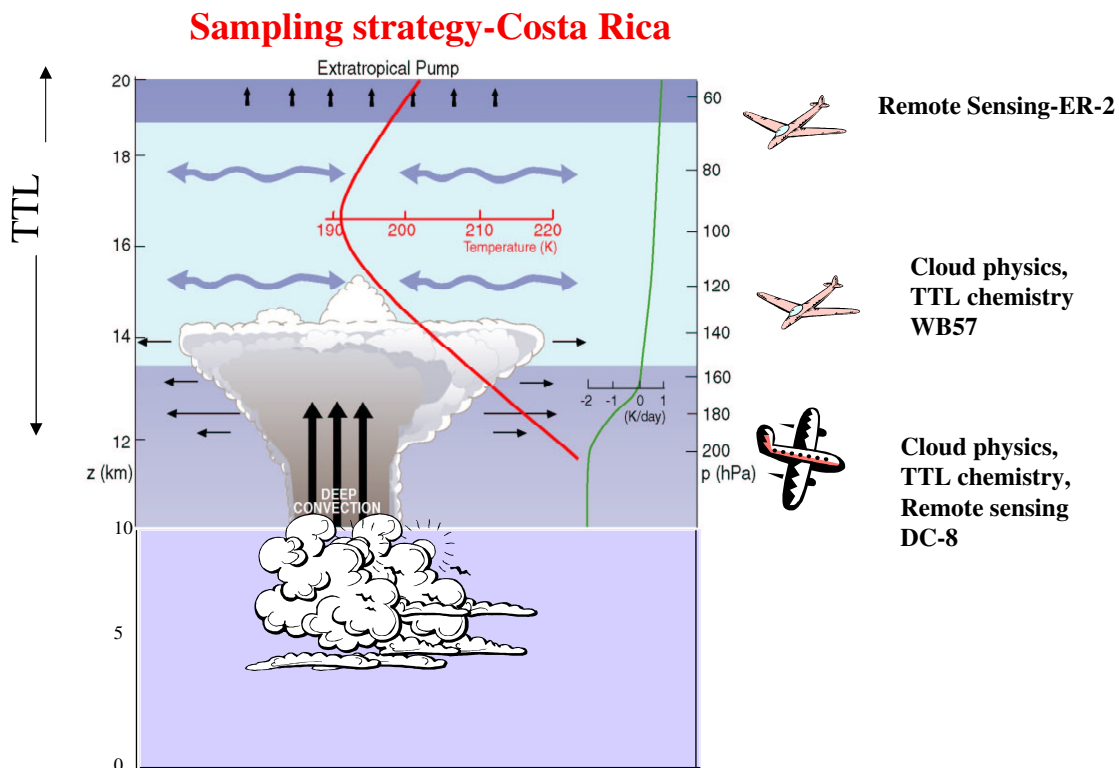


Fig. 1. A schematic of the tropical atmosphere. The red curve denotes a typical temperature profile, whose minimum near 16 km is the tropical tropopause. The green curve is a typical radiative heating profile, which switches from cooling to heating near 13 km. The solid black areas mark the rapid ascent which occurs in cumulus towers. The horizontal shaded areas mark horizontal transport, which carries air away from the central convection. Three aircraft, the ER-2, WB-57 and DC-8 will be used

1.1 Background

1.1.1 The tropical tropopause layer

A number of workers have recently noted that the layer of the

tropical atmosphere between about 12 km (~ 200 hPa, $\theta \sim 350$ K) and the cold point tropopause (16–17 km, 100–90 hPa, $\theta \sim 380$ K marked by the minimum in the red curve in Fig.1) has mixed characteristics intermediate between those of the troposphere and stratosphere. Although the cold point tropopause (altitude of the temperature minimum see Figure 1) is important for understanding stratospheric dehydration, and for infrared radiative forcing, the coldpoint has no special significance for most aspects of the meteorology and chemistry of the tropical atmosphere. It is not a material surface. In fact, some tropospheric circulations (such as overshooting convection, monsoon circulations, and equatorial waves) can extend for some distance above the cold point tropopause. Thus, it seems appropriate to extend the definition of the transition layer between the tropical troposphere and stratosphere to include the first few kilometers above the coldpoint. We refer to this region as the Tropical Tropopause Layer (TTL). The TTL as defined here includes the entire region between the level at which the temperature profile begins to depart from the moist adiabatic profile enforced by tropospheric convection (~ 12 km in convectively active regions) to the level in the stratospheric overworld beyond which the influence of tropospheric circulations becomes insignificant (~ 50 hPa, ~ 20 km, $\theta \sim 470$ K).

Within the TTL, as defined above, the vertical profiles of a number of parameters undergo rapid change. For example, in the lower portion of the TTL (~ 12 – 14 km) convective mass fluxes (and clear sky radiative cooling rates, denoted by the green curve in Fig. 1) decrease rapidly with height, corresponding with the main convective outflow. The annual mean convective mass flux out of the boundary layer between 15°N and 15°S is about 3.0×10^{11} kg/s, and about 50% of the mass flux from the boundary layer reaches the base of the TTL. However, the annual flux across the 100 hPa surface (near the coldpoint) is about 10^{10} kg/s, which is only $\sim 3\%$ of the flux of air out of the tropical boundary layer. There are also vertical variations in the horizontal transport, and above 14 km, where convective transport and mixing are small, large-scale horizontal transport processes (marked by horizontal arrows in Fig. 1) become increasingly important for meridional transport and mixing of trace constituents.

An understanding of the processes determining the transport and transformation of constituents within the TTL is essential for understanding the controls on the humidity of the stratosphere, the chemical boundary condition for the stratosphere, and impact of changes in climate variables, such as surface temperature and convective energy, on the composition of the stratosphere. In addition, while it is known that photochemistry within the TTL leads to rapid ozone production, the interplay of the convective processes (that transport short-lived compounds that fuel ozone production from

the lower troposphere), *in-situ* photochemistry, and large scale dynamics remains poorly constrained.

The transport and transformations within the TTL are also important for understanding the fate of compounds transported into the tropical upper troposphere and the chemical boundary condition for the stratosphere. The particular reactive species that reach this region, and their concentrations, depend on which source regions provide input via deep convection (Western Pacific, Amazonia, Central America). The above estimates of mass fluxes indicate that only a small fraction of the air leaving the tropical boundary layer actually crosses into the tropical stratosphere. For short-lived or soluble constituents, the fraction reaching the stratosphere will be even smaller. However, these estimates are very uncertain and the flux of compounds into the stratosphere will depend on the precise balance of different physical and chemical processes in the TTL. Better quantification of inputs from different source regions and of reaction and transport removal processes is essential for establishing the chemical boundary condition for the stratosphere, and understanding how this will change.

1.1.2 Tropical Cirrus Clouds

Cirrus clouds are high, cold clouds composed of ice crystals. In the tropics, cirrus form at altitudes between ~10km (-35°C, 30000 ft) and ~16.5 km (-80°C, 60,000 feet). Among other places, tropical cirrus are generated at the tops of cumulonimbus clouds. These deep convective clouds pump water vapor and ice crystals to the upper troposphere creating the stratiform clouds seen as the top of an anvil. The cirrus anvils can spread to cover vast areas and persist for several hours. Tropical cirrus are also frequently observed in locations remote from deep convection, perhaps existing as remnants of convective storms or perhaps formed by other processes acting on the water vapor mainly derived from deep convection. In the few kilometers at and just below the tropopause, laminar, optically thin (often subvisible) cirrus occur frequently.

Tropical cirrus clouds play an important, but complex, role in the Earth's climate system. Cirrus ice crystals scatter incoming sunlight, reducing the solar radiation reaching Earth's surface, which results in a surface cooling effect. Cirrus clouds also absorb upwelling infrared radiation emitted by the surface and lower atmosphere, effectively reducing the infrared energy escaping the Earth-atmosphere system. The interaction between cirrus and infrared radiation heats the upper troposphere and, indirectly, has a surface warming effect. The net effect of tropical cirrus on surface temperatures depends on several factors including cloud height, cloud thickness, and ice crystal sizes. The effects of cirrus clouds are both local and large scale. Large scale and local circulations can generate

cirrus. In fact, recent research suggests that a significant fraction of the cirrus in the tropics is only peripherally related, if at all, to deep convective sources. The cirrus examined in these studies is found primarily in the layer at the base of the TTL (10-15 km) where most tropical convection reaches its level of neutral buoyancy. These clouds are radiatively active and do induce feedbacks to the large-scale water budget and global circulation. A thorough understanding of the radiation and water budgets in the tropical upper troposphere is critical to better model the global climate since solar energy absorption in the tropics is the heat engine driving the entire atmospheric circulation and much of this heat is exported out of the tropics through upper tropospheric motions.

The ultimate role of tropical cirrus in future climate change involves feedback effects. For example, anthropogenic greenhouse gases can increase the surface temperature, possibly resulting in increased frequency and intensity of convective storms. Increased convection intensity could alter tropical cirrus cloudiness, with corresponding effects on the Earth radiation budget and additional surface temperature changes. Hence, the net effect of increased greenhouse gas concentrations on surface temperature depends on the response of convection and cirrus to the changing environment. Prediction of these feedback effects requires understanding of the full cirrus lifecycle from generation in deep convection to horizontal spreading and ultimate dissipation. Understanding the balance between remote and local dynamical response to intensifying deep convection is a key issue, i.e. whether the local induced subsidence field is enhanced with resulting less or shorter-lived cirrus. Tropical cirrus may also be changing in response to anthropogenic aerosols. Particles from industrial activity or biomass burning may affect ice nucleation in the convective updrafts, ultimately changing the numbers and sizes of cirrus ice crystals. Likewise particulate and gaseous emissions that produce particulates, from either aircraft or volcanic eruptions, could alter cirrus properties. These cirrus modifications would ultimately affect radiation budgets and climate. While we know little about the composition or origins of aerosols in the tropical upper troposphere, recent work suggests that tropical cirrus that can be traced to deep convection do show sensitivity to their convective sources. New research suggests that cirrus that originate from convection near major islands in the western Pacific tend to be composed of higher numbers of small particles compared to cirrus that originate in purely maritime convection. Recent field programs have shown surprisingly large amounts of organics, as well as metal and carbonaceous particles in the upper troposphere.

2. TC4 Science questions

Question 1: How can space-based measurements of geophysical parameters, particularly those known to possess strong variations on small spatial scales (e.g., H₂O, cirrus, chemical radicals), be validated in a meaningful fashion?

Resolution of many of the issues related to global climate change and atmospheric chemistry will require remote sensing measurements from satellite instruments with near global spatial coverage and multi-year temporal coverage. For example, understanding how cirrus clouds impact regional and global upper tropospheric humidity clearly requires analysis of large-scale fields of cloudiness and H₂O abundance. Remote sensing will constitute an important part of the measurement campaign by providing the horizontal distributions of cloud properties and gas concentrations at a variety of spatial and temporal scales. Cirrus cloud properties also vary on small spatial scales, and in situ observations of ice crystal size distributions, total condensed water, and extinction will be critical for validating algorithms applied to remote sensing measurements.

There are numerous examples of field programs involving aircraft and balloon platforms that have successfully linked with satellite validation ranging back over at least two decades. The SOLVE-2 program was aimed at validating SAGE III, which obtains profiles of aerosols, ozone, and a number of other chemical species at high latitudes. Measurements obtained during SOLVE-1/THESEO-2000 provided validation of chemical ozone loss rates, O₃ and H₂O profiles, and polar stratospheric cloud detection and analyses (e.g., denitrification inferred from PSC formation temperature) from the Naval Research Laboratory Polar Ozone and Aerosol Monitor (POAM) III satellite instrument. Aircraft measurements of CO from the DC-8 during TRACE-P provided validation of MOPITT data on Terra. Satellite remote sensing was a central theme of CRYSTAL-FACE, which was a precursor mission to TC4. CRYSTAL-FACE provided validation opportunities for Terra, Aqua and TRMM. Not only were cloud property retrieval algorithms tested, but also specific case studies were proposed by the satellite groups and carried out. Some of these involved clear sky data as well as cloudy data. The TC⁴ field campaign will support validation efforts of the entire "A train" –Aura, CALIPSO, CloudSat, PARASOL and Aqua. The A-Train, is named because the satellites form a train beginning and ending with satellites whose names start with the letter "A". All the satellites will pass overhead within about a fifteen minute time period.

The Aura satellite, a principal focus of TC⁴, provides essential information on the spatial and temporal variability of key constituents in the TTL region (such as ozone, water vapor, CO, and thin cirrus clouds) with horizontal and vertical resolutions not previously available from satellite observations. Satellite observations in this region are generally more challenging than measurements at higher

altitudes, and validation of these data from suborbital platforms is essential for the success of Aura. In addition, Aura does not provide the full suite of observations required to determine the chemical boundary condition for the stratosphere, the processes involved in stratospheric dehydration, the water balance of the upper troposphere, and the controls on upper tropospheric ozone.

The Aura validation teams have numerous requests for validation. For example, remote measurements (lidar data) would be extremely useful for profiles of O₃ and H₂O. The use of both the DC-8 and a high altitude aircraft for in situ profiles from the ground to 20 km is considered highly desirable in order to optimize the sampling of air that affects the satellite measurements (especially for TES and OMI). OMI measurements are sensitive to boundary layer pollution (NO₂ in particular); both remote and in situ data are considered useful for this. Sondes (for O₃ and H₂O profiles) for validation near aircraft flights are important. Coordination with aircraft flights will be attempted whenever weather conditions allow. 3D winds and temperature are needed for validation of gravity waves and HIRDLS data in the TTL.

In-situ observations from TC⁴ will provide measurements at high spatial resolution that are necessary not only to validate the satellite data sets but also to test the various hypotheses that have been put forth regarding how the water vapor abundance of the troposphere and stratosphere is maintained. Measurements of the isotopic composition of water vapor, available from both orbital (e.g., TES) and sub-orbital (e.g., balloon and aircraft) instruments, have particular promise for constraining models of atmospheric humidity. In situ measurements of H₂O and HDO exhibit considerable variability along level flights of the WB-57. A scatter diagram of D vs. H₂O reveals a regular pattern similar to that exhibited by Aura TES retrievals of these parameters. Measurements of correlations of quantities such as D vs. H₂O by aircraft instruments, at the same pressure level and for similar atmospheric conditions as the satellite observations will be critical for validating space-borne observations of HDO.

CALIPSO, CloudSat, and PARASOL and Aqua are in nearly coincident orbits with Aqua and Aura. CALIPSO and CloudSat are designed to measure aerosol and cloud properties. The lidar on CALIPSO will provide backscatter profiles through aerosol layers, sub-visible cirrus and thin cirrus as well as a detailed mapping of tops of optically thick clouds. Additional information on cirrus particle size and emissivity will be available from CALIPSO's infrared imaging radiometer. The millimeter wavelength radar on CloudSat will measure the vertical structure of clouds and provide estimates of their ice/water content. Aqua is a multi-instrument spacecraft with extensive calibration heritage that can contribute to the overall science objectives of TC⁴. Most notably the MODIS/CERES

instruments are aimed at measuring cloud microphysical and radiative properties, while AIRS is designed to retrieve water and temperature profiles, cloud properties and ozone abundance.

When taken together, the A-Train measurements will provide an unprecedented set of coincident observations that will allow for implementation of a new generation of algorithms for retrieving cloud and aerosol properties globally. Airborne in situ and remote sensing measurements will be critical for validation of these retrievals. TC⁴ will provide a unique validation opportunity.

Question 2: How do convective intensity and aerosol properties affect cirrus anvil properties?

Recent studies have shown that the response of surface temperature to increasing greenhouse gas concentrations depends sensitively on the processes controlling tropical cirrus anvil production. As greenhouse gases drive up the sea surface temperature, convection may become more intense. However, it is not clear that increased convective intensity implies larger, longer-lived cirrus anvils. In stronger convective systems, the removal of water by droplet and ice crystal precipitation may be more efficient, resulting in decreased ice mass outflow into the anvil. Evaluation of this sensitivity using satellite data has proven challenging because of problems determining convective intensity and cirrus anvil properties from satellite measurements. Also, local compensating subsidence may be appreciably enhanced which might also decrease cirrus lifetime and extent. A recent study that combined ground-based cloud radar observations with geostationary satellite-derived trajectories found evidence that tropical cirrus properties did vary when cirrus were observed to advect from convection near large western Pacific Islands compared to cirrus from purely maritime sources. Using TRMM data, the properties of the former population of clouds were derived from convection that tended to be more intense, and these clouds tended to have higher concentrations of smaller particles.

In TC⁴, an attempt will be made to relate the convective and stratiform stages of the cumulonimbus storm system development. The goal is to sample several cumulonimbus systems during the deployment. These case studies will be extremely useful for modelers attempting to simulate cirrus anvil generation. Several modeling groups will use sophisticated dynamical / microphysical/chemical models to simulate the convective systems and cirrus anvils sampled during TC⁴. The objective here is to improve understanding of the processes controlling the cirrus anvil production and evolution. These processes include the dynamics of the convection and the outflow anvil, cloud microphysics (droplet activation, ice crystal nucleation, coalescence, precipitation, etc.), and interactions between dynamics, microphysics, and radiation. These case-study modeling efforts will

serve both to improve the detailed cloud models and to provide insights for development of GCM cloud parameterizations.

It should be noted that there have been several previous studies in the tropics related to deep convection. For instance, GATE, TOGA-COARE, and CEPEX all investigated the role of convection in the tropical energy budget. STEP on the other hand investigated the role of convection in transporting water vapor into the stratosphere. In TC⁴ we will not only bring new instruments to bear on some of these issues, but also have different goals. For example, we will measure the properties of anvils in detail, which was not done in the previous missions. We will also investigate the role of sub-visible cirrus in exchange between the stratosphere and troposphere. In general we will investigate the full range of processes at work in the TTL.

In addition to convective intensity, anvil properties can also be impacted by the aerosols which form nuclei to activate the water droplets at the base of clouds, heterogeneous nuclei which may lead to freezing inside clouds, or heterogeneous nuclei which may lead to particle formation in the anvils, or in other types of cirrus. Data collected in CRYSTAL FACE indicate a connection between the anvil properties and the aerosols in the boundary layer and in the free troposphere.

Question 3: How do cirrus anvils evolve over their life cycle?

In addition to investigating cirrus anvil production processes, we also hope to improve understanding of cirrus anvil evolution processes. The coverage of cirrus in the tropics depends on anvil lifetimes and the conversion of anvil outflow into self-maintaining cirrus layers. However, a substantial portion of tropical cirrus is not directly associated with deep convection. While it is known that solar and infrared radiative heating in cirrus anvils can drive thermal instability and small-scale convection within the anvils, it is not known to what extent other factors such as a high background humidity or large scale vertical motion contribute to tropical cirrus longevity. Factors likely to affect cirrus longevity include upper tropospheric humidity, large-scale dynamics, and wind shear, which in turn may be driven by radiative forcing impacted by cirrus. Extremely strong convective systems can generate cirrus with tops in the highest few kilometers of the troposphere. The final stage of these very high cirrus is unclear. As the larger ice crystals fall out, leaving behind optically thin cirrus, the clouds may be lofted by radiative heating, resulting in persistent thin cirrus as often observed near the tropopause. These thin tropopause layer clouds can also be formed *in-situ* due to adiabatic ascent associated with equatorial waves such as the Kelvin wave.

Our goal is to address these issues by measuring cirrus anvil properties through as much of the cloud lifecycle as possible using

airborne, ground-based, and satellite instruments. These measurements will characterize the cloud structure, ice crystal size distributions, ice water content, ice crystal single-scattering properties, radiative fluxes, relative humidity, and wind velocities. Along with the cloud measurements, modeling studies will be undertaken to understand the processes controlling the evolution of cirrus anvils.

Much of the cirrus cloud cover in the tropics is not directly attached to (or necessarily originating from) deep convective systems. We anticipate sampling many such layers during TC⁴. Using in-situ measurements of trace gases transported to the upper troposphere by convection (e.g., CO, CH₃I, HDO, etc.), along with trajectory analyses, we hope to improve our understanding of the origin of these isolated cirrus in the tropics.

Question 4: What controls the formation, maintenance, and distribution of thin cirrus in the Tropical Tropopause layer, and what is the influence of thin cirrus on radiative heating and cooling?

Optically thin cirrus clouds are common in the tropics. The role of these clouds in TTL processes is not presently understood. They may be only curiosities. However, they may also play a central role in controlling the moisture budget of air that enters the stratosphere, and even in moving air across the tropopause. The properties of these clouds are not well characterized. Recent work finds that the properties of cirrus above 15 km are distinctly different from tropical cirrus in the 10-15 km layer. Laminar TTL cirrus are observed 14% of the time using lidar data collected at the central Pacific Island of Nauru. These laminar cirrus tend to be observed above 15 km, are geometrically thin (0.4 km mean thickness) and have optical depths that average 0.03. Several researchers have attempted to explain the maintenance of these clouds. These clouds radiatively heat when no lower clouds are present and this heating would cause the clouds to dissipate. Satellites, including Aura, frequently observe these clouds but satellites alone do not provide enough information to understand the lifecycle of clouds or constrain their influence on radiative heating without detailed in situ measurements.

If we are to better understand these clouds, we need in-situ observations of the particle sizes, so that we can evaluate their role in dehydration. We need measurements of atmospheric heating rates in the vicinity of the clouds. We also need to understand the chemistry of these particles, whether they are relatively pure ice, or may be coated with chemicals, such as nitric acid or organics, that may alter their properties. For instance, it has been found that organic aerosols are common in parts of the tropical upper troposphere, and that they are poor ice nuclei. Therefore supersaturations may be higher than

expected. Likewise coating cirrus with nitric acid will produce a net loss of nitric acid due to sedimentation where the cirrus form, and may alter the reactive nitrogen budget. Finally we need to better understand whether these clouds are generated by blow off from anvils of cumulus towers, from vertical motions generated by upwind convection, or whether they are generated in-situ either by large scale uplift and cooling, or by various types of tropical waves.

Question 5: What are the physical mechanisms that control (and cause) long-term changes in the humidity of the upper troposphere in the tropics and subtropics?

The response of the hydrological cycle to changes in the concentration of greenhouse gases is perhaps the single most important source of uncertainty in predicting future changes to Earth's climate and composition. The Earth radiates energy to space from an average altitude of about 6 km. Hence variations in radiatively active gases, of which water vapor is the most important, above that level are of great importance to Earth's radiation budget. The small amounts of water vapor in the upper troposphere (UT) exert enormous leverage on Earth's radiative balance. Of particular importance is the moisture in the subtropical regions. These dry regions have a large cooling effect on the whole tropics. Understanding the mechanism that controls the humidity of the subtropics is key to determining the nature of the water vapor feedback on climate.

The standard picture of the tropical troposphere is of large areas of gentle downwelling punctuated by isolated convective regions of extremely rapid ascent, which make up only a small fraction of the total area. The outflow from these convective regions is largest around 200 hPa (base of TTL), and as this air subsides the water vapor mixing ratio relaxes to very low values (10 ppmv or less). However, observations show that the subtropics are not as dry as this simple picture would imply, hence there must be additional moisture sources that hydrate the regions of the tropics characterized by descent. There are three hypotheses for the supply of this moisture: Evaporation of precipitation, evaporation of detrained cloud particles, and lateral transport. Current thinking points to the role of cirrus heating in maintaining the humidity of air being transported into the subtropics. While the condensed mass is not sufficient to explain this maintenance, the heating due to cirrus could result in vertical and lateral transports of water vapor into the upper troposphere thereby maintaining the upper tropospheric humidity against the large-scale subsidence.

Which of these hypotheses are correct, or more realistically the relative contribution of the three sources to the subtropical moisture budget, has major implications on how subtropical humidity will

change in response to climate warming, and hence the water vapor feedback on climate. Knowing the dominant mechanism, if any, also has implications for the design of climate models to accurately simulate tropospheric water vapor and water vapor feedbacks. For example, the first two hypotheses require accurate representation of microphysical processes, whereas the third hypothesis requires accurate representation of large-scale winds and transient wave activity.

Question 6: What are the source regions, identities, concentrations and chemical fates of short-lived compounds transported from the tropical boundary layer into the TTL. (i.e., what is the chemical boundary condition for the stratosphere?)

Until recently, the chemical precursors of the stratospheric radicals and aerosol, with the notable exception of water vapor, were thought to be compounds with long tropospheric lifetimes. This greatly simplified defining the chemical boundary condition for the stratosphere because globally-averaged surface measurements of these long-lived compounds could be used. For example, sulfur was thought to be carried mainly by carbonyl sulfide, nitrogen by N_2O , and halogens by the relatively long-lived halocarbons.

It has become increasingly clear, however, that short-lived compounds transported to the tropopause region of the tropics significantly alter the chemistry of the global stratosphere. The amount of OCS transported across the tropopause accounts for no more than half of the sulfur aerosol present in the lower and middle stratosphere. The remainder may come from small volcanic eruptions venting into the lower stratosphere, or from tropospheric sulfate and sulfur gases that are transported across the tropical tropopause. Thus, our understanding of how the “background” sulfate aerosol layer is maintained is incomplete. Bromine monoxide concentrations in the lower stratosphere appear to reflect the input of very short-lived bromine containing organic, and perhaps inorganic, compounds, possibly leading to a much larger role for catalytic loss of lower stratospheric ozone by halogens than is considered in most models. Finally, the concentration of reactive nitrogen, NO_y , and ozone are non-zero at the tropical tropopause. Release of NO_x from NO_y carried across the tropopause will likely have important implications for the efficiency of ozone loss by halogen cycles in the lower stratosphere. The NO_y/O_3 ratio can provide an important test of the realism of transport models for both the lower stratosphere and upper troposphere provided the sources of both species are understood.

Observations of short-lived sulfur, nitrogen, and halogen-containing compounds in the region of the tropical tropopause are sparse. Acquiring such measurements is essential to accurately assess the effect on ozone of future changes in halogen loading,

stratospheric sulfate aerosol abundance, and changes in tropical convection that might be associated with climate change. Estimates of the ozone depletion potential of short-lived halogen species depend on a quantitative evaluation of the efficiency of transport from source regions into the TTL and subsequent transport across the tropical tropopause. An understanding of the relative roles of (slow) large-scale transport and rapid convective transport and a better understanding of the chemistry of short-lived species in the UT and TTL is crucial to the improvement of such estimates. The observations of short-lived species envisioned for TC⁴ will address these issues and will provide important new understanding of dynamics in the UT and TTL regions. The proposed species for measurement have a range of photochemical lifetimes (e.g., 0.003 days for CH₂I₂; 4 to 7 days for CH₃I; 36 days for CHBr₃), and thus can be used to diagnose transport characteristics of the TTL on a variety of spatial and temporal scales.

Question 7: What are the mechanisms that control ozone below and within the Tropical Tropopause Transition layer? What is the chemical nature of the outflow from the convective region of the Western Pacific?

Ozone concentrations in the TTL are determined by a complicated interplay of convective processes (that transport from the lower troposphere both ozone and short-lived compounds that fuel further ozone production), *in-situ* photochemistry, and large-scale dynamics. Diagnosing this diversity of processes – occurring over large spatial and time scales – provides a challenging, but important, observational problem. To date, very few observations are available to test our understanding of the mechanisms that control ozone in the TTL.

Photochemistry within the TTL is thought to lead to significant *in-situ* ozone production. This production results primarily from the oxidation of CO by OH in the presence of nitrogen oxides. Ozone formation due to photolysis of molecular oxygen can also be important, because the stratospheric ozone column is relatively low in the tropics. Since the chemical lifetime of ozone with respect to photochemical loss is long (several months), the TTL is a region of significant net production for tropospheric ozone.

Convection plays a key role in influencing the distribution of tropical ozone, both in terms of mixing ozone and its precursors out of the boundary layer over continental source regions (e.g., regions of biomass burning), and in mixing extremely low ozone values from either the marine boundary layer over the Pacific or unpolluted continental areas into the upper troposphere, as shown by analyses of ozonesonde data. Lightning associated with convective systems will also provide a source of NO_x, enhancing photochemical ozone production.

Analyses of ozone sonde profiles from Samoa have shown that ozone mixing ratios usually start to increase in the TTL around 14 km, well below the tropical tropopause, although the largest change in gradient in the ozone mixing ratio is near the thermal tropopause. The increase in ozone may be caused by the suppression of vertical mixing associated with convection above 14 km, and that the positive correlation they find between potential temperature and ozone above 14 km is consistent with slow large scale ascent, positive radiative heating, and photochemical production of ozone. They also argue that some of the ozone originates from the stratosphere, based on correlations with N_2O .

Increases in ozone well below the thermal tropopause are found at tropical ozonesonde sites in the Pacific, the Atlantic, and Africa. (The thermal tropopause is the World Meteorological Organization defined tropopause based on the lapse rate, which is generally lower in altitude than the cold point tropopause). Inspection of individual profiles shows that this is not always the case, particularly in the western Pacific. The significant longitudinal gradients in tropical ozone, with values over the Atlantic higher than those over the Pacific year-round, extend all the way to the thermal tropopause.

Long-lived tracers in TC⁴ should provide the foundation for diagnosing the processes that are responsible for atmospheric transport on the largest time and space scales. They should also provide a bridge tying together the objectives for the mission in mid-tropospheric chemistry, input processes to the stratosphere in the Tropopause Transition Layer, black carbon sources and distributions, and convective cloudiness and transport of water vapor. The tracers must have measurable gradients in the operational regions with distinct morphologies.

1. CO_2 . The land has very large exchange fluxes of CO_2 between the surface and the atmosphere. The signals from these fluxes appear above the stable marine PBL, maintaining distinctive gradients between the marine PBL and the mid-troposphere such as observed in CRYSTAL-FACE, providing a unique tracer for convective redistribution. The seasonal cycle of CO_2 also offers the best age-of-air tracer for the TTL.

2. SF_6 and/or HCFCs. Concentrations of these industrial gases are growing rapidly in the atmosphere due to sources predominantly in the northern hemisphere. These gases display distinctive North/South gradients and thus provide the best indicators of the hemisphere of origin for air in the study domain. They also represent independent age-of-air tracers, albeit usually less sensitive than the CO_2 seasonal cycle.

TC⁴ data on CO_2 and SF_6 will also have intrinsic interest for understanding the global carbon cycle. The TRANSCOM intercomparisons of global CO_2 models shows that most simulations

agree with available surface data for CO₂ and SF₆, even though they give divergent results for high-altitude gradients of these gases. TC⁴ data could provide a major result to help sort this out.

Question 8: What mechanisms maintain the humidity of the stratosphere?

Water vapor in the stratosphere is important not only for its radiative forcing, but also for its role in stratospheric chemistry. Stratospheric water vapor concentrations affect both the production of OH radicals and the formation of polar stratospheric clouds. These polar stratospheric clouds play an integral role in polar ozone destruction.

Water vapor enters the stratosphere almost exclusively through the tropical tropopause. The dryness of the stratosphere is caused by freeze-drying of air as it crosses the cold tropical tropopause. Water vapor in excess of saturation condenses on ice crystals that fall out of the slowly rising air, preventing the condensed water from getting into the stratosphere. The result of this freeze-drying is extremely dry air in the lowermost tropical stratosphere. Water vapor concentrations increase slowly due to methane oxidation as air is transported upward and poleward by the stratospheric circulation.

Remote sensing and in-situ measurements indicate a trend of increasing water vapor concentrations in the stratosphere in recent decades followed by a sudden decrease from 2000 through 2005. The long-term trend cannot be fully explained by trends in tropical tropopause temperature or methane concentrations. The recent decrease in stratospheric humidity has been detected by multiple instruments and appears to be broadly correlated with changes in tropical tropopause temperatures. Given the importance of stratospheric water vapor there is a need to understand the detailed processes controlling water vapor concentrations entering the stratosphere in the tropics.

Changes in the humidity of the stratosphere can profoundly affect stratospheric chemistry and climate. However, our ability to understand how stratospheric humidity has or will change is limited because the precise physical mechanisms responsible for the aridity of the stratosphere are unknown. There are currently several different hypotheses for the dehydration of air entering the stratosphere. One set of hypotheses is centered on convective-scale motions involving overshooting cloud turrets and ice particle sedimentation. Another set is focused on slow ascent and large-scale quasi-horizontal motions through regions where the cold-point temperatures are anomalously low, such as the “cold trap” of the Western Pacific. Testing of all these hypotheses requires improved observations, and an improved understanding of transport processes in the TTL. Understanding what maintains the temperature distribution at the tropical tropopause is

also important, and likely involves both convection and larger scale forcings, such as tropical waves at many scales from gravity waves to the Quasi-Biennial Oscillation (QBO).

3. Science Implementation

The TC4 mission design was driven by the science goals described above. The mission will occur during the months of July and August, 2007 in the region near Costa Rica. It is anticipated that many of the flights will occur in the Gulf of Panama, where convection is very persistent. Measurements from ground sites, aircraft, and satellites will be made.

3.1 Deployment Site

Aircraft will be based at Juan Santamaria airport in Costa Rica. Ground-based instruments will be located in Panama, along the Gulf of Panama. The primary target region is the Gulf of Panama and the surrounding waters where deep convection is known to occur frequently in July.

3.2 Aircraft

Several aircraft will be used for in situ and remote sensing of aerosols, ice crystals, meteorological fields, radiative fluxes, and gas concentrations. The ER-2 and WB-57 are NASA aircraft based at Dryden Flight Research Center and Johnson Space Center, respectively. The University of North Dakota operates the NASA DC-8.

The ER-2 aircraft will be flown in the lower stratosphere and used for remote sensing. The WB-57 will be used for in situ sampling of cirrus anvils, aerosols, gas concentrations, and radiative fluxes in the tropopause region. The DC-8 will operate at the base of the TTL and provide remote sensing as well as in situ data.

3.3 Ground Sites

Instrumented sites will include a NASA radar and a suite of trailer based instruments operated by Pennsylvania State University.