# Draft of Tropical Composition, Cloud and Climate Coupling Experiment ($TC^4$)

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## Introduction: the basic components

Two closely related field programs have been proposed to investigate the tropical tropopause region in the 2004 to 2006 time frame. Here we present a plan of action combining these two programs in a manner that meets both of their objectives.

The first proposed mission is the Tropical Composition and Climate Coupling experiment ($TC^3$). The $TC^3$ concept arose from a realization that many aspects of the chemical, dynamical, and physical processes occurring in the tropical upper troposphere and in the layer surrounding the tropical tropopause are not well understood. Elucidating the key processes in this region is essential for progress on issues involving global climate change, stratospheric ozone depletion, and global tropospheric chemistry. This mission grew from the planning activities associated with the Aura satellite validation program. Although Aura observations will provide crucial information on the spatial and temporal variations of a number of important properties of this region, carefully planned and executed airborne observations are also required, both to validate Aura data and to provide critical observations not available from satellite.

The second proposed experiment is CRYSTAL TWP, Cirrus Regional Study of Tropical Anvils and Cirrus Layers in the Tropical Western Pacific. This experiment, which has been in the planning stages for nearly a decade, is an extension of the CRYSTAL FACE (Florida Area Cirrus Experiment) project that took place during July of 2002, in Southern Florida. A major goal of CRYSTAL is to better understand the roles that the anvils of deep convective clouds, and tropical cirrus in general, play in humidifying the upper troposphere and lower stratosphere, and in the Earth's radiation balance. Changes in the radiation balance impact deep convection via stability, impact large-scale circulation via horizontal gradients and stability, which in turn impacts deep convection and large-scale UT transport processes. Hence, CRYSTAL also seeks to understand cumulus physics, and its link to precipitation efficiency. CRYSTAL is also aimed at augmenting and validating satellite observations, including those of Aura, Aqua, CloudSat, CALIPSO, and PARASOL.

**Table 1** lists the major questions that $TC^3$ and TWP seek to answer. There is considerable overlap between the major questions of the two missions, providing an opportunity to combine the missions. Table 1 also details how these missions will address the 23 questions posed by the NASA Earth Science Enterprise for its research strategy during 2000-2010. The specific ESE questions, which are organized into categories of trends and variability, forcings, responses to the forcings, consequences, and predictions, are listed in Appendix 1.

Much of the focus of CRYSTAL TWP and $TC^3$ is on the region referred to as the Tropical Tropopause Layer (TTL). However, it is recognized that an understanding of the flux of material into the TTL requires constituent measurements in the troposphere, including convectively disturbed regions. An understanding of the role of water vapor and ozone in the climate system requires observations below the lower boundary of the TTL in the free troposphere. Similarly, measurements in the lower stratosphere are required to understand how processes in the TTL influence humidity and other properties of the stratosphere.

Below we will first provide an overview of the TTL and of the role of cirrus clouds in global climate. Then we will discuss the scientific rationale for each of the questions in Table 1. We will then describe the field missions that we propose to address these questions.

Table 1 Major questions addressed by $TC^4$

| Scientific question | ESE Question[1] | Mission |
|---|---|---|
| 1. 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? | V1,V4, F1,R1, R4,C1,P2, P3,P4 | $TC^3$-TWP |
| 2. What are the physical mechanisms that control (and cause) long-term changes in the humidity of the upper troposphere in the tropics and subtropics? | V1,F1,R1, R6,C1,P2, P3 | $TC^3$-TWP |
| 3. What controls the formation and distribution of thin cirrus in the Tropical Tropopause layer, and what is the influence of thin cirrus on radiative heating and cooling rates, and on vertical transport? | V1,F1,R1, C1, P2,P3 | $TC^3$-TWP |
| 4. What are the chemical fates of short-lived compounds transported from the tropical boundary layer into the Tropical Tropopause layer. (i.e., what is the chemical boundary condition for the stratosphere?) | V4,F1,R1, R4,R6,C, P4 | $TC^3$ |
| 5. What are the mechanisms that control ozone within and below the Tropical Tropopause Transition layer? | V4,F1,R4, R6,P2,P3, P4 | $TC^3$ |
| 6. How do convective intensity and aerosol properties affect cirrus anvil properties? | V1,F1,R1, C1,P1,P2, P3 | TWP |
| 7. 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? | V1,F1,R1, C1,P1,P2, P3 | TWP |
| 8. How can space-based measurements of geophysical parameters, particularly those known to possess strong variations on small spatial scales (e.g., $H_2O$, cirrus), be validated in a meaningful fashion? | V1,F1,R1, R4,R6, C1,P1,P2, P3,P4 | $TC^3$-TWP |

[1]The Earth Science Enterprise questions are listed in Appendix 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 , $\theta$ ~350 K) and the cold point tropopause (16–17 km, 100–90 hPa, $\theta$ ~ 380 K) has mixed characteristics intermediate between those of the troposphere and stratosphere (e. g. *Highwood and Hoskins* [1998], *Thuburn and Craig* [2002]). This layer was referred to as the *substratosphere* by Thuburn and Craig. Although the cold point tropopause (altitude of the temperature minimum) 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. For this reason, we refer to this region as the Tropical Tropopause Layer (TTL) rather than the substratosphere. 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 *Gettelman and Forster* [2002]) to the level in the stratospheric overworld beyond which the influence of tropospheric circulations becomes insignificant (~50 hPa, ~20 km, $\theta$ ~470 K).

Within the TTL, as defined above, a number of parameters undergo rapid change in the vertical. For example, in the lower portion of the TTL (~12–14 km) convective mass fluxes (and clear sky radiative cooling rates) 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 $3.0 \times 10^{11}$ 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 [*Rosenlof and Holton* 1993], which is only ~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 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 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 flux of compounds into the stratosphere will depend on the precise balance of different physical and chemical processes in the TTL. Better quantification of these processes is essential for establishing the chemical boundary condition for the stratosphere, and understanding how this will change.

***Tropical Cirrus Clouds***

Cirrus clouds are high, cold clouds composed of ice crystals. In the tropics, cirrus form at altitudes of ~10km (-35C, 30000 ft) to ~16.5 km (-80C, 60,000 feet). Among other mechanisms, 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 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 turn they can affect not only the local radiation budget and dynamics, but also the large-scale radiation budget and dynamics. A thorough understanding of the radiation budget in the tropics is critical to better model the global climate since solar energy absorption in the tropics is the heat engine driving the entire atmospheric circulation.

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. We know little about the composition or origins of aerosols in the tropical upper troposphere, or lower stratosphere. Recent field programs have shown surprisingly large amounts of organics, as well as metal and carbonaceous particles.

***Question 1: 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. This trend cannot be explained by trends in tropical tropopause temperature or methane concentrations. 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 [e.g., *Sherwood and Dessler* 2000]. 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 [e.g. *Holton and Gettelman* 2001]. Testing of all these hypotheses requires improved observations, and an improved understanding of transport processes, in the TTL.

***Question 2: 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 (*Pierrehumbert*, 2000)

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 (*e.g.*, *Held and Soden*, 2000; *Pierrehumbert*, 2000). There are three hypotheses for the supply of this moisture: Evaporation of precipitation, evaporation of detrained cloud particles, and lateral transport.

Which of these hypotheses are correct, or more realistically the relative contribution of the three sources to subtropical moisture, has major implications on how subtropical humidity will change in response to climate warming, and hence the water vapor feedback on climate (*e.g.*, *Held and Soden*, 2000; *Pierrehumbert*, 2000). 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 3: What controls the formation 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 dehydrating the air that enters the stratosphere, and even in moving air across the tropopause (e.g. *Jensen et al*. 1996; *Holton and Gettleman*, 2001). 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 4: What are the chemical fates of short-lived compounds transported from the tropical boundary layer into the Tropical Tropopause layer ? (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 solely by carbonyl sulfide, OCS, nitrogen by $N_2O$, and halogens by the relatively long-lived halocarbons.

It has become increasing 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 (*e.g.*, *Weisenstein et al*., 1997). 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 (*e.g*., *Ko et al*., 1997; Pfeilsticker *et al*., 2000), possibly leading to a much larger role for catalytic loss of lower stratospheric ozone by halogens than is considered in most models (*Dvortsov et al*., 1999). Finally, the concentration of reactive nitrogen, $NO_y$, and ozone are non-zero at the tropical tropopause (*Strahan*, 1999). 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 (e.g., *Murphy et al*., 1993).

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 (*Ko and Poulet*, 2002). The observations of short-lived species envisioned for $TC^4$ 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 $CH_2I_2$; 4 to 7 days for $CH_3I$; 36 days for $CHBr_3$), and thus can be used to diagnose transport characteristics of the TTL on a variety of spatial and temporal scales.

***Question 5: What are the mechanisms that control ozone below and within the Tropical Tropopause Transition layer?***

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.

Our current understanding of tropical tropospheric ozone in general is based primarily on insights drawn from analyses of data from aircraft campaigns and ozonesondes, and on model studies. In the upper tropical troposphere (z>12 km), analysis of the few profiles obtained by the NASA ER-2, have demonstrated that $HO_x$ photochemistry and its impact on ozone in this region is poorly understood (McKeen et al., 1997, Folkins et al., 1997, Jaegle et al., 1997, Wennberg et al., 1998). $HO_x$ concentrations are much larger than expected based on $H_2O/O_3$ photochemistry. The high levels of $HO_x$ observed, along with high $NO_x$, possibly associated with biomass burning, suggest elevated ozone production. Below 12 km, (restricted by the flight altitude of the DC-8), major campaigns have taken place in the south tropical Atlantic (TRACE-A), or in the Pacific, flying out of Hawaii, Fiji, and Tahiti (PEM-Tropics A and B). Analyses of data from these campaigns have shown the importance of ozone precursor emissions from biomass burning in the dry season, and have also invoked an important role for lightning as source of $NO_x$ upwind of the region of the measurements (Thompson *et al.*, 1996; Jenkins *et al.* 1997; Schultz *et al.*, 1999; Staudt *et al.*, 2002a,b). Over both the Pacific and South Atlantic photochemical production of ozone provides a net source for ozone above about 7 km and a net sink below, a consequence of the rapid decrease in water vapor with height. Over the tropical Pacific, production accounts for only about half of the column ozone loss below 12 km, indicating that there is significant transport of ozone to the Pacific (e.g., Schultz *et al.*, 1999; Wang *et al.*, 2001).

As is clear from the above discussion, 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 (Kley et al., 1996; Oltmans et al., 2001). 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 (Folkins *et al.* 1999), although the largest change in gradient in the ozone mixing ratio is near the thermal tropopause. Folkins *et al.* (1999) argue that the increase in ozone is 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 (Logan, unpublished work). 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 (Logan, 1999; Thompson *et al.*, 2002). A comparison of ozone and temperature profiles from the eastern and western Pacific, as well as from the eastern Atlantic, is given in Figure 1.

Long-lived tracers in $TC^4$ 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 measureable 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 hemispere. 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.

$TC^4$ 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 $CO_2$ and $SF_6$, even though they give divergent results for high-altitude gradients of these gases. $TC^4$ data could provide a major result to help sort this out.

***Question 6: How do convective intensity and aerosol properties affect cirrus anvil properties?***

Recent studies have shown that the response of surface temperature to increasing greenhouse 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.

In $TC^4$, 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 $TC^4$. 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 $TC^4$ 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 7: 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 spreading by wind shear. 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 these secondary convective motions extend the lifetime of tropical anvils. Other factors likely to affect cirrus anvil lifetime 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 (*Boehm and Verlinde*, 2000).

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, ship-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 $TC^4$. Using in-situ measurements of trace gases transported to the upper troposphere by convection (e.g., CO, $CH_3I$, HDO, etc.), along with trajectory analyses, we hope to improve our understanding of the origin of these isolated cirrus in the tropics.

***Question 8: How can space-based measurements of geophysical parameters, particularly those known to possess strong variations on small spatial scales (e.g., $H_2O$, cirrus), be validated in a meaningful fashion?***

Resolution of many of the issues discussed above 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 $H_2O$ 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. In-situ observations will provide measurements at high vertical resolution, which might be necessary to test, for example, the various hypotheses that have been put forth regarding how the low aridity of the stratosphere is maintained.

There are numerous examples of field programs involving aircraft, linked with satellite validation ranging back over at least two decades. The present SOLVE-2 program is 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 provided validation of chemical ozone loss rates, $O_3$ and $H_2O$ 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. Satellite remote sensing was a central theme of CRYSTAL-FACE. CRYSTAL-FACE provided validation opportunities for Terra, Aqua and TRMM. Not only were cloud property retrieval algorithms tested, but 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 $TC^4$ field campaign will support validation efforts of the entire "A train" –Aura, CALIPSO, CloudSat, PARASOL and Aqua. Appendix 2 provides a description of the A-Train, so named because the satellites form a train beginning and ending with satellites whose names start with A. All the satellites will pass overhead within about a fifteen minute time period.

The Aura satellite, a principal focus of $TC^3$, will provide essential information on the spatial and temporal variability of key constituents in this region (such as ozone, water vapor, and thin cirrus clouds) with horizontal and vertical resolutions not previously available from satellite observations. Satellite observations in this region will be very challenging; validation of the satellite data from aircraft and balloons is essential for the success of Aura. In addition, Aura will 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. Aqua is also a multi-instrument spacecraft. Most notably the MODIS/CERES instruments are aimed at measuring cloud infrared properties, while AIRS is designed to retrieve water and temperature profiles, cloud properties and ozone abundance.. Aqua is already in orbit, and its instrument compliment is well known.

CALIPSO, CloudSat, and PARASOL are smaller spacecraft in nearly coincident orbits with Aqua and Aura. CALIPSO and CloudSat are designed to measure aerosol and cloud properties. CALIPSO is a lidar that should provide detailed cloud top mapping, as well as back-scatter profiles through aerosol layers, sub-visible cirrus and thin cirrus. CloudSat is a radar that will measure the vertical structure of clouds. PARASOL is a polarization sensitive wide field of view imaging radiometer, similar to POLDER, also aimed at characterizing clouds and aerosols.

## Observing Strategy for $TC^4$ and Related Validation Efforts

$TC^4$, as outlined below is designed to elucidate the scientific issues discussed above, and at the same time is intended to provide essential validation data for Aura, as well as other satellites such as CALIPSO, CloudSat, Aqua, and PARASOL in the tropical region.

***Measurement Strategy***

The scientific questions outlined in Table 1 will be addressed (and related hypotheses tested) by the combined analysis of measurements from satellite instruments together with aircraft, ground or ship based, and balloon measurements from several tropical and subtropical sites, and related theory and modeling studies. Aura (and other satellite) observations within the UT/LS will provide information on the spatial, seasonal, and interannual variations while the aircraft deployments will focus on smaller spatial scale process studies (and providing high vertical scale resolution observations for validation of satellite measurements in the tropics, and especially in the TTL). The $TC^4$approach will involve synergistic science between satellite and non-satellite platforms.

In the intensive field campaigns we envision a multi-platform approach to measurements, with the platforms staggered in different altitude regimes. Since satellite overpasses occur during only a few minute time frame, it is difficult to use a single aircraft to profile the entire atmospheric column of interest with close temporal coincidence with the satellite overpass. It is also essential to obtain a good measure of horizontal structure along satellite track. This can be accomplished by flying aircraft at multiple levels along the same ground track. Many of the satellite sensors (not CALIPSO, or CloudSat, which are nadar viewing only) have extended cross-track sampling swaths, the location of the aircraft tracks can be adjusted in response to occurring conditions to encounter the desired natural target, such as cloudy or clear conditions. In addition, due to the vast size of tropical convective systems, it is not practical to use aircraft to profile vertically over great depths, while also exploring these systems in detail in the horizontal. Multiple aircraft also provide a means to measure the composition (e.g., tracers of convection) of air near the boundary layer that is lifted to higher altitudes, where it is sampled later by a different aircraft. Use of multiple aircraft also allows in-situ instruments to be placed into the footprint of the remote sensing aircraft instruments. The operation of multiple aircraft could be spatially coordinated though a central in flight command aircraft, or ground based station. Such real-time coordinated flights were performed in CRYSTAL-FACE with 6 aircraft at a time with great success. In CRYSTAL-FACE, aircraft location data were obtained from a link to the Federal Aviation Administration (FAA). For $TC^4$, we propose to add a satellite down link capability to each of the platforms to provide real-time GPS location.

An example of the altitude spacing is presented in Table 2. Fig. 2 expands on this information.

Table 2. Generic platforms and their roles[a]

| Goal | Aircraft altitude range | Examples |
|---|---|---|
| Remote sensing of the TTL | Well above TTL (near 20 km) | ER-2, WB-57, Proteus, Balloons |
| Horizontal and Vertical profiling mainly in the stratosphere | Stratosphere and TTL 15-20km | WB-57, ER-2, Proteus, Altus, Global Hawk, , Balloons, Sondes |
| To probe anvils, Horizontal and Vertical profiling mainly in the TTL | TTL, 12-17 km | WB-57, ER-2, G-5(Hiaper) |

| | | |
|---|---|---|
| Sample mid-level convective clouds near base of TTL, measure chemical composition and tracers, remote sensing from below TTL | UpperTroposphere 5 km to 12 km | DC-8, G-5 P-3 |
| Sample Boundary layer tracers; cloud radar sensing | Boundary Layer, Sea level to 5 km | P-3, C-130, G-5 |

[a] Note we assume here that only aircraft with relatively long flight duration will be acceptable due to to large physical region that needs to be investigated. Therefore smaller possible aircraft are not listed.

Most of the choices of altitude range in Table 2 are straightforward, and aircraft are easily identified to fill the roles. As discussed further below in the instruments section there are two resource related issues involving the first three goals in Table 2. First it is not clear that a single aircraft can carry all all the remote sensing instruments that are needed for the A-Train validation and other issues (row one of Table 2). For instance CRYSTAL-FACE used two aircraft for this goal, and $TC^4$ is a larger mission. Second, it is greatly to be preferred to have one aircraft that is essentially operating in clouds in the TTL (row three), while another is profiling in the stratosphere, above cloud top. Both of these roles were played by the W-B57 in CRYSTAL-FACE , compromising the science. However, this may require using two ER-2s, or similar aircraft, in $TC^4$, one to perform all or part of the function in the first row, and the other to perform the function in the second row.

***Measurements addressing Science Questions 1 thru 3 of Table 1.***

The observations of $H_2O$ and temperature that will be obtained by HIRDLS, MLS and TES in the tropical tropopause region will provide important information on the seasonal and longitudinal variability of conditions in the upper troposphere and lower stratosphere. The cirrus ice measurement from MLS, once validated, may provide important constraints on the details of whether significant amounts of precipitable water vapor are lofted across the tropopause.

Aircraft and balloon measurements are required to:

1. Test the accuracy of the Aura (MODIS, AIRS, CloudSat, and other satellite) measurements of $H_2O$, temperature, and cirrus ice content in the tropical tropopause region;
2. Determine the vertical and horizontal structures of fields of $H_2O$, HDO, and temperature in the tropics and whether these structures are suitably resolved by the satellite instruments;
3. Determine, at high vertical resolution, the isotopic composition of $H_2O$ and distribution of tracers of vertical motion that have a wide range of lifetimes (e.g., $SF_6$, $CO_2$, CO, $CH_3I$, radon).
4. Determine the local radiative balance in the TTL.

Determination of the vertical and horizontal structures, and whether these structures are suitably resolved by the space-based instruments, necessitates obtaining correlative observations in:

1. regions where we expect the largest vertical gradients and the minimum abundance of $H_2O$ to occur (e.g., the Western Pacific),
2. regions with cold tropopause (Western Pacific) and warmer tropopause (Eastern Pacific),
3. both moist and dry regions in UT ,
4. regions where transport between different air masses (e.g., moist and dry regions), and fine-scale structures in $H_2O$, are predicted to occur.

It is also important to obtain measurements in different seasons because of possible seasonal differences in basic state (e.g., vertical distributions) and transport mechanisms (e.g., cross-tropopause transport).

As detailed below in the balloons and sondes section, the development of a light weight "water sonde" capability that would fly together with ozonesondes and radiosondes from existing observational stations in the tropics (e.g., the SHADOZ network) would provide data essential for combining the information gained from an extensive airplane campaign with near global (but poorer vertical resolution) measurements of $H_2O$ from satellites.

Measurements of cloud properties from CALIPSO/CloudSat will also be valuable for understanding the influence of clouds on the humidity of the atmosphere, and on the properties of thin cirrus. Ice water content data from CloudSat will reveal important information about moistening processes in the upper troposphere. CALIPSO will map out the locations and thickness of thin cirrus, which when correlated with water vapor data will help reveal how these clouds play a role in near tropopause processes. Aircraft measurements of ice crystal size distributions will be essential to constrain models of dehydration by these clouds.

***Measurements addressing Science Question 4 of Table 1***

Measurements of a suite of chemical constituents are required in the TTL to address issues (hypotheses) related to the fate of short-lived compounds and the chemical boundary condition for the stratosphere. For example, measurements of:

1. BrO and precursors (to determine sources of stratospheric bromine),
2. IO and precursors (to determine the role of IO in stratospheric $O_3$ destruction),
3. NO, $NO_2$, $NO_y$, $HNO_3$, $HNO_4$, PAN, acetone, and other oxygenated organic compounds (to determine the role of oxygenated hydrocarbons in PAN and $O_3$ production in the UT), and
4. aerosol properties as well as the abundance of both organic and inorganic precursors of stratospheric sulfur (to understand contribution of short-lived sulfur compounds to stratospheric sulfate aerosol layer)

Because most of these compounds are short-lived and/or have inhomogeneous sources, a single (or even a few) profile in the tropics will not be adequate. Observations must be obtained in various geographical regions and during several seasons to assure representative sampling. Also, observations across the subtropical jet will enable better understanding of composition in the lowermost stratosphere.

These measurements will provide high-resolution profiles for validation of: AURA MLS, and SCIAMACHY limb observations of BrO; SCIAMACHY limb observations of IO; TES and HIRDLS observations of, e.g., $NO_2$, $HNO_3$, and PAN; and AURA and other satellite observations of aerosol properties.

***Measurements addressing Science Question 5 of Table 1***

Tropical ozone is affected by a complex interplay of dynamics, precursor emissions, and photochemical sources and sinks. $TC^4$ and the Aura satellite together will provide an unprecedented opportunity to address the mechanisms that control the ozone distribution in the tropics in general, and in the TTL in particular. *In-situ* data will allow reliable assessment of the photochemical source of ozone in the TTL for the first time, while the satellite data will place the aircraft data in the large scale context. We emphasize that prior measurements characterizing the photochemistry of tropospheric ozone have been restricted to altitudes below 12 km, and that it is crucial to obtain data above 12 km from a variety of locations.

HIRDLS and MLS will provide ozone data in the UT/LS, while TES and OMI will provide data for the entire troposphere (when cloud free). In addition ozone will be measured by SCIAMACHY. This suite of measurements will define the seasonal, longitudinal and latitudinal variability of ozone in a manner presently unavailable, particularly for the northern tropics where we do not even have ozonesonde data. (At present, there is only one ozonesonde site in the northern inner tropics, Paramaribo, Surinam, 6°N). TES will also provide measurements of CO and $NO_x$ (UT only), while OMI will provide $NO_2$ columns that should help define source locations. Aircraft measurements are required to:

1. Test the ability of the Aura measurements to resolve vertical and horizontal gradients for ozone, CO, and $NO_x$.

2. Measure the species of importance for the ozone budget. A minimum set of species is: In-situ and remote ozone and $H_2O$; in-situ $H_2O$, $CH_4$, CO, $NO_y$ species, $HO_x$ radicals, non-methane hydrocarbons (NMHC), and $N_2O$ (as tracer for stratospheric air). For understanding of the $HO_x$ budget, measurements of acetone, formaldehyde (HCHO), and peroxides are also required. There is a great deal of overlap between the species required to investigate the ozone budget and those related to the fate of short-lived species in the TTL. We stress, however, that complete vertical profiles are required, down to the boundary layer. The chemical composition of the TTL cannot be investigated in isolation from the rest of the troposphere.

***Measurements addressing Science Question 6 and 7 of Table 1***

A key objective of CRYSTAL-TWP is to evaluate the sensitivity of cirrus anvils to their generating convective systems using a case-study approach. We plan to characterize the convective systems (structure, mass fluxes, updraft velocities) using airborne and ship or ground-based Doppler radar. Then, in-situ and remote sensing instruments will be used to characterize the aerosols leading to the clouds, the ice crystal size distributions, cloud structure, radiative properties, and the evolution of cirrus anvils produced by these convective systems. Past field experiments have generally focused on either the convection and precipitation production processes or the properties of the cirrus anvils. These data will compliment those on CloudSat and CALIPSO.

Another objective is to understand the evolution of the anvils. $TC^4$ will address this issue 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, wind velocities and relationship to generating aerosols. Along with the cloud measurements, modeling studies will be undertaken to understand the processes controlling the evolution of cirrus anvils. CRYSTAL-FACE studies hope to validate and improve models so that their use in TWP environment without a TOGA-CORE-like observing system (with many sondes and ships) is justified. CloudSat and CALIPSO data will reveal a great deal about the large scale structure of anvils throughout the tropics, and aircraft studies of individual anvils will compliment that data with detailed in situ measurements.

***Measurements addressing Science Question 8 from Table 1***

One of the major goals of $TC^4$ will be to validate measurements obtained by instruments on Aura, and by instruments on other "A" train satellites. In Table 3 we delineate measurements we will make that correspond to parameters of direct interest to these instruments. One of our primary goals will be to fly coordinated flight tracks with all of the platforms in the footprints of the satellites as they pass overhead. These should produce horizontal data transects at a number of altitude levels of the geophysical quantities measured by the satellite instruments. The various satellite instrument teams are also likely to have retrieval issues that they wish to clarify with direct measurements. For instance, the HIRDLS team might want to know if it can retrieve a particular gas in the presence of subvisible cirrus. In that case, we would attempt to locate subvisible cirrus in the HIRDLS footprint and measure the composition of this air mass during an overpass, in conjunction with radiative parameters such as cloud optical depth that are involved in the retrieval algorithm. We plan to have satellite team members in the field during $TC^4$ to guide flight planning.

Another interaction between the satellite instruments and the field program is to synergistically work on science problems that neither can consider independently. For example, field programs lack the near global spatial coverage and multi year temporal coverage of satellites. Hence the satellites tell us how representative field measurements may be. On the other hand, field measurements are critical for measuring parameters that are not measured from space, and for defining small-scale variability of parameters that is often necessary for fully understanding physical, chemical, and radiative processes. The dialogue established between members of satellite instrument teams and the field program community during the planning stages of $TC^3$ and CRYSTAL-TWP has set the groundwork for the highly successful accomplishment of synergistic science.

**Balloons and Sondes**

The Aura instrument teams have requested that a series of balloon flights be conducted approximately 9 to 12 months after launch, from a series of locations *including the tropics* and in a fashion coordinated with Aura overpasses (EOS Aura Science Data Validation Plan, Version 1.0, http://eos-chem.gsfc.nasa.gov/ mission/images/aura_validation_v1.0.pdf).

Balloon observations are the only means for validating data from EOS Aura instruments for the middle to upper stratosphere (e.g., 20 to ~40 km). These balloon flights would contribute significantly to the science of $TC^4$ by providing measurements of $H_2O$ isotopes, properties of clouds and aerosols, and chemical composition (e.g., Rinsland *et al.*, 1998; Sen *et al*., 1998; Steele *et al*., 2002) at altitudes considerably higher than can be reached by either the ER-2 or WB-57 aircraft.

Balloon observations during September and/or October from Ft. Sumner, New Mexico (34.5°N, 104°W) are required for AURA validation. Such observations will also allow for studies of the long-term stability of the stratospheric Brewer-Dobson circulation [e.g., extension of the existing $CO_2$ time series (*Andrews et al.*, 2001), providing an “age of air record” that would span the UARS and Aura eras] and an independent assessment of stratospheric photochemistry by measurement of a wider range of species than will be measured by Aura instruments.

Balloon observations in the tropical Western Pacific are highly desirable, but probably not feasible due to the need for a water landing capability. However, tropical observations from Juazeiro do Norte, Brazil (7°S, 39°W) (where NASA has successfully carried out several flights of the OMS in-situ payload) will contribute to science goals of $TC^4$ and provide data crucial for AURA validation. Such data would provide observational constraints on profiles of $H_2O$ isotopes for altitudes of the UT, TTL and LS that would be important for addressing Science Questions 1 and 2 of Table 1 (e.g., thermodynamic history of air parcels should be retained, to some degree, by $H_2O$ isotopes over Brazil even if the actual injection of air into the stratosphere occurs elsewhere). Tracer observations over Brazil would also provide constraints on transport in the TTL for this geographic region and provide further information on longitudinal variations in the TTL (Science Questions 4 and 6). Most importantly, validation of EOS Aura measurements over Brazil, where vertical volume mixing ratio gradients, background aerosol, and ambient temperature are expected to be distinctly different than at mid-latitudes, will provide confidence in the scientific interpretation of EOS Aura data in the tropical Western Pacific. Balloons from Brazil can give information on TTL properties at a longitude where they won't be sampled by aircraft and in addition can give observations above 20 km where longitudinal variations are small in the tropics so that the results will aid interpretation of West Pacific aircraft data by extending the vertical domain to altitudes inaccessible to high-altitude aircraft.

A key part of $TC^4$ hinges on obtaining high vertical resolution profiles of $H_2O$ throughout the tropics. Measurement of $H_2O$ from lightweight hygrometers is the only feasible way to obtain this information. We propose, as part of Aura Validation and the $TC^4$ mission, that support be given for the deployment of a large number of hygrometers at various stations in the tropics, during the time periods of $TC^4$ airplane activity. Ideally, such hygrometers would be launched simultaneously with ozonesondes. Suitable deployment sites exist between the SHADOZ (Southern Hemisphere Additional Ozonesondes) and SOWER (Soundings of Ozone and Water in the Equatorial Region) programs. It is essential that the measurements provided by these hygrometers be validated prior to the start of the mission (e.g., the instrument must have demonstrated good accuracy and precision for $H_2O$ as low as ~2.5 ppmv, and must have fast enough response to resolve structures on relatively small vertical scales, especially above cirrus clouds). It is also desirable for the hygrometers to be lightweight (less than 4 to 6 lbs, depending on whether 1 or 2 pieces) and able to be launched without coordination with air traffic control.

**Ships**

It will be highly desirable to include at least one ship in the $TC^4$ mission, a logical choice being NOAA's R.V. Ron Brown. The R.V. Ron Brown currently has a C-Band Doppler Radar, Wind Profiler, and Radiosondes as well as various oceanographic and meteorological sensors. Ground stations played an important role in CRYSTAL/FACE. We expect that surface observing platforms would be very useful in the oceans to provide a platform for radars that can observe convective activity. The ship-based radar can be used to vector the aircraft to and around the convection to maximize the sampling. A suite of remote sensing instruments, in addition to those already on the R.V. Ron Brown, can observe the cloud fields before, during and after the aircraft observations. These data can provide a spatial and temporal view of the cloud systems that is difficult to obtain from constantly moving aircraft. Finally radiosonde launches before, during and after the cloud sampling would be important for initializing numerical models.

The Japanese have a research vessel, the Mirai, with similar capabilities to the R.V. Ron Brown that makes regular cruises to the TWP region. Participation of this vessel, and the Japanese scientists, would be a welcome addition to $TC^4$. With 2 vessels, establishing a radiosonde station on Chuuk Island to also make coordinated soundings would provide a significant enhancement to knowledge of the large-scale environment and forcing and could significantly improve the analysis by large-scale meteorological centers (e.g., NWS and ECMWF) to support CRYSTAL modeling objectives."

**Instrumentation Needs for $TC^4$**

The following tables summarize desired $TC^4$ observations, instrument availability, the science questions (1-7, from Table 1) being addressed, and the relevant contribution to validation of satellites. In the priority column, the priority is given first for the $TC^3$ goals and then for the TWP goals. As discussed later we assume that two missions will be flown, one in the summer with a TWP emphasis and one in the winter with a $TC^3$ emphasis in terms of the goals of the flights. It is assumed that every effort will be made to fly every instrument that is ranked as priority 1 or 2 by either $TC^3$ or TWP priorities. The distinction between $TC^3$ and TWP priorities is made to provide guidance in the event that one of the missions is reduced in size or objectives. We draw some conclusions about the platform requirements, based on the instrument requirements, below.

Table 3a Generic instruments on boundary layer platform. (Profiling capability from the boundary layer to ~5 km is required. Candidate aircraft are P-3, C-130). In CRYSTAL FACE this was done with a Twin Otter, and P-3.)

| Observation | Priority | Instrument status | Science Question | Satellite Validation |
|---|---|---|---|---|
| $O_3$ | 1,2 | X | 4,5 | HIRDLS, MLS, OMI, TES, AQ |
| $H_2O$ vapor | 1,1 | C | 1,2 | HIRDLS, MLS, TES, AQ |
| CCN | 2,1 | C | 3,6 | |
| Aerosol, IN composition | 2,1 | C | 3,6,7 | OMI, PA |
| Aerosols-size, shape, phase | 2,1 | C | 3,6,7 | HIRDLS, MLS, OMI, TES, AQ, CS, CA, PA |
| Precipitation Doppler Radar | 3,1 | C | 3,6,7 | HIRDLS, AQ,CA |
| Longwave Radiation and Solar Spectral Irradiation | 2,1 | C | 3,6,7 | HIRDLS, MLS, TES AQ, PA |
| CO, $CH_4$, | 1,2 | C | 4,5 | HIRDLS, MLS, TES |
| $CO_2$ | 2,2 | X | 4,5 | |
| $N_2O$ | 3,3 | X | 4,5 | HIRDLS, MLS, TES |
| $SF_6$ | 2,3 | X | 4,5 | |
| NO | 1,2 | X | 4,5 | |
| $HNO_3$, PAN, $NO_2$ | 1,2 | X | 4,5 | OMI |
| Acetone, HCHO, and peroxides | 1,2 | X, D | 4,5, | OMI, TES |
| NMHC, including short-lived tracers, HCFCs, halocarbons | 1,2 | X | 4,5 | |
| T, winds, P | 1,1 | C | | AQ, CS,CA |

| | | | |
|---|---|---|---|
| $^{210}Pb$, $^{222}Rn$, $^{85}Kr$ | 3,3 | D | 1, 2, |
| GPS downlink | 1,1 | D | |

NOTES: Priority:1=Mission critical, consider redundancy if needed, begin to develop instruments in advance if needed. Priority 2= Central to goals, redundancy not needed, develop through NRA as needed. 3= useful to have if space and funding available. First priority listed is for TC3 goals, second priority is for TWP goals. Status: X = exists/flown in previous missions, C= exists/flown on CRYSTAL-FACE, D = instrument development required. Satellites: CA=CALIPSO, CS=Cloud Sat, AQ=Aqua, PA=PARASOL.

Table 3b Generic instruments on upper troposphere aircraft. (This platform should cover the altitude range from 5-12 km. Candidate aircraft are DC-8 and several others. In CRYSTAL FACE this was done with a Citation.)

| Observation | Priority | Instrument status | Science Question | Satellite Validation |
|---|---|---|---|---|
| $O_3$ | 1,1 | C | 4,5 | HIRDLS, MLS, OMI, TES,AQ |
| $H_2O$ vapor | 1,1 | C | 1,2,3,6,7 | HIRDLS, MLS, TES,AQ |
| $H_2O$ total | 1,1 | C | 1,2,3,6,7 | MLS,AQ |
| $H_2O$ total water isotopes | 2,2 | D | 1,2,3,6,7 | TES |
| IN, CCN | 2,1 | C | 2,6,7 | |
| Aerosol and IN composition | 2,1 | C | 2,6,7 | PA, OMI |
| Clouds, Aerosols, particle size, shape, phase | 2,1 | C | 2,6,7 | HIRDLS,MLS, OMI, TES, AQ, CS, CA, PA |
| Precip radar | 3,3 | X | 6,7 | CS |
| Cloud radar | 3,1 | X | 6,7 | CS,CA |
| Water vapor lidar | 2,1 | X | 1,2,3,6,7 | HIRDLS,CS,AQ |
| Ozone lidar | 1,2 | X | 1,2,3,4,5 | HIRDLS, MLS, OMI, TES,AQ |
| Microwave temperature profiler | 1,2 | X | 1,3,6,7 | HIRDLS, MLS,TES, AQ |
| Temperature lidar | 3,3 | D(daytime) | 1,3,6,7 | HIRDLS, MLS,TES, AQ |
| Cloud lidar | 1,1 | X | 2,3,6,7 | HIRDLS,AQ,CS,CA , PA |
| Longwave Radiation and Solar Spectral Irradiation | 1,1 | X | 3,6,7 | HIRDLS, MLS, TES AQ,CS,CA, PA |
| Cloud extinction | 3,1 | C | 3,6,7 | AQ,CS,CA |
| CO, $CH_4$ | 1,2 | X | 4,5,6,7 | HIRDLS, MLS, TES |
| $CO_2$ | 2, 2 | X | 4,5 | |
| $N_20$ | 3,3 | X | 4,5 | |
| $SF_6$ | 2,3 | X | 4,5 | |
| NO | 1,2 | X | 4,5 | HIRDLS, MLS, TES |
| $HNO_3$, PAN, $NO_2$ | 1,1 | X | 4,5 | HIRDLS, MLS, OMI, TES |
| $HO_x$ | 1,3 | X | 4,5 | MLS |
| Acetone, HCHO, and peroxide | 1,2 | X | 4,5 | OMI, TES |
| NMHC, including short-lived tracers, HCFCs, halocarbons | 1,2 | X | 1,2 4,5 | |

| | | | | |
|---|---|---|---|---|
| $^{210}$Pb, $^{222}$Rn, $^{85}$Kr | 3,3 | D | 1,2,4 | |
| T, winds, P | 1,1 | C | | AQ, CS,CA |
| GPS downlink | 1,1 | D | | |

NOTES Priority:1=Mission critical, consider redundancy if needed, begin to develop instruments in advance if needed. Priority 2= Central to goals, redundancy not needed, develop through NRA as needed. 3= useful to have if space and funding available. First priority listed is for TC3 goals, second priority is for TWP goals. Status: X = exists/flown in previous missions, C= exists/flown on CRYSTAL-FACE, D = instrument development required. Satellites: CA=CALIPSO, CS=Cloud Sat, AQ=Aqua, PA=PARASOL.

Table 3c Generic instruments on TTL aircraft. (This aircraft profiles from about 12-17 km, in regions with extensive cloud cover. In CRYSTAL-FACE this was done with the W-B57. The ER-2 is also capable of working in this region).

| Observation | Priority | Instrument status | Science Questions | Satellite Validation |
|---|---|---|---|---|
| $O_3$ | 1,1 | C | 5 | HIRDLS, MLS, OMI, TES,AQ |
| $H_2O$ vapor | 1,1 | C | 1,2,3,6,7 | HIRDLS, MLS, TES,AQ |
| $H_2O$ total | 1,1 | C | 1,2,3,6,7 | MLS,AQ |
| $H_2O$ total water isotopes | 1,1 | C | 1,2,3,6,7 | TES |
| $H_2O$ vapor isotopes | 1,1 | D | 1,2,3,6,7 | TES |
| Aerosol, IN composition | 2,1 | C | 2,3,6,7 | PA, OMI |
| Clouds, Aerosols, particle size, shape,phase,ice | 1,1 | C | 2,3,6,7 | HIRDLS, MLS, OMI, TES, AQ, CS, CA,PA |
| Clouds forward scanning lidar | 2,2 | D | 2,3,6,7 | HIRDLS,AQ,CS,CA, PA |
| Outgoing Longwave Radiation and Solar Spectral Irradiation | 1,1 | C | 2,3,6,7 | HIRDLS, MLS, TES AQ, PA |
| Cloud extinction | 2,1 | C | 2,3,6,7 | AQ, CS, CA,PA |
| CO, $CH_4$, | 1,2 | C | 1,4,5,6 | HIRDLS, MLS, TES |
| HCl | 2,3 | C | 5 | HIRDLS,TES |
| $N_2O$, $CO_2$, CFCs | 1, 2 | C | 1,4 | HIRDLS, MLS, TES |
| $SF_6$ | 2,3 | X | 1,4,5,6 | |
| $HO_x$ | 1,3 | X | 4,5 | MLS |
| $NO_x$ | 1,2 | C | 4,5 | HIRDLS, MLS, OMI, TES |
| BrO, ClO | 1,3 | X | 4,5 | MLS, OMI |
| IO | 3,3 | D | | |
| $HNO_3$, PAN, $NO_y$ | 1,2 | C | 4,5,6 | HIRDLS, MLS, TES |
| $ClNO_3$ | 2,3 | C | 4,5 | HIRDLS, MLS |
| Short-lived organics | 1,1 | X | 4,5,6 | |
| Acetone, HCHO, peroxide | 1,3 | D | 4,5 | OMI |
| $SO_2$ | 2,3 | D | 4 | OMI, TES (volcanic) |
| T, winds, P | 1,1 | C | | AQ, CS,CA |
| $^{210}Pb$, $^{222}Rn$, $^{85}Kr$ | 3,3 | D | 4 | |
| GPS downlink, | 1,1 | D | | |

NOTES: Priority:1=Mission critical, consider redundancy if needed, begin to develop instruments in advance if needed. Priority 2= Central to goals, redundancy not needed, develop through NRA as needed. 3= useful to have if space and funding available. First priority listed is for TC3 goals, second priority is for TWP goals. Status: X = exists/flown in previous missions, C= exists/flown on CRYSTAL-FACE, D = instrument development required. Satellites: CA=CALIPSO, CS=Cloud Sat, AQ=Aqua, PA=PARASOL.

Table 3d Generic instruments on stratosphere/ TTL profiling aircraft (This aircraft must be capable of profiling to altitudes as low 12 km. Candidate aircraft are the ER-2 and WB-57. This function was central to SOLVE, and was served by the ER-2. The stratospheric function was not central to CRYSTAL FACE, and limited profiles were done with the WB-57)

| Observation | Priority | Instrument status | Science Questions | Satellite Validation |
|---|---|---|---|---|
| $O_3$ | 1,1 | c | 4,5 | HIRDLS, MLS, OMI, TES, AQ |
| $H_2O$ vapor | 1,1 | c | 1,2,3,6,7 | HIRDLS, MLS, TES, AQ |
| $H_2O$ total | 1,1 | c | 1,2,3,6,7 | MLS, AQ |
| $H_2O$ total water isotopes | 1,1 | c | 1,2,3,6,7 | TES |
| $H_2O$ vapor isotopes | 1,1 | D | 1,2,3,6,7 | TES |
| Aerosol composition | 2,2 | C | 3,6,7, | PA, OMI |
| Clouds, Aerosols, particle size, shape, phase | 2,2 | C | 3,6,7 | HIRDLS, MLS, OMI, TES, AQ, CS, CA, PA |
| CO, $CH_4$ | 1,2 | C | 1,4,5,6 | HIRDLS, MLS, TES |
| HCl | 1,3 | C | 5 | HIRDLS,TES |
| $N_2O$, $CO_2$, CFCs | 1,2 | C | 1,4 | HIRDLS, MLS, TES |
| $SF_6$ | 2,3 | X | 1,4,5,6 | |
| $HO_x$ | 1,3 | X | 4,5 | MLS |
| $NO_x$ | 1,2 | C | 4,5 | HIRDLS, MLS, OMI, TES |
| BrO, ClO | 1,3 | X | 4,5 | MLS, OMI |
| IO | 3,3 | D | 5 | |
| $HNO_3$, PAN, $NO_y$ | 1,2 | C | 4,5,6 | HIRDLS, MLS, TES |
| $ClNO_3$ | 1,3 | C | 4,5 | HIRDLS, MLS |
| Short-lived organics | 1,1 | X | 4,5,6 | OMI, TES |
| Acetone, HCHO, peroxides | 2,3 | D | 4,5 | OMI |
| $SO_2$ | 2,3 | D | 5 | OMI, TES (volcanic) |
| T, winds, P | 1,1 | C | | AQ, CS,CA |
| $^{210}Pb$, $^{222}Rn$, $^{85}Kr$ | 3,3 | D | 4,5 | |
| GPS downlink | 1,1 | D | | |

NOTES: Priority:1=Mission critical, consider redundancy if needed, begin to develop instruments in advance if needed. Priority 2= Central to goals, redundancy not needed, develop through NRA as needed. 3= useful to have if space and funding available. First priority listed is for TC3 goals, second priority is for TWP goals. Status: X = exists/flown in previous missions, C= exists/flown on CRYSTAL-FACE, D = instrument development required. Satellites: CA=CALIPSO, CS=CloudSat, AQ=Aqua, PA=PARASOL.

Table 3e Generic instruments on remote sensing aircraft (ER-2 and Proteus served this role in CRYSTAL FACE, the aircraft needs to operate well above cloud tops, for example at 20 km. Global Hawk and several other aircraft may be able to operate at these levels.)

| Observation | Priority | Instrument status | Science Question | Satellite Validation |
|---|---|---|---|---|
| Precip/Cloud radar | 2,1 | C | 2,6 | CA |
| Small Water vapor lidar | 2,2 | D | 1,2,3,6,7 | HIRDLS,CS,AQ |
| Small Ozone lidar | 1,2 | D | 1,2,4,5 | HIRDLS,MLS,TES, OMI, AQ |
| Microwave T profiler | 2,2 | C | 1,2,3,6,7 | HIRDLS,MLS,TES, OMI |
| Temperature lidar | 3,3 | D | 1,2,3,6,7 | HIRDLS,MLS,TES, OMI |
| Cloud lidar | 1,1 | C | 2,6,7 | HIRDLS,AQ,CS,CA |
| Outgoing Longwave Radiation and Solar Spectral Irradiation | 1,1 | C | 2,6,7 | HIRDLS, MLS, TES AQ, PA |
| Far IR spectrometer, Microwave radiometer | 2,1 | C | 2,6,7 | AQ,CS, CA |
| Michelson interferometer | 2,2 | X | 1,2,4,5 | HIRDLS,MLS,TES, OMI |
| Sub mm radiometer | 2,1 | C | 2,3,6,7 | HIRDLS, MLS, TES, AQ,CS,CA |
| Dropsondes | 1,1 | C | | MLS, AQ |
| Visible spectral radiometers, imagers, scanners for ground truthing | 2,1 | C | 2,5,6,7 | HIRDLS, MLS, OMI, TES, PA,AQ,CS,CA |
| DOAS Profiler | 1,3 | D | 1,2,4,5 | HIRDLS,MLS,TES, OMI |
| T, winds, P | 1,1 | C | | AQ, CS,CA |
| GPS downlink | 1,1 | D | | |

NOTES: Priority:1=Mission critical, consider redundancy if needed, begin to develop instruments in advance if needed. Priority 2= Central to goals, redundancy not needed, develop through NRA as needed. 3= useful to have if space and funding available. First priority listed is for TC3 goals, second priority is for TWP goals. Status: X = exists/flown in previous missions, C= exists/flown on CRYSTAL-FACE, D = instrument development required. Satellites: CA=CALIPSO, CS=Cloud Sat, AQ=Aqua, PA=PARASOL.

We draw the following conclusions based on these tables. First several instruments need to be developed. While many of these already exist for some platforms, they may need duplication for several platforms. We also need to have GPS location information downlinked from all the aircraft. That technology exists, but hasn’t been implemented on NASA aircraft.

Several instruments would be useful, and important for A-Train validation, if they can be made small enough, such as an ozone lidar for a stratospheric remote sensing platform. If it is not possible to develop them, then existing instruments on the lower altitude aircraft can fill in.

With respect to platforms, the boundary layer instruments (Table 3a) should be compatible with a P-3 or Electra payload. The base of the TTL payload (Table 3b) is within the capabilities of the NASA DC-8. The platform requirements for the aircraft working within the lower part of the TTL, where convection occurs (3c) are compatible with the W-B57. The platform requirements for the aircraft doing in-situ chemistry in the lower stratosphere are compatible with an ER-2. The remote sensing payload (3e) may need to be carried by two aircraft such as the Proteus and another ER-2, based upon the experience in CRYSTAL-FACE. If resources are not available to provide these platforms, or their equivalents, then it may prove possible to combine the roles of the aircraft in Table 3c, 3d.

**Flights Locations and Schedule**

To address the above science goals aircraft measurements will be required in both (tropical) moist and (subtropical) dry regions, in both convective and non-convective regions, in the region of the tropopause cold pool and minimum water vapor (which may not coincide). (The tropopause cold pool refers to the region of lowest tropopause cold trap temperature). It is desirable to sample a variety of lower atmospheric chemical conditions including those that are mainly marine, and those which are influenced by continental outflow, for example from biomass burning. It is also important to be able to fly between the surface and the lower stratosphere. This necessitates at least two major missions, in different seasons, as well as several "mini-missions". The major missions are described below, while the mini-missions are outlined in Appendix 3.

Table 4 and 5 presents a list of possible locations for the proposed major missions, and the criteria that are being used to select the sites.

Table 4 criteria for NH winter experiment

| location | Singapore | Guam | Darwin | Kwajalein | Hawaii | Costa Rica |
|---|---|---|---|---|---|---|
| **Lat/long** | 1.3°N, 103.9°E | 13.4°N, 144.4°E | 12.5°S, 130.6°E | 9°N, 168°E | 21.3°N, 157.9°W | 10°N,276°E |
| **Adequate runway/ hangers** | yes | yes | yes | No, runway too short ofr ER-2, Hangers not available | yes | yes |
| **Proximity to tropopause cold pool** | yes, end of range | yes | no | yes | no | yes (secondary minimum) |
| **Proximity to high maritime clouds** | maybe | yes, end of range | yes | yes | no | no |
| **Proximity to low water vapor regions** | maybe | yes | no | yes | no | yes (secondary minimum) |
| **Madden-Julian Oscillation** | yes | yes | yes | yes | maybe | slight |

Table 5 criteria for NH summer mission

| location | Singapore | Guam | Darwin | Kwajalein | Hawaii | Costa Rica |
|---|---|---|---|---|---|---|
| **Lat/long** | 1.3°N, 103.9°E | 13.4°N, 144.4°E | 12.5°S, 130.6°E | 9°N, 168°E | 21.3°N, 157.9°W | 10°N, 276°E |
| **Adequate runway/ hangers** | yes | yes | yes | no | yes | Yes, can't hanger ER-2 and WB57 |
| **Proximity to maritime convec-tion** | yes | marginal | no | no | yes | yes |

Table 4 and Figure 3-7 suggest that Guam (13.4°N, 144.4°E) or Singapore (1.3°N, 103.9°E) are the best potential bases of operation for a Northern Hemisphere winter mission. All the phenomena of interest can be reached from these locations and there are adequate facilities to base the aircraft. The aircraft will likely stop at Barbers Point, Hawaii (21.3°N, 157.9°W) on the way to and from the U.S. to the Western Pacific. This would allow flights to the south from Hawaii.

Northern Hemisphere winter deployments based in Guam or Singapore will enable flights to sample (i) convective and non-convective regions (fig. 5), (ii) high and low UT water vapor (and cross steep gradients in UT $H_2O$)(fig. 3), (iii) cold traps in TTL (fig. 4, fig. 6, fig. 7) and (iv) regions of minimum $H_2O$ near the tropopause (fig. 3, fig. 7). A few flights from Hawaii (transits plus local) would enable an even larger contrast, sampling lower UT water vapor, the tropopause air upstream from the cold trap, and a region where large lateral transport in the UT is expected.

Measurements in the tropical western Pacific are crucial for $TC^3$. The tropopause temperatures are coldest here and the region of low water vapor largest. This is probably the dominant region in terms of control of stratospheric humidity, and in-situ measurements in this region are vital. This applies not only for understanding small-scale processes but also for evaluation of AURA measurements. The extreme values, gradients, variability, and fine-scale structures in $H_2O$ and other constituents could be very different in this region than elsewhere, and so even if other tropical correlative measurements are available there is no guarantee results apply in this region. One difficulty with a tropical Western Pacific mission in the Northern Hemisphere winter is the Madden Julian Oscillation. In this oscillation, which is most pronounced in the Eastern Hemisphere during Northern Hemisphere winter, the outgoing long wave radiation, and hence the deep convective clouds undergo a 30-60 day oscillation (Fig. 8). Therefore, there is a chance that convection would be suppressed during a significant portion of a mission of a month's duration.

Basing for the summer Northern Hemisphere Mission is less obvious. The summer mission is oriented more towards studying convective systems rather than the large scale setting of the convection. Hence the convection needs to be close to the base of operations. Since many high altitude aircraft require an hour to climb to altitude, it is preferrable if the convection is within an hour of the base, without the base being affected by it. While the coldest tropopause temperatures are still located in the tropical western Pacific (Fig. 6), the climatological outgoing long wave radiation is lower near Coast Rica, suggesting that high maritime clouds are more prevalent there. Before a decision is reached on the basing for the summer mission, data on the probability of finding high maritime clouds within an hour of Guam and Costa Rica during June, July and August need to be thoroughly examined. We also need to evaluate the chance that weather at the airport would be suitable for operations when convection is nearby.

Measurements in the Eastern and Western tropical Pacific are also important for understanding tropical ozone. There have not been tropospheric field campaigns in either region, except for very few flights from the PEM-West and TRACE-P missions. In the Western Pacific the influence of convection and that of photochemical production from $NO_x$ generated by lightning would be a major focus, as well as the influence of the Asian monsoon; sources of precursors from fossil and biomass fuels will likely be present, and biomass burning in the dry season. From Costa Rica, it will be possible to sample the effects of ozone precursors from biomass burning in northern South America and West Africa in the northern winter, and of biomass burning in Brazil in July to October; convection and the effect of $NO_x$ from lightning on ozone can also be investigated, providing a contrast with the western Pacific. The variety of chemical environments sampled in these regions will provide key validation opportunities for Aura.

*Schedule*

TC[4] is envisioned as a campaign similar to SOLVE and CRYSTAL-FACE. We hope that sufficient resources are available to field a theory team, including members of the Aura and other "A" train instrument teams, to aid in real time data analysis, flight planning, and validation activities.

There are strong seasonal variations in tropopause height and temperature, deep convection, and minimum $H_2O$ in the lower stratosphere, and it is therefore important to characterize the TTL in (at least) NH winter and summer. Also, as there strong interannual variability in the TTL due to, for example, ENSO and stratospheric QBO, multi-year measurements are needed. Finally, observations across the Pacific are need to fully understand the physical, chemical, and radiative characteristics of the TTL.

A strawperson schedule, which must be carefully related to satellite launch schedules, is:

- **Western Pacific (NH winter – primary focus on TC3 goals): Winter 2004/2005**
- **Western or Eastern Pacific (NH summer – primary focus on CRYSTAL goals) : Summer 2005**

CloudSat, CALIPSO and PARASOL are currently scheduled for launch in Oct. 2004. Aura is currently scheduled for launch in early 2004.

Table 6 and 7 outline a possible distribution of flights during a winter and a summer field mission. Experience from many field programs suggests that science flights can be done every second or third day. Hence the 15 flights in Table 6, and 7 may require about 37 days from time of arrival at the mission base site to complete. Due to the distances involved, and the Hawaii science flights in Table 6 the winter mission would require an extended period to arrive at the mission base site. Most aircraft can probably reach Guam in two flights from the West Coast. Including the science flights from Hawaii, these numbers suggest that the deployment both ways will require about 15 days total. As noted above, it would be desirable to have the full complement of aircraft platforms, and ships, available for deployments in both NH winter and NH summer.

In the winter deployment in Table 6 the two flights from Hawaii, and the 7 flights to study the tropopause cold pool/TTL are not tightly coupled to convective clouds. These can be achieved in any phase of the Madden-Julian oscillation. They are likely to include significant segments in clear air, or regions with only subvisible cirrus present. As such they should be ideal for many calibration flights involving the A-Train. We anticipate that the A-Train will have specific flight profiles that need to be flown. These are difficult to anticipate until launch and testing of the sensors. Hence the specific flight plans will be designed at a much later date, just prior to the mission. However, we anticipate that flights will be needed both along the track of the sensors, and cross track. Since the sensors do not all view the same location, there may be several flights dedicated to different sensor needs. Other instruments on the A-Train will desire scenes with clouds. These scenes will be covered in the 8 flights dedicated to outflow and convection studies. Due to the length of the Madden Julian oscillation we will try to adjust the mission to maximize the convection flights. Shortly before the deployment begins we should be able to judge the phase of the oscillation. We may shuffle the Hawaii flights to the start or end of the mission, in order to increase the chance or capturing convection. Likewise the convection flights may be concentrated during a portion of the mission when the oscillation is favorable. Based on daily observations at Kapingamarangi and Nauru we found that the range of coldpoint tropopause temperatures associated with MJO (25-70 day filtered data) is about 4 K, and the same range occurs also for the higher frequency (6-25) day data. There is also an interesting effect in that the minimum coldpoint tropopause temperature occurs 2-10 days prior to the minimum OLR associated with the MJO. This behavior of the coldpoint is clearly related to Kelvin wave activity, which seems to be the main driver of intra-seasonal variation in the coldpoint temperature. Thus, even during suppressed MJO periods we expect higher frequency variations in the cold point temperature that will allow us to achieve our objectives.

Another deployment issue is the possibility of an ENSO, which could significantly shift the pattern of convection in the Pacific. Fortunately, these are predictable some time in advance. However, they might shift our preferred deployment location from Guam to Hawaii. This possibility and how to respond to it require further analysis.

Table 6 example of distribution of flights in a winter time mission in the tropical Western Pacific***

| Number of multi-aircraft missions dedicated to goal* | Goal** | Description of flight plan |
|---|---|---|
| 2 | Obtain profile in mid-Pacific at all levels from boundary layer to mid-stratosphere | All aircraft fly as far south from Hawaii as possible along A-train path and return. Done in the initial transit, and in the final transit. Sample ozone, short-lived halocarbons, inorganic halogens, $HO_x$ and $NO_x$ radicals, aerosols, etc. as high as possible. Sample longitudinal structures in the the free troposphere of ozone, HOx and NOx radicals and their precursors, tracers of convection and lightning activity, etc |
| 7 | Profile tropopause cold pool region at all levels from boundary layer to mid-stratosphere.<br>Examine TTL properties, and their relations to lower troposphere/stratosphere | Fly across tropopause cold pool with all aircraft along A-train path. Sample tropical tropopause layer, subvisible cirrus. Do multiple (3) legs with a radiation-measuring package at the tropopause to get tropopause cooling rates. Sample ozone, short-lived halocarbons, inorganic halogens, $HO_x$ and $NO_x$ radicals, aerosols, etc. as high as possible. Sample longitudinal structures in the the free troposphere of ozone, HOx and NOx radicals and their precursors, tracers of convection and lightning activity, etc. |
| 5 | Outflow sampling | Sample clouds, water vapor, tracers, and radiation in aged (hours-days) convective outflow and tropopause cold pool outflow. |
| 3 | Deep convection | Characterize maritime deep convection/anvil system, including convective mass fluxes, updraft speeds, anvil microphysics, radiative fluxes, turbulence, tracer distribution, aerosols, etc. We should be able to do these within 100km of ship. |

*not including transit flights, which will have science instruments in operation, and will be stacked if possible

** it is assumed that all flights will coordinate with the A-train. While the example of flying along the spacecraft track is given in the Table, the actual flight plans might be cross track, or other patterns as requested by the satellite teams to meet their goals.

*** no prioritization of the different goals, beyond the number of flights allocated to them, is intended.

Table 7 example of distribution of flights in a summer time mission in the tropical Western Pacific***

| Number of multi-aircraft missions dedicated to goal* | Goal** | Description of flight plan |
|---|---|---|
| 5 | Deep maritime convection | Characterize maritime deep convection/anvil system, including convective mass fluxes, updraft speeds, anvil microphysics, radiative fluxes, turbulence, tracer distribution, aerosols, etc. We should be able to do these within 100km of ship. |
| 2 | Deep continental convection (if mission is from Costa Rica) | Characterize continental deep convection/anvil system, including convective mass fluxes, updraft speeds, anvil microphysics, radiative fluxes, turbulence, tracer distribution, aerosols, etc. |
| 5 | Examine TTL properties | Sample tropical tropopause layer, subvisible cirrus, relative humidities, ozone and its photochemical precursors, aerosols, radiative fluxes, etc. Do multiple (3) legs with a radiation-measuring package at the tropopause to get tropopause cooling rates. Sample ozone, short-lived halocarbons, inorganic halogens, $HO_x$ and $NO_x$ radicals, aerosols, etc to maximum altitude. Sample longitudinal structures in the the free troposphere of ozone, HOx and NOx radicals and their precursors, tracers of convection and lightning activity, etc. |
| 3 | Outflow sampling | Sample clouds, water vapor, tracers, and radiation in aged (hours-days) convective outflow. |

*not including transit flights, which will have science instruments in operation, and will be stacked if possible.

** it is assumed that all flights will coordinate with the A-train. While the example of flying along the spacecraft track is given in the Table, the actual flight plans might be cross track, or other patterns as requested by the satellite teams to meet their goals.

*** no prioritization of the different goals, beyond the number of flights allocated to them, is intended.

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Appendix 1. NASE Earth Science Grand Questions

The NASA Earth Science Enterprise has recently posed 23 grand questions that need to be addressed. These are divided into questions related to trends and variability, forcings, responses to the forcings, consequences, and predictions.

ESE Science Questions

Earth's Natural Variability and Trends

V1 Is the global cycling of water through the atmosphere accelerating?

V2 How is the global ocean circulation varying on climatic time scales?

V3 How are global ecosystems changing?

V4 How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases?

V5 Are polar ice sheets losing mass as result of climate change?

V6 What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?

Primary Forcings of the Global Earth System

F1 What trends in atmospheric constituents and solar radiation are driving global climate?

F2 What are the changes in global land cover and land use, and what are their causes?

F3 How is the Earth's surface being transformed and how can such information be used to predict future changes?

Responses of the Earth System to Natural and Human-Induced Disturbances

R1 What are the effects of clouds and surface hydrologic processes on climate change?

R2 How do ecosystems respond to environmental change and affect the global carbon cycle?

R3 Will climate variations induce major changes in the deep ocean?

R4 How do stratospheric trace constituents respond to climate change and chemical agents?

R5 Will changes in polar ice sheets cause a major change in global sea level?

R6 What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

Consequences of Changes in the Earth System for Human Societies

C1 How are variations in local weather, precipitation and water resources related to global climate change?

C2 What are the consequences of land cover and land use change?

C3 To what extent are changes in coastal regions related to climate change and sea-level rise?

Prediction of Future Changes in the Earth Climate and Global Environment

P1 To what extent can weather forecasting be improved by new global observations and advances in satellite data assimilation?

P2 To what extent can transient climate variations be understood and predicted?

P3 To what extent can long-term climatic trends be assessed or predicted?

P4 To what extent can future atmospheric chemical impacts be assessed?

P5 To what extent can future atmospheric concentrations of carbon dioxide and methane be predicted?

Appendix 2 The A-Train and validation issues

The A-Train of satellites, (so called because the spacecraft co-orbit, pass over within about 15 min, and are led and followed by spacecraft starting with the letter A) have an equator crossing time of about 13:30 local time. Table A2.1 provides details of the sensor compliments.

Table A2.1 Sensor complement and related products of the A-train (from Stephens et al., 2002).

| Spacecraft | Payload | Characteristics | Cloud and aerosol products |
|---|---|---|---|
| AQUA Lead constellation spacecraft | MODIS | 36 channel visible radiometer, 2300-km wide swath, variable resolution from 0.25 to 1 km. | Land, ocean and atmospheric products. The latter include cloud and aerosol optical depths and particle size information, as well as cloud emissivity, cloud-top height. |
| | AIRS/AMSU-A /HSB | Combination of IR and microwave sounders. Swath of ± $50^o$, resolution of IR sounder ~10km | Temperature and moisture profiles in clear atmosphere. Some cloud properties. |
| | AMSR-E | 6 channel microwave radiometer. 1445 km swath, asymmetric FOV with variable resolution from ~6X4km (89 GHz) to 43X75km (6 GHz). | Liquid water path, column water vapor, liquid precipitation. principally confined to ocean regions. |
| | CERES | Broad band and spectral radiances converted to fluxes, resolutions at nadir – 20km | Top-of-atmosphere radiation budget. Primary product is time-mean fluxes but instantaneous fluxes are also produces |
| CLOUDSAT Lags Aqua by a variable amount but less than 120 sec | 94 GHz radar (CPR) | 500m vertical range gates from surface to 30km. High sensitivity, FOV approximately 1.4 km. | Cloud profile information, liquid and ice water content profiles, precipitation. The information is obtained by combining the radar measurements with AQUA measurements including MODIS and AMSR-E as well as with the CALIPSO lidar. |
| CALIPSO Separation is maintained by CloudSat. Lags CloudSat by 15 ± 2.5 sec. | Lidar (CALIOP) | 532 and 1064 nm channels with depolarization. FOV of approximately 300m and 70m resolution. | Cloud profile information primarily of upper tropospheric clouds. Optical depth of thin cirrus. Aerosol profiles with attached optical depth estimates. Aerosol information requires averaging over 10s km especially in daylight. |
| | IIR | 3 channel IR radiometer with a FOV of 1km, swath 64km. | Cirrus cloud optical properties. |
| PARASOL Lags CALIPSO by ~ 2 minutes | POLDER | 9 channel polarimeter with channels in the visible and near infrared. Resolution of 5m, swath of ~ 400km. | Cloud and fine-mode aerosol optical depths and particle sizes. |
| AURA Lags AQUA by about 15 minutes | HIRDLS | IR Limb Sounder | Trace gases and stratospheric aerosol |
| | MLS | Microwave Limb Sounder, <1 km vertical res., 100-500 km horizontal | Trace gases, ice content of thin upper tropospheric cloud. |

| | | | |
|---|---|---|---|
| | TES | IR imaging spectrometer, 0.5X5 km resolution, narrow swath and variable pointing, 2.5 to 3.5 km vertical resolution | Trace gases, could also provide high spectral resolution data on clouds |
| | OMI | UV grating spectrometer, 13X24 km resolution | Ozone and aerosol index. |

Several of the A-Train instruments scan over wide fields of view. These include OMI, all of the AQUA instruments, and PARASOL. Validation of these instruments should be much simpler than those of AURA since the aircraft will be able to choose from a wide variety of targets while still remaining within the instrument swath.

Fig. A2.1 illustrates the typical atmospheric views from the 4 Aura instruments during portions of 3 consecutive orbits. OMI swaths extend across track and nearly fill in the gaps between the orbits. MLS looks ahead of Aura about 3000 km, and takes a profile about every 165 km along the track. It requires about 7 min for Aura to pass over this MLS point during which time the Earth turns about 200 km near the equator. Hence the TES nadar profile, obtained every 550 km along the track, is shifted about 200 km across the track from MLS. The TES limb view is further shifted by several hundred km across track. HIRDLS looks behind AURA, and has profiles spaced across track, with the first one being several hundred km west of the MLS points. (HIRDLS has several observational modes with different resolution.) In Fig. A2.1 the size of the symbols roughly indicates the footprint.

As Fig. A2.1 makes clear the various Aura sensors don't actually have overlapping footprints. Hence there are several strategies for validating these instruments. One could choose narrow field of view instruments such as HIRDLS and TESS and fly along the spacecraft footprint track. The distance between observations is roughly 500 km, and aircraft such as the ER-2, or DC-8 could fly between two footprints in about 40 min. Alternatively one could fly cross track patterns. The distance between the Aura tracks of MLS, TES and HIRDLS is also about 500 km. Hence the aircraft could fly through the footprints in about 40 min. Since the footprints are also offset in time (ie MLS passes over 7 min before the TES nadar footprint, which is 15 min flight time away), the aircraft should be able to be present in several footprints during an overpass.

The choice of the types of flight plans will be made in consultation with the Aura science teams, and may vary between flights depending on the goal. For instance Aura itself plans to deal with the footprint offset by creating spatial fields of data for each of the sensors and comparing these fields. This approach assumes there is no sub-grid variation, which could be tested with aircraft flights in a box pattern around a 500 km square. There may also be retrieval issues facing one or more instrument. In that case it may be desirable to stay within the footprint of the instrument as much as possible and follow it along the track. Another possibility would be to extensively profile in the vertical in one footprint, so that multiple short (20 min-250 km) legs are flown either along or across track with each aircraft profiling over a few km altitude.

CloudSat and CALIPSO have very small fields of view on the order of 1 km wide, which are continuous along the spacecraft track. The targets of these instruments, clouds, tend to be rapidly time varying. How these fields of view will compare with those of Aura instruments is not clear at the moment. While aircraft can easily be navigated into such small fields of view, it will be necessary for the spacecraft to have determined accurately where its footprints are located in order to do so. Cross track observations will probably not be useful for these spacecraft. Instead flights along the track with vertical profiles will be needed.

While observations within the spacecraft footprints will be done, it should also be possible to improve our understanding of the spacecraft data by employing similar remote sensing instruments on the remote sensing aircraft and doing in situ profiles in its tracks. For example lidars and radars similar to those on CALIPSO and CloudSat can be flown, and in situ data can be used to test their ability to retrieve information such as ice water content. Such data were already obtained in CRYSTAL FACE.

Appendix 3: Mini-missions in support of TC3.

The goals of $TC^3$ include characterizing the seasonal and interannual variability of the TTL, as well as providing AURA validation under different conditions. Meeting these goals will require mini-missions in addition to the major campaigns. The large-scale campaigns of necessity give a relatively limited number of flight-days within the TTL. Neither do they provide any contrast of the western and eastern Pacific in a given season. Mini-missions from Costa Rica, such as those planned under the AVE (AURA Validation Experiment) umbrella, would provide additional opportunities to meet the $TC^3$ science goals, as well as providing validation opportunities for AURA. Costa Rica provides a base for reaching a variety of dynamical and chemical environments. The instrumentation package for AVE/$TC^3$ is given in Table A1.

Flights from Costa Rica could sample both the Eastern Pacific and the tropical Atlantic. They could also sample regions to the north and/or south of the ITCZ, depending on season. Such flights can be useful in two different ways. The first and most obvious use is to permit cost-effective repeated observations. Many of the processes that add and remove water vapor from air in the TTL (e. g., convective overshoots and thin cirrus) are common to the entire tropics and can be readily observed from Costa Rica. The second use is in a sense the opposite, to provide complementary observations to those made out of the West Pacific. The TTL over the East Pacific near Central America is a very different environment than that over the West Pacific warm pool; in this case observations over the East Pacific are needed to obtain a representative understanding of controls on near-tropopause water vapor.

Preliminary analysis of results from a mini-mission out of Costa Rica demonstrates that important insights into the mechanisms controlling $H_2O$ in the stratosphere can be obtained from this location (E. Moyer, J. Anderson, pers. communication). Ttropopause over Central America reaches temperatures within about 3K of those that occur over the West Pacific warm pool, the deep convective processes that occur in the two regions are not qualitatively different. Flights out of Costa Rica can intersect anvil outflows with attendant evaporation of ice particles, overshooting cumulus towers that deposit water in the stratosphere, local variations in tropopause temperature, and convection-induced gravity waves. Measurements taken in these conditions can still help provide an understanding of the microphysics of deep convection and its effect on ambient water vapor.

Repeated flights out of Costa Rica can provide more opportunity to observe intermittent events that span the entire tropics. Preliminary flights out of Costa Rica (E. Moyer, J. Anderson, pers. Communication) fortuitously observed the beginnings of a tropics-wide cooling of the near-tropopause region; such coolings occur in most summers and may be an important cause of near-tropopause dehydration. Such intermittent events would not necessarily be caught on a single several-week large mission. Costa Rica provides a cost-effective base for the repeated monitoring needed to understand the time-variability of the tropics.

Costa Rica provides a complementary research site to the West Pacific "cold-trap". The West Pacific is interesting as the location of the coldest tropopause temperatures, and therefore as a source of extremely dry air. But the West Pacific is not likely to set the water vapor concentration of *every* air parcel that reaches the stratosphere, nor is it necessarily the easiest location from which to disentangle the different physical processes involved in dehydration. In the West Pacific, the season of minimum tropopause temperatures corresponds to the season of the strongest deep convection. It may be difficult from observations made solely in that time and location to differentiate between dehydration within convective processes and dehydration by slow ascent through regional cold pools. In the East Pacific near Central America, on the other hand, convective activity is minimal during winter when coldest tropopause temperatures occur, allowing an undisturbed view of near-tropopause air movements and in-situ cirrus formation. Conversely, convective activity is strongest when the tropopause is relatively warm, allowing purely convective effects to be studied without the confusion of simultaneous in-situ cirrus formation.

Costa Rica is also a good location for investigation of $HO_x$ and ozone chemistry. Measurements of the complete suite of species providing sources for $HO_x$ and $NO_x$ (and hence ozone production and loss) are not available above 12 km anywhere in the tropics. They are required in locations other than the equatorial TWP, where tropospheric ozone appears to be lower than anywhere else in the tropics [Kley et al., 1996; Thompson et al., 2003]. The troposphere in the equatorial TWP appears to be a particularly clean chemical environment, except when influenced by incursions of polluted air from eastern Asia, or by unusual events, such as the massive Indonesian fires of 1997/98. Measurements of ozone profiles from San Cristobal in the eastern Pacific (1°S, 90°W) and from Surinam (6°N, 55°W) in the Western Atlantic show that there are significant ozone gradients in the middle and upper troposphere in the regions accessible from Costa Rica, as shown in Figure 1 [Thompson et al., 2003]. This location could be used to make measurements of air masses influenced by lightning associated with convective storms. This region is also potentially influenced by biomass burning from the northern tropics (Dec.-March), and there is good evidence that it is impacted by biomass burning in the southern tropics (July-Oct.). Current knowledge suggests that a range of chemical conditions could be sampled from Costa Rica, so that the chemical production and loss rate for $HO_x$, $NO_x$, and ozone could be well-characterized.

Table A1. Generic instruments on stratosphere/ TTL profiling aircraft for AVE/$TC^3$ flights in the eastern Pacific. Candidate aircraft are the ER-2 and WB-57.

| Observation | Priority | Instrument status | Science Questions | Satellite Validation |
|---|---|---|---|---|
| $O_3$ | 1 | X | 4,5 | HIRDLS, MLS, OMI, TES |
| $H_2O$ vapor | 1 | X | 1,2,6,7 | HIRDLS, MLS, TES |
| $H_2O$ total | 1 | X | 1,2,6,7 | MLS |
| $H_2O$condensed isotopes | 2 | D | 1,2,6,7 | |
| $H_2O$ vapor isotopes | 2 | X | 1,2,6,7 | TES |
| Aerosol, IN composition | 2 | C | 4 | PA, OMI |
| Clouds, Aerosols, particle size, shape, phase | 2 | C | 4 | HIRDLS, MLS, OMI, TES, AQ, CS, CA, PA |
| CO, $CH_4$ | 1 | C | 1,4,5 | HIRDLS, MLS, TES |
| $N_2O$, $CO_2$, CFCs | 2 | C | 1,4 | HIRDLS, MLS, TES |
| $SF_6$ | 3 | C | 1,4 | |
| $HO_x$ | 2 | X | 4,5 | MLS |
| $NO_x$ | 2 | C | 4,5 | HIRDLS, MLS, |

| | | | | |
|---|---|---|---|---|
| | | | | OMI, TES |
| BrO, ClO, IO | 2 | X/D | 4,5 | MLS, OMI |
| $HNO_3$, $NO_y$ | 2 | C | 4,5 | HIRDLS, MLS, TES |
| Short-lived organics | 1 | C,D | 4,5 | OMI, TES |
| T, winds, P | 1 | C | | AQ, CS,CA |
| $^{210}Pb$, $^{222}Rn$, $^{85}Kr$ | 3 | D | 4,5 | |
| GPS downlink | 1 | D | | |

NOTES: Priority:1=Central to $TC^3$ goals, 2= Important to goals, 3= useful to have. Status: X = exists/flown in previous missions, C= exists/flown on CRYSTAL-FACE, D = instrument development required. Satellites: CA=CALIPSO, CS=Cloud Sat, AQ=Aqua, PA=PARASOL.