Experimental Design Overview for OTREC: Organization of Tropical East Pacific Convection

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1 Summary

The vertical structure and spatial distribution of deep atmospheric convection is of critical importance to tropical weather and climate. The eastern Pacific ocean and the southwest Caribbean are very poorly understood compared to other tropical regions and exhibit a great deal of diversity in convective behavior. An observational program is therefore proposed to determine the characteristics of deep convection in this region.

The tools for this project would be dropsondes deployed in a grid to evaluate mesoscale thermodynamic and vorticity budgets and the Hiaper Cloud Radar to determine the characteristics of cloud populations. Both of these tools would be deployed on the NSF/NCAR Gulfstream V aircraft. Basing in Costa Rica would provide easy access to both regions.

Similar observations have been made in Atlantic and western Pacific weather disturbances. The east Pacific differs from these regions in that a strong cross-equatorial gradient in sea surface temperature exists, with cool ocean temperatures on and south of the equator and the warmest waters adjacent to the Mexican and Central American coasts. The resulting atmospheric flow from cold to warm ocean introduces additional convective forcing processes and a large range of sea surface temperatures that do not exist in the previously studied regions. In contrast, the southwest Caribbean exhibits uniform ocean temperatures, but differs from the Atlantic and Western Pacific by virtue of its very dry free troposphere. The two regions together thus provide a broad range of atmospheric conditions that have not been previously studied using modern observational tools.

An additional reason for studying this region is the existence of frequent tropical easterly waves. These waves have been shown to intensify in the east Pacific for reasons at least partly due to their interaction with deep convection. The mechanisms of this interaction are likely to act in a wide range of tropical disturbances and their clarification thus has broad importance. Easterly waves are also a nursery for the formation of many tropical cyclones worldwide.

Intellectual Merit: Virtually all ascending motion in the tropical atmosphere is associated with deep moist convection. Atmospheric circulations in the tropics at all scales are given form by the pattern of this ascent and tropical rainfall is tightly associated with the rising air. Therefore even the most basic understanding of tropical weather and climate depends on determining the form and distribution of deep atmospheric convection and its mechanisms of interaction with broader circulations. The current project would significantly extend our knowledge of these factors in a region where convection is poorly understood.

Broader Impacts: Enhancing our understanding of how convection changes with changes in environmental conditions has two broader impacts: (1) Confidence in satellite measurements of

convective properties is increased by comparing these measurements with in situ observations. There are some particularly troublesome forms of convection in this region in which different types of remote measurements give different answers. “Ground truth” supplied by this project could resolve this issue. (2) The fidelity of parameterizations of deep convection in global weather and climate models is difficult to verify. Observations of the type proposed here, coupled with cloud-resolving modeling would provide the information needed to test and improve existing parameterizations and develop new ones.

In addition to direct scientific impacts, the project would enhance scientific connections with Costa Rica and particularly Colombia, which has recently emerged from a devastating period of civil unrest. The project would also familiarize a younger generation of investigators, including students, with the arts of airborne measurements and of running a field program, thus instilling the knowledge and self confidence needed to undertake their own efforts in the future.

2 Program Rationale

To cite from the Scientific Program Overview (SPO):

> The character of deep convection and the means by which it is forced are of supreme importance to all tropical circulations, including tropical cyclones, tropical waves, the Madden-Julian oscillation, the ITCZ, and the Hadley and Walker cells. The purpose of this proposal is to make the measurements in the east Pacific and southwest Caribbean that are needed to understand how convection there works together with the large scale circulations in this region.
>
> Convection in the east Pacific and southwest Caribbean differs from that in previously studied areas of the western Atlantic and Pacific in that sea surface temperatures (SSTs) are lower and boundary layer forcing is stronger. Convection forms in different circumstances in the east Pacific and in the southwest Caribbean; in the former, strong SST gradients drive potent forcing, whereas in the latter, convection forms where these gradients are weak and the mid-troposphere is often very dry. However, upstream orographic forcing from Central America may be operating there. Forms of convection exist in the east Pacific intertropical convergence zone (ITCZ) that until recently were not recognized in satellite-based estimates of precipitation and convective vertical structure.
>
> Tropical easterly waves and related phenomena are ubiquitous in the tropical regions of the world. Aside from being significant weather makers in their own right, such waves are frequent precursors to tropical cyclones. East Pacific waves appear to result either from African waves that reintensify in the far east Pacific or else they form there. This formation or reintensification appears to result from a combination of barotropic and convective energy conversions. The latter depends sensitively on the vertical structure of the convection, which brings us back to the issues raised above. The way convection interacts with easterly waves is likely to be characteristic of this interaction for many types of tropical disturbances.

Observational tools developed in the last decade, the use of which was perfected in recent field programs, can address the above questions in the tropical east Pacific and the southwest Caribbean.

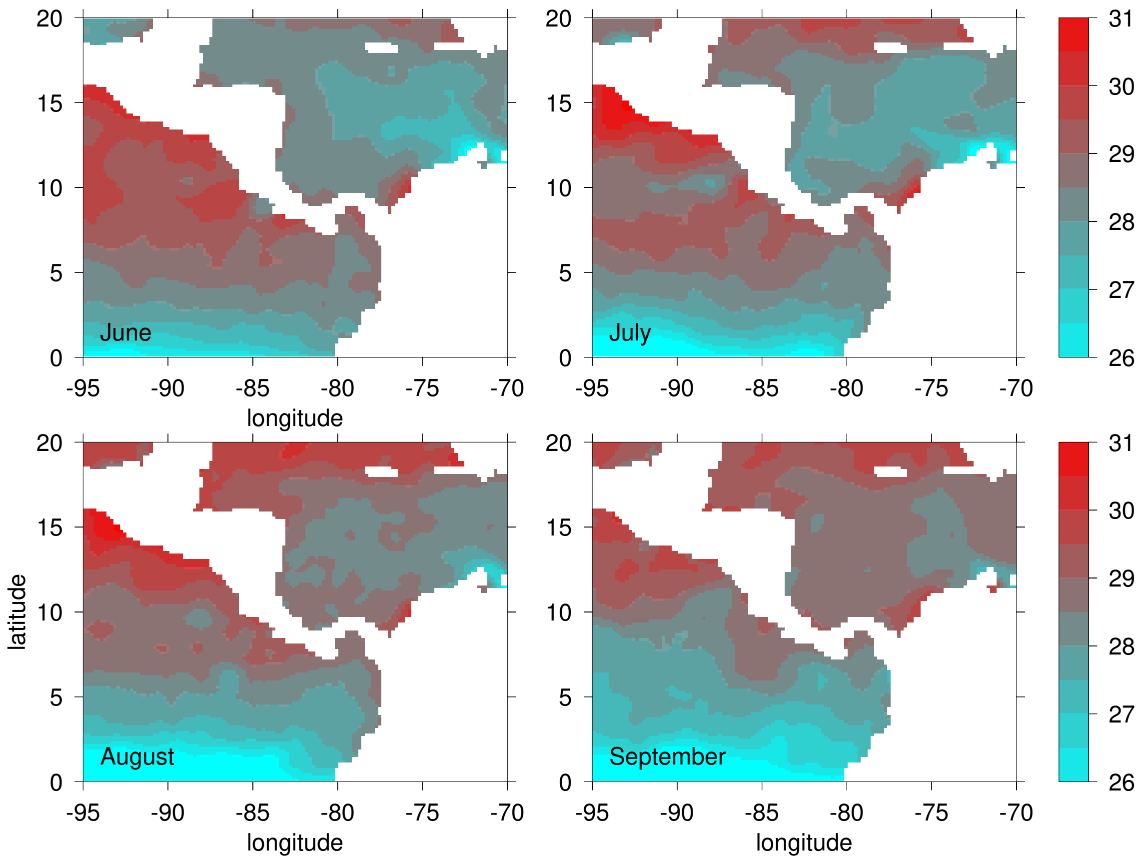

Figure 1: SSTs in the east Pacific and SW Caribbean from June through September, 2014.

2.1 Background

2.1.1 Mean State

Figure 1 shows monthly average AVHRR optimum interpolation v2 sea surface temperatures (SSTs) for June through September, 2014. The most obvious feature is the strong NS gradient in SST in the east Pacific for all 4 months, in contrast to the nearly uniform SSTs in the SW Caribbean. The warmest SSTs are on the Mexican Pacific coast and isotherms tend to retreat northward over the summer. As 2014 was not an El Niño year, this SST pattern is likely to be typical of most years, including the proposed year of field observations, 2019.

Figure 2 shows monthly average scatterometer surface winds in the east Pacific and SW Caribbean. The cross-equatorial flow up the SST gradient terminates in the surface intertropical convergence zone (ITCZ) near $8 - 10$ N with little variation over the summer. However, the winds north of this zone and east of 105 W switch on the average from light and variable in June to easterly in July and August to westerly in September. The SW Caribbean jet is strongest in June and July and weakens in August and especially in September.

The monthly average surface divergence is shown in figure 3. In September and to a lesser extent in June, surface convergence reaches north to the Mexican and Central American coast. However, during July and early August the divergent region retreats southward west of 85 W. This is correlated with easterly winds in the east Pacific and is associated with large-scale patterns giving rise to the "mid-summer drought" in southern Mexico and Central America during this

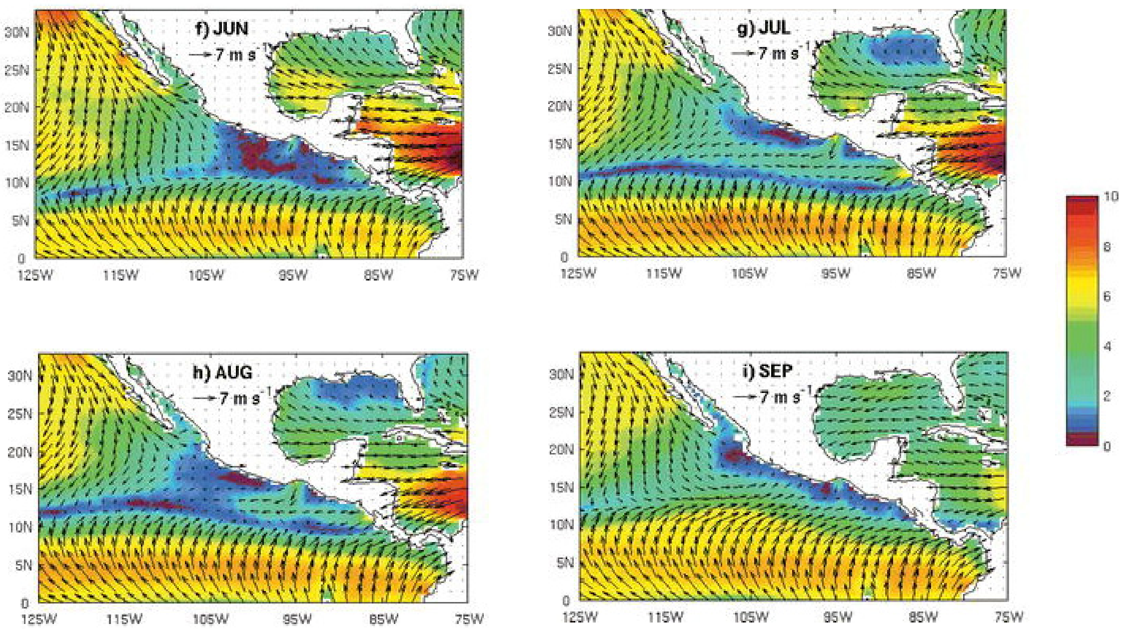

Figure 2: Monthly QuikSCAT surface winds from 1999 to 2005. The wind scale is in meters per second. (Adapted from Romero-Centeno et al., 2007.)

period (Amador et al., 2006; Romero-Centeno et al., 2007). Note that surface convergence exists for all months near the Caribbean coasts of Nicaragua, Costa Rica and Panamá, though it is perhaps somewhat weaker in September, corresponding to the weakening of the SW Caribbean jet.

Rainfall types and their probabilities, as inferred from the Tropical Rainfall Measurement Mission (TRMM) satellite are shown for the entire tropics for the months June, July, and August (JJA) in figure 4 (see Houze et al., 2015; Zuluaga and Houze, 2015). Rainstorms are classified into three categories, deep convective cores (very deep with strong radar echoes), wide convective convective cores (large aggregates of somewhat weaker convection), and broad stratiform regions (large areal coverage, exhibits a radar bright band).

Deep convective cores are largely absent over the oceans. Wide convective cores exhibit a maximum in the Pacific near the Colombia-Panamá border, but mostly exist north of the surface ITCZ west of this point. Comparison figure 3 shows little overlap between surface convergence in JJA and wide convective cores.

East Pacific and SW Caribbean rainfall have a high probablility of taking the form of broad stratiform regions. The hole in this category of rainstorm ($85-95$ W, > 8 N),and to a lesser extent wide convective cores, corresponds to the Costa Rica Dome (Wyrtki, 1964), a semi-permanent region of ocean upwelling and cooler waters. As discussed in the SPO, stratiform precipitation has traditionally been associated with the late stage of deep mesoscale convective systems, which have top-heavy mass flux profiles. However, recent work disputes this characterization of rainstorms in the east Pacific and consideration is being given to the possibility that at least some broad stratiform regions are actually high concentrations of weak convective cells that produce mostly snow crystals that aggregate and form bright bands as they fall out (Houze et al., 2015).

The most intense broad stratiform region is in westerly planetary boundary layer flow off the Pacific coast of Colombia. This is the Chocó jet region. Extremely large annual rainfalls exist on the Colombian coast in this area. Jet strength and rainfall peak in September (Poveda and Mesa,

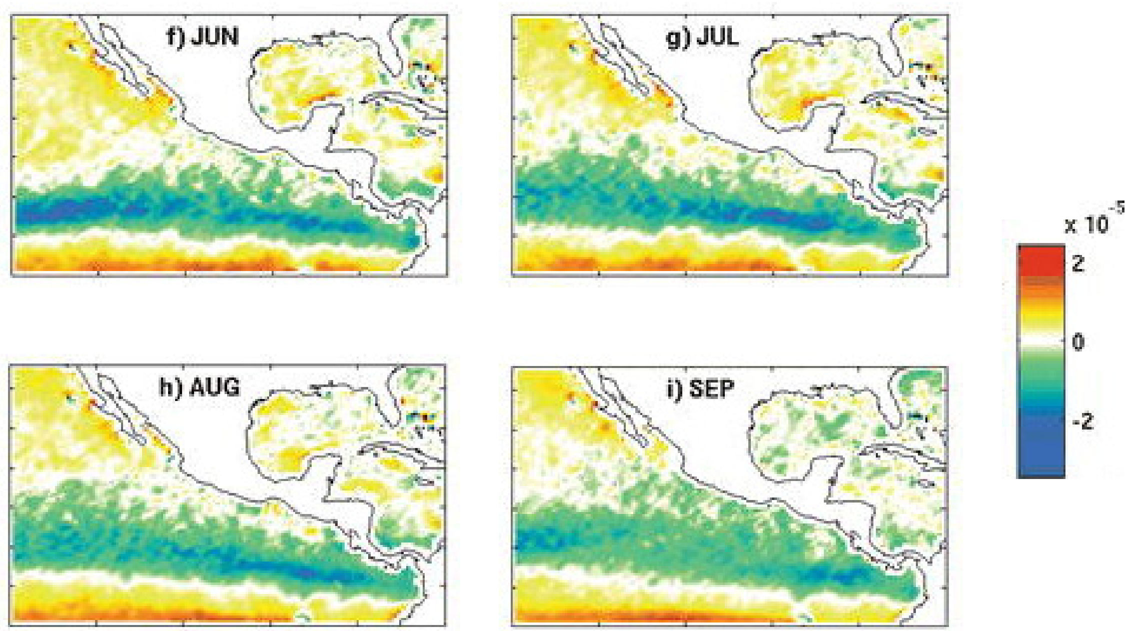

Figure 3: Monthly QuikSCAT surface divergence in inverse seconds from 1999 to 2005. See figure 2 for axis labels. (Adapted from Romero-Centeno et al., 2007.)

2000), coincident with the weakening of the SW Caribbean jet.

2.1.2 Easterly Waves

The tropical east Pacific experiences the frequent passage (every 6 d or so in the summer) of easterly waves. The track density of these disturbances (measured in terms of vorticity maxima) is shown in figure 5a from Serra et al. (2010). Figure 5b shows where tracks form and figure 5c shows where they decay. Maxima of track formation exist on the northern coast of Colombia and Venezuela and at two locations separated by the Costa Rica Dome near 87 W and 97 W. Tracks tend to decay well upstream near 60 W, over Central America, and at a few points further west. Taken together, these results suggest that many east Pacific easterly waves form somewhat to the north of the surface ITCZ in the far eastern Pacific.

Kerns et al. (2008; see figure 6) also tracked vorticity maxima in the east Pacific with results that are in rough agreement with those of Serra et al. (2010). However, the tracks of Kerns et al. are somewhat to the south of those of Serra et al., with many tracks originating off the Pacific coast of Colombia in the Chocó jet region.

Intraseasonal oscillations (ISOs) have a large effect on east Pacific easterly waves. Figure 7 shows that easterly waves gain more kinetic energy from both barotropic conversion (upper panels) and from convection (lower panels) during westerly wind episodes (left panels) than during easterly episodes (right panels) (Rydbeck and Maloney, 2014). Both processes contribute heavily west of about 100 W, but convection dominates east of 90 W, just to the south of Panamá. This argues for the importance of convection in the Chocó jet to easterly wave intensification. Notice that the Chocó jet vanishes at 850 hPa during the easterly ISO phase. Rydbeck and Maloney (2014) also showed that deep convection moves to the south during easterlies and to the north during westerlies, as occurs in the seasonal changes described by Romero-Centeno et al. (2007).

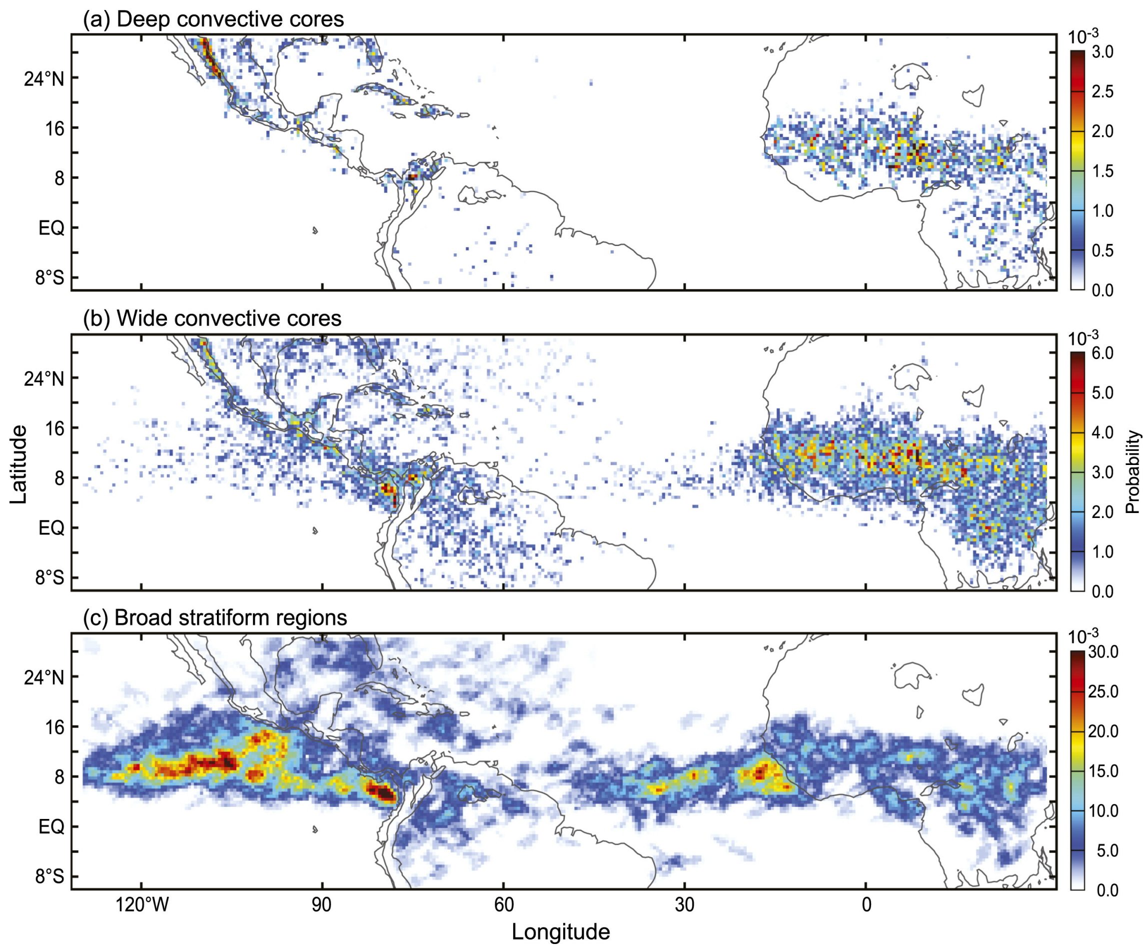

Figure 4: Distribution of probabilities of three different types of rain-producing systems, as derived from TRMM precipitation radar measurements for the months JJA of 1998-2012 (from Zuluaga and Houze, 2015).

3 Project Goals

The goals for OTREC are now presented in the context of the above background information.

Uncover the factors that control the formation of deep convection in the tropical east Pacific and the southwest Caribbean, two very different regimes. Deep convection forms regularly out of planetary boundary layer air where none existed previously in two areas of our domain, in the cross-equatorial flow in the east Pacific and in the SW Caribbean jet as it impinges on the Central American coast. In the cross-equatorial flow, convective inhibition decreases and convective available potential energy increases as the boundary layer air moves to the north over warmer SSTs, resulting eventually in the development of deep convection.

Perhaps even more interesting is the shallow-deep transition in the SW Caribbean, where SST gradients are weak and the free troposphere tends to be very dry. A surface convergence zone of uncertain origin exists near the coast. Upstream influence from Central America could be an issue here, as discussed in the SPO. Radar observations of the convection as well as possible changes in the environment observable by dropsondes will provide data for comparison with numerical models

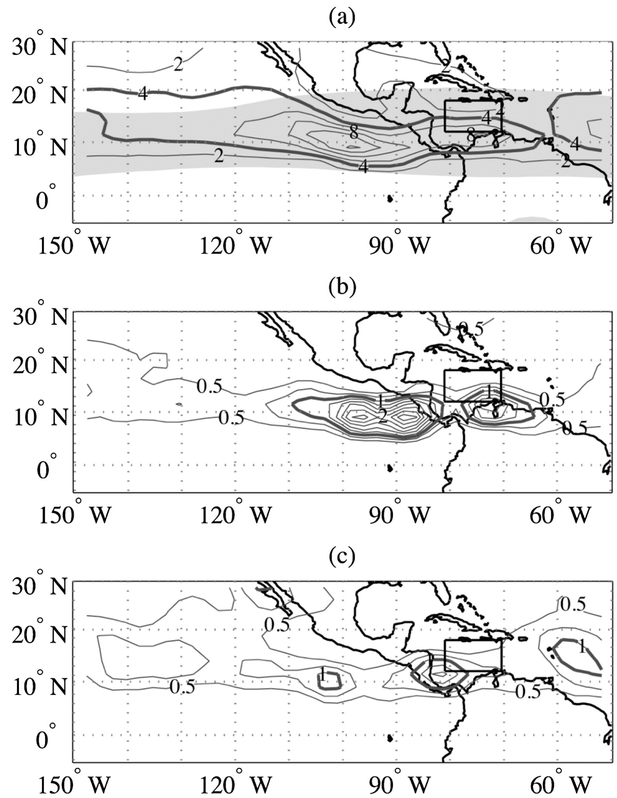

Figure 5: (a) Density of tracks of vorticity maxima averaged over $600-850$ hPa for June-November 1989-2007. The shaded region shows high OLR variability in the tropical depression frequency band. (a) Density of track formation. (c) Density of track dissolution (from Serra et al., 2010).

of the shallow to deep transition for both of these cases.

Determine the form that convection takes in these regions, in particular the shape and magnitude of the vertical mass flux profile, thermodynamic budgets, and the gross moist stability as a function of environmental conditions. Determining the properties of mesoscale ensembles of convection as a function of the environment is of high priority for two main reasons. First, this information will drive the improvement of cumulus parameterizations in global weather and climate models. Second, this will provide “ground truth” to help resolve ambiguities in satellite determinations of convective properties. In particular, delineating the types of convection that produce radar bright bands and learning how to distinguish different cases in satellite-based convective algorithms are needed. Convection in the east Pacific ITCZ, in the Chocó jet, and possibly in the SW Caribbean are at issue.

Addressing these issues requires observing a wide range of convective behaviors. The east Pacific and SW Caribbean provide this in a small area. Great variability exists in convective behavior with latitude in the ITCZ, in the different phases of easterly waves, and in the SW Caribbean.

The other aspect of convection that needs to be sorted out is environmental forcing. As discussed in the SPO, precipitation in the flat SST regions of the western Atlantic and Pacific is a function of surface moist entropy (or latent plus sensible heat) fluxes and the gross moist stability. The latter is related to the instability index, which is a measure of low to mid-tropospheric moist convective instability. There are indications that east Pacific convection behaves similarly (Raymond, 2016),

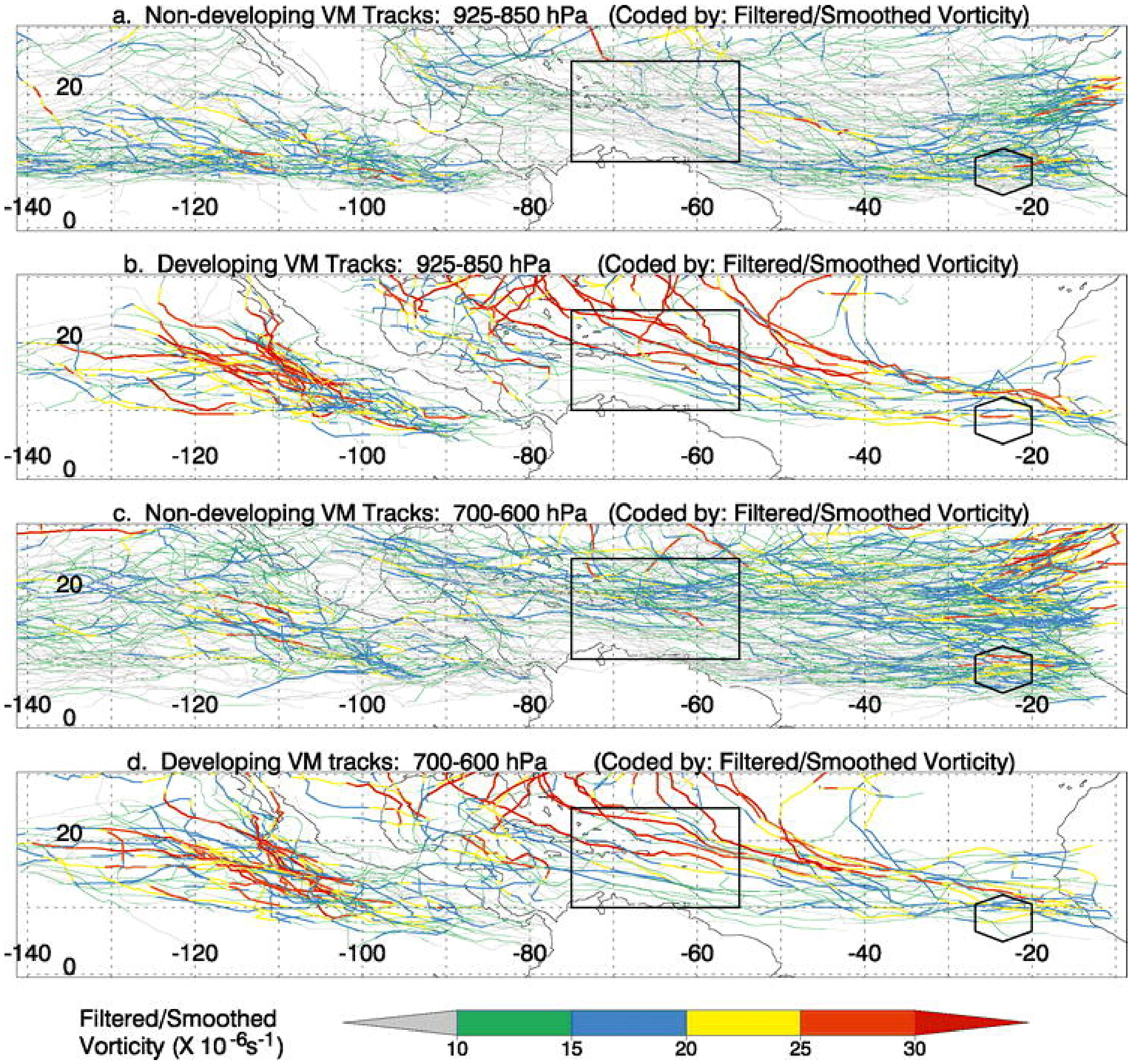

Figure 6: Tracks of vorticity maxima in two layers, $850-925$ hPa and $600-700$ hPa, divided into those that developed or did not develop into tropical cyclones (from Kerns et al., 2008).

but this may not be the whole story. Ekman balance models appear to be successful in roughly determining the planetary boundary layer winds in the cross-equatorial flow up the SST gradient and in fixing the location of the low-level ITCZ, at least in the absence of significant deep convection. Whether the boundary layer convergence predicted by Ekman balance is an additional determining factor in the location of deep convection has yet to be verified for individual cases in addition to climatological averages.

Characterize the interaction of convection with tropical disturbances, especially with tropical easterly waves. Easterly waves are the most frequent weather disturbances in the tropical east Pacific and in the SW Caribbean. As figure 7 shows, there appear to be significant differences between easterly wave growth rates in the easterly and westerly phases of the ISO. According to these results, there are two main regions of eddy kinetic energy growth due to convection in the westerly phase, one east of 90 W and south of 10 N, the other between 100 W and 110 W. In the easterly phase of the ISO, convective kinetic energy growth due to convection is weaker

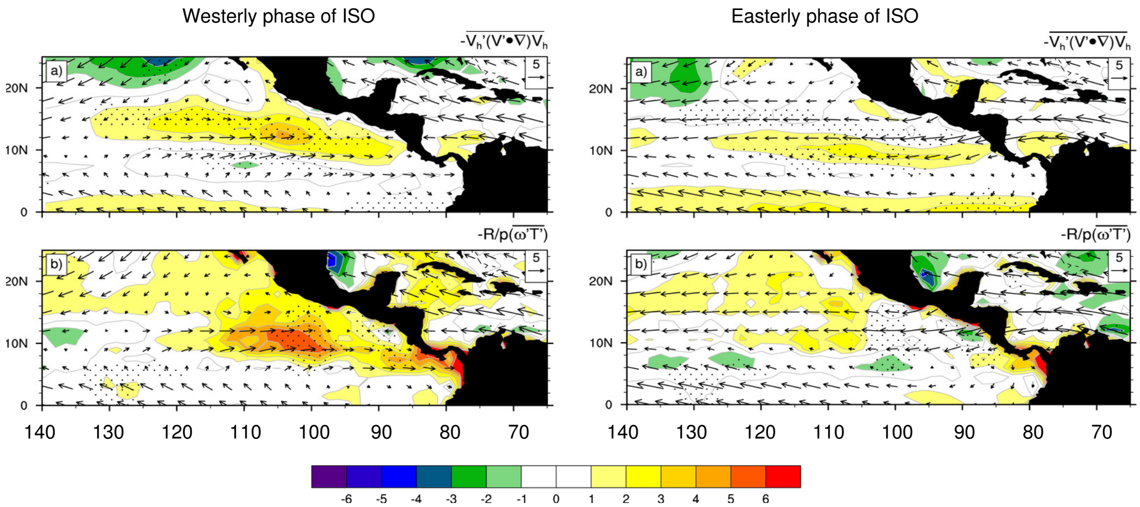

Figure 7: Vertically integrated eddy kinetic energy tendency due to barotropic conversion (upper panels) and conversion from eddy available potential energy (lower panels). The left panels are for the westerly phase of the intraseasonal oscillation and the right panels are for the easterly phase. Values are times 10^{-5} m^2 s^{-3}. The arrows show 850 hPa winds with perturbations due to tropical cyclones removed. June-October ERA-Interim data from 1991 to 2010 were used. Adapted from Rydbeck and Maloney (2014).

everywhere, but the weakening is less pronounced east of 90 W. Barotropic growth is weaker and further south in the easterly phase, but in both phases this growth mode is weak east of 90 W. The vorticity tracking results shown in figures 5 and 6 support this result, though the exact locations of intensification east of 90 W differ slightly among the three studies.

Determination of mesoscale vorticity profiles, budgets, and tendencies is an alternative approach to the interaction of convection with easterly waves. This approach was fruitful in understanding the intensification of tropical cyclones in the TPARC/TCS08 and PREDICT projects (Raymond et al., 2014; also see the SPO) and we expect it to be equally useful here. Convection with top-heavy mass flux profiles can be expected to spin up mid-level vorticity, whereas bottom-heavy fluxes augment the low-level circulation.

Somewhat less certain is the origin of easterly waves (or vorticity maxima, which may not entirely coincide with easterly waves) upstream of the above intensification region. The difference in tracks shown in figure 5 on one hand, and in figures 6 and 7 on the other is significant. There is no doubt that some easterly waves cross Central America enroute from points east, as figure 5 shows. However, the provenance of vorticity maxima appearing first in the Chocó jet off the coast of Colombia, as seen in figures 6 and 7, is unknown.

4 Experimental Design and Observational Requirements

4.1 Location and Timing

We are nominally planning for deployment in the summer of 2019. Any 8 week period in 1 June through 1 October would be satisfactory, though we would prefer August-September for two reasons: this spans the change from seasonal easterlies to westerlies in the Pacific and the Chocó jet is strongest in September. Figure 8 shows the proposed operating area, with important locations in

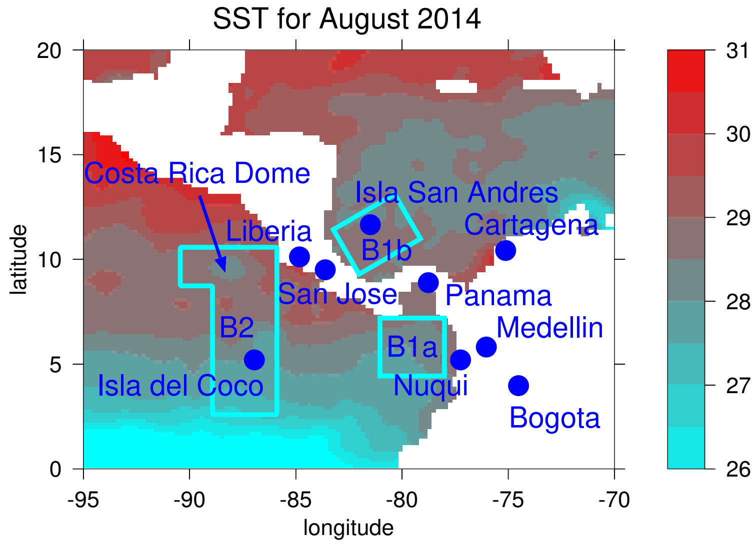

Figure 8: Map of operating area with average August 2014 SSTs (deg C), locations mentioned in the text, and approximate positions of proposed operational areas.

dark blue and the boxes indicating in situ observations of convection and easterly waves outlined in light blue.

4.2 Observational Tools

4.2.1 Gulfstream V

In order to address the above project goals, we need a high altitude, long range aircraft to deploy dropsondes from the upper troposphere to measure mesoscale fields of the usual meteorological variables, and a downward-looking cloud radar to document the reflectivities and vertical hydrometeor velocities in shallow and growing convection. The obvious choice is the NSF/NCAR Gulfstream V (GV) aircraft equipped with the AVAPS dropsonde system and the Hiaper Cloud Radar (HCR).

The dropsondes will be analyzed to produce fields of potential temperature, mixing ratio, pressure, and wind with our three-dimensional variational analysis system (Lopéz and Raymond, 2011). This system applies mass continuity as a strong constraint, allowing the calculation of mesoscale vertical velocities from dropsonde horizontal winds.

All dropsonde data will be forwarded to the GTS so that global models will be able to ingest these data.

The HCR is a W-band Doppler radar with wavelength 3.2 mm. The beam width is 0.68° at 3 dB, which corresponds to a beam size of about 120 m at a range of 10 km. Doppler velocities can be measured to within roughly 0.5 m s^{-1} with an unambiguous velocity of 7.75 m s^{-1}. Range resolution is $30 - 150$ m and the sensitivity is approximately -25 dBZ at 10 km range according to NCAR/EOL documentation. The standard dwell time is 0.1 s (Peisang Tsai, personal communication).

The HCR can be operated in either fixed mode, e.g., nadir pointing, or a scanned in a plane (approximately) normal to the axis of the aircraft. Operation in scanning mode increases the area covered but reduces the along-track resolution. It also results in slantwise rather than vertical Doppler velocity measurements and is useful when cloud targets are sparse, e.g., when convective cells are small and widely spaced and when particle fall speeds are not needed. The mode used depends on the goals of the observations.

The radar will have two main jobs. First, it will be used to identify the onset of precipitation in shallow and growing convection and measure the distributions of reflectivity and particle fall velocity in such systems. Taking the upper end of the fall velocity spectrum as the air velocity is a crude way of doing this. However, Kollias and Albrecht (2002) have demonstrated a more accurate method that depends on the existence of Mie scattering resonances that exist for millimeter cloud radars. Once the air velocity is determined, hydrometeor terminal velocities can also be estimated. In regions of widely scattered shallow convective clouds, nadir pointing may not sample sufficient cloud data. Use in scanning mode would allow a survey of cloud size, depth, and radar reflectivity at the price of particle fall velocity information and along-track resolution.

The second job will be to identify regions with bright bands where aggregates of snow crystals fall through the freezing level. As Kollias and Albrecht (2005) have shown, bright bands in cloud radars are manifested as a step increase in reflectivity at the melting level rather than a peak in reflectivity there. This is because the moistened aggregate and the resulting smaller raindrop are both in the Mie scattering range for millimeter radars, which is not true for centimeter wavelength radars. Nadir pointing would be preferred when the areal coverage of bright bands is large.

The radar would also be able to make measurements in deep convection down to the level where attenuation becomes important, perhaps to the freezing level in most tropical convection.

The HCR imposes significant performance penalties on the G-V, with an operational ceiling of roughly 40000 ft, maximum endurance of 8 hr, and maximum climb and descent rates of 1000 ft/min. We can accomplish the goals of OTREC while operating within these limitations.

The requirements of the dropsonde program result in some compromises in radar results for boundary layer clouds; in order to obtain full mass flux profiles from the dropsonde analysis, we must operate at $12 - 13$ km above sea level. This increases the beam size and decreases the radar sensitivity somewhat. For planetary boundary layer convection, the larger beam size will result in some confounding of the particle terminal velocity spectrum with variations in air vertical velocities within the radar beam. However, our primary interest is in the qualitative intensification and deepening of shallow convection, which will not be obscured by this problem. Furthermore, comparison with numerical models of growing convection can be made via the derived radar response in the model rather than with raw model variables such as grid-scale vertical velocity and hydrometer spectra. Bright band and deep convection observations would be largely unaffected by this issue due to the larger horizontal scales of vertical motion in these cases. An artifact introduced by the motion of the aircraft is Doppler broading of the hydrometeor velocity spectrum due to the non-zero radar beam width. However this effect (of order 1 m s^{-1} for GV speeds) is unlikely to be an issue for what we plan to do (Bruce Albrecht, personal communication).

We considered asking for the High Spectral Resolution Lidar (HSRL), as it was found to be valuable in the CSET project (Bruce Albrecht, personal communication), but it wouldn't appear to add enough value in addressing our stated objectives, given its additional cost ($136K) and complication (extra weight on board the GV), as the HCR better documents the characteristics of developing precipitation in shallow convection than does the HSRL.

Figure 8 shows the three proposed operational areas for the GV. B1a covers the area of the Chocó jet, one of the more problematic regions for satellite rainfall algorithms and a potential origin or intensification region for easterly waves. Mass flux profiles as well as bright band detection would help clarify the actual nature of the "broad stratiform region" identified there. Vorticity and vorticity tendency profiles would be useful in identifying the creation, passage, and intensity change of easterly waves in this region.

Area B1b is designed to examine the development of deep convection in the SW Caribbean jet as it approaches Costa Rica. The box is oriented with the onshore flow of the SW Caribbean jet.

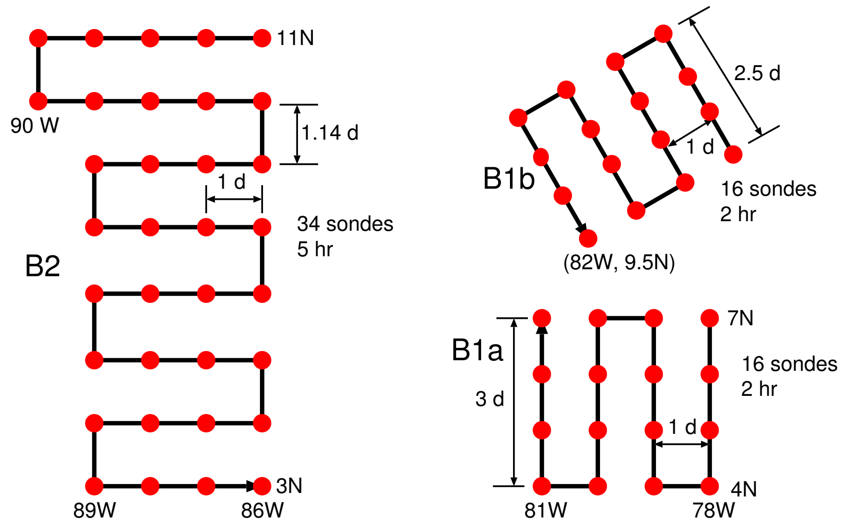

Figure 9: Proposed flight tracks for each of the areas delineated in figure 8. The red dots are dropsonde deployments and the arrow denotes the direction of traversal. Sonde spacings are shown in degrees.

Easterly waves passing through the more northerly corridor shown in figure 5 would be sampled in this region as well. Observational techniques used in B1a also apply to B1b. These two regions can be explored on the same flight.

Area B2 would be used to explore the north-south variation in convective properties across the ITCZ. The small westward extension near 10 N would facilitate coverage of convection both within and outside of the Costa Rica Dome area. A second function of flights into B2 would be to monitor easterly waves that had passed through B1a and/or B1b on the previous day. Since easterly waves in this region tend to move westward at about 6 deg d^{-1}, the spacing between B1a/b and B2 is about right. B2 encompasses at least part of the region in which easterly waves intensify. (See section 2.1.)

Examination of figure 8 suggests that either San José or Liberia in Costa Rica would be a satisfactory site for GV operations. A base in Costa Rica is particularly suitable, given the participation of Marcial Garbanzo and Walter Fernández of the University of Costa Rica in the project.

Detailed examples of flight patterns are illustrated in figure 9. In the Pacific, the oceanic diurnal cycle is governed by waves moving off of the land that are generated by the diurnal cycle of convection over land, as discussed in the SPO. In order to follow approximately the diurnal maximum, which starts in the early morning near land and moves offshore, patterns B1a and B2 start nearest land and move away. The pattern durations are computed assuming a cruise speed of the GV of about 7.5 deg hr^{-1} (450 kt). If patterns B1a and B1b are flown on the same flight in that order, then the total flight duration including 2 hr of ferry is about 7 hr, with 32 dropsondes deployed. For pattern B2, the total flight duration is also about 7 hr including 2 hr of ferry, with 34 dropsondes. For all of these an extra 0.5 hr is added for taxi, takeoff, climbout, and landing. The total flight times differ only slightly between bases in San José and Liberia.

Repetition of these patterns is very important in order to be able to reduce noise by compositing results. Assuming 10 flights for each pattern sums to 140 research hours and 660 dropsondes. Our request of 160 total hours of flight time and 750 dropsondes thus leaves 20 hours for ferry between Colorado and the site plus contingencies as well as 90 spare sondes for deployment in case of sonde failure and other issues. For 8 weeks = 56 days of flight time, this amounts to a flight every 2-3

Cost element	Cost
GV Core (Gulfstream V 160 hr)	\$1,474K
AVAPS (750 dropsondes)	\$711K
HCR (cloud radar)	\$240K
HARP (radiation)	\$85K
CDS (data services)	\$116K
Total	\$2,626K

Table 1: Cost estimate for the Gulfstream V operation as provided by NCAR/EOL.

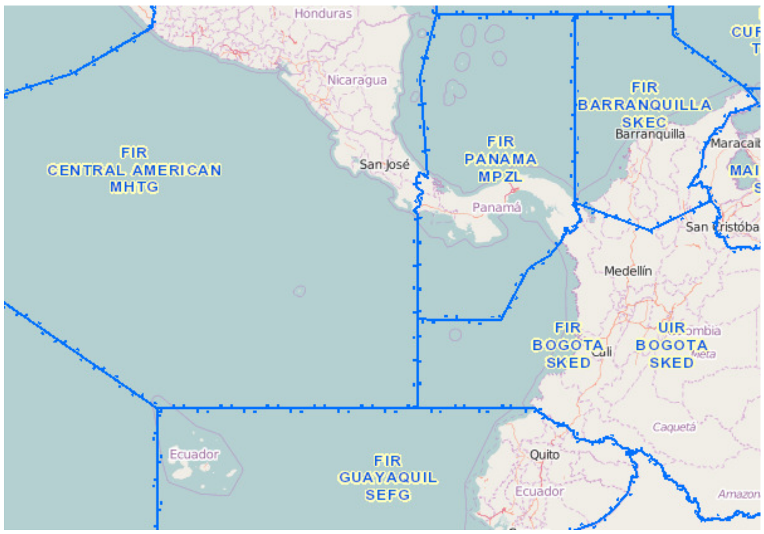

Figure 10: FIR boundaries in OTREC operational area (from http://gis.icao.int/gallery/).

days. If the B1a/B1b pattern is followed by the B2 pattern the following day, there would be pairs of flights every 5-6 days. This nicely matches the frequency of easterly wave occurence in the east Pacific.

We are not interested in coordinating flights precisely with easterly wave passages. Instead, we wish to sample all phases of the easterly wave cycle, including trough, ridge, southerly flow and northerly flow. Thus, we expect to have a somewhat less regular pattern of flights than the above discussion would indicate.

Some thought was given to coordinating flights with overpasses of the Global Precipitation Measurement (GPM) satellite, but this is likely to be impractical given the narrow swath of the satellite-borne precipitation radar and the low frequency of interesting convection at any given location and time. Thus, comparison with GPM results will likely have to be statistical in nature.

The desired operational flight level would be approximately $FL400$, which is above most of the commercial air traffic. Area B2 is mostly clear of traffic according to the Flightradar24 cellphone app. The areas B1a and B1b have potential air traffic conflicts due to the proximity of Panamanian and Costa Rican international airports as well as upper level traffic to and from South America. However, B1a in the Chocó jet is largely free of scheduled traffic before about 0800 CST (GMT - 6 hr; Costa Rica time) according to Flightradar24. Launching at 0500 CST would result in arrival at the starting point of B1a around 0600 CST, allowing completion of this pattern by 0800 CST. Arrival at B1b would then be about 0900 CST, with completion by about 1100 CST and return to base by about 1130 CST. Flights into area B2 could be made with roughly the same timing. With

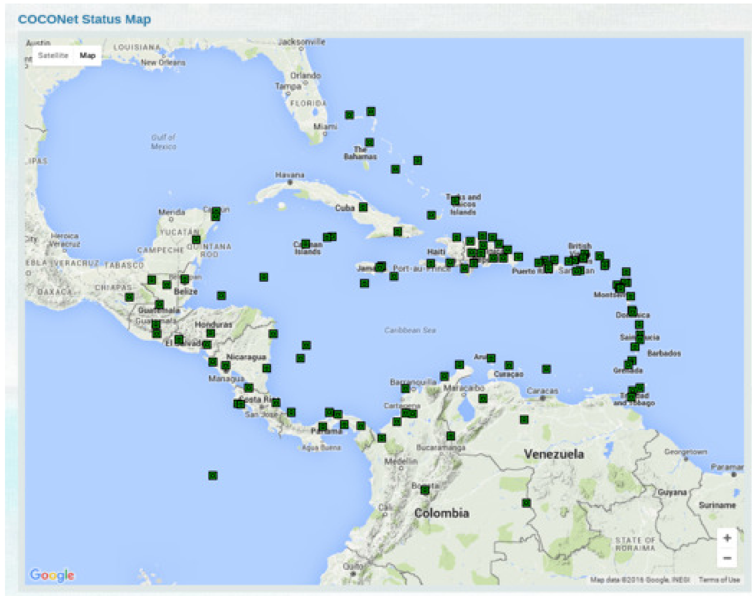

Figure 11: Network of COCONet GPS sites (from http://coconet.unavco.org/).

this flight timing, operations from Liberia probably would not be possible due to airport operating hours and early morning fog. However, this timing would be ideal for operations from San José, as mornings are generally clear and the early return time would avoid the problem of afternoon thunderstorms.

If dropping dropsondes in the vicinity of commercial air traffic is a problem in B1a and B1b, we may be able to operate at lower altitudes in these regions, say flight levels ($FL300 - FL320$). Flightradar24 shows that most traffic in the area operates above $FL320$.

Figure 10 shows the Flight Information Regions (FIRs) in the Central American area. We would need to operate in the Central American, Panamá, and Bogotá FIRs.

4.2.2 Ground-Based Facilities

For operational and scientific reasons, we need to monitor the existence and characteristics of upstream easterly waves as they approach Central and northern South America and the east Pacific. Active radiosonde sites exist in San José, Bogotá, and Isla San Andrés, but they typically launch only one sounding a day at most. We propose to install a portable radiosonde in Costa Rica, co-located with a radar wind profiler in Santa Cruz, Guanacaste Province that is operated by Marcial Garbanzo of the University of Costa Rica.

In addition, COCONet (http://coconet.unavco.org/) is an array of GPS precipitable water sites installed in the Caribbean, Central America, and northern South America. These measurements see the higher column-integrated humidity of easterly waves, and with the rather dense network of sites (see figure 11), they should help us monitor incoming waves. Note however that not all of these sites appear to be working properly. The functionality of the sites needs to be explored. Yolande Serra and David Adams are interested in working with these data and possibly in installing additional GPS instruments at selected sites.

Colombia has an array of about 100 GPS sites independent of COCONet according to Daniel Hernández (personal communication) of the National University of Colombia in Bogotá. He is interested in analyzing these for meteorological purposes. This could be useful to OTREC for the purpose of tracking easterly waves across Colombia.

Zhiming Kuang would like to make oxygen isotope measurements on rainwater from the ITCZ with the idea of determining whether convection there has top-heavy or bottom-heavy vertical mass fluxes – the former would draw in water vapor from a deeper layer than the latter, thereby changing the ratio. Comparison would be made with rain from nearby continental deep convection, which is likely to have top-heavy mass flux profiles. The advantage of this technique is that long-term averages unavailable from aircraft measurements could be obtained. An excellent site for the ITCZ measurements would be Nuquí, Colombia (see figure 8), which is subject to onshore flow from the Chocó jet. Nuquí is a tiny, isolated hamlet on the Pacific coast which nevertheless has turboprop air service several times a week. It is a base for ecotourism and appears to have the facilities needed to make these measurements. The staff of the Faculty of Mines in Medellín have based scientific studies in Nuquí. An alternative site would be the port of Buenaventura, but this has significant security issues and is a bit too far south. Security in Nuquí would have to be assessed befor operating there, though current reports from the British Foreign Office are encouraging.

The Government of Colombia operates three dual polarization C-band Doppler radars located near Bogotá, Cartagena, and on Isla San Andrés. SIATA (Sistema de Alerta Temprana del valle de Aburrá) in Medellín operates a similar radar on a ridge overlooking the city. (See figure 8 for locations.) The SIATA radar records data, which are made available for research purposes (personal communication, Carlos Hoyos, Manuel Zuluaga). SIATA also records information from the Colombian Government radars. Thus, excellent upstream precipitation and Doppler wind measurements would be available in Colombia.

The Panamá Canal Authority also operates a meteorological radar, with observations available on the web in real time. Whether these data are recorded is unknown, requiring further investigation.

5 Project Management

Compared to projects with multiple observing platforms and randomly occurring targets such as tropical storms, OTREC should be straightforward to manage, as flight patterns are generally fixed and the only decisions are which pattern to fly and when. The most difficult parts are likely to be the orchestration of the international collaborations and obtaining permission to fly and deploy dropsondes in foreign jurisdictions. The PI already has a head start on this process; we are working with Marcial Garbanzo and Walter Fernández in Costa Rica as well as Daniel Hernández and Manuel Zuluaga in Colombia. Connections with investigators and government officials remain to be developed in Panamá.

5.1 Core Group

With financial help from NSF via John Braun of UCAR, an initial meeting was organized by Željka Fuchs and David Raymond of New Mexico Tech at NCAR in Boulder, CO 24-25 August 2015. From this meeting a "core group" of investigators with a strong scientific interest in the project emerged:

- David Adams, National Autonomous University of Mexico
- Larissa Back, University of Wisconsin
- Peter Bechtold, ECMWF

- Walter Fernández, University of Costa Rica
- Željka Fuchs, New Mexico Tech
- Marcial Garbanzo, University of Costa Rica
- Daniel Hernández, National University of Colombia, Bogotá
- George Kiladis, NOAA, Boulder
- Zhiming Kuang, Harvard University
- Eric Maloney, Colorado State University
- Graciela Raga, National Autonomous University of Mexico
- David Raymond, New Mexico Tech
- Yolande Serra, University of Washington
- Sharon Sessions, New Mexico Tech
- Adam Sobel, Columbia University
- Manuel Zuluaga, National University of Colombia, Medellín

5.2 Pre-Field Phase

We need to organize a meeting of the core group along with Costa Rican and Colombian investigators before the field phase of the project. The purpose of this meeting would be to discuss what each individual plans to contribute to OTREC and to coordinate these contributions. It would be good to have this meeting in Costa Rica to make it easier for our Costa Rican and Colombian colleagues to attend.

New data will be continuously examined that might be relevant for the execution of the project. In summer of 2018 we would plan to execute a virtual "dry run", testing our ability to predict formation or intensification of easterly waves in the east Pacific and SW Caribbean using satellite data and model forecasts. Verification would be via examination of global model analyses from NCEP and ECMWF.

One or more exploratory trips to arrange facilities for the field phase would be needed. NCAR/EOL has operated out of San José's airport previously. More investigation would be needed if we were to consider operating out of the Liberia airport.

5.3 Field Phase

During the field phase we need only a small meeting room for an operations center with good Internet connectivity. Standard products online at the National Hurricane Center, the University of Wisconsin, and other sites should be sufficient for flight planning. Once the base of operations is determined, an operations center would be established at an appropriate hotel or other location. An NCAR-supplied operations center (NCAR cost estimate about $300K) may not be necessary, due to the simplicity of the operational aspects of this project.

PI Raymond would make decisions as to resource allocation in consultation with the core group of investigators. Dr. Željka Fuchs would work with Raymond to implement organizational aspects of the project as well as pursuing her own scientific interests.

The main decision that needs to be made in the field phase is when to fly the pre-defined patterns with the GV so as to distribute observations more or less equally over the phases of easterly waves. There may be an occasional unusual event, such as the traversal of the east Pacific by an equatorial Kelvin wave or interesting activity in the southern ITCZ, which might warrant deviation from the pre-defined plan, but most of the project resources would be spent on the targets defined above.

Decisions would be based on model analyses and forecasts, sounding and satellite data, and data from Colombian radars. Lessons learned from the previous summer's dry runs would be applied. Students would be used in this forecasting exercise under the guidance of senior investigators.

Two experienced mission scientists are available for the project, PI Raymond (most recent projects: TPARC/TCS08, NRL P-3, 2008; PREDICT, GV, 2010) and Carlos López of New Mexico Tech (mission scientist in PREDICT, GV, 2010). One of our goals is to train new mission scientists so that they have the experience and self confidence to plan and execute airborne field programs in the future.

Rainwater samples for oxygen isotope analysis would be taken on a daily basis at strategic sites. Under consideration is Nuquí, Colombia, located in the Chocó jet where it impinges on land. Comparison with convective characteristics determined by GV operations would be helpful.

5.4 Post-Field Phase

Our New Mexico Tech group has extensive experience analyzing both airborne dropsonde and Doppler radar data. The three-dimensional variational scheme developed for TPARC/TCS08 and PREDICT would be used to grid the data. This scheme works by minimizing a penalty function that enforces adherence to observations, mass continuity, and a desired level of smoothing. Model results are not used so that model preconceptions are not introduced into the analysis. This demands that the data exhibit approximately uniform density in space with no major holes, though precisely regular spacing of observations is not required.

HCR has an even higher data rate than previous airborne radars, as full Doppler spectra are recorded (Wen-Chau Lee, personal communication). Advances in computer and storage technology make it feasible to handle these data and we don't anticipate significant problems in this regard.

We anticipate making our analyses of these data available initially to all members of the core group and ultimately to all investigators. We further anticipate having a workshop of the core group (including Costa Rican and Colombian investigators) about a year after the field phase of the project to share preliminary results from the project. An article in the Bulletin of the American Meteorological Society or EOS would be a desired result of this workshop.

Subsequently we would seek to organize a special session at an AMS or AGU meeting to report results from the project.

6 Data Management Plan

From the National Science Foundation Directorate for Geosciences Data Policy:

> Plans for the dissemination and sharing of research results will be traceable from the beginning to the end of a project (proposal, review, and annual/final report). The primary goal of this procedural change is to assure that products of research help NSF achieve its mission to promote the progress of science and engineering.

We plan to ask NCAR/EOL to develop a field catalog for OTREC, with the policy that all primary data pertinent to the project, whether produced by EOL or by an external agent, shall be included in the catalog within a reasonable period of time. Data shall be in a format approved by EOL and shall be accompanied by metadata sufficient to interpret the data and the context in which it was obtained. Once quality control is completed on project data, they will become publicly accessible.

EOL has a program to create long-term web-accessible archives of data from the field catalog and other related sources along with metadata in their EMDAC system. This will make primary data and metadata available to the scientific community over the long term.

Beyond archiving primary data in a web-accessible form, investigators are increasingly being asked to provide beginning-to-end documentation of the process by which data are transformed into published results. The choice of how to do this is left up to individual investigators. However, one possible alternative is to deposit the results of one's data analyses along with accompanying metadata in EMDAC. This relieves the individual of the responsibility of maintaining a private, web-accessible archive over a long period of time. OTREC investigators are encouraged to use this solution to the long-term data stewardship and research documentation problems.

7 References

Amador, J. A., E. J. Alfaro, O. G. Lizano, and V. O. Magaña, 2006: Atmospheric forcing of the eastern tropical Pacific: A review. *Progress in Oceanography*, **69**, 101-142.

Houze, R. A. Jr., K. L. Rasmussen, M. D. Zuluaga, and S. R. Brodzik, 2015: The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the Tropical Rainfall Measuring Mission satellite. *Rev. Geophys.,* **53,** 994-1021, doi:10.1002/2015RG000488.

Kerns, B., K. Greene, and E. Zipser, 2008: Four years of tropical ERA-40 vorticity maxima tracks. Part I: Climatology and vertical vorticity structure. *Mon. Wea. Rev.,* **136,** 4301-4319.

Kollias, P., B. A. Albrecht, and F. Marks Jr., 2002: Why Mie? Accurate observations of vertical air velocities and raindrops using a cloud radar. *Bull. Am. Meteor. Soc.,* **83,** 1471-1483.

Kollias, P., and B. Albrecht, 2005: Why the melting layer reflectivity is not bright at 94 GHz. *Geophys. Res. Letters,* **32,** L24818, doi:10.1029/2005GL024074.

López Carrillo, C., and D. J. Raymond, 2011: Retrieval of three-dimensional wind fields from Doppler radar data using an efficient two-step approach. *Atmos. Meas. Tech.*, **4**, 2717-2733.

Poveda, G, and O. J. Mesa, 2000: On the existence of Lloró (the rainest locality on earth): Enhanced ocean-land-atmosphere interaction by a low-level jet. *Geophys. Res. Letters,* **27,** 1675-1678.

Raymond, D. J., S. Gjorgjievska, S. Sessions, and Ž. Fuchs, 2014: Tropical cyclogenesis and mid-level vorticity. *Australian Meteorological and Oceanographic Journal*, **64**, 11-25.

Raymond, D. J., 2016: Convection in the east Pacific intertropical convergence zone. *Geophys. Res. Letters*, in press.

Romero-Centeno, R., J. Zavala-Hidalgo, G. B. Raga, 2007: Midsummer gap winds and low-level circulation over the eastern tropical Pacific. *J. Climate,* **20,** 3768-3784.

Rydbeck, A. V., and E. D. Maloney, 2014: Energetics of east Pacific easterly waves during intraseasonal events. *J. Climate,* **27,** 7603-7621.

Serra, Y. L., G. N. Kiladis, and K. I. Hodges, 2010: Tracking and mean structure of easterly waves over the Intra-Americas sea. *J. Climate,* **23,** 4823-4840.

Wyrtki, K., 1964: Upwelling in the Costa Rica dome. *Fish and Wildlife Service Fishery Bulletin*, **63**, 355-372.

Zuluaga, M. D., and R. A. Houze Jr., 2015: Extreme convection of the near-equatorial Americas, Africa, and adjoining oceans as seen by TRMM. *Mon. Wea. Rev.,* **143,** 298-316.