1 ITCZ Subproject of EPIC2001

1.1 Scientific Background

The intertropical convergence zone (ITCZ) is an important component of the coupled ocean-atmosphere system in the tropical east Pacific. It is the upward branch of a cross-equatorial direct thermal circulation or Hadley cell, which is ultimately driven by the cross-equatorial sea surface temperature (SST) difference (Schubert, Ciesielski, Stevens, and Kuo, 1991). The associated clouds modulate the radiative fluxes and the resulting precipitation affects the salinity of the underlying ocean mixed layer. The winds associated with transient disturbances of various time scales on the ITCZ, such as squall lines, easterly waves, and the Madden-Julian oscillation, can strongly affect surface heat and moisture fluxes. Finally, the associated cyclonic wind stress curl is a powerful driver of oceanic upwelling.

The EPIC2001 Overview and Implementation Plan (Raymond et al., 1999; hereafter OV) poses three questions about the east Pacific ITCZ:

- What mechanism or set of mechanisms forces convection in the east Pacific ITCZ?
- What factors are responsible for the fluctuations in strength and position of the east Pacific ITCZ on weekly time scales?
- How do the characteristics of ITCZ convection vary through the diurnal cycle?

OV also asks the following question:

- What are the distributions of longwave and shortwave radiative fluxes at the ocean surface, the latent and sensible heat fluxes out of the ocean, the precipitation rate, and the wind stress curl in various conditions?

We begin by elaborating on each of these themes.

1.1.1 Convective Forcing

Mechanisms for convective forcing divide naturally into two categories, those which are mechanical in nature, in that they induce lifting of boundary layer air, and those which are thermodynamic, in that they somehow increase parcel instability or enhance the ability of parcels to ascend through deep layers via changes in the temperature and humidity profiles. Mechanisms we believe we can test are listed below:

1. Mechanical mechanisms:
    (a) *Ekman pumping*: If the ITCZ is a region of cyclonic vorticity in the boundary layer, then fluid dynamics suggests that there should be convergence and ascent in this region as a result of surface friction. Both time-independent (Charney, 1971) and time-dependent (Holton, Wallace, and Young, 1971) versions of this theory have been proposed.

   (b) *Geostrophic adjustment of cross-equatorial flow*: Low-level flow resulting from a cross-equatorial pressure gradient eventually reaches a latitude at which its eastward velocity is in geostrophic balance with the north-south pressure gradient. Low-level convergence occurs at this latitude. According to Tomas, Holton, and Webster (1999), this convergence is the origin of the ITCZ.

2. Thermodynamic mechanisms:

   (a) *SST forcing*: Hot air rises, so air warmed the most by the highest SSTs should rise preferentially. SST is useful as a rough guide in locating deep atmospheric convection. However, we already know that it does not tell the full story. In the east Pacific, the warmest SSTs (in non-El Niño years) occur well to the north of the ITCZ. In the equatorial west Pacific, the regions of highest SSTs are notably lacking in deep convection (Waliser and Graham, 1993).

   (b) *Entropy flux forcing*: SSTs affect the atmosphere only indirectly, via their effect on sea-air latent and sensible heat fluxes, or alternatively, moist entropy fluxes. The other major factor governing fluxes besides SST is the boundary layer wind speed. Thus, regions of high SST and strong winds should produce the most deep convection according to this hypothesis (Raymond, 1995, 1997; Emanuel, 1995). There are regions of the world (SW Caribbean, NW Indian Ocean) in which SSTs are high and the winds are strong, but in which deep convection is rare. These regions are characterized by dry air aloft, which is apparently capable of suppressing convection by virtue of its tendency to entrain environmental air, even in the presence of considerable convective available potential energy (CAPE). Pre-existing mid-level humidity is thus hypothesized to play a controlling role in such environments.

   (c) *Variations in cloud buoyancy*: Virtual temperature profiles don't differ much from place to place in the tropics, due to the propensity of gravity waves to redistribute buoyancy perturbations. However, slow manifold disturbances such as easterly waves are known to have small effects on equilibrium temperature profiles (Reed and Recker, 1971; Reed, Norquist, and Recker, 1977; Thompson, Payne, Recker, and Reed, 1979). Furthermore, weak inversions are known to play an important role in suppressing deep convection over tropical oceans (Kloesel and Albrecht, 1989). The role of these buoyancy profile variations needs to be further assessed.

   Entrainment of dry air can also affect cloud buoyancy. Thus, a certain value of convective available potential energy (CAPE) may yield deep convection in moist conditions, but only shallow convection if the environment is dry. Though this point has been understood qualitatively for a long time, only recently have we been able to quantitatively evaluate buoyancies in clouds, using radiometric techniques to measure in-cloud temperature (Jorgensen and LeMone, 1989; Wei, Blyth, and Raymond, 1998). EPIC2001 provides an excellent opportunity to evaluate this effect. Furthermore, the results of such an investigation would be extremely important to the cloud forcing issue.

Determining which are the operative mechanisms will aid in the development and testing of cumulus parameterizations.

1.1.2 ITCZ Fluctuations

As figure 4 of OV shows, the deep convection over the east Pacific warm pool is highly transient, consisting of westward-moving disturbances which tend to intensify into tropical cyclones. These disturbances have been identified with African easterly waves (see, e. g., Rappaport and Mayfield, 1992).

The identification of these disturbances as easterly waves prompts us to ask why these waves are quiescent or decaying in their long trip from Africa, only to intensify in the east Pacific. Zehnder (1991), Mozer and Zehnder (1996), and Zehnder, Powell and Ropp (1999) have identified two factors which may explain this localized intensification. First, the shift to northeasterly winds on the west side of an easterly wave generates localized winds through the northeast-southwest-oriented gaps in the Central American topography. These gap winds, which extend over the east Pacific warm pool, may intensify surface fluxes sufficiently to initiate deep convection. Second, the gap winds appear to interact with the ITCZ in a manner which tends to promote cyclogenesis. The precise nature of this interaction remains unclear, though the ITCZ near 95° W appears to move to the north under these conditions.

Ferreira and Schubert (1997) presented an alternate view that barotropic instability of the east Pacific ITCZ is responsible for the development of wavelike disturbances and tropical cyclones in this region.

Molinari, Knight, Dickinson, Vollaro, and Skubis (1997) showed that the development of east Pacific disturbances was associated with a reversal in the the north-south potential vorticity gradient at low levels over the southwestern Caribbean. This result may be related to the observations of Maloney and Hartmann (2000) which show a correlation between the phase of the Madden-Julian oscillation (MJO) in the east Pacific and the frequency of tropical cyclogenesis there. According to Maloney and Hartmann, a westerly wind anomaly at 850 mb on the equator in the east Pacific correlates with stronger ambient cyclonic vorticity and weaker deep-tropospheric wind shear north of the equator. Both of these factors are known to be favorable to tropical cyclogenesis.

1.1.3 Diurnal Cycle

One additional source of temporal fluctuations in the ITCZ is the diurnal cycle. The local influence of the daily cycle of solar radiation on the atmosphere and ocean is thought to be responsible for diurnal variations in cloudiness and rainfall, though propagating dynamical signals from the diurnal cycle over nearby continents cannot be discounted in the east Pacific.

As over other tropical ocean regions, convection in the east Pacific ITCZ shows a substantial diurnal cycle. A complete picture of the full diurnal cycle is needed to make sense out of mass, moisture, and energy budgets in the Hadley circulation, and in the diurnal variability of ocean forcing. Airborne in situ and Doppler radar observations have yet to be made through the full diurnal cycle for tropical oceanic convection. One of the goals of this project is to make such observations. It is possible that the diurnal cycle changes character between active and suppressed phases of the easterly wave and Madden-Julian oscillation cycles. Such behavior was seen in TOGA COARE, where large convective systems were maximal at night, while smaller convection was strongest in the afternoon (Chen and Houze, 1997). Thus, the diurnal cycle needs to be observed in both active and suppressed phases.

1.1.4 Ocean Forcing

Different atmospheric environments, e. g., different profiles of buoyancy, humidity, and wind, can yield very different kinds of convection. These different convective types can have very different effects on the ocean. For instance, low-shear "popcorn" convection may produce only weak turbulent boundary layer flux perturbations, whereas well organized squall lines could be expected to create strong winds and thus strong fluxes at the surface. Similar variations in precipitation efficiency and the extent of stratiform cloud cover can occur. The precipitation has a strong effect on the salinity of the mixed layer, and hence on its density. Stratiform cloudiness is an important player in the determination of the radiative heating of the ocean. For these reasons it is important to determine what form convection takes over the east Pacific warm pool, and how it varies with easterly wave phase, MJO phase, and the diurnal cycle. This will aid in the development of models of oceanic forcing by the atmosphere.

1.2 Effect of El Niño

Figure 1 shows the mean Reynolds SST between 90° W and 100° W, averaged over July and August 1997 and the same period of 1998. In 1997 there was a strong El Niño, while 1998 exhibited strong La Niña conditions. In both years there was a strong north-south SST differential across the equator. The main difference was the presence of a strong equatorial cold tongue in 1998, a feature which was largely absent in 1997.

Satellite imagery shows that a summertime ITCZ existed in both years. During the 1997 El Niño the deep convection extended further south than in 1998, as one would expect from the latitudinal distribution of SST. Thus, in the event that an El Niño occurs in the project year, we may need to move the target region for ITCZ observations somewhat further south. This would somewhat reduce the on-station time of the NCAR Electra (see below), but with small adjustments in flight patterns we believe that the goals of the project could still be accomplished.

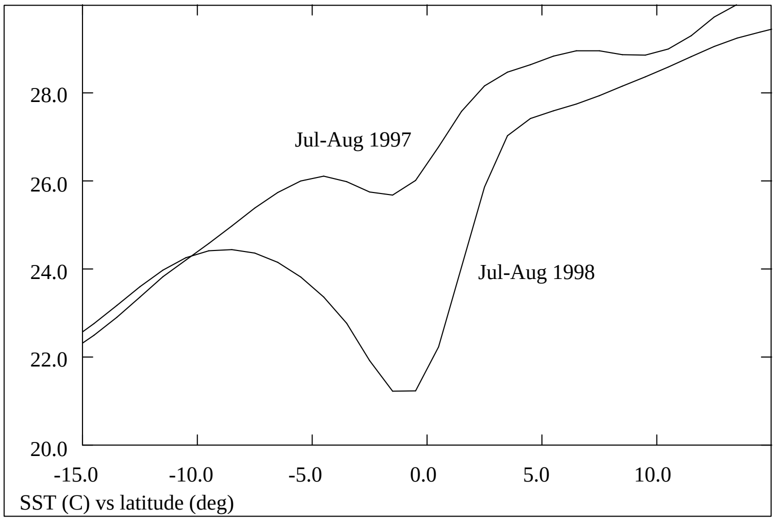

Figure 1: Reynolds SST for July-August of 1997 and 1998 averaged over 90° W to 100° W.

1.3 Proposed Observational Facilities

Virtually all of the measurements proposed for EPIC2001 in OV will be helpful in dissecting ITCZ dynamics in the east Pacific. However, four measurement platforms are of primary interest for the ITCZ part of the project, the NCAR Electra and NOAA WP-3D aircraft, the NOAA ship Ron Brown, and the TAO moorings along 95° W. These platforms will generally operate in a coordinated fashion so as to maximize the scientific benefit from them. In particular, WP-3D and Electra flights will generally be scheduled together in order to obtain coordinated measurements in the ITCZ and in the cross-equatorial inflow. In addition, the Electra will make some radar and in situ measurements of clouds within range of the C-band radar on board the Ron Brown for purposes of rainfall calibration. Operations will mostly be made along 95° W to take advantage of the enhanced TAO mooring array at this longitude. An additional ship has been requested primarily for oceanographic work in conjunction with the Ron Brown. This vessel will also carry an S-band precipitation radar and will make surface flux measurements.

1.3.1 NOAA WP-3D Aircraft

Figure 2 shows the proposed flight plan for the WP-3D. The belly and tail radars will be operated in two-sided FAST mode for the full duration of the flight in order to document convection along the way. However, the main missions of the aircraft will be to deploy dropsondes on the outbound leg and expendable ocean probes (AXBTs, AXCTDs, and AXCPs) on the return leg, and to make in situ measurements of the marine layer structure from the equator to the ITCZ. Fluxes of heat, moisture, and

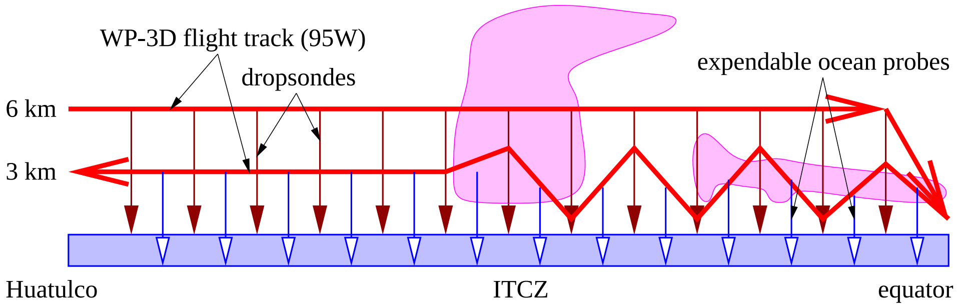

Figure 2: Proposed flight plan for the NOAA WP-3D.

momentum at the surface and at the marine layer top will also be made. Most missions will fly outbound to the equator and back along the 95° W line, but some may spend more time documenting the east-west structure of easterly waves and the underlying ocean response. (See the next section.) The dropsonde measurements will be made at a latitude interval of 1°, and will yield winds, temperature and humidity in a cross-section below 6 km along 95° W from the Mexican coast to the equator. A total of 16 flights, each of 9 h duration, has been requested for the period 18 July through 29 August, 2001. This number of flights is roughly the minimum required to simultaneously sample all phases of the diurnal, easterly wave, and MJO cycles.

1.3.2 NCAR Electra Aircraft

Figure 3 shows the proposed primary flight plan for the Electra. The Eldora radar will be operated on the outbound and return legs as well as during the convergence box and the cloud penetrations. Rather than attempting to repeatedly sample single clouds, the Electra will sample multiple clouds in all stages of development at several flight levels, say, cloud base, 1.5 km, 3 km, 4.5 km, and 6 km, in order to build up a statistical picture of cloud dynamical and microphysical characteristics in the ITCZ. The ferry sections of the flight will allow convection to be sampled as a function of latitude from the Mexican coast to the ITCZ. To the extent that winds in clouds are representative of the environment, environmental winds in regions with scattered or greater precipitating cloudiness will be sampled. The winds so obtained in the convergence box can be used to calculate mean convergence and vorticity through the depth of the convection in the ITCZ. The outbound leg will be used to sample boundary layer conditions as a function of latitude, while the return leg will sample mid-level moisture as a function of latitude. These ferry flight measurements don't cost much extra and will provide some redundancy to the WP-3D dropsonde and in situ measurements. Figure 4 shows an alternate Electra flight plan dedicated to dropsonde and expendable ocean probe deployment as well as radar mapping over the scale of an easterly wave. Cloud penetrations are omitted in favor of obtaining flows over a larger spatial scale in this pattern. We will request

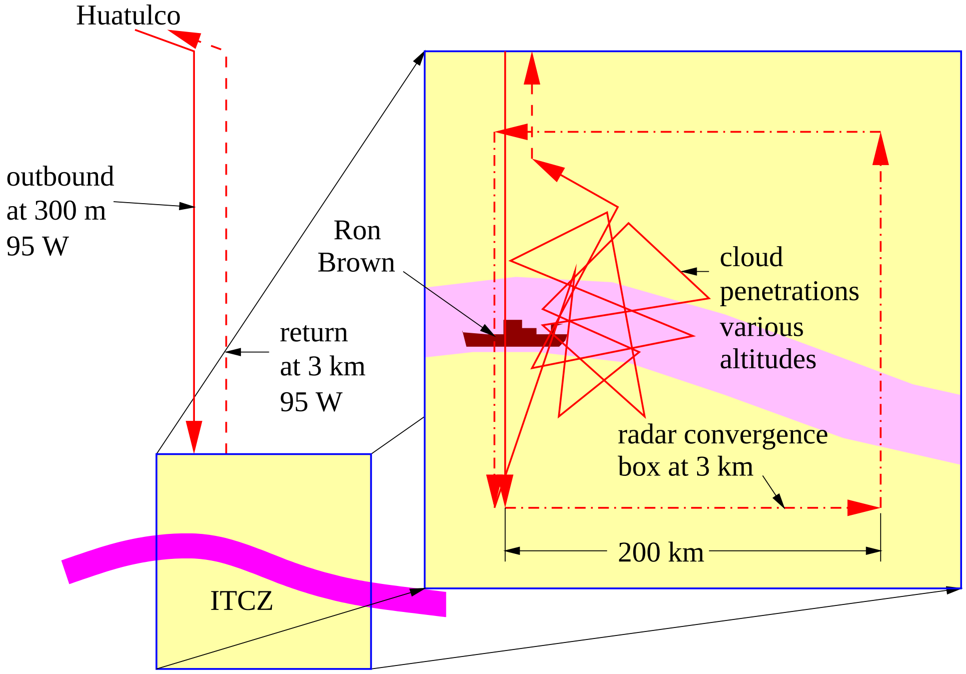

Figure 3: Proposed primary flight plan for the NCAR Electra.

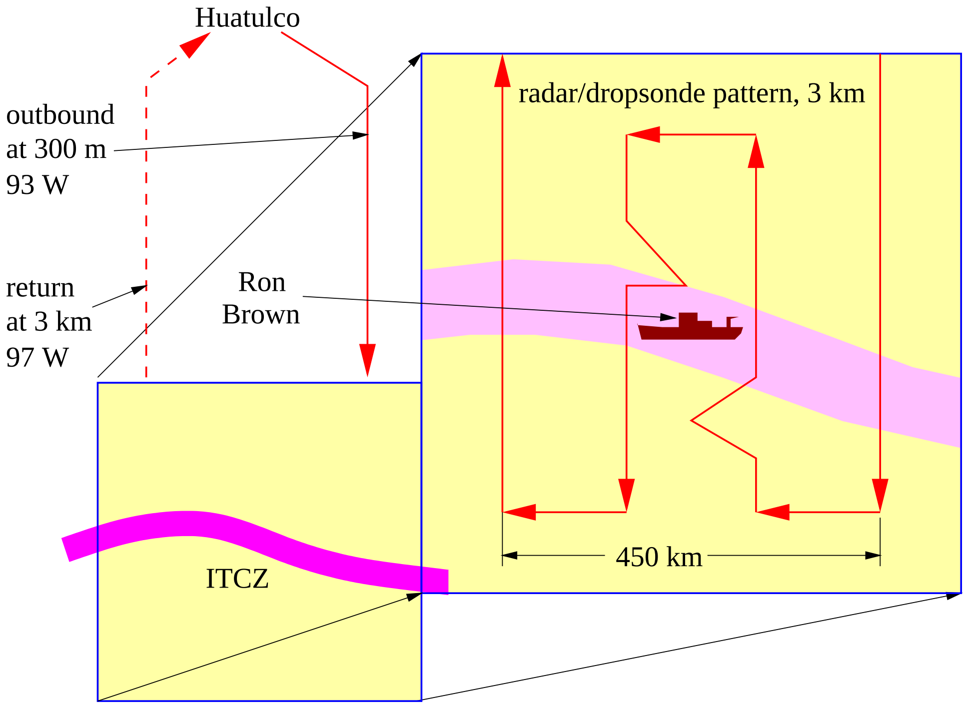

Figure 4: Proposed alternate flight plan for the NCAR Electra.

120 h (16 flights of 7.5 h duration) of Electra time for a period coincident with the period requested for the WP-3D. For each primary pattern flight, roughly 4 h will be consumed in ferry to and from the ITCZ, 2 h in the convergence box, and 1.5 h in cloud penetrations. For each alternate pattern flight roughly 2.5 h will be consumed in ferry and roughly 5 h will be used in the mapping pattern. In the event that both dropsondes and ocean probes cannot be deployed from the Electra, we will use 5 WP-3D flights to execute this pattern and dispatch the Electra to the ITCZ inflow region. Given range limitations on the Electra, such flights would be limited to north of about 3° N.

1.3.3 NOAA Ship Ron Brown

The NOAA ship Ron Brown has been requested for 55 days during the months of August and September, 2001. Of this time, 21 days will be spent during August in the ITCZ (8° N to 10° N) along 95° W. This overlaps the requested period for the two aircraft. Surface turbulent and radiative fluxes, aerosols, standard meteorological variables, and precipitation will be among the parameters measured in situ. In addition, there will be radiosonde soundings, C-band Doppler radar measurements, as well as millimeter wavelength Doppler cloud radar and lidar measurements. The C-band and millimeter Doppler radar measurements will be used to estimate rainfall rates, with calibration help from in situ cloud measurements from the Electra aircraft. The soundings will give us atmospheric structure above the 6 km elevation reachable by the WP-3D dropsondes. Oceanographic measurements will also be made. The Ron Brown measurements will above all provide 24 h time continuity of measurements in the ITCZ, which will help us understand the diurnal cycle in this region.

1.3.4 Enhanced TAO Moorings

The TAO moorings at 95° W at the equator, 2°, 5°, and 8° north and south have been augmented with additional moorings at 3.5° N, 10° N, and 12° N. They have also been enhanced with the addition of atmospheric pressure sensors, optical rain gauges, and downwelling shortwave and longwave radiation sensors, as well as additional oceanographic instrumentation.

1.4 Proposals in this Bundle

The proposals included in this bundle are as follows:

- *Fairall et al.*: Ship-based cloud and precipitation air-sea interaction studies in EPIC2001 (Also included in atmospheric boundary layer and stratus bundles.)
- *Molinari and Zehnder*: Structure and Evolution of the East Pacific ITCZ Under the Influence of Easterly Waves and the Madden-Julian Oscillation in EPIC2001

- *Raymond*: Convective Forcing Mechanisms Over the East Pacific Warm Pool in EPIC2001
- *Rutledge, Petersen, Cifelli, and Houze*: Shipboard Radar Observations of Precipitating Convection in EPIC2001
- *Zhang, Shay, and Bond*: Airborne Observations of Coupled Atmospheric and Oceanic Profiles Along 95° W TAO Mooring Line During EPIC2001 (Also included in ocean bundle.)

Some of the above proposals appear in more than one bundle because they span bundle topics.