A Proposal for

Shipboard Radar Observations of Precipitating Convection in EPIC2001

Submitted to

National Science Foundation
Division of Atmospheric Sciences
Large-scale Dynamic Meteorology

Principal Investigator

Prof. Steven A. Rutledge

Co-Principal Investigators

Walter A. Petersen, Ph.D.
Robert Cifelli, Ph.D.

Department of Atmospheric Science
Colorado State University
Ft. Collins, CO 80523-1371

e-mail: rutledge@radarmet.atmos.colostate.edu
Phone: (970) 491-8283
FAX: (970) 491-8449

A. Project Summary

The proposed research is a contribution to EPIC2001, a process study designed to improve understanding and modeling of seasonal-to-decadal climate variability over the eastern tropical Pacific. EPIC2001 (Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System 2001) is an activity of the U.S. CLIVAR Program. EPIC2001 consists of four components focusing on (a) intertropical convergence zone/warm-pool phenomena, (b) cross-equatorial inflow into the intertropical convergence zone, (c) upper ocean structure and mixing, and (d) an exploratory study of boundary layer cloud properties in the southeasterly tradewind regime. The field phase of EPIC2001 is scheduled for a 6 week period during the interval July-September 2001.

The work proposed for the intertropical convergence zone/warm pool region asks four questions: (1) What mechanism or set of mechanisms forces convection in the east Pacific ITCZ? (2) What factors are responsible for the fluctuations in strength and position of the east Pacific ITCZ on weekly time scales? (3) How do the characteristics of ITCZ convection vary through the diurnal cycle? (4) 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? Answering these questions will tell us how the atmospheric convection in the east Pacific ITCZ/warm pool works together with the other components of the ocean-atmosphere system in the east Pacific. Both airborne and ship-based observations are proposed.

Successful attainment of the objectives listed above will rely heavily on the collection of radiosonde and C-band Doppler radar observations from the R/V Ronald H. Brown (RHB). Herein, we propose to assume planning, staffing and scientific responsibilities for both the RHB C-band Doppler radar operations and collection of ship-based soundings aboard the RHB during the ITCZ intensive observation phase of EPIC2001. Our proposed scientific analysis focuses on the utilization of RHB radar and sounding data to examine the vertical and horizontal structure of rainfall and ITCZ convection and their respective variability as a function of synoptic conditions (e.g., phase and forcing of easterly waves), sea surface temperature, and planetary boundary layer structure. Further, round the clock sampling provided by the RHB radar will provide the requisite dataset for studying the diurnal cycle of convection and precipitation. We will also examine the relationship between boundary layer recharging through latent and sensible heat fluxes as a function of convective organization. This latter objective will be done in collaboration with the oceanographic component of EPIC. Cloud microphysical processes in a bulk sense will also be diagnosed from the radar observations. Considered as a whole, the data collection and analysis discussed in this proposal will not only provide new insights about the convection in the undersampled east Pacific ITCZ, but will also constitute an important validation dataset for numerical simulations of this convection. Our proposed research will be patterned after our analysis of the shipboard radar data collected in TOGA COARE.

B. TABLE OF CONTENTS

Section

A. Project Summary .... **i**

B. Table of Contents .... **ii**

C. Project Description **1**

I. Introduction **1**

II. Results from Prior Support **2**

III. Overview of EPIC2001 ITCZ Subproject **3**

IV Scientific Objectives for This Proposal **9**

V. Work Plan **12**

VI. Personnel **13**

D. Bibliography **14**

E. Biographical Sketch **16**

F. Budget Justification **21**

G. Statement of Current and Pending Support **22**

H. Facilities, Equipment and Other Resources **23**

C. Project Description

I. Introduction

The "East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System" (EPIC2001) seeks to understand coupled atmospheric and oceanic processes associated with the development and maintenance of the equatorially asymmetric northeastern Pacific cold-tongue/ITCZ system (e.g., Weller et al., 1999). One key objective of EPIC2001 is the documentation of the location, strength, and characteristics of deep convection in the eastern Pacific ITCZ and its relationship to the atmospheric boundary layer and oceanic mixed layer. Detailed observations of the convection associated with the eastern Pacific ITCZ is scheduled for the months of August and September, 2001, as part of the EPIC2001 field campaign.

Climatologically, convection in the EPIC2001 domain (Mexican warm-pool) is modulated by monsoonal effects associated with the heating of the South and Central American land masses and

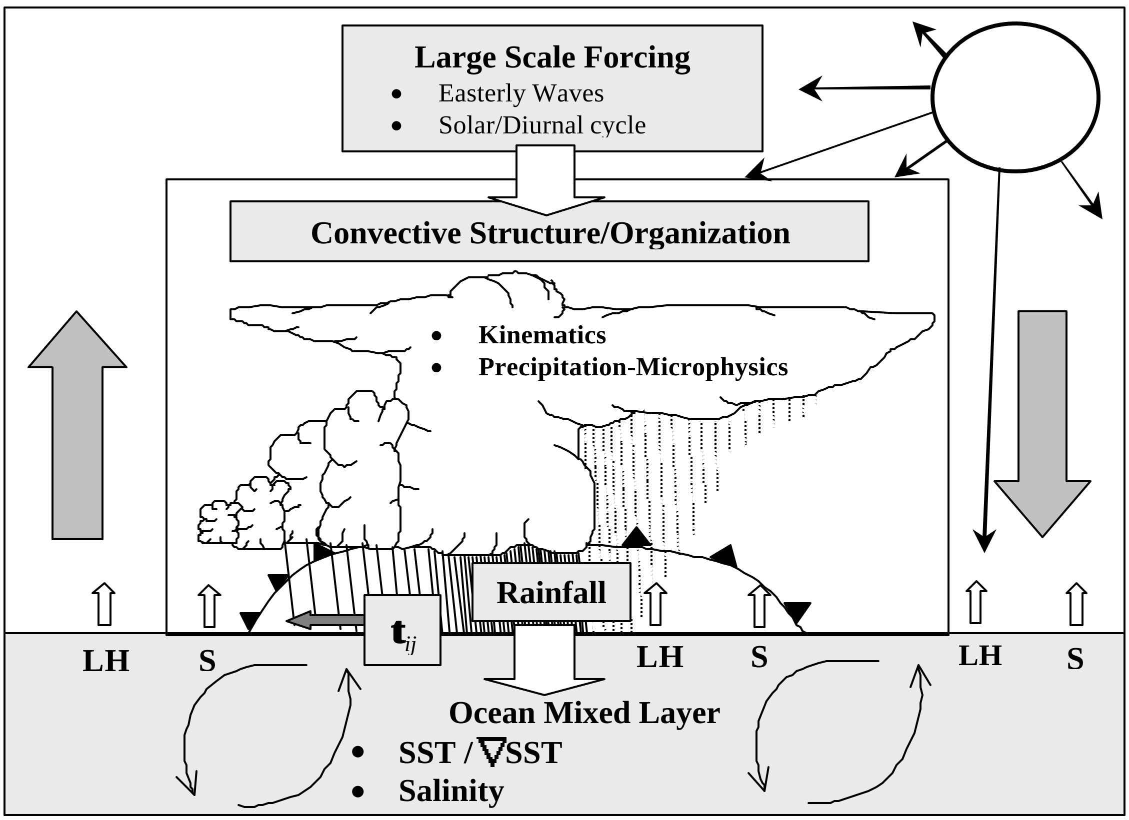

Figure 1. Illustration of processes and feedbacks to be examined in proposed study. LH and S are Latent and Sensible heat fluxes respectively. τ_{ij} represents wind stress

regional/local variations in the underlying sea surface temperature (Weller et al., 1999). Intraseasonally, convection and surface sensible and latent heat fluxes are all modulated by the diurnal cycle associated with solar heating, and transient synoptic-scale disturbances occurring over time scales ranging from 3-5 days (e.g., easterly waves; Weller et al., 1999; Serra et al., 2000) to 30-60 days (e.g., Madden-Julian Oscillation, MJO). In turn, migrating convective systems, attendant rainfall, and cool, dry, downdrafts enhance surface fluxes of freshwater, heat and momentum across the air-sea interface, subsequently affecting the ocean mixed layer depth, heat and salinity budgets (Fig. 1).

Successful study of the coupled ocean-eastern Pacific ITCZ system will rely heavily on the collection of radiosonde and C-band Doppler radar observations from the Research Vessel R/V Ronald H. Brown (RHB). The RHB will conduct continuous radar operations during the month of August 2001, covering a 3 week period on station in the ITCZ and approximately 10 days of transit time to and from the ITCZ (see EPIC2001 Overview and Implementation Plan). Our proposal addresses this specific component of EPIC2001. Before discussing these specific science objectives, we will first review Results from Prior Support pertaining to our work in TOGA COARE, which will be followed by an Overview of the EPIC2001 ITCZ Project.

II. Results from Prior Support

1. NA37$J0202, $435,000, 15 March 1994 to 1 January 1997
   (PI, Prof. S. A. Rutledge);
   Studies of Precipitating Cloud Systems in TOGA COARE Using Shipboard Doppler Radar Data

2. NA67RJ0152, $220,000, 23 May 1997 to 22 May 2000
   (PI, Prof. S. A. Rutledge);
   Further Analysis of the Shipboard Radar Data from COARE: Rainfall, Convective Organization and Surface Fluxes

Selected Results

a. Convective organization and rainfall

In several papers we addressed the modulation of convective organization with phase of the Madden-Julian Oscillation, determined the rainfall contributions by various modes of convective organization (isolated cells, short lines of convection, lines of convection with attendant stratiform precipitation, and large areas of stratiform precipitation with embedded, randomly organized convection), and examined the diurnal cycle of rainfall. Rickenbach and Rutledge (1998) classified the shipboard radar data into these various convective modes, and found that nearly 4/5 of the rainfall observed by the shipboard radars was associated with squall line systems with trailing stratiform rain, which were most frequent during periods of low level westerly wind maxima. In contrast, isolated cells contributed 12% of the total rainfall, and were most prevalent during periods of both very weak and very strong surface winds. Short et al. (1997) performed an intercomparison of rainfall rates from various methods, developed estimates for daily mean rain rates, and also verified the nocturnal rainfall maxima for this region. Petersen et al. (1996) identified the peak lightning flash rates in phase with the peak convective rainfall. Both of these features were found to precede the peak in cold cloud area by several hours. Petersen et al. (1999) carried out dual-Doppler observations from the two ship radars to study convective drafts and lightning, and compared the ship case to another system observed by the airborne Doppler platforms to identify relationships between vertical structure, draft magnitudes, and lightning flash rates for oceanic convection. Johnson et al. (1999) argued for a tri-modal distribution of convective heights in COARE, identifying a cumulus congestus population in addition to the trade cumulus and deep cumulonimbus populations. The congestus population was found to be in good agreement with the presence of stable layers identified in sounding data. Saxen and Rutledge (2000) found that the relationship between cold cloud areal coverage and rainfall could be markedly improved by including a correction based on the magnitude of the tropospheric vertical shear.

b. Vertical structure

DeMott and Rutledge (1998a,b) focussed on the vertical structure of COARE convection, examining statistics of echo tops and 30 dBZ reflectivity contour heights. Echo tops were greatest during the convective phases and post-westerly wind burst phases of the MJO. Echo top and 30 dBZ heights were also influenced on shorter timescales (relative to the MJO) by intrusions of dry subtropical air. Maximum convective heating occurred at the highest elevations during the convectively inactive phases of the MJO, and at the lowest elevations during the convectively active phases. These variations were found to be consistent with the variation of Convective Available Potential Energy in these periods.

c. Surface fluxes and upper ocean structures

In Saxen and Rutledge (1998), ship-based radar observations revealing convective organization were coupled with observations from the IMET buoy to examine relationships between sensible and latent heat fluxes and convective organization. This type of analysis provides critical information for validating coupled ocean-atmosphere models. We anticipate carrying out similar work in EPIC2001. Models of E. Pacific ITCZ convection are particularly poor at simulating the ocean-atmosphere coupling in this region. One of the primary goals of EPIC2001 is to improve these sorts of simulations. Saxen and Rutledge (1998) focussed on three types of convection, isolated convection, and MCS-scale linear convection with and without trailing stratiform precipitation. All three types of convection altered the surface fluxes in a similar manner, producing greatly enhanced fluxes during the convectively-active phase with weaker enhancements during the recovery phase. However, the duration of the convectively active and recovery phases were quite different. For example, the recovery phase ranged from 3 hours for isolated convection, to more than 9 hours for MCS systems with trailing stratiform precipitation (the recovery phase ended when the wind speed and air-sea temperature difference returned to pre-storm values). The magnitude of the surface fluxes was also found to be highly dependent on convective organization. MCS scale linear systems with trailing stratiform precipitation produced the largest values of sensible and latent heat fluxes (peak values of 60 and 250 W m^{-2}, respectively). Systems without trailing stratiform precipitation produced peak fluxes about one half of these values, emphasizing the important role of trailing stratiform precipitation (through enhanced wind speeds and air-sea humidity differences). Finally, Pinkel et al. (1997) used radar data to study the surface manifestation of solitons, identified as coherent wave-like structures associated with enhanced Bragg scattering from the ocean's surface.

d. Cloud-resolving model studies

Lastly, an effort is presently underway in collaboration with Dr. M. Moncrieff's group at NCAR to utilize the COARE radar data for the purpose of validating cloud-resolving model simulations. We have taken a statistically-based approach where various moments of the convective cloud populations from the radar data (rain rates, convective depths, organizational characteristics) are compared with the same statistics from the model simulations. We intend to carry out similar studies in conjunction with the modeling studies that will follow the EPIC2001 observational phase. This work is presently being written up for publication (Carpenter et al.). This research from TOGA COARE places us in a good position to transfer these same analysis techniques and scientific questions to the EPIC2001 program. Moreover, we will also be able to contrast the findings in the W. Pacific with those in the E. Pacific.

III. Overview of EPIC2001 ITCZ Subproject

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 (Fig. 1). The winds associated with transient disturbances of various time scales on the ITCZ, such as squall lines, easterly waves (e.g., Fig. 2), 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.

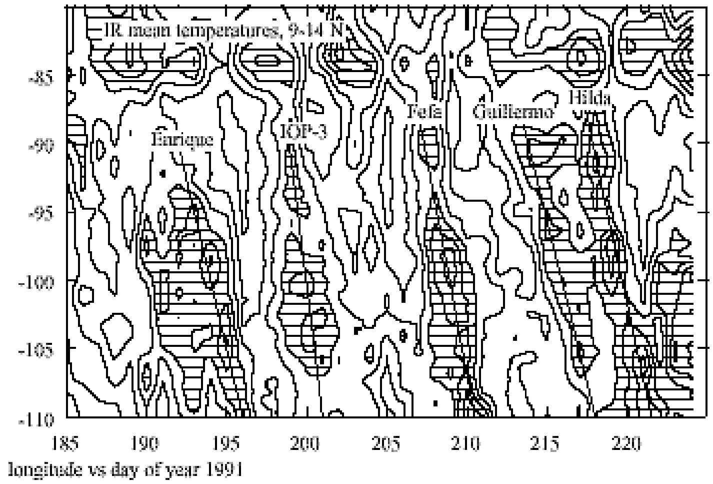

Figure 2. Infrared brightness temperature from GOES-7 averaged over the latitude range 9°-14° N for the summer of 1991. The contour interval is 10 K and horizontal hatching indicates temperatures less than 260 K and is a tracer of easterly waves. The four named waves indicate disturbances that developed into tropical storms. IOP-3 represents a non-developing wave. Reprinted from Raymond et al. (1998).

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

1. What mechanism or set of mechanisms forces convection in the east Pacific ITCZ?

2. What factors are responsible for the fluctuations in strength and position of the east Pacific ITCZ on weekly time scales?

3. 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.

i. 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 that can be tested via combined observations from atmospheric and oceanic instrument platforms planned for deployment during EPIC2001 are listed below:

1. Mechanical mechanisms:

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.

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:

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 Nino 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).

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.

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). The combined air and shipborne measurements planned for EPIC2001 will provide 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.

ii. ITCZ Fluctuations

Deep convection over the east Pacific warm pool is highly transient, consisting of westward-moving disturbances (Fig. 2) which tend to intensify into tropical cyclones. These disturbances have been identified with African easterly waves (e.g., Rappaport and Mayfield, 1992). The identification of these disturbances as easterly waves poses the question; why are these waves 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 that 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 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.

iii. Diurnal Cycle

One additional source of temporal fluctuations in the convection found 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. 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 (Short et al. 1997; Chen and Houze, 1997). Thus, the diurnal cycle needs to be observed in both active and suppressed phases.

iv. Ocean Forcing

Different atmospheric environments (e.g., different profiles of buoyancy, humidity, and wind) can yield very different kinds of convection (e.g., Rickenbach and Rutledge, 1998). 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 (e.g., Saxen and Rutledge, 1998). 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.

Effect of El Nino. Strong El Nino conditions prevailed in 1997, while strong La Nina conditions occurred in 1998. In both years there was a strong north-south SST differential across the equator (cf., OV). 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 summer time ITCZ existed in both years. During the 1997 El Nino 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 Nino 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 airborne platforms such as the NCAR Electra (see below), but with small adjustments in flight patterns the goals of the project could still be accomplished.

b. 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 NOAA ship Ronald Brown, the NCAR Electra, the NOAA WP-3D aircraft, 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 wind profiler for making precipitation measurements in the vertical plane, and will make surface flux measurements.

i. NOAA Ship Ron Brown

The NOAA ship Ronald H. Brown (RHB) 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 WP-3 and Electra aircraft. Primary measurement platforms on the RHB for the study of convection include the C-band Doppler radar and radiosonde soundings. Millimeter wavelength Doppler cloud radar and lidar measurements will also be collected. The C-band and millimeter Doppler radar measurements will be used to estimate rainfall rates and to document the 4-D structure of convection (kinematic and microphysical properties), with calibration help from in situ cloud measurements via the Electra aircraft. In addition to airborne dropsonde soundings, soundings from the RHB will provide boundary layer and lower free tropospheric sampling at relatively high temporal resolution (6 launches/day) in addition to providing atmospheric structure above the 6 km elevation (not sampled by the WP-3D dropsondes). Surface turbulent and radiative fluxes, aerosols, standard meteorological variables, precipitation, and oceanographic measurements will be among the parameters measured in situ on the RHB. *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*.

ii. NOAA WP-3D Aircraft

Figure 3 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 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

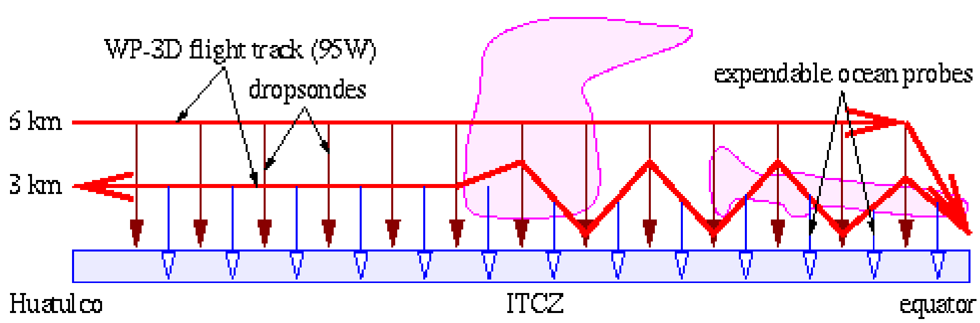

Figure 3. Proposed flight plan for NOAA WP-3D.

cross-section below 6 km along 95° W from the Mexican coast to the equator. A total of 16 flights, each of 9h duration, has been requested for the period 18 July - 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.

iii. NCAR Electra Aircraft

Figure 4 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

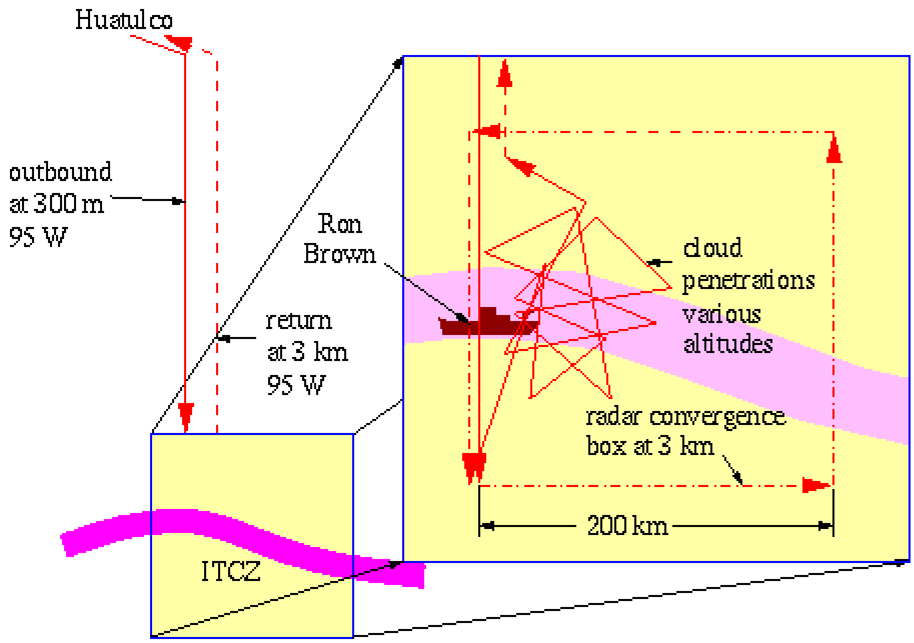

Figure 4. Proposed flight pattern for the NCAR Electra

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 will provide some redundancy to the WP-3D dropsonde and in situ measurements. An alternate flight pattern for the Electra has also been developed, and is 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. A total of 120 hours (16 flights of 7.5h duration) of Electra time will be requested for a period coincident with that of the WP-3D. For each primary pattern flight, roughly 4h 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 2.5h will be consumed in ferry and roughly 5h will be used in the mapping pattern. In the event that both dropsondes and ocean probes cannot be deployed from the Electra, 5 WP-3D flights will be used to execute this pattern and the Electra will be dispatched to the ITCZ inflow region. Given the range limitations on the Electra, such flights would be limited to latitudes north of about 3°N.

iv. Enhanced TAO Moorings

The TAO moorings along 95°W situated 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.

c. Proposals submitted in support of EPIC2001 ITCZ objectives

Proposals that have been concurrently submitted for consideration under the EPIC2001 ITCZ objectives include the following:

Fairall et al.: Ship-based cloud and precipitation air-sea interaction studies in EPIC2001 (Also included under EPIC2001 atmospheric boundary layer and stratus objectives.)

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, and Cifelli: 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 under EPIC2001 oceanic objectives.)

IV. Scientific Objectives for This Proposal

a. Background

The first successful deployment of inertially stabilized, shipborne Doppler weather radars (MIT and NASA TOGA C-band radars) was coordinated by the Colorado State University (CSU) Radar Meteorology group under the direction of the PI (Rutledge et al., 1993). CSU, with key participation from NCAR, NASA, and Texas Tech University, operated these radars during both the TOGA COARE and CEPEX field campaigns. The radar data collected during these field experiments provided an unprecedented view of tropical oceanic cloud structure in the west Pacific warm pool. These observations resulted in a wide variety of studies including: qualitative and quantitative descriptions of the 3-D convective cloud structure (e.g., Rickenbach and Rutledge, 1998; DeMott and Rutledge 1998a; Petersen et al., 1999); quantitative estimates of rainfall (e.g., Short et al.,1997); descriptions of the temporal and spatial variability of the convection as it related to the diurnal cycle, large-scale thermodynamic forcing and intraseasonal oscillations (e.g., Petersen et al., 1996; DeMott and Rutledge 1998b; Johnson et al., 1999); cloud electrification (Petersen et al., 1996, 1999); study of the coupling between atmospheric convection, rainfall and forcing of the western Pacific Ocean mixed-layer (Saxen and Rutledge, 1998), and the relationships between IR cloud tops and rainfall estimates (Saxen and Rutledge, 2000). See Section II above for more details.

Following COARE and CEPEX, the first C-band Doppler radar operations aboard the RHB were conducted during the TEPPS field campaign under the direction of Profs. R. Houze and S. Yuter (U. of Washington). Shipboard C-band Doppler radars were also successfully deployed in the NASA TRMM (Tropical Rainfall Measuring Mission) South China Sea Monsoon Experiment (SCSMEX) and the recently completed NASA TRMM KWAJEX Experiment. In SCSMEX, the NASA TOGA (Dr. R. Cifelli, CSU, Chief Scientist) and BMRC CPOL radars were used to document the vertical and horizontal structure of convection during the onset of the south east Asia monsoon (Lau et al. 2000). In KWAJEX, the radar on the RHB (Dr. R. Cifelli, Chief Scientist) was used by NASA to provide dual-Doppler coverage of tropical convection with the Kwajalein S-band radar.

b. Proposed research and methodology

The work outlined in this proposal focuses on the utilization of RHB radar and sounding data to examine the four-dimensional structure of ITCZ convection, precipitation, and its variability as a function of latitude, synoptic conditions, SST, and moist entropy fluxes (e.g., Fig. 1). The radar data collected during

EPIC2001 will enable both case studies and statistical studies to be completed (e.g., Rickenbach and Rutledge, 1998; DeMott and Rutledge, 1998a,b; Petersen et al., 1999) yielding a comprehensive description of the spectrum of deep convective clouds (e.g., Johnson et al., 1999; Fig. 1), their morphology, as well as their temporal and spatial variability.

Combining RHB radar and sounding data with large-scale analyses (e.g., NCEP, NASA-DAO, ECMWF etc.) and model simulations will place the observations of convective morphology within the context of large-scale tropospheric structure (e.g., phase of easterly waves, MJO etc.). Within identified large-scale meteorological regimes, quantitative estimates of precipitation computed from RHB C-band radar reflectivities can be subsequently related to convective morphology and oceanic mixed layer buoyancy fluxes (e.g., Saxen and Rutledge, 1998). Radar derived convective morphologies will also be examined relative to atmospheric boundary layer recharge times and to sea surface wind stress fields. This work will effectively couple atmospheric convection to oceanic mixed layer and planetary boundary layer responses on short time scales (e.g., Saxen and Rutledge, 1998). Finally, the shipboard radar data will also be combined with "external" ancillary data sets such as lightning (TRMM-LIS; VLF and long range NLDN data), GOES VIS/IR, passive microwave data (e.g., SSM/I; TRMM), and TRMM precipitation radar to further study convective lifecycles and microphysical structure in addition to placing the convection within a statistical framework of the "large-scale". In summary, the data collected will allow us to address the following fundamental questions, each central to the overarching goals of EPIC2001:

1. How does the characteristic vertical/horizontal structure of the convection change with different phases of an easterly wave passage (e.g., Serra et al. 2000 in TEPPS)? Similarly, how are rainfall statistics modulated as a function of easterly wave phase? Studies from the west Pacific (Reed and Recker, 1971) and the east Atlantic (Hudlow, 1979; Thompson et al., 1979) suggest significant modulation of convective organization and precipitation in these regions; however, the impact of synoptic-scale disturbances on convection in the east Pacific ITCZ is largely unknown.
2. What are the atmospheric boundary layer recovery times (through sensible and latent heat fluxes) after convective events and how do these recovery times vary as a function of convective structure? These results can be determined by combining the convective organization information revealed from the ship-board radar data with surface meteorological data from the RHB, R/V New Horizon, and TAO moorings. Results from the west Pacific (Saxen and Rutledge, 1998) suggest that the modulation of both surface latent and sensible heat fluxes varies significantly with the type of convective organization that is present. Comparison with similar results from the EPIC2001 region will help determine the geographic variability of the interaction between the atmospheric boundary layer and convection.
3. What is the diurnal cycle of convection and rainfall in this region and how is the diurnal cycle modulated by large-scale forcing events (e.g., easterly waves)? These issues are ideally suited for study using the RHB C-band radar since it will be scanning 24 hours/day at a fixed location in the East Pacific ITCZ. Results of the diurnal cycle pattern can be compared to similar analyses from ship-board radar in the east-central Pacific (TEPPS), central Pacific (KWAJEX), and west Pacific (TOGA COARE) to examine differences across the Pacific basin.
4. How are precipitating convective systems in the far eastern Pacific different from those previously observed in the central (KWAJEX), western (TOGA COARE), and TEPPS (120° W) regions of the Pacific Ocean in terms of morphology (organizational characteristics etc.), evolution, and kinematic structure?
5. To what degree are warm-rain coalescence and ice processes important to the microphysics of rainfall production in the east Pacific ITCZ? How do the relative fractions of warm and cold cloud processes (related to vertical profiles of latent heating and mass flux) vary with large scale forcing? The former question can be addressed by examining vertical profiles of radar reflectivity (e.g., variability in first echo heights and the gradient of reflectivity above/below the melt level). The latter issue can be examined by correlating reflectivity profiles with large-scale analyses of easterly waves, MJO, etc. (looking for systematic changes in precipitation structure as a function of wave position).

The microphysical nature of item (5) is complementary to those issues raised in items (1) and (4). *Indeed, considered as a whole, items 1-5 constitute an important validation tool for the representation of eastern Pacific ITCZ convection in numerical models.*

It will be essential to combine radar (reflectivity and radial velocity data; technical specifications of the RHB C-band radar listed in Table 1) and sounding data collected from the RHB since sounding data will be critical to placing radar observations within the context of the large scale environment (changes in the planetary boundary layer and free troposphere) and to document mesoscale effects produced by precipitating systems (cold pools, etc). This will help us to better define "regimes" (assuming there are different regimes) in which convection occurs. Hence, in addition to costs for operating the radar, our budget includes $40K for soundings, planning for 6 launches per day in the ITCZ region as well launches while the ship transits to and from the ITCZ region (we assume a 10% failure rate for the calculation of expendables).

In order to characterize rainfall production from ITCZ convection, rain maps will be generated using Z-R (reflectivity-rainfall) relationships derived from a variety of sources. These sources include acoustic rain gauges on TAO moorings within radar-range of the RHB; in-situ aircraft measurements (primarily from the NCAR Electra), S-band profiler measurements on the R/V New Horizon, and disdrometer measurements of drop size distributions from the RHB and New Horizon.

Dual frequency radar sampling utilizing the RHB 35 GHz cloud radar and C-band radar measurements can be exploited to study the variability of microphysical processes during the ITCZ portion of the EPIC2001 cruise (e.g., comparison of 35 GHz radar cloud-base height and C-band first precipitation height echo statistics in order to characterize precipitation production process – drop coalescence – variability). We will collaborate with other investigators responsible for cloud radar operation to examine these issues.

We will also deploy ancillary instrumentation on the RHB including a CCN (Cloud Condensation Nuclei) counter and an electric field mill. The former will be used to measure variations in CCN concentration and the impact on convection while the latter will be used to measure the vertical component of the ambient electric field, and variations of the electric field associated with convection. Both instruments will be provided by Prof. Earle Williams (MIT) at no cost to the project. We also intend to borrow several disdrometers from the NASA/TRMM project for use on board ship in EPIC2001.

Table 1. Technical Specifications of Ronald H. Brown C Band Radar

Radar Parameter	**Value**
Peak Output Power (kW)	250
Wavelength (cm)	5.36
Pulse Width (microsecond)	0.5, 0.8, 1.2, 2.0
Antenna Gain (dB)	~44
Elevation Range (°)	-0.5 - 85
Antenna height Above Waterline (m)	33
Beam width (degree)	0.95
Minimum Detectable Signal (dB)	-114
Maximum Scan Speed (°/sec)	36
PRF (Hz)	250-2100
Polarization	Linear horizontal
Variables	Z_H, V_R, σ
Data System	SIGMET IRIS

c. Radar calibration and inventory of spare parts

During EPIC2001, periodic calibration procedures will be necessary to test the performance of the radar and assess any calibration drift. Several procedures will be implemented:

A. Sphere calibrations using a metal sphere (both tethered and released) a fixed distance from the radar;
B. Solar calibrations will also be performed to assess both the radar elevation and pointing angles as well as to provide an independent measure of backscattered power to the radar;
C. Internal ZAUTO calibrations will be performed daily using a signal generator and the IRIS software to test the response of all radar components rearward of the antenna wave-guide, and;
D. For suitable targets (e.g., large MCS's), comparison with the TRMM Precipitation Radar (accurately calibrated) will be performed.

Previous budget constraints prevented the new C-band radar system on the RHB from being outfitted with an adequate supply of radar and computer system spare parts. Such spares are crucial for the success of an extended data collection period at sea. Based on the existing inventory of equipment and our experience from prior field campaigns, various spare parts will need to be purchased in advance of the EPIC2001 cruise. We expect to borrow some spares from our own inventories, however additional items will need to be purchased. These spare parts are detailed in the budget request and total $33K.

d. Proposed scanning strategy

In order to use the RHB C-band radar measurements to determine both the rainfall and kinematic/microphysical characteristics of ITCZ convection, a scan strategy that employs periodic full volume-sector scans with a relatively large range of elevation angles and adequate vertical resolution will be required. The CSU group developed the radar scan strategy that was implemented during TOGA COARE (Short et al. 1997) and we envision using a similar strategy as a model for the EPIC2001 ITCZ radar program. Specifically, we propose utilizing a full-volume (360°) 20-21-tilt scan sequence operating on a 10 minute repeat cycle. The tilt sequence will either be the "FAR" (20-tilt, default mode) or the "EVAD" (21-tilt) as outlined below in Table 2. The main difference between the two sequences is the increased vertical resolution at upper heights in the "EVAD", which is necessary for accurate kinematic retrievals (Matejka and Srivastava, 1991). Note that the "FAR" mode has increased vertical resolution at low-levels which is better suited for rain mapping purposes. Because the EVAD (Extended Velocity Azimuth Display) kinematic retrieval technique can only be used in situations where radar echo surrounds the radar, the "FAR" scanning mode will be utilized most of the time. Assuming the antenna is rotated at 15°/sec, the 20-21-tilt sequence will be completed in approximately 8 minutes. The remainder of the 10 minute cycle will be filled with a 2-tilt low PRF (Pulse Repetition Frequency) surveillance volume (0.8°, 1.5°) and selected RHI's (Range Height Indicator) in echo regions of interest.

Table 2. Proposed EPIC2001 ITCZ Scan Strategy for RHB C-band Radar

Proposed "FAR" mode Gate Spacing = 250m PRF = 1000	**Proposed "EVAD" mode** Gate Spacing = 250m PRF = 1000
Elevation Angle (°)	**Elevation Angle (°)**
0.8, 1.5, 2.3, 3.4, 4.5, 5.7, 6.9, 8.2, 9.6, 11.3, 13.0, 15.0, 17.2, 19.8, 22.5, 26.5, 33.0, 39.0, 45.8, 53.4	0.8, 1.5, 3.2, 5.5, 7.9, 10.3, 12.7, 15.1, 17.6, 20.0, 22.6, 25.1, 27.8, 30.5, 33.2, 36.1, 39.1, 42.2, 45.4, 48.9, 53.4

In the event that coordinated aircraft and ship radar operations will be performed, sector-volume scanning may be desired to achieve better temporal sampling of selected echo features. In these cases, we propose implementing back-to-back "FAR" scans over a specified azimuth sector (run-time approximately 4 minutes each), followed by the same surveillance and RHI scans as described above for full-volume operations.

IV. Work Plan

Year 1 activities will focus on field campaign planning/logistics, and data collection efforts. Year 2 will focus on QC of the radar and sounding data, followed by analysis of those data together with relevant ancillary datasets per objectives 1-5. Preparation and submission of publications will occur during year 3.

The PI and CO-PI's will be heavily involved in the planning/execution of the field campaign and will also attend various EPIC2001 planning and data analysis meetings.

V. Personnel and Experience

Prof. Steven Rutledge (CSU, PI): Led deployment of the ship radars in TOGA COARE and CEPEX. Lead roles in the following experiments involving radar: PRE-STORM, COPS, WISP91, DUNDEE, TOGA COARE, CEPEX, MCTEX, STERAO, TRMM/LBA and STEPS. Scientific Director of the CSU-CHILL National Radar Facility.

Dr. Rob Cifelli (CSU, Co-PI): Co-Chief Radar Scientist TOGA COARE, Chief Radar and Sounding Scientist SCSMEX and KWAJEX. Lead TOGA Radar Scientist TRMM-LBA.

Dr. Walter Petersen (CSU, Co-PI): Lead role in TRMM-LBA (radar and aircraft coordination). Co-Chief Radar Scientist (MIT radar) TOGA COARE. Lead Scientist CLEX. Scientist COPS. Sounding operations in operational (NWS, USN) and research sectors.

At least one student will be involved in this research effort, and possibly more, if additional sources of support can be identified. Also Robert Bowie, Master Technician at the CSU-CHILL Radar Facility, will provide technical support of the radar at sea. Mr. Bowie has extensive radar experience, including stints at sea during COARE and CEPEX.

D. Bibliography

Carpenter, S. J., S. A. Rutledge, X. Wu, and M. W. Moncrieff, 2000: Comparison of long-term two-dimensional cloud system simulations with shipboard radar observations during TOGA .COARE. In preparation.

Charney, J., 1971: Tropical cyclogenesis and the formation of the intertropical convergence zone. *Lectures in Applied Mathematics*, **13**, American Mathematical Society, 355-368.

Chen, S. S., and R. A. Houze Jr., 1997: Diurnal variation and life-cycle of deep convective systems over the tropical Pacific warm pool. *Quart. J. Roy. Meteor. Soc.*, **123**, 357-388.

DeMott, C. A., and S. A. Rutledge, 1998a: The vertical structure of TOGA COARE convection. Part I: Radar echo distributions. *J. Atmos. Sci*., **55**, 2730-2747.

DeMott, C. A., and S. A. Rutledge, 1998b: The vertical structure of TOGA COARE convection. Part I: Modulating influences and implications for diabatic heating. *J. Atmos. Sci*., **55**, 2748-2762.

Emanuel, K. A., 1995: The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. *J. Atmos. Sci*., **52**, 3960-3968.

Ferreira, R. N., and W. H. Schubert, 1997: Barotropic aspects of ITCZ breakdown. *J. Atmos. Sci*., **54**, 261-285.

Holton, J. R., J. M. Wallace, and J. A. Young, 1971: On boundary layer dynamics and the ITCZ. *J. Atmos. Sci*., **28**, 275-280.

Hudlow, M.D., 1979: Mean rainfall patterns for the three phases of GATE. *J. Appl. Meteor*., **18**, 1656-1669.

Johnson, R. H., T. M. Rickenbach, S. A. Rutledge, P. E. Ciesielski and W. H. Schubert, 1999: On the distribution of tropical clouds. *J. Climate*, **12**, 2397-2418.

Jorgensen, D. P., and M. A. LeMone, 1989: Vertical velocity characteristics of oceanic convection. *J. Atmos. Sci*., **46**, 621-640.

Kloesel, K. A., and B. A. Albrecht, 1989: Low-level inversions over the tropical Pacific -- thermodynamic structure of the boundary layer and the above-inversion moisture structure. *Mon. Wea. Rev.*, **117**, 87-101.

Lau, K.M., Y.Ding, J.T. Wang, R. Johnson, T. Keenan, R. Cifelli, J. Gerlach, T. Rickenbach, S.C. Tsay, and P.H. Lin, 2000: A report of the field operations and early results of the South China Sea Monsoon Experiment (SCSMEX). *Bull. Amer. Meteor. Soc*., in press.

Maloney, E. D., and D. L. Hartmann, 2000: Modulation of eastern north Pacific hurricanes by the Madden-Julian oscillation. *J. Climate*, (In press).
(See also http://www.atmos.washington.edu/maloney/hurricanes/hurr.html).

Matejka, T., and R.C. Srivastava, 1991: An improved version of the Extended Velocity-Azimuth Display Analysis of single-Doppler radar data. *J. Atmos. Oceanic Technol*., **8**, 453-466.

Molinari, J., D. Knight, M. Dickinson, D. Vollaro, and S. Skubis, 1997: Potential vorticity, easterly waves, and eastern Pacific tropical cyclogenesis. *Mon. Wea. Rev.*, **125**, 2699-2708.

Mozer, J. B., and J. A. Zehnder, 1996: Lee vorticity production by large-scale tropical mountain ranges. Part I: Eastern north Pacific tropical cyclogenesis. *J. Atmos. Sci*., **53**, 521-538.

Petersen, W. A., S. A. Rutledge and R. E. Orville, 1996: Cloud-to-ground lightning observations in TOGA COARE: Lightning location algorithms and selected results. *Mon. Wea. Rev*., **124**, 602-620.

Petersen, W. A., R. C. Cifelli, S. A. Rutledge, B. S. Ferrier, and B. F. Smull, 1999: Integrated observations of storm kinematics and electrification. *Bull. Amer. Meteor. Soc*., **80**, 81-90.

Pinkel R., M. Merrifield, M. McPhaden, J. Picaut, S. A. Rutledge, D. Siegel and L. Washburn, 1997: Solitary Waves in the western Equatorial Pacific Ocean. *Geophysical Research Letters*, **24**, 1603-1606.

Rappaport, E. N., and M. Mayfield, 1992: Eastern north Pacific hurricane season of 1991. *Mon. Wea. Rev.*, **120**, 2697-2708.

Raymond, D. J., 1995: Regulation of moist convection over the west Pacific warm pool. *J. Atmos. Sci*., **52**, 3945-3959.

Raymond, 1997: Boundary layer quasi-equilibrium (BLQ). The Physics and Parameterization of Moist Atmospheric Convection, Roger K. Smith ed., NATO ASI Series, Kluwer, 387-397.

Raymond, D., S. Esbensen, M. Gregg, and N. Shay, 1999: EPIC2001: Overview and implementation plan. (See http://www.physics.nmt.edu/raymond/EPIC2001/).

Reed, R. J., D. C. Norquist, and E. E. Recker, 1977: The structure and properties of African wave disturbances as observed during phase III of GATE. *Mon. Wea. Rev.*, **105**, 317-333.

Reed, R. J. and E. E. Recker, 1971: Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific. *J. Atmos. Sci.*, **28**, 1117-1133.

Rickenbach, T. M., and S. A. Rutledge, 1998: Convection in TOGA COARE: Horizontal scale, morphology and rainfall production. *J. Atmos. Sci.*, **55**, 2715-2729.

Rutledge, S. A., R. Cifelli, C. DeMott, W. Petersen, T. Rickenbach, J. Lutz, R. Bowie, M. Strong and E. Williams, 1993: The shipboard deployment of the MIT C-band radar during TOGA COARE. *Preprints, 26th International Conference on Radar Meteorology,* American Meteorological Society, 24-28 May 1993, Norman, Oklahoma.

Saxen, T., and S. A. Rutledge, 1998: Surface fluxes and boundary layer organization in TOGA COARE: Sensitivity to convective organization. *J. Atmos. Sci*., **55**, 2763-2781.

Saxen, T., and S. A. Rutledge, 2000: Surface rainfall-cold cloud fractional coverage relationship in TOGA COARE. *Mon. Wea. Rev*., In press.

Schubert, W. H., P. E. Ciesielski, D. E. Stevens, and H.-C. Kuo, 1991: Potential vorticity modeling of the ITCZ and the Hadley circulation. *J. Atmos. Sci*., **48**, 1493-1509.

Serra, Y., 2000: Observations of 3-6 day variability in the east Pacific ITCZ. In preparation.

Short, D. A., P. A. Kucera, B. S. Ferrier, J. C. Gerlach, S. A. Rutledge, and O. W. Thiele, 1997: Shipboard radar rainfall patterns within the TOGA COARE IFA. *Bull. Amer. Meteor. Soc*., **78**, 2817-2836.

Thompson, R. M., S. W. Payne, E. E. Recker, and R. J. Reed, 1979: Structure and properties of synoptic-scale wave disturbances in the intertropical convergence zone of the eastern Atlantic. *J. Atmos. Sci.*, **36**, 53-72.

Tomas, R. A., J. R. Holton, and P. J. Webster, 1999: The influence of cross-equatorial pressure gradients on thhe location of near-equatorial convection. *Quart. J. Roy. Meteor. Soc.*, **125**, 1107-1127.

Waliser, D. E., and N. E. Graham, 1993: Convective cloud systems and warm-pool surface temperatures: Coupled interactions and self-regulation. *J. Geophys. Res.*, **98**, 12881-12893.

Wei, D., A. M. Blyth, and D. J. Raymond, 1998: Buoyancy of convective clouds in TOGA COARE. *J. Atmos. Sci.*, **55**, 3381-3391.

Weller, R., and coauthors, 1999: A science and implementation plan for EPIC2001: An eastern Pacific investigation of climate processes in the coupled ocean-atmosphere system. Available at http://www.atmos.washington.edu/gcg/EPIC2001/

Zehnder, J. A., 1991: The interaction of planetary-scale tropical easterly waves with topography: A mechanism for the initiation of tropical cyclones. *J. Atmos. Sci.*, **48**, 1217-1230.

Zehnder, J. A., D. M. Powell, and D. L. Ropp, 1999: The interaction of easterly waves, orography, and the intertropical convergence zone in the genesis of eastern Pacific tropical cyclones. *Mon. Wea. Rev.*, **127**, 1566-1585.

E. Biographical Sketches

Steven A. Rutledge

Present Position:	Professor and Head Department of Atmospheric Science Colorado State University Ft. Collins, CO 80523 (970) 491-8283 Scientific Director CSU-CHILL National Radar Facility

Education

B.S. (1978) -	Physics, University of Missouri - St. Louis, St. Louis, Missouri
Ph.D. (1983) -	Atmospheric Sciences, University of Washington, Seattle, Washington

Experience

1999-	Professor and Head, Department of Atmospheric Science, Colorado State University
1994-1999	Professor of Atmospheric Science, Colorado State University
1990-1994	Associate Professor, Colorado State University
1988-1990	Assistant Professor, Colorado State University
1983-1988	Assistant Professor, Oregon State University
1978-1983	Graduate Research Assistant, University of Washington

Dr. Rutledge's interests are in mesoscale meteorology, atmospheric electricity, radar meteorology and cloud physics. He is a member of the TRMM Science team and was Co-chair for the MCTEX Science Steering Committee and the STERAO-A Deep Convection Science Steering Committee. He was the Lead Scientist for the TRMM-LBA field campaign. He also serves as the Scientific Director of the CSU-CHILL National Radar Facility.

Five relevant publications

Saxen, T., and S. A. Rutledge, 1998: Surface Fluxes and Boundary Layer Recovery in TOGA COARE: Sensitivity to Convective Organization. *J. Atmos. Sci.*, **55**, 2763-2781.

DeMott, C. A., and S. A. Rutledge, 1998: The Vertical Structure of TOGA COARE Convection. Part I: Radar Echo Distributions. *J. Atmos. Sci.,* **55**, 2730-2747.

DeMott, C. A., and S. A. Rutledge, 1998: The Vertical Structure of TOGA COARE Convection. Part II: Modulating Influences and Implications for Diabatic Heating. *J. Atmos. Sci.,* **55**, 2748-2762.

Rickenbach, T. M., and S. A. Rutledge, 1998: Convection in TOGA COARE: Horizontal Scale, Morphology, and Rainfall Production. *J. Atmos. Sci.*, **55**, 2715-2729.

Petersen, W. A., S. A. Rutledge, and R. E. Orville, 1996: Cloud-to-Ground Lightning Observations in TOGA COARE: Lightning Location Algorithms and Selected Results. *Monthly Weather Review*, **124**, 602-620.

Five closely related publications

Petersen, W. A., R. C. Cifelli, S. A. Rutledge, B. S. Ferrier and B. F. Smull, 1999: Shipborne Dual-Doppler Operations During TOGA COARE: Integrated Observations of Storm Kinematics and Electrification. *Bull. Amer. Meteorol. Soc.*, **80**, 81-90.

Johnson, R. H., M. Rickenbach, S. A. Rutledge, P. E. Ciesielski and W. H. Schubert, 1999: Trimodal Characteristics of Tropical Convection, *J. Climate*, **12**, 2397-2418.

Saxen, T. R., and S. A. Rutledge, 2000: Surface Rainfall – Cold Cloud Fractional Coverage Relationship in TOGA COARE: A Function of Vertical Wind Shear. *Monthly Weather Review*, **128**, 407-415.

Cifelli, R. C., S. A. Rutledge, D. J. Boccippio, and T. Matejka, 1996: Horizontal Divergence and Vertical Velocity Retrievals From Doppler and Wind Profiler Observations. *J. Atmos. Ocean. Tech*., **13**, 948-966.

Cifelli, R. C., and S. A. Rutledge, 1998: Vertical Motion, Diabatic Heating, and Rainfall Characteristics in N. Australia Convective Systems. *Quart. J. Roy. Meteor. Soc.*, **124**, 1133-1162.

Other Collaborators (past 48 months; manuscripts)

Prof. Earle R. Williams, MIT

Dr. Thomas Keenan, BMRC

Graduate students advised

Theses or dissertations completed since 1991:

Scott Randell, M.S., 1991
Kevin Manning, M.S., 1992
Erik Rasmussen, Ph.D., 1992
Nicolas Powell, M.S., 1992
Walter Petersen, M.S., 1992
Lawrence Carey, M.S., 1994
James Scott, M.S., 1994
Robert Cifelli, Ph.D., 1995
Charlotte DeMott, Ph.D., 1996
Tom Rickenbach, Ph.D., 1996
Jonathon Erdman, M.S., 1996
Tom Saxen, M.S., 1997
Terry Schuur, Ph.D., 1997
Walter Petersen, Ph.D., 1997
Tim Lang, M.S., 1997
Bard Zajac, M.S., 1998
Christine Butler, M.S., 1998
Rita Roberts, M.S., 1998
David Ahijevych, M.S., 1998
Lawrence Carey, Ph.D., 1998
Jesse Ryan, M.S., 1999
Michael Gauthier, M.S., 1999

Ph.D. Advisor

Prof. Peter V. Hobbs, University of Washington

Biographical Sketch

Walter A. Petersen

Present Position — Research Associate
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
(970) 491-6944

Education

B.S. (1990)	Mathematics, Southern Utah University, Cedar City, Utah
M.S. (1992)	Atmospheric Science, Colorado State University, Fort Collins, Colorado
Ph.D. (1997)	Atmospheric Science, Colorado State University, Fort Collins, Colorado

Experience

1997-	Research Associate, Colorado State University
1990-1997	Graduate Research Assistant, Colorado State University
1986-1990	Station Manager, FAA Weather Observatory, Cedar City, Utah.
1984-1986	Meteorological Technician, WSCMO, Great Falls, Montana.
1981-1983	Aerographers Mate, U. S. Navy, USS Ranger CV-61

Dr. Petersen's interests are in cloud dynamics/microphysics, atmospheric electricity, radar meteorology, and tropical meteorology. He is a member of the AGU Committee on Space and Atmospheric Electricity.

Five Relevant Publications

Petersen, W.A., L.D. Carey, S.A. Rutledge, J.C. Knievel, N.J. Doesken, R.H. Johnson, T.B. McKee, T. Vonder Haar, and J. F. Weaver, 1999: Mesoscale and radar observations of the Fort Collins flash flood of 28 July 1997. *Bull. Amer. Meteorol. Soc.*, **80**,191-216.

Petersen, W.A., R.C. Cifelli, S. A. Rutledge, B.S. Ferrier and B.F. Smull, 1999: Shipborne dual-Doppler operations during TOGA COARE. Integrated observations of storm kinematics and electrification. *Bull. Amer. Meteorol. Soc.*, **80**, 81-97.

Petersen, W.A., and S.A. Rutledge, 1998: On the relationship between cloud-to-ground lightning and convective rainfall. *J. Geophys. Res*., **103**, 14025-14040.

Simpson, J., J. B. Halverson, B. S. Ferrier, W. A. Petersen, R. H. Simpson, R. Blakeslee, and S. L. Durden, 1998: On the role of "Hot Towers" in tropical cyclone formation. *J. Meteorol. Atmos. Phys.*, **67**, 15-35.

Petersen, W.A., S.A. Rutledge, and R.E. Orville, 1996: Cloud-to-ground lightning observations from TOGA COARE: Selected results and lightning location algorithms *Mon. Wea. Rev*.,**124**, 602-620.

Ph.D. Advisor

Prof. Steven A. Rutledge, Colorado State University

Biographical Sketch

Robert Cifelli

Present Position	Research Associate Department of Atmospheric Science Colorado State University Fort Collins, CO 80523 970 49-8516

Education

B.A. (1983)	Geology, University of Colorado, Boulder, Colorado
M.S. (1986)	Hydrogeology, West Virginia University, Morgantown, West Virginia
Ph.D. (1996)	Atmospheric Science, Colorado State University, Fort Collins, Colorado

Experience

1999-	Research Associate, Colorado State University
1997-1999	Assistant Research Professor, University of Maryland Baltimore County, Baltimore, Maryland and TRMM Office, NASA Goddard Space Flight Center, Greenbelt, Maryland
1996-1997	Visiting Fellow, CIRES, University of Colorado, Boulder Colorado
1990-1995	Graduate Research Assistant, Colorado State University
1987-1990	Hydrogeologist, Industrial Compliance Incorporated, Golden, Colorado

Dr. Cifelli's research interests include scanning radar and wind profiler retrieval techniques and the kinematic, microphysical, and precipitation characteristics of tropical Mesoscale Convective Systems. He is member of the NASA TRMM Science team and served as co-chief radar scientist in TOGA COARE, chief scientist during the SCSMEX and KWAJEX campaigns, and a lead scientist in the TRMM LBA campaign. He is a member of both the American Meteorological Society and the American Geophysical Union.

Five Relevant Publications

Cifelli, R., and S.A. Rutledge, 1994: Vertical motion structure in Maritime Continent mesoscale convective systems: Results from a 50-MHz profiler. *J. Atmos. Sci.,* **51**, 2631-2652.

Cifelli, R., S.A. Rutledge, D.J. Boccippio, and T. Matejka, 1996: Horizontal divergence and vertical velocity retrievals from Doppler radar and wind profiler observations in tropical convection. *J. Atmos. Oceanic Technol.*, **13**, 948-966.

Cifelli, R., and S.A. Rutledge, 1998: Vertical motion, diabatic heating, and rainfall characteristics in N. Australia convective systems. *Quart. J. Roy. Meteor. Soc.*, **124**, 1133-1162.

Cifelli, R., C.R. Williams, D.K. Rajopadhyaya, S.K. Avery, K.S. Gage, and P.T. May, 2000: Drop size distribution characteristics in tropical Mesoscale Convective Systems. *J. Appl. Meteor*., in press.

Petersen, W.A., R. Cifelli, S.A. Rutledge, B.S. Ferrier, and B.S. Smull, 1999: Shipborne dual-Doppler operations during TOGA COARE: Integrated observations of storm kinematics and electrification. *Bull. Amer. Meteor. Soc.*, **80**, 81-97.

Ph.D. Advisor

Prof. Steven A. Rutledge, Colorado State University

G. Statement of Current and Pending Support

Current Support for Steven A. Rutledge as of 1/4/2000

Agency	Project Title	K$/ YR	Role	Period Covered	Commitment (months)
National Science Foundation	The CSU-CHILL Radar Facility	598	CO-PI	5/1/95 to 4/30/00	1 summer 1 academic
National Science Foundation	Dynamical and Electrical Studies of Convective Cloud Systems	122	PI	2/1/98 to 1/30/01	1 summer
National Aeronautics and Space Administration	Validation Studies and Algorithm Refinement in Support of TRMM	160	CO-PI	6/1/97 to 9/30/99	1 academic
National Oceanic and Atmospheric Administration	Analysis and Modeling of the Transport of Lightning-Generated Nox and Other Chemical Species in Convective Cloud Systems	58	PI	1/1/97 to 6/30/00	1 summer
Colorado State University	Resident Instruction Support				7 academic

B. Pending Support for Steven A. Rutledge as of 1/4/2000

Agency	Project Title	K$/ YR	Role	Period Covered	Commitment (months)
National Science Foundation	Dynamical, Microphysical and Electrical Studies of Convection in STEPS	370	PI	4/1/00 to 3/31/03	1 academic
National Oceanic and Atmospheric Administration	Investigation of ENSO-Forced Variability in Deep Convection through Development and Use of Enhanced Data Sets	293	Co-PI	5/1/00 to 4/30/03	1 academic
National Aero-nautics and Space Administration	Analysis of Data from TRMM/LBA to Validate TRMM Satellite Algorithms and Models	591	PI	6/1/00 to 5/31/03	1 academic
National Science Foundation	This proposal (EPIC)	606	PI	8/1/00	1 academic

H. Facilities, Equipment and Other Resources

Adequate computer and related facilities exist in the Department of Atmospheric Science to support this work. The Radar Meteorology Group has 12 PC's and workstations, several tape drives, and over 50 GB of disk space.