A RESEARCH PROPOSAL
TO THE
NOAA OFFICE OF GLOBAL PROGRAMS OFFICE

Investigation of Cloud and Precipitation Aspects of Air-Sea Interaction in the Eastern Pacific: Analysis of ETL Ship-Based Data from EPIC2001

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ENDORSEMENTS:

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A. Abstract

Investigation of Cloud and Precipitation Aspects of Air-Sea Interaction in the Eastern Pacific:
Analysis of ETL Ship-Based Data from EPIC2001
NOAA Environmental Technology Laboratory
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Total proposed cost: $705,000 Budget Period: October 1, 2002 - September 30, 2005

This is a proposal for analysis of data obtained in the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC). The Environmental Technology Laboratory (ETL) has collaborated with other investigators to collect extensive data in the ITCZ the ABL/Cold Tongue, and the Stratocumulus Region during the EPIC2001 field program. The work proposed here will involve analysis of data sets, primarily from three sets of ETL systems on the *NOAA Ship Ronald H. Brown* (the flux/MBL system, the cloud radar/microwave radiometer system, and the lidar system). We will collaborate with investigators from CSU, UW, OSU, WHOI and UNAM.

The scientific objectives of the ITCZ study will involve improving parameterizations of turbulent and radiative fluxes and MBL structure in precipitating systems in two tasks:

- For the turbulent fluxes a major issue is the role of mesoscale variability since standard bulk parameterizations are based on point measurements. These will be extended to account for subgridscale variability to be valid for large-scale numerical applications.
- Microphysical properties of convective outflows (midlevel and cirrus) will be determined and related to the cloud radiative properties.

For the ABL/Cold Tongue study we will investigate the role of surface fluxes in driving diurnal and spatial variability of entire PBL (cloud and sub-cloud layers). This will involve:

- Comprehensive characterization of clouds, surface fluxes, and PBL profiles from the stratocumulus region, into the shallow convection and finally into the ITCZ.
- Examination of the relative contributions of turbulent and radiative fluxes to the surface heat budget of the ocean and determination of cloud forcing of surface fluxes in a region that is a problem for coupled ocean-atmospheric models.

The scientific objectives of Stratocumulus region studies will involve improved bulk cloud-radiative parameterizations, methods for retrieving cloud microphysical, properties, and investigation of the relative roles of cloud-top entrainment and drizzle production on the dynamics of stratocumulus. This will be achieved through:

- Comprehensive characterization of clouds, surface fluxes, and PBL profiles using a variety of *in situ* and remote sensing systems on the *Ronald H. Brown*.
- Evaluation of various bulk models of stratocumulus cloud radiative transfer properties using resulting cloud microphysics (integrated liquid water, drop size and number concentration) determined with ship-board remote sensors
- Examination of the coupling of condensation dynamics, microphysics, and precipitation production using lidar, cloud radar, and aerosol observations combined with LES simulations with explicit cloud/aerosol microphysics.

B. Results from Prior Research

NOAA Award : Climate Global Change Program, 10/1/00-9/30/02
Amount : $896 K
Title : Ship-Based Cloud and Precipitation Air-Sea Interaction Studies In Epic-2001, C. Fairall PI

This project supports participation by three research groups at ETL in the East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC). The specific scientific objectives of this project are:

- To improve parameterization of turbulent and radiative fluxes in the ITCZ
- To improve descriptions of PBL structure in precipitating systems
- Relate cloud microphysical properties of convective outflows to cloud radiative properties
- Investigate the role of surface fluxes in driving diurnal and spatial variability of the PBL
- Examine the relative contributions of turbulent and radiative fluxes to the surface heat budget of the ocean
- Improve bulk cloud-radiative parameterizations

The first year of the project involved preparation for and participation in the first leg of the field program (EPIC2001); the second year involved participation in the second leg of the field program and preliminary processing of the data.

1.1 Field Work Accomplishments

The primary accomplishment of this project was successful participation in the EPIC2001 field program. We deployed a variety of in-situ and remote sensing systems on the NOAA Ship *Ronald H. Brown* (RHB) for a research cruise in the Eastern Tropical Pacific. The RHB departed San Diego on September 5th, 2001 and began recording data at 14 N, 103 W on September 10th. Measurements continued at a number of station keeping sites as well as during transits in the EPIC experimental region, resulting in continuous measurements under the ITCZ (Leg I) and within the stratus regime (Leg II) until the RHB arrived in Arica, Chile on October 25th 2001.

The NOAA/ETL instruments proposed for EPIC-2001 were successfully deployed; data processing and analysis are proceeding on schedule. This ship track allowed measurements in the ITCZ, the ABL/Cold Tongue and Stratocumulus regimes in the Eastern Pacific. The measurement systems included a direct flux measurement system (direct covariance turbulent, radiative, rain fluxes), near-surface bulk meteorology (Ts, Ta, RH, wind speed/direction, bulk fluxes), ceilometer (cloud base height), 3 GHz Doppler radar profiler (precipitation Doppler spectra), 0.92 GHz Doppler radar wind profiler (MBL wind and turbulence profiles), 20.6, 31.65, 90.0 GHz radiometer (integrated column vapor and liquid water), 35 GHz Doppler cloud radar (cloud microphysical profiles), BNL portable radiation package (direct/diffuse solar, IR fluxes) and new technology lidar with simultaneous Doppler winds and water vapor DIAL (wind and water vapor profiles). Six preliminary data sets have been submitted to NCAR/JOSS for the

EPIC archive. The resulting data sets and processing status is summarized briefly in the following sections. A large selection of data sets, images and reports can be found at: ftp://ftp.etl.noaa.gov/et7/anonymous/cfairall/EPIC/epic2001/ .

1.2 *Data Processing*

The multiple components of the turbulent and radiative flux system, wind profiler and ceilometer operated successfully for the duration of the cruise. Basic time series and diurnal cycles have been computed for selected variables, and processing of the direct covariance turbulent fluxes is ongoing.

The radar/radiometer package operated successfully with only brief gaps in the vicinity of the Galapagos, primarily due to frequency operation restrictions. The radar and radiometric data sets have been fully processed to provide integrated, calibrated radar reflectivities and retrieved column integrated liquid water and vapor amounts. Initial cloud microphysical retrievals are in progress, and collaborative activities have been established with the University of Washington group to investigate drizzle mechanisms, cloud microphysics in the context of mesoscale structure, reflectivity statistic comparisons with the C-band radar, satellite comparisons and diurnal cycles.

This was the first ship deployment of the Doppler/DIAL lidar, so it was necessary to integrate the system with a motion stabilization scanner to obtain accurate pointing accuracy for the best possible wind velocity and direction products from a moving platform. Additionally, a second laser was added for DIAL measurements and additional lines investigated to minimize absorption for increased sensitivity and range in tropical regions with significant water vapor amounts. Completely new processing software had to be written. The DIAL water vapor data reduction is in progress. Wind velocity profiles for the entire cruise have been processed and the images and data are posted at http://www.etl.noaa.gov/~bmccarty/EPIC/wind.html.

1.3 *Publications*

Feingold, G., and S. M. Kreidenweis, 2002: Cloud processing of aerosol as modeled by a large eddy simulation with coupled microphysics and aqueous chemistry. *J. Geophys. Res.*, to appear.

Feingold, G., and B. Morley, 2002: Aerosol hygroscopic properties as measured by lidar and comparison with in-situ measurements. *J. Geophys. Res.*, submitted.

Hazen, D. A., B. B. Stankov, E. R. Westwater, C. W. Fairall, and Y. Han, 2002: Radiometric observations at 20, 30, and 90 GHz during EPIC2001. *Radio Sci.*, to be submitted.

Petersen, W. A., R. Ciffeli, D. J. Boccippio, S. A. Rutledge, and C. W. Fairall, 2002: Convection and easterly wave structure observed in the Eastern Pacific warm-pool during epic-2001. *J. Atmos. Sci.*, submitted.

C. Statement of Work

1. Introduction

1.1 Statement of the problem

Radiative surface cooling associated with clouds and turbulent interfacial fluxes associated with clear and cloudy boundary-layer dynamics are primary factors in producing the observed sea surface temperature structure of the Eastern Pacific and play a major role in the regional moisture transport balance (Tian and Ramanathan, 2002). However, these cloud systems are notoriously difficult to properly simulate in GCMs. Boundary-layer structure, cloud optical properties, surface radiative fluxes, and cloudtop height are all directly dependent on the balance of fluxes at the bottom (surface) and top (entrainment) of the boundary layer. In deep convective regions, cloud radiative forcing is dominated by large optically thick cloud masses that extend over much greater areas than the primary updraft region that generates the clouds. The ice/water microphysical processes that determine the radiative properties of these clouds are poorly observed and poorly modeled. Because of their spatial variability, convective systems also present formidable problems in air-sea flux parameterization, which currently assume uniform conditions. In stark contrast to the tropical convective clouds driven by strong local updrafts, marine stratocumulus clouds are generated by boundary-layer turbulent mixing working against weak synoptical scale subsidence. The optical properties of these clouds are determined by the balance of surface evaporation, entrainment and radiative cooling combined with the boundary layer aerosol properties (Albrecht, 1989; Menon et al., 2002). Aerosols enter the problem in a complicated way through influences on the size distribution of cloud droplets, which in turn influence solar radiative interactions and the drizzle production in the clouds.

1.2 Proposed work

Three divisions at ETL participated in the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC) field program in September - October, 2001. This experiment, called EPIC2001, is a study of air-sea interaction in the eastern Pacific along the 95 W longitude zone. This is a joint NOAA/NSF project to study air-ocean coupling in the intertropical convergence zone (ITCZ) and stratus clouds associated with the equatorial cold tongue in the Eastern Pacifc near the Galapagos Islands. ETL's main participation was on the *NOAA Ship Ronald H. Brown* which hosted the ETL flux system, Doppler cloud radar, two different microwave radiometers, a combined Doppler/water vapor lidar, and the ship’s C-band scanning Doppler radar. The ETL observation system was designed to obtain the combination of near-surface and profile data to investigate the relative roles of turbulent and radiative surface fluxes in deep convective systems (the ITCZ), the transition through the equatorial cold tongue, and in the stratocumulus region. The field program was completely successful. Preliminary processing of the raw data is nearing completion and initial releases from most sensors have been submitted to the EPIC archive; the remainder will be submitted by September 2002.

We now propose a three-year investigation to:

* complete the basic data analysis (including intercomparisons /calibrations)
* integrate certain combinations of the data to produce higher order data sets
* improve parameterizations of surface turbulent and radiative fluxes
* improve/develop cloud parameterizations (radiative transfer and microphysics)
* conduct model validations (cloud resolving and/or large-eddy simulation models)

*determine the balance of surface processes in the three regions of EPIC and compare to other regions
*Evaluate surface cloud radiative forcing and how it is related to cloud properties
*examine the coupling of ocean mixed layer processes with atmospheric processes

2. The EPIC2001 Field Program

2.1 Background on EPIC

The EPIC (Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System; Weller et al., 1999) program was born out of the inability of coupled ocean-atmosphere models to adequately predict the behavior of the atmosphere and ocean in the east Pacific region. EPIC is a part of the U. S. CLIVAR (Climate Variability and Change) program and consists of a combination of long term monitoring, intensive process studies, and modeling designed to increase our understanding of the east Pacific system and its interactions with its surroundings. EPIC2001 is a particular set of closely related process studies conducted during for a 7 week period between 5 September and 25 October of 2001 under the aegis of the overall EPIC program. These studies are focused on the dynamics of the cross-equatorial Hadley circulation along 95W, during the period in which it is strongest, and on associated processes which govern the SST and upper ocean structure.

NSF and NOAA/OGP funded the 2001 field program in elements bundled into ``super proposals'', each dealing with a particular aspect of the problem. The four bundles respectively address (1) the east Pacific ITCZ, (2) the cross-equatorial ITCZ inflow, (3) ocean processes, particularly in the east Pacific warm pool, and (4) the southern hemisphere stratus region. The scientific background for this project is given in the EPIC plan (Weller et al., 1999) and in the EPIC2001 Overview and Implementation Plan (Raymond et al., 1999).

2.2 EPIC 2001 Observational Tools

The specific observational tools deployed for EPIC2001 are listed briefly below:

* *NCAR C-130 aircraft* (*in situ, dropsondes, AXBT*): Study the airmass transformations and mesoscale structure in the cross-equatorial inflow into ITCZ convection along 95 W as far south as the south edge of the ITCZ. Document the north-south structure and variability in time of ocean currents, temperature, and salinity profiles along 95W .

* *NOAA WP-3D aircraft (in situ, dropsondes, AXBT, radar)* : Study 3-D mesoscale characteristics of convection and its environment over the east Pacific warm pool. Examine the spatial structure of ocean perturbations due to easterly waves.

**Galapagos Islands-based rawinsondes* : Document air mass transformations and their temporal variability in the cross-equatorial flow at the equator near 95 W.

**NOAA ship Ronald H. Brown atmospheric measurements and ocean measurements*: Document the structure of atmospheric convection as well as rainfall and its temporal variability in the ITCZ, ITCZ inflow, and stratus regions, and characterize fluxes (turbulent and radiative) and atmospheric aerosols. Examine the response of the ocean to atmospheric forcing, with particular emphasis on shortwave radiation absorption and entrainment from below into the ocean mixed layer.

**NSF R/V New Horizon (ocean temperature, salinity, light transmission, and conductivity microstructure profiles, horizontal currents, air-sea fluxes and precipitation, vertically pointing S-band radar)* : Examine the small scale spatial variability of the ocean in the ITCZ near the *Ron Brown* and along 95 W .

**Enhanced TAO moorings along 95 W* : Document the annual cycle of surface atmosphere temperature, pressure, wind, humidity, incoming shortwave and longwave radiation, and upper ocean temperature, salinity, and currents along 95 W .

**IMET mooring at 20 S , 85 W* : Document atmospheric energy fluxes in the stratus region south of the equator.

2.3 EPIC2001 Ship Observations

The *NOAA Ship Ronald H. Brown* (RHB) and the NSF ship *R/V New Horizon* jointly participated in EPIC2001. The RHB was equipped with a suite of instruments for measurements of atmospheric and oceanographic processes. The emphasis was on observations of precipitating systems, clouds, and atmospheric boundary layer structure and their coupling to oceanic mixed layer structure through the sea surface temperature field. Oceanographic measurements were the responsibility of the University of Washington (UW) and the University of California at Santa Barbara (UCSB). Rawinsondes and C-band Doppler radar operations were handled by Colorado State Univeristy (CSU) on leg I and by UW on Leg II. Aerosol and air chemistry measurements were done by the National University of Mexico (UNAM). A more detailed list of sensors and functions can be found at ftp://ftp.etl.noaa.gov/et7/anonymous/cfairall/EPIC/epic2001/cruise_instr/Instr-epic01_e.pdf.

The scientific objectives of the RHB deployment were:

*To observe and understand the ocean-atmosphere processes responsible for the structure and evolution of the large-scale atmospheric heating gradients in the equatorial and northeastern Pacific portions of the cold-tongue/ITCZ complex, including

(a) mechanisms governing temperature and salinity field evolution across the oceanic cold tongue through the ITCZ

(b) atmospheric planetary boundary layer structure and evolution from the equator through the ITCZ, primarily in the southerly monsoonal regime; and

(c) the processes determining the existence, character and strength of deep convection in the northeast Pacific ITCZ.

*To observe and understand the dynamical, radiative and microphysical properties of the extensive boundary layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime and their interactions with the ocean below.

On the first leg of the cruise, the ship operated predominantly in the ITCZ region near the TAO buoy at 95 W 10 N for joint measurements with the *R/V New Horizon* and the NCAR C-130 and the NOAA P-3 research aircraft. The RHB made a transect of the cold tongue region from 10 N to 0 N along the 95 W TAO buoy line with a diversion to the Galapagos Islands to exchange personnel (see Fig. 1). The second leg of the cruise started at the Galapagos Islands. For leg II the observations shifted focus to the study of the Stratocumulus region (see Fig. 1). The transect south along 95 W was continued toward 10 S and then tracked toward 85 W 20 S where the IMET buoy maintained by WHOI was changed out. The final portion of the EPIC cruise track was between the IMET buoy and Arica, Chile.

The *R/V New Horizon* spent roughly three weeks working near the RHB during its stay near 10 N 95 W. The New Horizon executed a mesoscale survey pattern around the RHB making oceanographic measurements of conductivity and temperature measurements with a towed Seasoar, horizontal currents with the ship's ADCP, and near-surface temperature and salinity. Meteorological measurements included sea-air fluxes and precipitation.

2.4 Preliminary ETL Results

EPIC2001 was a very large undertaking for ETL: 24 ETL scientist sailed on the RHB on at least one deployment leg (between Seattle and Arica) and 10 others participated in setup/teardown in port. In this section we will just give a few examples to illustrate some of the work being done with preliminary versions of the data (see section B for URLs to more complete data listings, etc).

The primary objective of legI was to study deep convection and its influence on air-sea interaction in the ITCZ. During the 18 days the RHB spent at 10 N 95 W we received about 600 mm of precipitation at the ship. As expected, the precipitation came in distinct bursts associated with the passage of easterly waves in the atmosphere (Petersen et al., 2002). Fig. 2 shows how strongly the surface fluxes were affected by the convective events: four events are apparent in the precipitation maxima in the upper panel. The convective events are characterized by large decreases (nearly 200 Wm^{-2}) in the net solar flux reaching the surface. There are also corresponding (but smaller) increases in the sensible and latent heat fluxes. There was a strong diurnal variation of precipitation with 80% of total accumulation between local midnight and noon. This variation was caused by squall lines propagating westward from land. A sample time-height cross section from the cloud radar shows one of the organized convective systems very clearly (Fig. 3). Note the deep cirrus outflow cloud ahead (starting about 0400) of the precipitation (mostly after 1500). This cloud system produced a 24-hr average net solar flux at the surface of 4 Wm^{-2}; that is the lowest 24-hr average ever recorded by the ETL flux group in a dozen tropical cruises.

On completion of the ITCZ study, the RHB departed 10 N 95 W and headed south, stopping periodically to service TAO buoys and take CTDs. The transect from 10 N to the equator gave a very clean depiction of the PBL transformation by airmass that crosses the equator and enters the ITCZ from the south. The boundary layer transition is associated with warm air from south of the equator that is stabilized by entering the equatorial cold tongue; as this stable air moves from the equator across the temperature front at 2-3 N it undergoes a rapid transition to convection (Fig. 4). This figure shows the wind speed (upper panel), sea (circles) and air (x's) temperatures (middle panel) and the sensible (circles) and latent (x's) heat fluxes as a function of latitude between 0 and 5 N. Note the sea surface temperature gradient is maximum at about 0.75 N while the wind speed and fluxes tend to peak near 2 N and then start to decline again. The NCAR C-130 obtained very similar results. These data on the PBL structure across the ITCZ-cold tongue complex will be a critical test for models.

Fig. 5 gives an example of remote sensing of cloud properties from legII. The liquid water path (upper panel) in the cloud is measured by two independent microwave radiometers. One is the ARM program standard 2-channel (23 and 31 GHz) system that we refer to as the *MAILBOX*: the other is a 3-channel (21, 31 and 90 GHz) ETL system referred to as *MMCR*. The lower panel shows backscatter intensity from the cloud radar with the cloud base height from the ceilometer. From the cloud radar we can determine the droplet size as a function of height in the cloud. This particular example shows moderate drizzle during the night and periods of clearing during the day. Daytime clearing was observed almost every day in the stratocumulus region even though the clouds were often 300-400 m thick at night. The diurnal cycle was much stronger that is typical off California (beyond the coastal influence). Because of this clearing, the net heat flux to the ocean averaged about 80 W/m^2 (in contrast to a net *cooling* of 30 W/m^2 observed at 10 N on legI). In this case the clouds have a smaller than expected effect on the surface heat budget of the ocean.

We have started to examine the radiative properties of the stratocumulus clouds using simple parameterizations of radiative transfer model results. To do this, we determine the mean transmission coefficient, Tr, for the cloud by dividing the observed solar flux by the expected clear sky solar flux at the surface. Once Tr is obtained for a specific solar zenith angle, we can infer the cloud optical thickness, τ. We are interested in parameterizing τ in terms of the cloud integrated liquid water path (LWP). Fig. 6 shows examples of relationships of τ to LWP using two different radiative transfer model parameterizations: one due to Stephens (1978) and one due to Dong et al. (1998). The Stephens parameterization yields a more scattered relationship, but that is misleading because the Dong parameterization uses LWP as part of the retrieval. Both methods indicate the clouds off Peru/Chile are less reflective than those off California but more reflective than those in the central equatorial Pacific. The conventional explanation is that the characteristic line describing the clouds is shifted upward by increased aerosols. We plan to study this issue in detail in our proposed research.

3.0 Scientific Objectives and Methods

3.1 Data processing, intercomparisons, and integration

All of our objectives require achieving high standards of quality in our data (through calibration, intercomparison, and reprocessing) and creating data sets that integrate information from multiple sensors. For example, five different systems on the *Ronald H. Brown* measured wind properties (ETL anemometers, rawinsondes, Doppler lidar, the C-band scanning Doppler radar, the 915 MHz Doppler wind profiler). These systems must be compared, problems corrected, and then integrated to provide a single high quality wind profile product that can be used by all EPIC investigators. Similarly, five different systems (radiative flux units, microwave radiometer, ceilometer, lidar, and the mm-wave cloud radar) measured different aspects of cloud properties. Similar lists can be made for precipitation, temperature/humidity, and turbulent fluxes.

EPIC2001 was the first deployment at sea of the ETL microwave radiometer system with an additional 90 GHz. This system was used because the standard microwave radiometers using channels at 21 GHz (more sensitive to vapor) and 31 GHz (more sensitive to liquid) have uncertainties in retrieved LWP in the tropics that are comparable to typical cloud LWP. Compared to the standard 31 GHz channel, 90 GHz is about 4 times as sensitive to cloud liquid water. Extensive work is required to assess the performance, calibration, and interpretation of this channel (Hazen et al., 2002). This is considered key to more accurate retrievals of low cloud liquid water amounts for EPIC2001.

ETL plans to collaborate with other EPIC investigators (see PROGRAM LINKAGES below) on numerous aspects of our proposed research. One major component is the study of the role of surface fluxes in the ocean mixed layer budgets. This requires the ocean microstructure measurements by Mike Gregg's group on the *Ronald H. Brown*, the spatial field measurements from Clayton Paulson's group on the *R/V New Horizon*, and the flux and near surface measurements made by ETL on the *Ronald H. Brown*. A similar study of the atmospheric boundary layer will be coordinated with UW using the transects from the NCAR C-130 and the fluxes and profiles from the *Ronald H. Brown*. Following the approach of the TOGA COARE flux working group, a careful platform (ship, buoy, aircraft) intercomparison will be done to generate the best estimates of fluxes (Burns et al., 1999; 2000)

3.2 Cloud Radiative Forcing Studies

One emphasis of our proposed work will be to use EPIC2001 observations to examine microphysical aspects of cloud forcing (CF) of the surface heat budget. CF, i.e., the difference in the mean flux and that which would be obtained in the absence of clouds, has seen extensive application as an index of the importance of clouds in the global heat balance (e.g., Ramanathan et al., 1995 for the tropics; Walsh and Chapman, 1998 for the Arctic). CF offers an important tool for diagnosing GCM treatments of cloud/radiative processes. Ramanathan et al. (1995) showed direct linkage between SFC and oceanic dynamics. Furthermore, Tian and Ramanathan (2002) have shown that CF is much more directly linked to atmospheric regional dynamics and moisture transports than, say, surface turbulent fluxes.

Cloud forcing can be inferred globally using satellite data at the top of the atmosphere (TOA, Ramanathan et al., 1989) and, although it is more indirect, at the surface. For surface cloud forcing (SCF), surface-based methods are more direct and more accurate, but provide limited sampling. Previous studies in the tropics have shown that the heavy water vapor burden in the boundary layer masks the longwave (LW) signal from clouds (Ramanathan et al., 1995) and SCF is dominated by the solar flux (LW SCF is about 5 to10 Wm^{-2} while SW SCF is -70 to -110 Wm^{-2}). In subtropical stratocumulus regimes, the solar component is more nearly balanced by the LW component and total SCF is perhaps closer to -30 Wm^{-2}.

The PACS enhanced monitoring program (Cronin et al., 2002) is expected to give good estimates from simple surface measurements of the annual cycle of SCF along 95 W and at the WHOI buoy site at 20 S 85 W. The interpretation of these long time series is critically dependent on detailed measurements obtained on the RHB during EPIC2001. The monitoring program will tell us what the SCF is, but the EPIC2001 data can tell us what cloud properties (cloud base height, thickness, droplet size, water/ice content, single vs multiple layers, etc) yielded the observed SCF. This increases the utility of this approach for GCM improvement because the GCM must get the correct SCF for the right reason. Our analysis will link observed radiative SCF with cloud properties following the approach of Intrieri et al. (2002) used for the Arctic. Our results will also be useful for improving satellite-based methods for deducing SCF.

3.3 ITCZ Studies

Turbulent Flux Parameterization. Developing and improving assessments of turbulent and radiative fluxes at the surface are critical to the PACS program. Bulk algorithms are widely used to estimate surface fluxes in numerical models and in applications (e.g., satellite retrievals) where highly detailed local information is not available. These are based upon similarity representations of the fluxes in terms of mean quantities

$$\langle w'x' \rangle = C_x \,\Delta X\, S = C_x \,\Delta X\, (U^2 + U_g^2)^{1/2}$$

where x can be the u,v wind components, the potential temperature, θ, the water vapor mixing ratio, q, etc, and C_x is the total transfer coefficient. ΔX is the sea-air difference in the mean value of x and S is the mean wind speed which is composed of a mean vector part (U and V components) and a gustiness part (U_g) to account for subgridscale variability. Fairall et al. (1996) linked Ug to variability associated with local boundary-layer convection. The COARE bulk algorithm is still being improved and version 3.0 was just released (Fairall et al., 2002). The EPIC 2001 cruise will provide more data to refine the algorithm; one major issue that still requires attention is the treatment of the effects of deep convection.

Several mechanisms for convective forcing and variability which involve the air-sea fluxes are discussed byYoung et al. (1992,1995). Large scale models (i.e., one that do not explicitly resolve convection), must account for variability associated with mesoscale convection (Vickers and Esbensen, 1998; Tong et al., 1998) to properly represent the balance of dynamics and thermodynamics driving the ITCZ cold-tongue complex. Numerical modeling work by Redelsperger et al. (2000) suggested that U_g can be additionally parameterized in terms of rainrate while Krueger and Zulauf (1997) used cumulus convective mass flux. The combination of the C-band Doppler radar, the vertically pointing precipitation profilers, and the direct flux measurements offer us a unique opportunity to examine such parameterizations with atmospheric data.

The Distribution and Radiative Impacts of High Clouds. Recent times have seen a resurgence of interest in high tropical cloud properties for their role in the chemistry of the upper troposphere and their influence on the water balance of the stratosphere (Dessler, 2002; Folkins et al., 1999). A continuing concern is the impact of high cirrus on the Earth's energy balance . It is now believed that most detrainment from tropical convection occurs below about 14 km (Folkins et al., 1999), while the radiative heating rate structure of the upper troposphere is still a matter of debate (Hartmann et al., 2001; Comstock et al., 2002). The combination of the cloud radar, 915 MHz wind profiling radar, surface downward radiative fluxes, and microwave radiometer allow us to examine this problem for the eastern equatorial Pacific (Matrosov et al., 1995). Our results can then be compared to those inferred for the western equatorial Pacific at Nauru by Comstock et al. (2002) and at Florida during CRYSTAL-FACE.

3.4 ABL Studies

The main focus of the ABL studies will be the balance of various terms of the surface energy budget coupled with the evolution of the atmospheric boundary layer structure as the flow crosses the equator and moves into the convergence zone. The presence of a fairly strong sea surface temperature gradient and a spatially varying large-scale convergence/divergence pattern leads to significant variations in surface fluxes and ABL properties. In EPIC2001 we obtained detailed information on ABL profile properties from the comprehensive ship-based remote sensors and the aircraft flights.

A variety of remote and *in situ* sensors will be used to address the diurnal cycle forcing of the ABL. The properties in this region are almost unexplored (Bond et al. 1992). The surface fluxes (turbulent and radiative) will provide the surface forcing and the combination of the wind profiler, Doppler lidar, and cloud radar will provide mean velocity and turbulence structure throughout the PBL up to an beyond the trade inversion. The DIAL lidar will provide information on the evolution of moisture profiles in the same layers. These measurements will complement the rawinsonde, C-band radar and aircraft measurements and will provide a continuous link between surface forcing and convective activity. This will provide an unprecedented look at shallow ('popcorn') convection and its role in moistening the upper PBL. The data will indicate the surface heat balance of the ocean in the ITCZ, shallow convection, and stratocumulus regimes.

3.5 Stratocumulus Studies

Cloud Microphysics Retrievals. Retrievals of cloud or drizzle microphysics using a combination of a cloud radar and microwave radiometer were first demonstrated by Frisch et al. (1995). The method is based on relating measurements to three parameters that characterize the cloud droplet spectrum as a lognormal distribution. Subsequent explicit modeling studies (Frisch et al. 1998) have shown the method is well-founded (essentially there is strong correlation between the 3rd and 6th moments of the distribution) and that the retrieval of the profile of liquid water is independent of the assumed distribution width. Frisch et al. (2000) have developed a method to reduce the sensitivity of the retrievals to the assumed value of the droplet distribution normalized width which compared with *in situ* aircraft measurements within ±0.03 gm^{-3} . Recent work by Frisch et al, 2002 shows that a good retrieval can be done without the use of the microwave radiometer integrated liquid water measurements for retrieving the droplet effective radius. This retrieval relies on the 35 GHz reflectivity alone and is not very sensitive to the cloud droplet concentration nor the spread of the droplet spectra.

So far, cloud retrievals have not been possible when backscatter from drizzle swamps the cloud signal. In those conditions, the Frisch method gives complete characterization of profiles of drizzle size and number concentration which, combined with the surveys of the C-band radar, give a unique view of drizzle in marine stratocumulus. The addition of the Doppler lidar will simplify the diagnosis of the presence of drizzle and improve retrievals (Eberhard et al. 1997) and may allow us to extend cloud retrievals to greater drizzle concentrations.. Also, the PBL aerosol measurements will allow us to examine relationships between aerosol and drizzle droplet concentrations (see below).

Cloud Radiative Flux Parameterization. One critical part of characterization of stratocumulus clouds is their effects on the radiative balance. Fairall et al (1990) and Dong et al. (1998) have developed methods based on measurement of downward radiative flux and cloud integrated liquid water content. Such parameterizations are similar to those found in climate models (e. g., Slingo 1989; Chou et al. 1995; Gultepe et al. 1996). The Fairall model was extended to broken clouds by Chertock et al. (1993). One source of ambiguity in these models is the number of cloud droplets. However, this is thought to be closely linked to the aerosol CCN concentration (White et al. 1995). This cruise, which will be the first to combine solar flux, cloud liquid water, cloud radar, and aerosol measurements, will allow us to examine this issue. We will also compare the solar transmission-derived optical depths to those from MODIS and MISR. This should help boost confidence in both techniques since they are each subject to slightly-different sources of error.

Aerosol-cloud interactions. The extent to which lidar backscatter increases with relative humidity RH provides very useful information on the hygroscopic properties of aerosol (Wulfmeyer and Feingold 2000; Feingold and Morley 2002). We will use lidar data to assess aerosol hygroscopicity in well-mixed, cloud capped boundary layers. Under the latter conditions, the vertical profile of RH is well-defined and the strong signal from cloud base (saturation) provides a valuable "calibration point". Humidigrams that define the increase in lidar backscatter as a function of RH can be derived. This approach will be applied to all data that meet the criteria of well-mixed, non-drizzling cloud-capped boundary layers. The variability in humidigrams will be correlated with source regions and long-range transport (using back trajectory analysis).

Precipitation formation. This will be addressed using surface observations of aerosol (total CN count) as well as cloud radar, radiometer, and lidar. Together these measurements provide important constraints for our large eddy simulation (LES) model. The LES is coupled to a size-resolving cloud microphysical model (Feingold et al. 1999a) which is has been applied in numerous stratocumulus drizzle simulations and is ideally suited for addressing the question of drizzle formation and its dependence on aerosol concentrations. We will use LES to explore sensitivity to aerosol parameters, liquid water path, boundary layer depth, and entrainment rates, and attempt to parameterize precipitation production in terms of such parameters.

Effect of precipitation on boundary layer dynamics. Precipitation redistributes heat and water vapor in the vertical and has a strong effect on boundary layer stability. The 35 GHz radar will be used to quantify rainrate using the technique of Frisch et al. (1995). We will examine the feasibility of incorporating lidar backscatter and/or fall-velocities into these retrievals. Doppler radars can also measure turbulence properties from velocity spectra so that a link between precipitation amount and boundary layer turbulence can be inferred (e.g. Stevens et al., 1998; Feingold et al. 1999b). Both model simulations and observations will be used to study this problem. A particularly interesting point is whether boundary layers can maintain well-mixed conditions when drizzle rate is significant.

5. Program Linkages

This proposal is related to ongoing work in the PACS/EPIC monitoring studies (Fairall at ETL and N. Bond at PMEL). Work will be done cooperatively on ITCZ and deep convective aspects with Rutledge and coworkers at CSU; the ITCZ transition to the equatorial cold tongue with S. Esbensen

(OSU) and Chris Bretherton (UW); the microphysics and radiative coupling of stratocumulus clouds with Chris Bretherton and Sandra Yuter (UW). ETL will work closely with M. Greg (UW - ocean microstructure measurements) and C. Paulson (OSU - ocean surveys on the *R/V New Horizon*) to determine the balance of processes forcing the ocean mixed layer.

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7. Figures

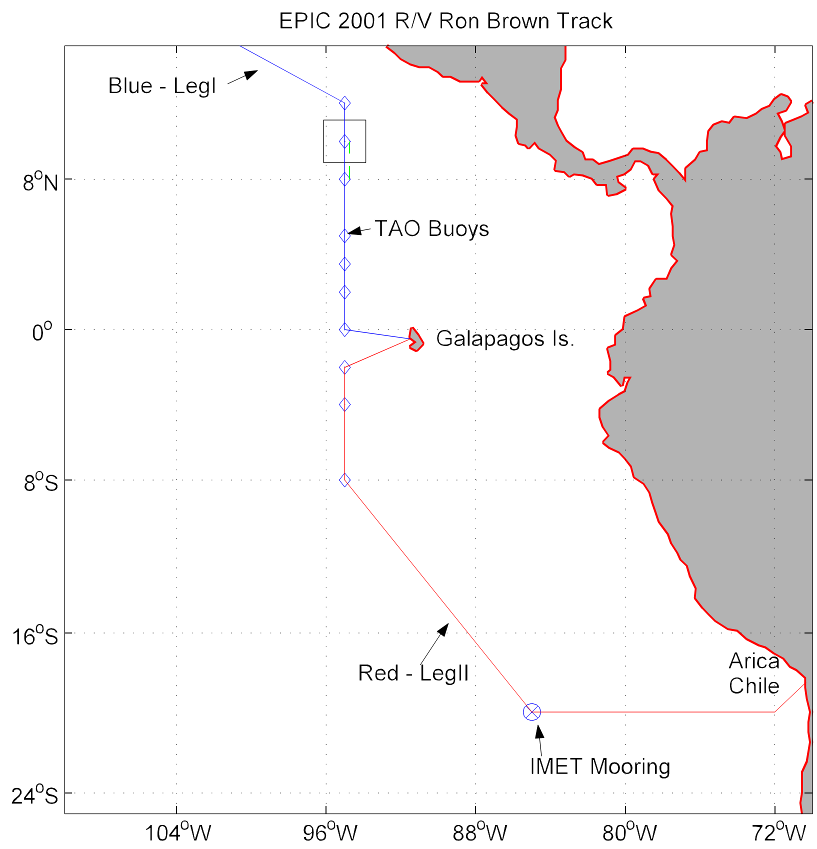


Figure 1. Cruise track for the *NOAA Ship Ronald H. Brown* for EPIC2001. The large square box indicates the primary ITCZ operation region. TAO buoys are the small circles; the WHOI IMET buoy at 20 S 85 W is indicated by the circled X.

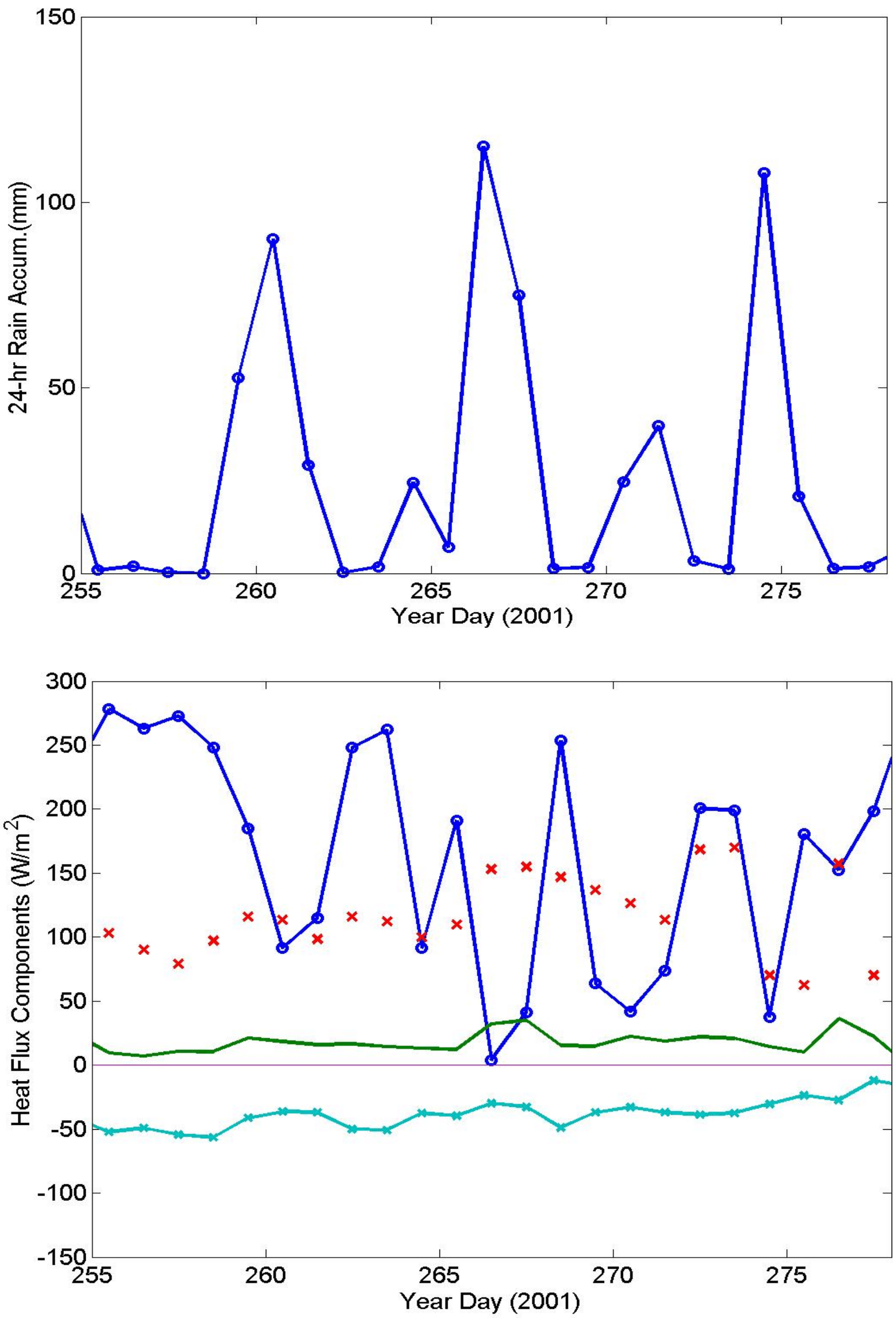


Figure 2. ITCZ time series of daily-averaged rainfall (upper) and flux components (lower panel). The flux components are net solar warming of the ocean (blue circles); net IR cooling (cyan); sensible heat (green line) and latent heat (red x's). The periodicity evident in the precipitation and fluxes is caused by the passage of atmospheric easterly wave disturbances.

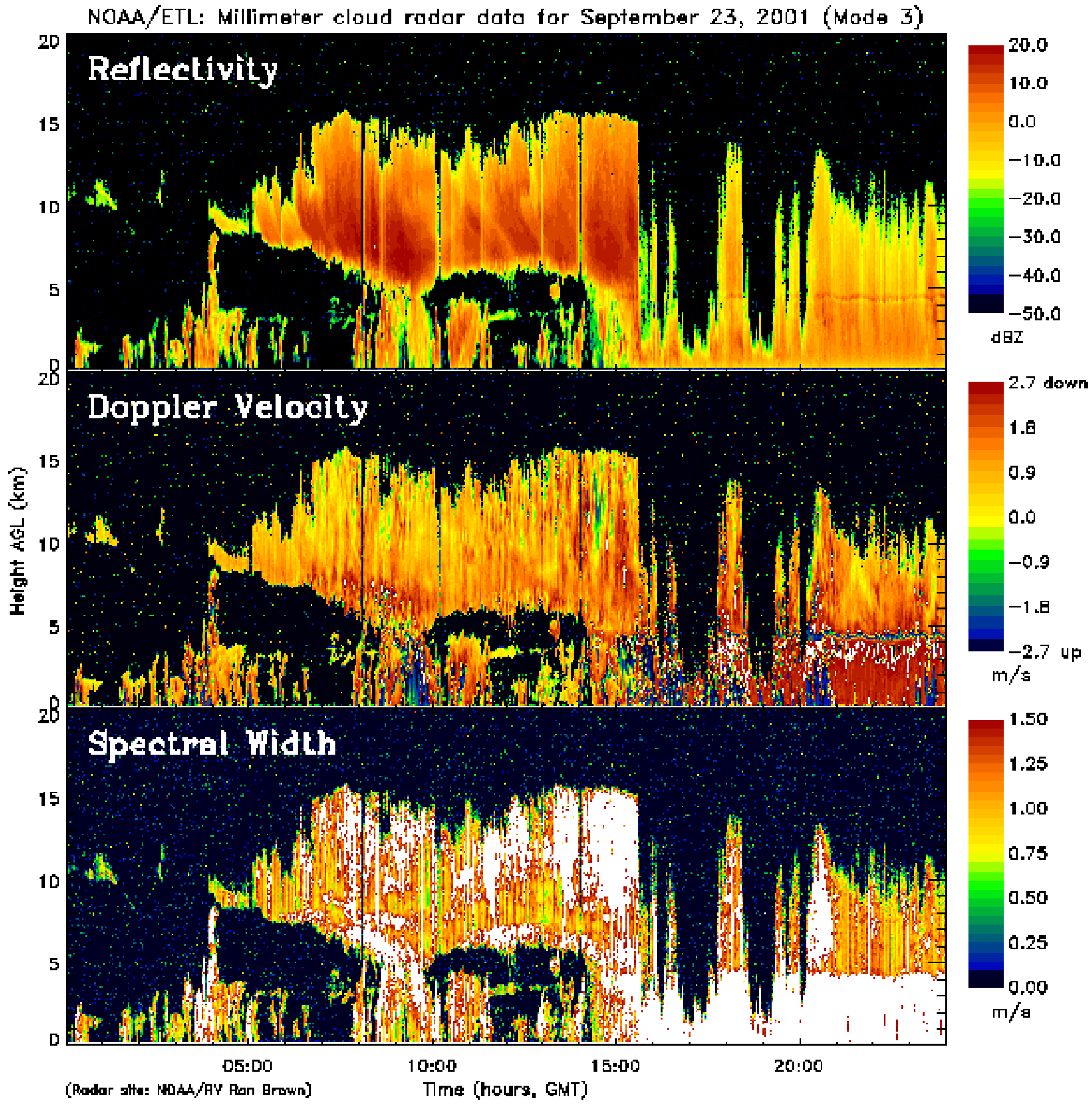


Figure 3. Time-height cross section from the 35 Hhz cloud radar for September 23, 2001 (Day 266) showing a period of deep convection. Upper panel shows the backscatter intensity (calibrated). The melting layer is apparent as the bright band at about 4.5 km near the end of the period; clouds above this altitude are predominantly ice. Middle panel is the mean Doppler shift of the return showing the fall velocity of the particles combined with the air motion. Heavy rain appears in blue and red colors. Attenuation of the return by heavy rain is apparent in the black vertical regions around 1700 and 1900.

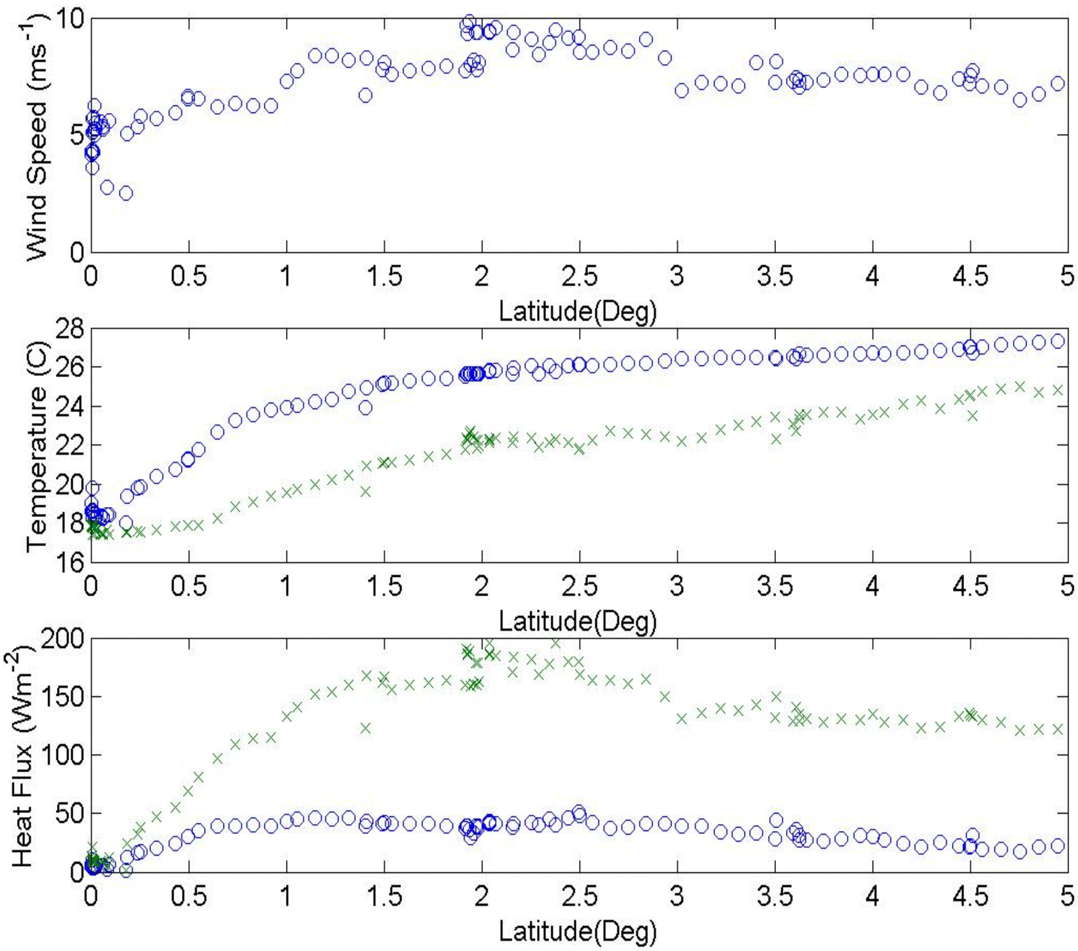
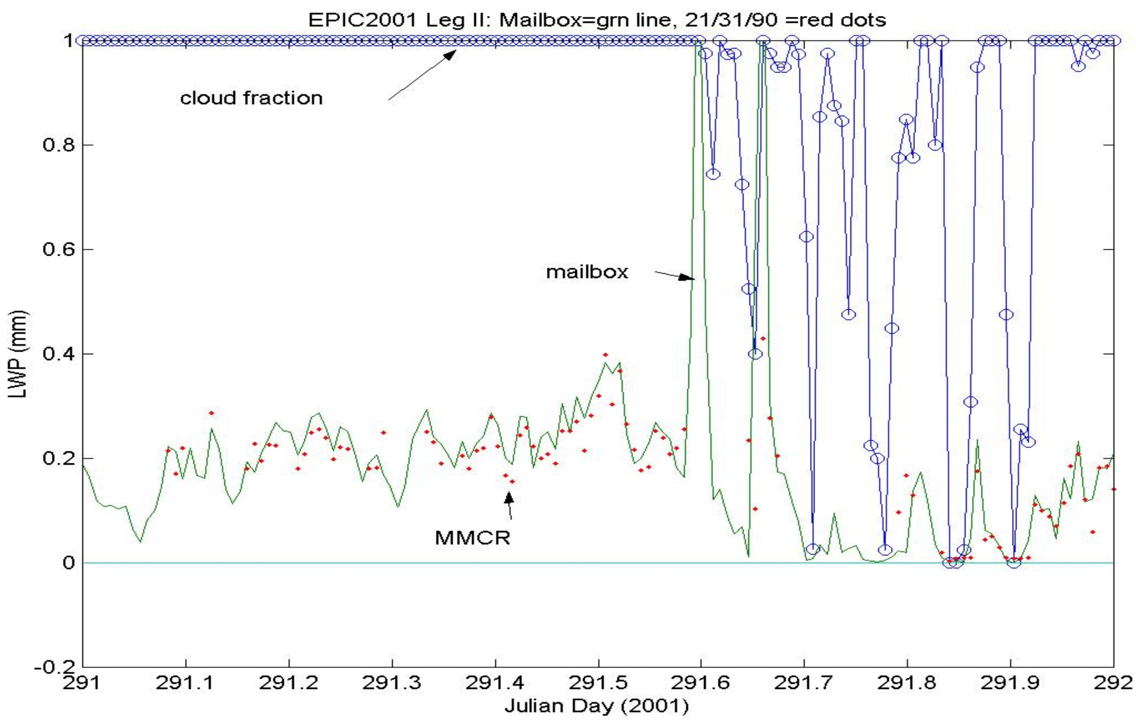


Figure 4. Near-surface properties measured on the transect from the S edge of the ITCZ, through the ITCZ entry region, and into the suppressed boundary layer at the equatorial cold tongue: wind speed (upper panel); SST- blue circle and air T - green x's (middle panel); sensible heat flux - blue circles and latent heat flux - green x's (lower panel). Fluxes are suppressed in the stable boundary layer caused by warm air crossing the cold tongue from the south. The warm SST front triggers convective turbulence which increases fluxes and mixes down higher momentum (thus, the increase in wind speed).



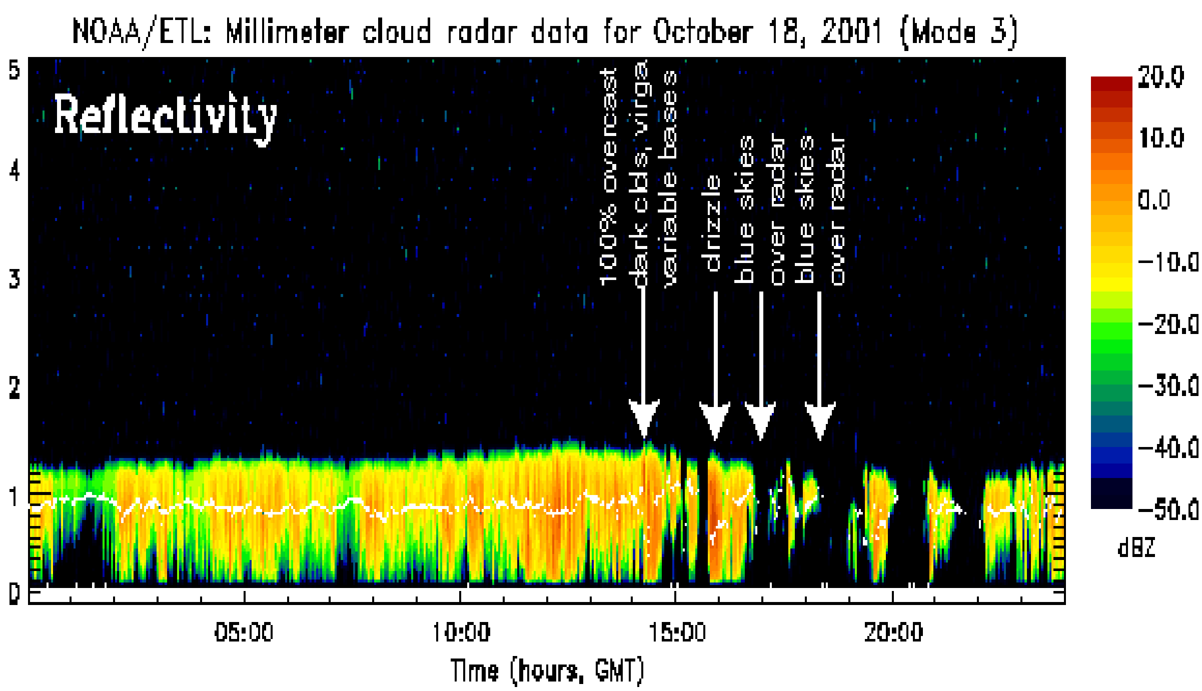
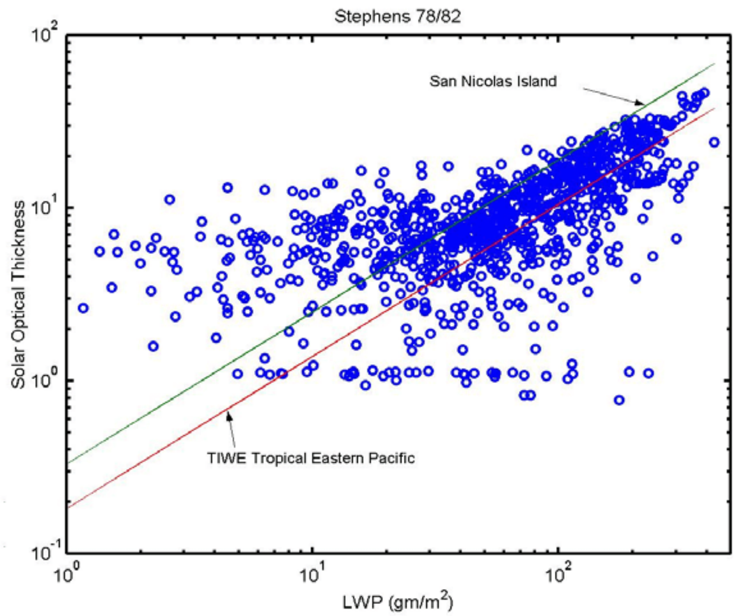


Figure 5. Stratocumulus cloud characteristics on Oct. 18, 2001. Upper panel: total liquid water path (LWP) from two microwave radiometer systems (green line and red dots) and cloud fraction from a ceilometer (blue circles). Lower panel: cloud radar backscatter intensity (color contours) and ceilometer cloud base heights (white dots).



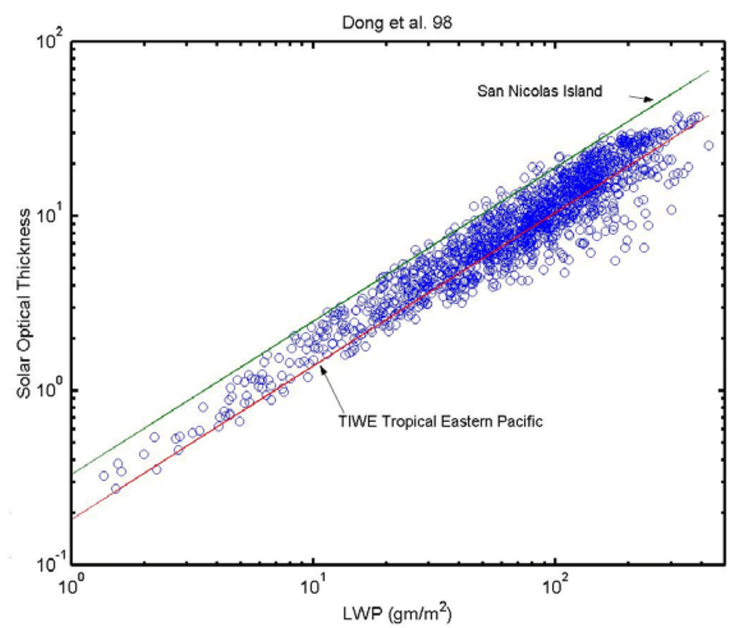


Figure 6. Optical thickness computed from μ=cosine(solar zenith angle), Tr, and LWP using the model of Stephens (1978, upper panel) and model of Dong et al. (1998, lower panel) as a function of LWP. The green line is a mean curve from measurements made at San Nicolas Island off the coast of California in 1987. The red line is from ship measurements made near the equator at 145 W longitude in 1992. These characteristic lines are typical of the kinds of relationships used in climate models.

D. Biographical Summaries

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PROFESSIONAL PREPARATION:

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RESEARCH AREAS:
Air-sea interaction, measurements of fluxes, remote sensing of boundary layer and cloud properties, atmospheric turbulence, cloud-radiative coupling, parameterizations of turbulent and cloud properties, atmospheric dispersion.

PROFESSIONAL APPOINTMENTS:

1971-1977	Adjunct Professor of Physics, Naval Postgraduate School, Monterey, CA.
1978-1983	Principal Staff Member, BDM Corporation, Monterey, CA.
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RECENT and RELEVANT PUBLICATIONS:

Fairall, C. W., J. E. Hare, and J. B. Snider, 1990: An eight-month sample of marine stratocumulus cloud fraction, albedo, and integrated liquid water. *J. Clim.*, **3**, 847-864.

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[13 other recent publications not shown in the interest of saving paper]

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Member of the National Academy of Sciences Committee on Coastal Meteorology: 1990-1993
General Co-Chairman of the 3rd International Symposium on Tropospheric Profiling: Hamburg, Germany, August, 1994
Associate Editor of Journal of the Atmospheric Sciences: 1991-1994
Member of the NSF Coastal Ocean Processes (CoOP) advisory committee: 1991-1994
Member, International Geophysical Union International Climate Dynamics and Meteorology Working Group A (Boundary Layers and Air-Sea Interaction), 1996-Present.
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PROFESSIONAL PREPARATION:

University of Colorado	Aerospace Engineering Sciences	Ph.D., 2002
University of Colorado	Aerospace Engineering Sciences	M.S., 1996
Colorado State University	Atmospheric Sciences	M.S., 1991
Pennsylvania State University	Meteorology	B.S., 1985

RESEARCH AREAS:
Lidar and radar remote sensing and synthesis, atmospheric radiation, climate processes and cloud interactions, thunderstorm dynamics, atmospheric optics, polar and tropical clouds, sea breeze structures

PROFESSIONAL APPOINTMENTS:

NOAA/ETL, Atmospheric Lidar Division;	May 1987 - Present
NOAA/ETL, Meteorological Applications Division;	September 1985 - April 1987
NOAA/Forecast Systems Laboratory;	May - August 1985

GRADUATE ADVISORS:

Judith Curry	University of Colorado
Graeme Stephens	Colorado State University
Dennis Thomson	Pennsylvania State University

RECENT and RELEVANT PUBLICATIONS:

Intrieri, J.M., C.F. Fairall, O.G.P. Persson, M.D. Shupe, and R.M. Moritz, 2002: Annual cycle of cloud forcing over the Arctic. *J. Geophys. Res*. (in press).

Intrieri, J.M., M. Shupe, B.J. McCarty, T. Uttal, 2002: Arctic cloud statistics from lidar and radar at SHEBA. *J. Geophys. Res*. (in press).

Key, J.R., and J.M. Intrieri, 2000: Cloud particle phase determination with the AVHRR. *J. Appl. Meteor*., **39**, 1797-1804.

Bretherton, C.S., S.R. DeRoode, C. Jakob, and J.M. Intrieri, 2000: A comparison of the ECMWF forecast model with observations over the annual cycle at SHEBA. *J. Geophys. Res*. (in press)

Intrieri, J.M., W.L. Eberhard, T. Uttal, J.B. Snider, Y. Han, J.A. Shaw, B.W. Orr, and S.Y. Matrosov, 1995: Multi-wavelength observations of a developing cloud system: The FIRE II 26 November 1991 case study. *J. Atmos. Sci.,* **52***,* 4079-4093.

Intrieri, J.M., G.L. Stephens, W.L. Eberhard, and T. Uttal, 1993: A method for determining cirrus cloud particle sizes using a lidar and radar backscatter technique. *J. Appl. Meteor.,* **32**, 1074- 1082.

Intrieri, J.M., C.G. Little, W.J. Shaw, P.A. Durkee, R.M. Banta, and R.M. Hardesty, 1990: The Land/Sea Breeze Experiment (LASBEX). *Bull. Amer. Meteor. Soc.*, **71**, 656-664.

Intrieri, J.M., A.J. Bedard, Jr., and R.M. Hardesty, 1990: Details of colliding thunderstorm outflows as observed by Doppler lidar. *J. Atmos. Sci.*, **47**, 1081-1098.

SCIENCE COMMITTEES, AWARDS, ASSOCIATIONS:

GEWEX Cloud System Study, Working Group V member
SHEBA Science Team member
FIRE Science Team member
ARM Science Team member
Committee on Laser Atmospheric Studies member
Gordon Conference Session Chairperson
Radiation Conference Session Chairperson
International Radiation Symposium Session Chairperson
Lidar Symposium Session Chairperson
WMO/Vaisala paper award finalist
NOAA outstanding paper award nominee
American Meteorological Society member
American Geophysical Union member
Optical Society of America member

COLLABORATORS AND AFFILIATIONS:

Jeff Key - University of Wisconsin
Judith Curry - Georgia Tech
Dave Turner - Pacific National Laboratory
Joe Shaw - Montana State University
Larabee Strowe - University of Maryland
James Pinto - University of Colorado
Chris Bretherton - University of Washington

E. Budget Details

1. Timetable

FY03

Complete turbulent flux processing and intercomparisons with R/V New Horizon and C-130 aircraft mean meteorology, turbulent and radiative fluxes.
Complete microwave radiometer studies and redo vapor/liquid retrievals
Create integrated wind and moisture profile data base
Begin cloud microphysical retrievals (ITCZ and stratus)

FY03

Create integrated cloud, turbulent and radiative flux data base
Continue improvements to cloud microphysical retrievals
Begin LES cloud-aerosol microphysics modeling
Begin evaluations of cloud forcing components
Begin parameterization of mesoscale convective effects on bulk flux parameterizations
Begin work with UW groups on stratocumulus entrainment and drizzle
Begin work with UW, UCSB, and OSU groups on ocean heat and moisture budgets.

FY03

Complete LES cloud-aerosol microphysics modeling
Evaluate parameterizations of drizzle production
Complete parameterization of mesoscale convective effects on bulk flux parameterizations
Complete cloud microphysical-radiative flux parameterization studies
Complete work with UW groups on stratocumulus entrainment and drizzle
Begin work with UW, UCSB, and OSU groups on ocean heat and moisture budgets.

2. Personnel Duties

C. Fairall will be the PI. General division of duties will be as follows:

Air-Sea covariance processing: J. Hare
Cloud radar: T. Uttal, M. Ryan, and D. Hazen
Microwave radiometer: D. Hazen
Lidar systems: J. Intrieri and B. McCarty
Precipitation analysis: G. Feingold, M Ryan, and S. Matrosov
Flux parameterization: A. Grachev, C. Fairall
ABL analysis: D. Wolfe, C. Fairall
ITCZ cloud retrievals: P. Zuidema, S. Matrosov, and J. Intrieri
Stratocumulus cloud retrievals: A. S. Frisch, S. Matrosov, and J. Intrieri
Stratocumulus modeling: G. Feingold
Data integration: M. Falls

The costs of this proposal include analysis, creation of datasets for sharing with other EPIC investigators, scientific interpretation, and modeling. The reprocessed air-sea flux, microwave, wind profile, and lidar data will be made available to the oceanographic component as quickly as possible.

F. Current and Pending Support

PI: C. Fairall, 1 Co-I; Amount: $419,400 for FY99-02: Status - current; NOAA PACS Program
C. Fairall: 2 mo/yr;
Title: Shipboard monitoring of stratocumulus cloud properties in the PACS region

PI: C. Fairall, 4 Co-I; Amount: $896,400 for FY00-02; Status - current; NOAA PACS Program
C. Fairall: 2 mo/yr; T. Uttal: 2.0 mo/yr; J. Intrieri: 1.67 mo/yr
Title: Shipbased cloud and precipitation air-sea interaction studies: EPIC2001

PI: J. Hare, C. Fairall Co-I; Amount: $291,700 for FY00-02; Status - current; NOAA Carbon Cycle
C. Fairall: 1 mo/yr;
Title: Direct measurements of gas transfer over the open sea: Instrumentation and techniques

PI: C. Fairall, 1 Co-I; Amount: $379,800 for FY01-04; Status - current; Office of Naval Research
C. Fairall: 2 mo/yr
Title: Measurement of sea spray droplet distributions at high winds

PI: Taneil Uttal, 4 Co-I;Amount: $407,500 for FY98-02; Status - current
T. Uttal: 3.0/year; NASA/CIRES/EOS
Title: Validation of CERES Cloud Retrievals over the Arctic with Surface-Based Millimeter-Wave Radar

PI- Taneil Uttal - 6 Co-I; Amount: FY 99-02 $353,000; Status - current; NASA FIRE-ACE
T. Uttal: 1.3 months/year; J. Intrieri: 2 months/year
Title: Ground Based and Remote Sensing of the Microphysical and Radiative Properties of Clouds: Comparisons with Mid-Latitude and Sub-Tropical Systems

PI: Taneil Uttal, 3 CO-I; Amount: FY01-FY03 $231,550; Status - current; NSF/SHEBA
T. Uttal: 2.0; J. Intrieri: 1.33
Title: Processing of Radar, lidar and radiomeer data sets to produce cloud microphysical and optical properties for the SHEBA annual cycle

PI: Intrieri and 1 Co-I; Amount: FY02-04 $209,000; Status - current; DOE/ARM
J. Intrieri: 2.5 months/year
Title: Using Radar, Lidar and Radiometer data from NSA and SHEBA to quantify cloud property effects on the Arctic surface heat budget