Enhanced Oceanic and Atmospheric Monitoring for the Eastern Pacific Investigation of Climate Processes (EPIC) Experiment

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The Eastern Pacific Investigation of Climate Processes (EPIC) is a five-year experiment to improve the understanding of the intertropical convergence zone (ITCZ), its interaction with the cool water that upwells along the equator in the eastern Pacific, and the physics of the stratus cloud deck that forms over the cool waters off South America. EPIC fieldwork began in 1999 and involves short-term process studies, embedded within longer-term enhanced monitoring built on the El Niño Southern Oscillation (ENSO) observing system. At this writing, we are half-way through the enhanced monitoring portion of the experiment and have just completed the two-month process study EPIC2001. In this report, we review the status of the EPIC program and present some preliminary scientific results from the enhanced monitoring data set.

The Perplexing Eastern Pacific Stratus Deck / Cold Tongue / ITCZ Complex

The eastern tropical Pacific near the Pan American land mass is characterized by southerly winds that blow from the cool waters off the coast of South America, across the equatorial cold tongue, and into the ITCZ (Figure 1). Cool southern hemisphere waters are shaded by a persistent stratus cloud deck, while convection tends to form in the ITCZ over the warm waters north of the equator. Variations to the stratus deck / cold tongue / ITCZ complex occur on a variety of time scales and can have far reaching consequences. During El Niño, the equator becomes anomalously warm, central Pacific trade winds weaken, and convective rainfall shifts eastward and equatorward across the tropical Pacific. As a consequence, global circulation patterns are affected, with stronger than normal Jet Streams over the eastern Pacific and extratropical storms and frontal systems that follow altered paths.

The eastern Pacific stratus deck / cold tongue / ITCZ complex also has a large annual cycle, despite the fact that the sun crosses the equator twice per year. From February through April, eastern Pacific equatorial waters are warm, trades are weak, and equatorial upwelling is reduced. In contrast, from August through October, equatorial waters are cool, stratus extends to the equator, trades are strong, and southerly winds and convection extend to Central America. North of the ITCZ, in the northeast Pacific warm pool, winds have a monsoon-like character, blowing onshore during the northern hemisphere summer and offshore during the northern hemisphere winter. At times, these circulations are accompanied by strong low-level jets through the gaps in the American cordillera. Positive wind stress curl associated with the gap winds and ITCZ cause localized upwelling, resulting in a cool area in the warm pool in association with an upward doming of the thermocline. As is typical in upwelling zones, the "Costa Rican Dome" has extremely productive fisheries.

Besides annual and interannual variability, there is also substantial variability on shorter timescales. ITCZ convection is not steady, but instead tends to occur episodically on time scales of a few days. This convective variability is thought by some to be related to the impingement of African easterly waves on the eastern Pacific, while others believe it to be an intrinsic instability of the atmosphere. In either case, this convective variability is intimately related to the development of east Pacific tropical storms. Indeed, the northeastern tropical Pacific warm pool is the most prolific producer of tropical cyclones per unit area in the world and, on average, 9 of these cyclones reach hurricane strength each year.

The frontal region between the warm ITCZ water and the equatorial cold tongue is also the site of active coupled ocean-atmosphere variability. As air blows across this front, the atmospheric boundary layer (ABL) becomes unstable, so that dry air and strong southeasterly momentum are carried down to near the surface. Thus, the sea surface temperature (SST) frontal region is also a frontal region in ABL winds and moisture. Undulations in the SST front by, for example, tropical instability waves are often reflected in the wind stress and cloud fields [Chelton *et al.*, 2001]. How these cloud and wind stress divergence and curl patterns feedback to affect the oceanic SST front is an area of active research.

General circulation models (GCMs), though steadily improving, are unable to properly reproduce much of this structure and variability. In particular, coupled GCMs tend to produce SSTs that are too warm south of the equator, and an equatorial cold tongue that is too cold, too narrow, and extends too far west. Likewise, coupled GCMs tend to produce too much convection south of the equator, due to either the presence of a spurious southern hemisphere ITCZ or due to a northern hemisphere ITCZ that migrates seasonally across the equator [Mechoso *et al.*, 1995]. Both features are unrealistic and are caused in part by poor parameterizations of low-level stratus cloud prevalent over the cold waters off South America [Philander *et al.*, 1996]. Ultimately, progress can be best made by obtaining a validation data set, and improving our understanding of the ocean-atmosphere boundary layer structure, its variability, and governing processes. Recognizing this, it was recommended that a comprehensive program be initiated directed towards quantifying the meridional structure of the eastern Pacific coupled ocean / atmosphere boundary layer complex. Thus was born EPIC.

EPIC Fieldwork

The scientific objectives of EPIC are:

1. To observe and understand the ocean-atmosphere processes responsible for the structure and

evolution of the large-scale heating gradients in the equatorial and northeastern Pacific portions of the cold tongue / ITCZ complex.

2. 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, their interactions with the ocean below, and the evolution of the upper ocean under the stratus deck.

EPIC fieldwork involves both long-term enhanced monitoring and short-term process studies. In September and October 2001, the process study EPIC2001 took place, involving two ships (NOAA ship Ron Brown and NSF R/V New Horizon), two aircraft (a NOAA P-3 and a NSF/NCAR C-130), and over 50 scientists and technicians from the U. S., Mexico, Chile, Ecuador, and Australia. EPIC2001 foci included an intensive ocean and atmosphere study in the convective region of the ITCZ near 10°N, 95°W; multiple transects along 95°W probing the coupled boundary layer structure from the equatorial region, across the SST front and into the ITCZ; and an exploratory study of the stratus deck cloud microphysics. To place these measurements within the large-scale, longer-term framework, EPIC2001 analyses will rely upon data from the EPIC enhanced monitoring array.

Enhanced monitoring for EPIC has built upon pre-existing and historical observing platforms, such as the historical NOAA National Data Buoy Center mooring site in the stratus deck region near 20°S, 85°W, the easternmost (95°W) line of the Tropical Atmosphere and Ocean (TAO) mooring array, and the NOAA ships which maintain the 95°W and 110°W TAO moorings (Figure 1). The TAO mooring array itself is a major element of the ENSO observing system [McPhaden *et al.*, 1998], with nearly 70 buoys arranged across the tropical Pacific between 8°S to 8°N along 10 meridional lines. Enhanced monitoring for EPIC began in late 1999 and will continue through 2003. The duration of the enhanced monitoring (3-4 years) is long enough to capture several annual cycles, and some aspects of ENSO-related variability. Below, we briefly describe each element of the EPIC enhanced monitoring system and provide an early glimpse of some intriguing results.

Boundary layer measurements from the NOAA ships servicing the TAO array

TAO moorings are typically recovered and redeployed on a yearly basis, and a NOAA ship visits each TAO line twice per year to perform repairs, as well as planned recoveries and deployments. The 95°W and 110°W TAO lines are visited during the fall by the NOAA ship Ron Brown and during the spring by the NOAA ship Ka'imimoana. Routine shipboard measurements include CTDs and underway ADCP and there is now a growing data base of meridional sections of ocean temperature, salinity, and horizontal velocity from these visits [Johnson *et al.*, 2000]. As part of EPIC enhanced monitoring, the 95°W and 110°W TAO cruises also support radiosonde launches to measure the atmospheric thermodynamic and wind structure. Additionally, during these cruises, the NOAA ships are instrumented with a package to make direct measurements of turbulent fluxes of heat, moisture, and momentum, downwelling solar and infrared (IR) irradiance, and accurate measurements of mean meteorology (air and sea temperature, relative humidity, wind). The package also includes microwave radiometer, S-band radar and ceilometer cloud and precipitation measurements which allow for the computation of low cloud statistics (integrated liquid water content, cloud base height, and fraction), cloud IR, visible optical thicknesses, and surface cloud radiative forcing. Cloud forcing, a key diagnostic variable in climate models, is the difference between downwelling radiation observed at the surface and what the radiation would be in the absence of clouds. Preliminary analyses of these data are available at: http://www7.etl.noaa.gov/programs/PACS/ .

During the first enhanced monitoring TAO transect along 95°W (November 23 through December 3 1999) there was a prominent SST cold tongue along the equator and the ITCZ was found near 7°N, 95°W (Figure 2). South of 7°N, the top of the ABL was near the 300°K virtual potential temperature isotherm and the zero isotach (v~0 contour), suggesting that the top of the ABL was a quasi-material surface and that there was little transfer between the ABL and upper atmosphere. The ABL was relatively cool, shallow, and statically stable over the cool waters south of the ITCZ (Figure 2a) and bears at least some resemblance to a density current.

Surprisingly, tall convective clouds in the ITCZ region had less of an effect on the surface solar radiation than the low-level stratiform cloud deck found on the northern edge of the cold tongue near 3°N (Figure 2b). The stratiform cloud were most likely formed locally through air-sea interactions since the strong cloud forcing at 3°N was coincident with high latent and sensible heat loss (Figure 2c). The meridional gradient in latent heat flux was quite large in the frontal region. Latent heat flux had a minimum (13 Wm^{-2}) at the center of the cold tongue near 1°S and maximum (130 Wm^{-2}) at the northern edge of the cold tongue near 3°N. Without ocean dynamics maintaining the SST gradient, or without other compensating heat fluxes, this large latent heat flux gradient could potentially remove the SST gradient in roughly a month. Clearly, good spatial sampling is required to properly resolve the structure of the cold tongue / ITCZ complex. However, there is also considerable temporal variability in the system and for this moorings provide an ideal measurement platform.

Enhanced 95°W TAO moorings

As part of EPIC enhanced monitoring, the easternmost TAO 95°W line (with sites at 8°N, 5°N, 2°N, 0°, 2°S, 5°S, and 8°S) has been enhanced with additional moorings at 3.5°N, 10°N, and 12°N to better resolve the front at the northern edge of the cold tongue and extend the line through the ITCZ and into the northeastern tropical Pacific warm pool. In addition to the standard TAO measurements (wind speed and direction, air temperature, relative humidity, and 1-m surface temperature and 10 subsurface temperatures to 500 m depth), each of these 10 buoys along 95°W was enhanced with shortwave and longwave radiometers, a rain gauge, barometric pressure, extra thermistors to better resolve the mixed layer, 7 conductivity sensors to measure salinity down to 120 m, and an acoustic Doppler current meter at 10 m depth. On the 5°N to 5°S moorings, where substantial shear exists near the surface, an acoustic current meter at 40 m was added. By applying a bulk flux algorithm to these data, latent and sensible heat flux can be computed. Thus, these data provide a picket fence of time series for heat, moisture, and momentum fluxes, and upper ocean temperature, salinity, and for horizontal currents along 95°W from the stratus deck region at 8°S through the cold tongue / ITCZ complex to 12°N.

TAO enhancements began in November 1999 and will continue through Fall 2003. Daily averages of nearly all quantities are telemetered to shore via Service Argos and made available within one day at Pacific Marine Environmental Laboratory maintained databases. Data are also made available in realtime to operational meteorological and oceanographic centers via the Global Telecommunications System (GTS). High-resolution ~10-minute data are available in delayed mode (typically within a couple months of recovery) via PMEL and national archives.

For more information and to access the data, see: http://www.pmel.noaa.gov/tao/epic/.

The 10°N, 95°W enhanced TAO buoy is of particular interest as this was the site of the ~20-day EPIC2001 ITCZ survey. For brevity we show here only incoming solar radiation, Q_{sol} (Figure 3a). While the record-averaged Q_{sol} was only 5 Wm^{-2} lower than climatology, there were many significant short-lived deviations. For example, September 2001 stands out as a remarkably dark and cloudy period, even by ITCZ standards. During one particularly dark day, the 24-hour averaged Q_{sol} was less than 5 Wm^{-2}. Likewise, although the buoy and ship data show essentially no cloud forcing at 10°N, 95°W during the first transect (Figure 2b and start of time series in Figure 3a), climatologically there is ~60 Wm^{-2} cloud forcing at this time of year. In May of both years, solar radiation dropped far below climatology and during the rainy season from May through November, 24-hour averaged Q_{sol} had large (~120 Wm^{-2}) variations on time scales of days to weeks. Typically, when the solar radiation dropped below ~100 Wm^{-2}, the net surface heat flux (not shown) tended to cool the ocean. However, because this is an upwelling region with sometimes strong and variable currents, SST variability in general depends upon the full three-dimensional heat balance.

IMET Stratus mooring

In order to observe air-sea interactions and upper ocean variability in the stratus cloud deck region west of Peru and Chile, a surface mooring was deployed at 20°S, 85°W in October 2000. The mooring is recovered and a new one with fresh instrumentation is deployed at the same site every 12 months, with the intent of collecting three years of data. The buoy has two complete IMET (Improved METeorological) packages measuring air and sea surface temperatures, humidity, barometric pressure, wind speed and direction, incoming shortwave and longwave radiation, and precipitation. Ocean measurements include a floating SST sensor at 5 cm depth, 16 temperature and 10 conductivity/temperature loggers in the upper 200 m, 3 Vector Measuring Current Meters, and an upward looking 300 KHz ADCP located at 150 m.

Hourly meteorological data are telemetered to WHOI via Service Argos. The data are purposefully withheld from assimilation by the operational numerical weather prediction models in order to examine the performance of these models under the stratus deck. Following post-calibration of the buoy's sensors, surface meteorological and air-sea flux data will be made available at the raw 1-minute sampling rate of the IMET sensors (contact rweller@whoi.edu).

At 20°S, 85°W, incoming solar radiation (Figure 3b) has a large annual cycle with a range of over 150 Wm^{-2} – nearly twice that found at 10°N, 95°W. Although the seasonal minimum was lower at 20°S, 85°W than at 10°N, 95°W, very dark days were not observed. The minimum 24-hour averaged Q_{sol} for the entire record was 65 Wm^{-2}. During the austral autumn from March through June 2000, there was little variability in Q_{sol}. In contrast, cloud forcing was largest and most variable from October 2000 through January 2001, when top of the atmosphere solar radiation was high and the surface temperatures were cold. However, no rainfall was observed throughout the entire record. Incoming solar radiation at 20°S, 85°W was on average 18 $W\ m^{-2}$ higher than climatology (Figure 3b). In fact, except for October and November 2000, every month averaged higher than climatology by nearly 10-40 Wm^{-2}. Analyses of the upper ocean heat budget will show where this excess heat goes and its climatic implications.

Conclusion

EPIC enhanced monitoring provides an invaluable data set for climate studies of the eastern tropical Pacific. A wide range of variability is observed, providing context for the EPIC2001 intensive process study analyses and insight into the structure and temporal variability of the coupled ocean-atmosphere system. While some of the EPIC enhanced monitoring data are available through the GTS and ingested into numerical weather prediction models and climate analyses, some are specifically withheld in order to be used as a benchmark in model performance analyses. Further, the cloud statistics derived from the enhanced monitoring will help improve cloud model parameterizations and satellite retrieval methods. With moorings near both the Central American and South American coasts, it is expected that this data set will be valuable for a host of coupled land-ocean-atmosphere climate studies, such as the North American Monsoon Experiment (NAME) and the Variability of the American Monsoon Systems (VAMOS) program.

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Figure List

Fig. 1. EPIC mooring array shown in relation to the September 1998 composite SST and European Center for Medium-Range Weather Forecasts wind fields.

Fig. 2. Ocean and atmosphere fields along 95°W as measured by the NOAA ship Ron Brown in November 1999. (a) Surface to 2000 m height meridional winds (in units m s^{-1}, positive from the south, shaded intervals of 2 ms^{-1}) and virtual potential temperature (in units °K, contour interval (CI) of 2°K). Triangles indicate locations of radiosonde launches. (b) Incoming solar radiation (blue) and solar radiation cloud forcing (green) (both in units Wm^{-2}). (c) Sensible (blue) and latent (green) heat loss by ocean (both in units Wm^{-2}). (d) Sea and air surface temperature difference (blue) and sea surface temperature (green) (both in units °C). (e) Surface to 200 m depth zonal current (in units ms^{-1}, positive from west, shaded intervals of 0.2 ms^{-1}) and potential temperature (in units °C, CI of 2°C). Inverted triangles indicate locations of CTD casts.

Fig. 3. Incoming solar radiation Q_{sol} (black) in relation to the Southampton Oceangraphy Centre climatological annual cycle (grey) (both in units Wm^{-2}) (a) as measured by the enhanced TAO mooring at 10° N, 95°W, and (b) as measured by the IMET stratus mooring at 20°S, 85°W.

Fig. 1

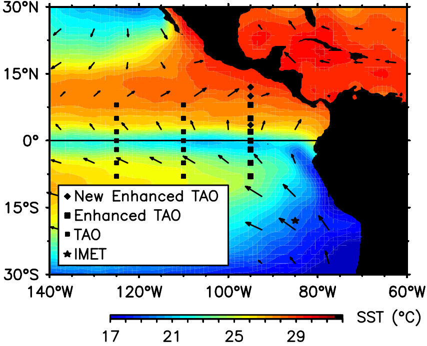
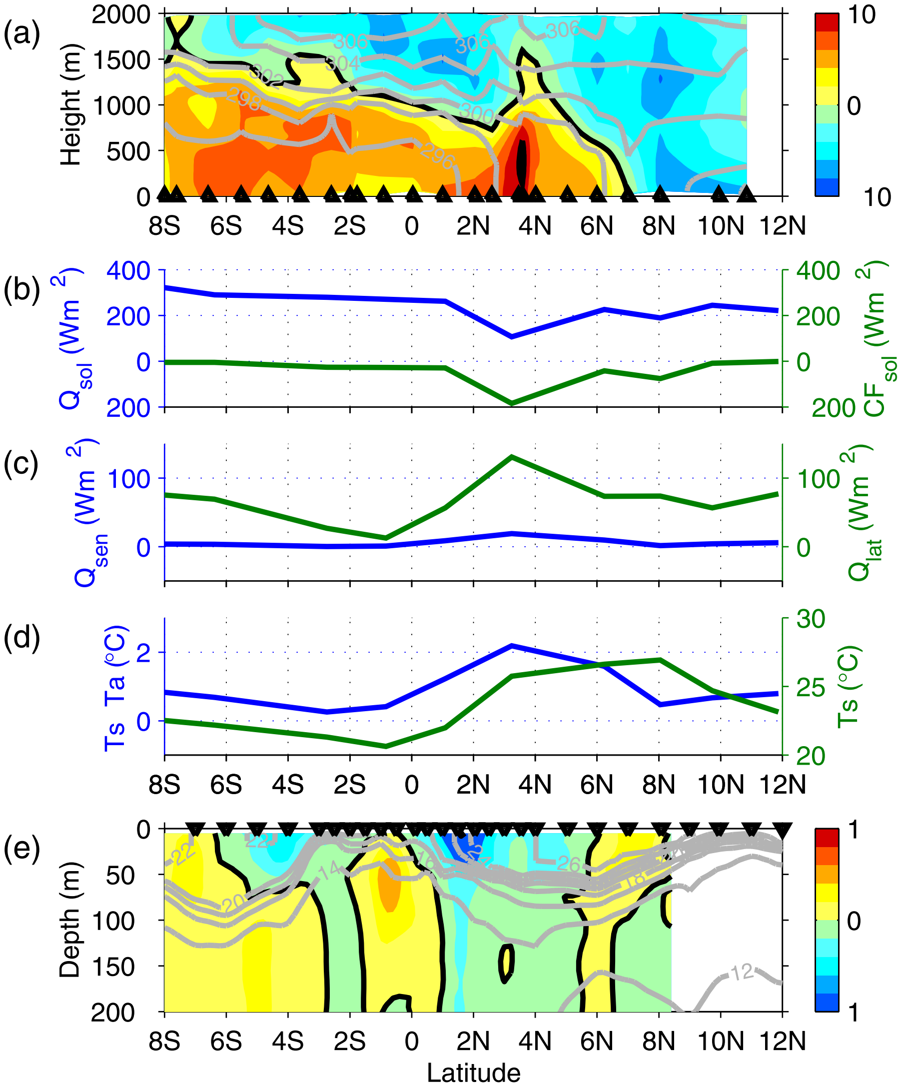

30°N
15°N
0°
15°S
30°S
140°W
120°W
100°W
80°W
60°W
◆ New Enhanced TAO
■ Enhanced TAO
■ TAO
★ IMET
SST (°C)
17
21
25
29

Fig. 2



(a)
Height (m)
2000
1500
1000
500
0
306
306
306
304
302
298
300
296
8S
6S
4S
2S
0
2N
4N
6N
8N
10N
12N
10
0
10
(b)
Q_{sol} (Wm 2)
400
200
0
200
CF_{sol} (Wm 2)
(c)
Q_{sen} (Wm 2)
100
0
Q_{lat} (Wm 2)
(d)
Ts Ta (°C)
2
0
Ts (°C)
30
25
20
(e)
Depth (m)
0
50
100
150
200
22
22
20
14
16
26
18
12
1
0
1
Latitude

Fig. 3