A meteorological overview of the second Pacific Exploratory Mission in the Tropics

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Abstract. Meteorological conditions over the central Pacific Basin are summarized during NASA's second Pacific Exploratory Mission in the Tropics (PEM-B) which was conducted during February–April 1999. Mean flow patterns during PEM-B are described. Important features near the surface include subtropical anticyclones, the South Pacific Convergence Zone (SPCZ), and the Intertropical Convergence Zone (ITCZ). The ITCZ is found to exhibit a double structure, with branches at -5°N and -5°S. Both the ITCZ and SPCZ are areas of widespread cloudiness and convection. Extensive lightning occurs over the land masses surrounding the Pacific Basin and over the central South Pacific Ocean itself. PEM-B occurs during a La Nina period of relatively cold sea surface temperatures in the tropical Pacific. Compared to climatology, the PEM-B period exhibits deep convection located west of its typical position, stronger than normal easterly trade winds, a relatively strong (weak) northern (southern) hemispheric jet stream, the SPCZ located west of its normal position, and an upper tropospheric cyclonic wind couplet that straddles the equator. Circulation patterns during PEM-B are compared with those of PEM-A which occurred during August–September 1996. PEM-B is found to exhibit a less organized ITCZ, a comparatively weak jet stream in the Southern Hemisphere, a relatively strong jet stream in the Northern Hemisphere, and enhanced convection over the central Pacific. Finally, meteorological conditions for selected flights are discussed utilizing streamlines, 10-day backward trajectories, thermodynamic soundings, and satellite imagery. Air parcels sampled by the aircraft are found to originate or pass over diverse regions, including Asia, South America, southern Africa, and Australia. Some parcels remain over the Pacific Ocean during the preceding 10-day period.

1. Introduction

The second Pacific Exploratory Mission in the Tropics (PEM-B) was conducted during March and April 1999 as part of NASA's Global Tropospheric Experiment (GTE) [McNeal et al., 1984]. The goal of PEM-B was to investigate tropospheric chemistry of the central and eastern portions of the tropical Pacific Basin. Its two major objectives were to provide baseline data for chemical species that determine the oxidizing power and aerosol loading of the region and to evaluate the chemical and dynamic factors controlling ozone, OH, and aerosol levels over this remote region [Raper et al., this issue]. The first PEM-Tropics mission (PEM-A) [Hoell et al., 1999], conducted over the same area during August–September 1996, revealed that the Pacific Basin exhibited a significant influence from biomass burning emissions. Conversely, PEM-B occurred during the southern tropical wet season, when the influence of biomass burning was expected to be much smaller.

PEM-B employed two NASA aircraft, the DC-8 based at Dryden Research Facility, California, and the P-3B based at Wallops Flight Facility, Virginia. Once leaving their home bases, the DC-8 operated out of Hawaii, Fiji (18°S, 178°E), Tahiti (18°S, 149°W), and Easter Island (28°S, 109°W), while the P-3B operated out of Hawaii, Christmas Island (2°N, 156°W), and Tahiti. The various flights stretched from Hawaii to the central South Pacific and from the coast of New Guinea to Easter Island [Raper et al., this issue, Figure 2]. A complete description of the various chemical species measured by the two aircraft is given by Raper et al. [this issue].

This paper presents a general overview of meteorological conditions over the South Pacific Basin during PEM-B (February 25 to April 19, 1999). Section 2 describes our data and methodologies. Section 3 describes large-scale flow patterns during the period, while section 4 examines their departures from climatology, and section 5 compares conditions during PEM-B with those from PEM-A. The remaining sections highlight weather conditions encountered on selected flights.

2. Data and Methodologies

We utilized global gridded meteorological analyses prepared by the European Centre for Medium-Range Weather Forecasts (ECMWF) [Bengtsson, 1985; Hollingsworth et al., 1986; ECMWF, 1995] to produce the various daily analyses and trajectories that are presented. The data were available 4 times daily (0000, 0600, 1200, and 1800 UTC) at 51 vertical levels with a T319 spherical harmonic triangular truncation, interpolated to a 0.5° × 0.5° latitude-longitude horizontal grid.

Ten-day backward trajectories were calculated using a kine-
Figure 1. Mean streamlines during PEM-B (February 25 to April 19, 1999) for (a–d) 300, 500, 700, and 1000 hPa. Major cyclonic and anticyclonic circulation centers are indicated as “C” and “A,” respectively.
matic model, i.e., employing the $u$, $v$, and $w$ wind components from the ECMWF analyses. Additional details about the trajectory model, along with a comparison between kinematic and isentropic trajectories, are given by Fuelberg et al. [1996, 1999, 2000]. Trajectories were calculated for clusters of points along the various DC-8 and P-3B flight tracks as described by Maloney et al. [this issue]. The cluster procedure acknowledges the effects of horizontal wind shear as well as uncertainties in the ECMWF analyses and trajectory methodology. Similar cluster procedures have been utilized by many previous investigators, e.g., Merrill et al. [1985], Kahl [1993], and Pickering et al. [1996]. Limitations of trajectories are described by Fuelberg et al. [2000], Maloney et al. [this issue], Stohl [1995], and Stohl et al. [1998].

Lightning data are from the Lightning Imaging Sensor (LIS) that is onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. The LIS detects total lightning, i.e., cloud-to-ground, intracloud, and cloud-to-cloud flashes during both day and night [Christian et al., 1999; Christian, 1999; NASA LIS Web site at http://thunder.msfc.nasa.gov/lis.html]. Since the orbit of the polar satellite housing LIS is inclined at 35°, LIS only observes lightning between 35°N and 35°S, i.e., in the tropics where it is most common. Although LIS achieves a 90% detection efficiency, its polar orbit does not provide continuous coverage. As a result, many flashes are not detected. Nonetheless, the data are useful for studying global patterns.

Satellite-derived rainfall estimates are from a passive microwave sensor called SSM/I that is onboard the Defense Meteorological Satellite Program (DMSP) series of satellites (DMSP Web site at http://www.ngdc.noaa.gov/dmsp/). Rainfall currently is computed daily over the region 45°S to 45°N at a spatial resolution of 0.25° x 0.25° latitude/longitude using data from three DMSP satellites. The Ferriday rainfall algorithm that is used in the calculations employs all four SSM/I frequencies as well as dual polarization information, with different algorithms used over land and ocean [Ferriday and Avery, 1994; NOAA Web site at http://www.csl.noaa.gov/climsat/].

3. Large-Scale Conditions

Streamlines representing time-averaged large-scale flow patterns during the PEM-B period are shown in Figure 1. These fields were obtained by averaging the ECMWF analyses between February 25 and April 19, 1999. Atmospheric transport is due to the actual winds that vary continuously in time, not by the mean flow. Nonetheless, meteorological systems in the tropics do exhibit less variability than those in the middle latitudes. Furthermore, these "time-averaged" flow patterns provide important information about large-scale conditions during PEM-B.

Several prominent circulation features are evident in the mission-averaged streamlines at 1000 hPa (~100 m above mean sea level (msl), Figure 1d). Major subtropical anticyclones are located over both the North and South Pacific Oceans: one center is north of Hawaii, while the second is near Easter Island in the South Pacific (28°S, 109°W). The north-easterly and southeasterly trade winds that emanate from these anticyclones converge to form the Intertropical Convergence Zone (ITCZ). The ITCZ represents the ascending branch of the Hadley circulation and corresponds to the meteorological equator. It is a region of enhanced cloudiness and precipitation.

Climatological charts of precipitation [Hu et al., this issue] and cloud cover [Waliser and Gautier, 1993] have revealed that the ITCZ over the central and eastern Pacific often consists of two parallel bands during Northern Hemispheric spring. The dominant band is located near 5°N, with the secondary band near 5°S. Hu et al. [this issue] describe this double structure during PEM-B, showing that the southern branch of the ITCZ actually became dominant during March 1999. This also is indicated in the patterns of satellite-derived precipitation shown in Plate 1a. The northern branch of the ITCZ becomes more active during April (Plate 1b), the second half of the PEM-B period. It is clear that low-level, Northern Hemispheric air streams into the Southern Hemisphere over much of the Pacific Basin during PEM-B (Figure 1d). Also, air exhibiting aged Northern Hemispheric chemical characteristics frequently was observed at low altitudes over the equatorial central and western Pacific to ~5°S, the typical position of the southern branch [Blake et al., this issue].

We carefully investigated locations of the ITCZ on a daily basis during the PEM-B period. The convergence zones were determined using analyses of the divergent wind component from ECMWF data, from patterns of convection deduced from satellite imagery, and using winds from a special network of buoys in the tropical Pacific. Results showed that the ITCZ exhibited major day-to-day variability during the period. Figure 2 shows this variability using visible imagery from the GOES 10 satellite. Only the northern branch of the ITCZ is well defined on some days, e.g., April 14 (Figure 2a). Conversely, only the southern branch of the ITCZ is well defined on other days, e.g., March 9 (Figure 2b). Both the northern and southern branches are evident on some days, e.g., March 31 (Figure 2c), while on other days neither branch is well defined, e.g., April 10 (Figure 2d).

An objective of PEM-B was to investigate atmospheric chemistry near the ITCZ. Several PEM-B flights traversed the two branches of the ITCZ, with highlights of those flights given in the following sections. Results indicate that the ITCZ is not a simple, relatively stationary interhemispheric boundary during PEM-B but exhibits considerable changes in both location and intensity. Furthermore, it is clear that the ITCZ is not as well defined during March–April (Figure 2d) as during the Northern Hemispheric summer and fall seasons that were sampled during PEM-A. Avery et al. [this issue] examine the variability of the ITCZ in greater detail, providing chemical data for the various scenarios.

The general cyclonic flow and convergence that are evident over Indonesia and Southeast Asia at 1000 hPa (Figure 1d) are associated with the developing summer monsoon. The convergence extending northwest to southeast from near New Guinea to the central South Pacific corresponds to the South Pacific Convergence Zone (SPCZ). Vincent [1994, 1998] provides an excellent review of the SPCZ, noting that it lies in a region of low-level moisture convergence between the predominantly northeasterly flow west of the eastern Pacific subtropical anticyclone and the cooler, predominantly southeasterly flow from the higher latitudes. The SPCZ is best defined during the austral summer months of January and February.

We examined locations of the SPCZ on individual PEM-B flight days (not shown). There is relatively little day to day variability along the northwest portion of the SPCZ where it merges with the ITCZ; however, there is more variability farther southeast. This variability masks the location of the SPCZ in the mission-averaged streamlines of Figure 1d. However, precipitation associated with that section of the SPCZ (Plate 1)
Figure 2. Visible imagery from GOES 10 showing four configurations of the ITCZ. (a) Only the northern branch of the ITCZ is well defined (April 14), (b) only the southern branch of the ITCZ is well defined (March 9), (c) both the northern and southern branches of the ITCZ are well defined (March 31), and (d) neither branch of the ITCZ is well defined (April 10).
Plate 1. Satellite-derived rainfall for (a) March 1999 and (b) April 1999 derived from the SSM/I instrument. Data provided by NOAA from their Web site at http://www1.etl.noaa.gov/climsat/images/.

is oriented northwest to southeast from near New Guinea to ~150°W. The spatial fluctuations in the SPCZ are due to the influence of nearby middle latitude cyclones [Vincent, 1994]. Specifically, these cyclones pass west to east across the middle latitudes, with their associated cold fronts advancing northeastward, eventually becoming stationary between ~15° and 20°S. At these tropical latitudes, there is little temperature gradient across the dissipating fronts—only the convergence remains. Thus the distant cyclones and their associated fronts periodically influence the strength and location of the SPCZ. Several PEM-B flights from Fiji and Tahiti passed near or through the SPCZ, and one of these is described in a later section.

Mean flow patterns at 700 hPa (~3 km msl, Figure 1c) are dominated by major subtropical anticyclones whose broad centers are located near Hawaii, Mexico, and over the South Pacific. Since the west-to-east ridge lines associated with these highs generally are poleward of the PEM-B flight area, easterly winds cover most of the tropical flight area at 700 hPa. Most of the mission-averaged streamlines are nearly parallel to the equator, suggesting relatively little interhemispheric transport.
at this altitude. The mean flow at 500 hPa (~5.5 km, Figure 1b) is somewhat more complex than at 700 hPa, with a reorientation of the Northern Hemisphere subtropical highs, and a well-defined trough oriented northeast to southwest from Hawaii to the equator. Much of the flow over the tropical Pacific is from the east. However, since the east to west ridge axis in the Southern Hemisphere is near Fiji and Tahiti, the PEM-B flights south of those sites generally encountered westerly flow in the middle troposphere. Transport from the southern to the Northern Hemisphere is evident over the central Pacific, the reverse of that occurring at 1000 hPa (Figure 1d).

The mission averaged flow at 300 hPa (~9 km, Figure 1a) exhibits the trough west of Hawaii as well as anticyclones over the western edge of the Basin. A difference between the averaged flows at 300 and 500 hPa is the clockwise circulation center at 300 hPa over the central equatorial Pacific. This same clockwise circulation occurs on a number of individual days at 500 hPa but is obscured in the mission averaged flow of Figure 1b, whereas it dominates the region at 300 hPa. As a result of this clockwise circulation, there is considerable interhemispheric transport in both directions over the central tropical Pacific. The Northern Hemisphere polar jet stream is located near 40°N (not shown). The axis of the subtropical jet stream extends from south of Hawaii, to Baja California, and then toward the East Coast of the United States. Jet level wind speeds in the Southern Hemisphere are much weaker than in the Northern Hemisphere due to the opposite seasons. The core of strongest Northern Hemispheric winds is located near 30°S.

Atmospheric vertical motion is important because it determines the vertical transport of chemical species and influences the formation of clouds and precipitation. Vertical motions provided with the ECMWF data were averaged over the PEM-B period, with the results for 700 hPa shown in Figure 3a. Areas of strongest descent (positive values) are located over the subtropical eastern Pacific, i.e., off the coasts of Baja California and South America, in association with the anticyclones seen in Figure 1. Later sections will show the strong low-level temperature inversions that are associated with this subsidence. Both Hawaii and Easter Island are located in regions of subsidence. Areas of greatest ascent (negative values) are located over the western Pacific near the ITCZ and SPCZ. Over the eastern Pacific the two bands of ascent that straddle the equator are associated with the two branches of the ITCZ that were described earlier. Small sinking motion is located over the equator itself. Hu et al. [this issue] provide additional details about vertical motion over the eastern Pacific. There are few centers of vertical motion in the middle latitudes because that area is dominated by transient eastward moving anticyclones and cyclones. The descent and ascent associated with these transient systems cancel during the time averaging process.

The mission averaged field of outgoing long wave radiation (OLR, Figure 3b) is consistent with the vertical motion patterns (Figure 3a). Regions of large OLR, representing minimal middle and upper cloudiness, are located near the areas of subsidence between Hawaii and Baja California and northeast of Easter Island. Areas of enhanced middle and upper cloudiness and corresponding smaller OLR are located over the western Pacific Basin, and they straddle the equator over the central and eastern Pacific. The equator itself is characterized by relatively large OLR, i.e., relatively few clouds due to the subsidence in that area. These patterns are consistent with those of satellite-derived precipitation (Plate 1).

Lightning is associated with deep convection and is a source of nitrogen oxides in the atmosphere [e.g., Lawrence et al., 1994]. Plate 2 shows lightning discharges between 35°N and 35°S during March and April 1999 from the Lightning Imaging Sensor (LIS) [Christian et al., 1999; Christian, 1999; NASA LIS Web site at http://thunder.msfc.nasa.gov/lis.html]. Lightning is more abundant during March than during April, with the land masses exhibiting the most flashes. One should note the large concentrations of lightning over Southeast Asia, Indonesia, Australia, Central America, and portions of South America. The streamline charts (Figure 1) suggest that these areas of lightning are upwind of specific PEM-B flights at particular altitudes. This will be confirmed by trajectory analyses in later sections. There also is a weaker maximum of lightning over the central South Pacific Ocean. Both the DC-8 and P-3B aircraft flew near many deep maritime convective clouds containing lightning.

4. Representativeness of the PEM-TB Period

It is important to determine whether the 1999 PEM-B period was anomalous or representative of a typical March and April. The El Nino/Southern Oscillation (ENSO) phenomenon is a major factor leading to year to year climate variability. Survey descriptions of ENSO are provided by Philander and Rasmusson [1985], Philander [1990], and Trenberth [1997], while Kiladis and Mo [1998] focus on its influence on the Southern Hemisphere. The 1997 and early 1998 period was characterized by a major El Nino event, i.e., very warm sea surface temperatures (SSTs) in the tropical Pacific Ocean. However, conditions changed abruptly to cold Pacific SSTs in mid 1998, with PEM-B occurring during a La Nina period which continued into year 2000. In fact, during the past 2
decades, only the 1988–1989 La Nina event was more pronounced in terms of the Multivariate ENSO Index (K. Wolter at the CDC Web site http://www.cdc.noaa.gov/ENSO).

To examine the representativeness of the PEM-B period in greater detail, we calculated vector departures between mean winds during the 1999 mission period and those for the previous La Nina event [Philander, 1990]. In addition, the SPCZ is displaced to the west of its usual position, with maximum convection over Indonesia and the western Pacific.

Streamlines of vector wind departures at 300 hPa (Figure 4b) also are consistent with cold phase conditions. Specifically, Arkin [1982] found an anomalous couplet of cyclonic circulation centers in the upper troposphere during periods of relatively cold SSTs. The two circulation centers straddled the equator, i.e., centers north and south of the equator. During PEM-TB, there is an anomalous cyclonic center over the northern tropical latitudes at 300 hPa (Figure 4b) and other middle and upper tropospheric levels (not shown). Farther south, a center of clockwise flow is located nearly over the equator. These centers correspond to features seen in the mission averaged streamline patterns (Figure 1a), specifically, the trough located southwest of Hawaii, and the clockwise circulation centered over the equator near Christmas Island.

Isotachs showing the departure of 300 hPa wind speeds during PEM-B from those of climatology are shown in Figure 4a. Once again, climatological values were subtracted from those of PEM-B. Upper tropospheric speeds over the southern hemispheric portion of the Pacific Basin generally are within 5 m s\(^{-1}\) of climatological values. However, in the Northern Hemisphere, greater departures are evident. Mean speeds of the southwesterly winds located southwest of Hawaii are as much as 15 m s\(^{-1}\) stronger than climatology. This contrasts with previous La Nina events during which the northern hemispheric subtropical jet over the central Pacific was weaker than normal [Matthews and Kiladis, 1999]. North of Hawaii, the polar jet stream is displaced north of its climatological position during PEM-B, causing weaker than normal westerlies in a band near 30\(^\circ\)N, and stronger than normal westerlies in a band near 50\(^\circ\)N. Thus greatest upper tropospheric outflow from the Asian continent is north of its typical location. During some previous La Nina phases, maximum speeds along the polar jet stream have been displaced west of their mean position [e.g., Chen et al., 1996]. However, there is no evidence of that displacement during the PEM-B period.

To summarize, most wind patterns during PEM-B are consistent with those of La Nina events. Anomalies in wind direction, speed, and precipitation are observed.

5. Comparisons Between PEM-A and PEM-B

The PEM-Tropics A mission examined the tropical Pacific Basin during August–October 1996. Since chemical data from PEM-Tropics A and B will be compared in other papers of this issue, it is informative to briefly compare meteorological conditions during the two missions. The complete meteorological overview of PEM-A is given by Fuelberg et al. [1999]. PEM-A occurred during a much weaker La Nina event than PEM-B.

At 1000 hPa the most striking contrast between the two missions is the position and strength of the ITCZ (Figure 1d here and Figure 2a of Fuelberg et al. [1999]). Specifically, during PEM-A the ITCZ was located near 10\(^\circ\)N, exhibiting strong convection from Central America westward to beyond the dateline. This convergence was associated with well defined cross equatorial flow from the Southern Hemisphere into the Northern Hemisphere. Conversely, the ITCZ is not well defined during PEM-B, with zones of convergence in both hemispheres. It is important to note that the direction of the predominant cross equatorial flow also is quite different during PEM-B, from the Northern into the Southern Hemisphere. These differences are due mainly to the contrasting seasons.

As a result of the better defined ITCZ during PEM-A, deep convection associated with that convergence was much stronger, persistent, and more widespread than during PEM-B (not shown). On the other hand, there is more lightning in the
overall tropics and subtropics during PEM-B than PEM-A, mostly occurring over the land masses (Plate 2 here and Plate 1 of Fuelberg et al. [1999]).

The location of the SPCZ also differs considerably between the two missions (Figure 1d here and Figure 2a of Fuelberg et al. [1999]). The SPCZ during PEM-A was located east of its position during PEM-B. Associated with these differing locations of the SPCZ, widespread deep convection during PEM-A extended from Indonesia to near Tahiti, i.e., east of its position during PEM-B.

Flow patterns in the upper troposphere (300 hPa, ~9.5 km) are consistent with the differing seasons of the two missions (Figure 1a here and Figure 2d of Fuelberg et al. [1999]). During PEM-A the Southern Hemispheric westerlies extended well into the tropics. Conversely, during PEM-B the Northern Hemispheric westerlies extend deep into the tropics, whereas the Southern Hemispheric westerlies are displaced south of their location during PEM-A. The Southern (Northern) Hemispheric polar jet stream is strongest during PEM-A (PEM-B).

A major finding from PEM-A was the occurrence of pollution plumes over the central South Pacific Ocean that apparently had originated over South America and southern Africa and then were transported eastward by the strong middle-latitude westerlies [e.g., Board et al., 1999]. However, it is clear that flow patterns during PEM-B are not as conducive to such transport, and there is much less burning material in the Southern Hemisphere to be transported. Thouret et al. [this issue] found fewer distinct layers of tropospheric ozone and water vapor during PEM-B than PEM-A.

6. Flights Near Hawaii and Christmas Island

The following sections highlight meteorological conditions encountered during selected individual PEM-B flights. Most of the flights described here are examined in greater detail in other papers of this issue.

The DC-8 first traveled from California to Hilo, Hawaii, from which three local flights were conducted. The GOES 10 visible image for the DC-8's transit to Hilo on March 6 (flight 5, Figure 5a) illustrates cloud features that were common over the North Pacific Ocean during the PEM-B mission. Cumulus and stratocumulus clouds are scattered over much of the area. The swirl of higher clouds off the coast of California is associated with a middle latitude trough that was advancing eastward. A second middle-latitude system is indicated by the band of middle and high clouds over the northwestern portion of the images. Transient middle-latitude systems were common in the Northern Hemisphere during PEM-B, and they influenced the strength and specific path of outflow from Asia into the Northern Hemisphere to be transported. Thouret et al. [this issue] found fewer distinct layers of tropospheric ozone and water vapor during PEM-B than PEM-A.

The DC-8 first traveled from California to Hilo, Hawaii, on March 6 (flight 4). The Harvard 3-D chemical flow patterns in the upper troposphere (300 hPa, ~9.5 km) are consistent with the differing seasons of the two missions (Figure 1d here and Figure 2a of Fuelberg et al. [1999]). The SPCZ during PEM-A was located east of its position during PEM-B. Associated with these differing locations of the SPCZ, widespread deep convection during PEM-A extended from Indonesia to near Tahiti, i.e., east of its position during PEM-B.

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Figure 5. (a) GOES 10 visible image for 2100 UTC March 6, 1999. The track of DC-8 flight 5 from NASA Dryden Research Facility, California, to Hilo, Hawaii, is superimposed. (b) Ten-day backward trajectories arriving at flight level along DC-8 flight 5 from Dryden Research Facility, California, to Hilo, Hawaii, at 0000 UTC March 7. Small arrows denote locations at daily intervals; large arrows denote locations at 5-day intervals.

Both PEM-B aircraft measured in situ temperature and humidity from which vertical profiles (soundings) could be obtained during maneuvers. The sounding derived from the DC-8's ramped ascent near 21.5°N, 128°W (Figure 6) is typical of soundings en route to Hilo. The sounding exhibits relatively humid conditions below ~850 hPa, with a well-mixed layer in the lowest 50–75 hPa. This moist layer is capped by the trade wind temperature inversion, with much drier air aloft. The inversion and dry air are due to subsidence associated with the subtropical anticyclone (Figure 3a). As a result, the boundary layer is essentially decoupled from the free atmosphere in these areas of subsidence. Winds below the inversion are from the north or northeast (the trade winds) but shift to the west at higher altitudes.

Ten-day backward trajectories arriving at the various altitudes and locations along DC-8 Flight 5 are shown in Figure 5b. For clarity, only one representative trajectory from each cluster is plotted on this and subsequent figures, and altitude vs. time plots for the many trajectories are not shown due to space considerations. (Complete trajectory data, including altitudes, are available at the Florida State University Web site (http://bertha.met.fsu.edu/~pem/trop-b) and at NASA's GTE site (http://www-gte.larc.nasa.gov). The trajectories (Figure 5b) show that much of the air encountered during the flight had originated far to the west, with many trajectories passing over the coasts of southern China, Japan, and Southeast Asia ~6 days earlier. Prior to this, many had traveled over parts of Asia, northern Africa, and even the North Atlantic Ocean. These long distances are possible due to the position and strength of the nearby jet stream (Figure 1). Air parcels arriving at the DC-8 when it was at relatively low altitudes generally did not travel as far as those arriving at higher flight altitudes. The P-3B also encountered considerable outflow from the Asian continent (not shown) during its transit to Hilo on March 12 (flight 4). The Harvard 3-D chemical...
consistent with the deep tropical easterlies seen in the sounding (Figure 8). Some trajectories crash into the oceanic boundary and were terminated before the end of the 10-day period; however, others complete the full interval. The longest trajectories travel ~50° longitude, remaining over the ocean the entire period.

Boundary layer measurements from PEM-B are used in several papers. Velocity and temperature data acquired at 22 Hz are related to various theories of turbulence by Cho et al. [this issue]. Weber et al. [this issue] examined regions of unusually large concentrations of sulfuric acid vapor near the ocean surface between Hawaii and Tahiti that occurred without particles of 3–4 nm. Boundary layer measurements of the hydroxyl radical near Christmas Island and Tahiti are described by Mauldin et al. [this issue]. They found that OH measurements under clouds were depressed by a factor of two when compared to data on either side of the cloud.

7. Flights Near Fiji

The DC-8 traveled from Hilo to Fiji on March 17 (flight 9) where it conducted three local flights. A major objective of PEM-B was to examine atmospheric chemistry near the SPCZ, and the first local flight from Fiji was designed for that purpose (flight 10 on March 21). Streamlines at 1000 hPa (~100 m sl,

The DC-8 first local flight from Hilo investigated sunrise photochemistry. A series of legs, mostly at ~7 km, was conducted southeast of Hilo near 15°N, 150°W. Only scattered cumulus clouds were over the area, and the 6.7 μm water vapor image (Figure 7a) shows that the middle and upper troposphere was relatively dry, in contrast to more humid conditions over Hilo. Ten-day backward trajectories arriving at flight altitude (Figure 7b) show that most air parcels originated from the west. Some had started over Southeast Asia, while many others had passed over northern Africa and southern Asia. Tan et al. [this issue] compare OH and HO₂ data with results from a photochemical box model over various areas of the PEM-B domain, including sunrise flight 13.

The P-3B traveled from Hilo to Christmas Island where it conducted six local flights, including same day sunrise and sunset flights on March 17 (flights 7 and 8) to investigate the time evolution of reactive hydrogen and sulfur species. Although most flight legs were in the lowest 1.5 km of the atmosphere, Figure 8 shows the sounding during an ascent to ~3 km near 0.5°N, 157°W. It is typical of most soundings taken near Christmas Island during the various flights. The sounding shows easterly trade winds throughout the layer. The air is relatively humid near the surface but begins to dry above 800 hPa. Although some stable layers are present, there is no well-defined trade wind inversion this close to the equator since the required subsidence is located in the subtropics (Figure 3a). Figure 9 shows back trajectories from the Christmas Island sunrise flight; trajectories were similar on the other flights from Christmas Island (not shown). The trajectories are

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**Figure 6.** Vertical profile of temperature (solid) and dew point (dashed), both in degrees Celsius, obtained by the DC-8 during flight 5 (March 6) between 2144 and 2216 UTC near 21.5°N, 128°W. The winds that are plotted on the right side follow the standard convention, with short barbs denoting 2.5 m s⁻¹ (~5 kt) and long barbs denoting 5 m s⁻¹ (~10 kt).

**Figure 7.** (a) GOES 10 6.7 μm water vapor image for 1800 UTC March 9, 1999. The track of DC-8 flight 6 out of Hilo, Hawaii, is superimposed. (b) Ten-day backward trajectories arriving at flight level along DC-8 flight 6 out of Hilo at 1800 UTC March 9. Small arrows denote locations at daily intervals; large arrows denote locations at 5-day intervals.
Figure 8. Vertical profile of temperature (solid) and dew point (dashed), both in degrees Celsius, obtained by the P-3B during flight 7 (March 6) from Christmas Island between 1757 and 1805 UTC near 0.5°N, 157°W. The winds that are plotted on the right side follow the standard convention, with short barbs denoting 2.5 m s⁻¹ (~5 kt) and long barbs denoting 5 m s⁻¹ (~10 kt).

Figure 10a) show the SPCZ as a line of convergence extending approximately west to east, just north of Fiji. The convergence separates northeasterly winds from southeasterly winds. The GOES 10 infrared image for the flight (Figure 10b) shows the major line of intense convection associated with the SPCZ. Storms tops were ~14 km. A weaker, secondary line of convection is located north of the main area. The DC-8's flight track intersected the main convection on both the outbound and inbound legs and extended just beyond the secondary area of storms.

Figure 11 contains soundings obtained by the DC-8 during spirals south of the SPCZ (22°S, 178°E, Figure 11a) and north of the SPCZ (15°S, 177°W, Figure 11b). The sounding south of the SPCZ exhibits southeasterly winds in the lowest levels, with generally westerly flow above ~700 hPa. Relatively humid air below ~830 hPa is capped by a strong inversion, with much drier air aloft. The profile suggests large-scale subsidence. The sounding north of the SPCZ indicates a quite different air mass. Specifically, winds near the surface are from the northeast (not the southeast), and winds at higher levels are almost due easterly. In addition, the temperature/dew point profile in this area does not suggest subsidence. Instead, the lower troposphere is somewhat drier than south of the SPCZ, while the middle and upper troposphere are more humid. There is no pronounced temperature inversion; only minor stable layers are indicated below 700 hPa. Time-height cross sections of ozone, water vapor, and aerosol scattering ratio derived using a differential absorption lidar reveal major contrasts in these constituents across the SPCZ [Browell et al., this issue].

Trajectories for the SPCZ flight (Figure 12) are presented at four levels, 850, 500, and 300 hPa, to differentiate between the transport at various altitudes. The SPCZ is a low-level phenomenon, and the trajectories arriving along northerly parts of the flight track at 850 hPa are considerably different from those arriving along the southern portions of the flight. Specifically, the former originate northeast of the flight track, while the latter originate south or southwest of the flight track. These different origins and paths are even more obvious with trajectories arriving at 500 and 300 hPa. These differences at higher altitudes are not directly related to the SPCZ, but to a ridge line that was oriented east-west near Fiji and the SPCZ (not shown). Pickering et al. [this issue] used a two-dimensional cloud resolving model to examine transport near the SPCZ during this flight. Results showed that the SPCZ was a barrier to mixing in the lower troposphere, but a mechanism for convective mixing of tropical boundary layer air from northwest of the SPCZ with upper tropospheric air arriving from the west.

The third local flight from Fiji (flight 12 on March 25) extended northwest toward the equator to examine atmospheric chemistry over the western equatorial Pacific (Figure 13a). The limited deep convection that occurred on this day did not appear to have large-scale organization. Since the flight...
ocurred so near the equator, most of the area was in deep easterly flow, similar to that observed north of the SPCZ on a previous flight (Figure 11a). The 10-day backward trajectories arriving at flight level (Figure 13b) show that the air had remained over the deep tropics during the previous 10 days, originating east of the flight track. Maloney et al. [this issue] show that such "aged marine" Southern Hemispheric air during PEM-B exhibited a very "clean" chemical signature.
8. Flights From Tahiti

The DC-8 traveled from Fiji to Tahiti on March 27 from which it conducted five local flights. The P-3B traveled from Christmas Island to Tahiti on March 27 and conducted four local flights. The ITCZ was poorly defined when traversed by the P3-B, with the aircraft only passing through scattered deep convection (Figure 14a). Backward trajectories from the flight track (Figure 14b) show that air sampled by the aircraft had a maritime history during the previous 10 days. Most trajectories in both hemispheres originated from the east, exhibiting the influence of the trade winds. Only a few trajectories had a westerly origin.

The DC-8's first local flight from Tahiti, occurring on March 31, was called the "Southern Survey" since it extended southeast into the middle latitudes (36°S, 132°W). The flight track is superimposed on an infrared satellite image in Figure 15a. The major weather feature was a middle latitude cyclone located far south of the flight near 45°S, 130°W. A frontal system extending north of the cyclone, and intersecting the flight track near 30°S, produced the arc shaped cloud band in the image. An older, weaker front located farther north, near 22°S, was associated with a less defined cloud band. The DC-8 passed into the lowest reaches of the stratosphere while at 39,000 feet along the southern tip of the flight. Flight level jet stream winds in that area reached 108 kt. Since PEM-B mostly was conducted in the tropics where the tropopause is quite high, this brief stratospheric excursion was one of only a few during the mission. The influence of stratospheric intrusions during PEM-B is discussed by Browell et al. [this issue]. The flight level trajectories in Figure 15b show that aged marine air was encountered during the tropical portion of the flight. However, as the aircraft headed south into the middle-latitude westerlies and the jet stream, the air sampled by the DC-8 had passed near Australia, southern Africa, and even the coast of South America. Maloney et al. [this issue] show that the chemical signatures of this middle latitude air exhibit a pollution signature that is consistent with these distant sources. However, this long range transport was much more common and intense during the earlier PEM-A mission.

The P-3B's fourth local flight from Tahiti (on April 7) extended northeast to the equatorial central Pacific (~13°S) (Figure 16a). Trajectories (Figure 16b) indicate that the aircraft encountered air with a maritime history during the previous 10 days. However, if the calculations had been extended beyond 10 days, it is likely that some of the trajectories would have originated near or over South America. Others may have traveled in the southern middle-latitude westerlies before recurving off the southwest coast of South America and arriving at the aircraft from the east. The Northern Hemispheric mirror image of this transport pattern is described by Maloney et al. [this issue].
The southern branch of the ITCZ was reasonably well defined on April 7, and the DC-8's fourth Tahiti local flight headed north to intersect it. The streamlines in Figure 17a show low-level convergence along the northern portion of the flight, near 4°S, that was associated with the ITCZ. The convergence produced scattered deep convection (Figure 17b). A weak cold front near Tahiti produced intense convection with frequent lightning in that area. One should note that trajectories for the flight (Figure 18) show little influence from the convergence near 4°S since there is relatively little wind direction change associated with it. Trajectories at 850, 500, and 300 hPa indicate aged marine air originating mostly from the east. Thus the ITCZ does not necessarily represent a major contrast in trajectory origins, especially in the middle and upper troposphere.

9. Homeward Bound

The P-3B traveled from Tahiti to Honolulu on April 10 (flight 17) and then back to California on April 11 (flight 18). Flight 17 crossed the poorly defined ITCZ which exhibited little deep convection (Figure 19a). Trajectories arriving along the flight (Figure 19b) show the transition from tropical easterly flow to the northern hemispheric middle latitude westerlies. Thus some trajectories remain over water during the previous 10 days, while the more northern trajectories extend back to Asia. During flight 18 to California (not shown), even more of the trajectories extend back to Asia due to strong westerlies at the more northern latitudes of the flight. This scenario also was seen earlier on the westbound flights from California (Figure 5). Clarke et al. [this issue] examine extensive dust and pollution plumes during flights 17 and 18, concluding that the plumes had originated over 10,000 km to the west, from sources in Asia.

The DC-8 traveled from Tahiti to Easter Island on April 14 (flight 19), and conducted one local flight out of Easter Island (flight 20) which extended north to ~5°S. This is a remote area of the globe for which relatively little chemical data are available. Trajectories arriving along the flight track (Figure 20) show a variety of origins. Since the southern portion of the flight was in the middle-latitude westerlies, these trajectories extend back to Australia and even southern Africa during the previous 10 days. However, farther north along the flight track, wind directions become easterly at most altitudes and much weaker. As a result, the trajectories show relatively short 10-day paths, with some extending back to South America. These trajectories are another example of the major variations in air mass origin that were encountered during individual flights of PEM-B.

The DC-8 traveled from Easter Island to Costa Rica on April 17 (flight 21). Both the northern and southern branches of the ITCZ that were described in section 3 were traversed during this flight. Weak low-level convergence associated with the southern branch near 5°S triggered only scattered convec-

Figure 16. (a) GOES-10 infrared image during P-3B flight 16 from Tahiti at 2100 UTC April 7. (b) Ten-day backward trajectories arriving at flight level along P-3B flight 16 from Tahiti at 1800 UTC April 7. Small arrows denote locations at daily intervals; large arrows denote locations at 5-day intervals.

Figure 17. (a) Streamlines at 1000 hPa at 0000 UTC April 8 based on ECMWF global gridded analyses. (b) GOES 10 infrared image during DC-8 flight 17 from Tahiti at 2100 UTC April 7.
The DC-8 traveled from Costa Rica to California on April 18 (flight 22). There was widespread deep convection along the southern part of the flight, and, like the previous day, the air sampled along this segment exhibited a strong pollution signature, having originated over northern South America, the Caribbean, and the southeast United States (not shown). As the aircraft headed north, the trajectories suddenly shifted orientations, now arriving from the west, as far away as south central Asia. The northern part of the flight was much less polluted.

The strong flow from the Caribbean and northern South America on April 17 (DC-8 Flight 21) is especially interesting (Figure 21b). Maloney et al. [this issue] found that this air exhibited a strong pollution signature, with greatly enhanced values of carbon and nitrogen species. Trajectories indicated that the sampled air was 1–5 days removed from its emission sources of biomass burning, lightning, and industrial pollution. They concluded that transport from Central and northern South America was an important mechanism for polluting the eastern Pacific during PEM-B.
climatology, the SPCZ was located west of its climatological position, deep convection was west of its typical position, and an upper level cyclonic wind couplet straddled the equator.

Meteorological conditions during PEM-B were quite different from those during PEM-Tropics A which was conducted during August to October 1996. Many of these differences were due to the contrasting seasons; however, some were due to the presence of the strong La Nina event during PEM-B. Two noteworthy differences were the better defined ITCZ during PEM-A, with associated transport from the Southern Hemisphere into the Northern Hemisphere. Also, second, the southern (northern) hemispheric jet stream was much weaker (stronger) during PEM-B than during PEM-A.

Meteorological conditions for selected flights were summarized. These included flights out of Hawaii, Fiji, Christmas Island, Tahiti, and Easter Island. Ten-day backward trajectories indicated that the aircraft encountered air with a variety of origins. Trajectories arriving along flight legs in the northern middle latitudes originated over portions of Indonesia, Asia, Africa, and Europe. Flight segments in the middle-latitude Southern Hemisphere originated over parts of Australia, southern Africa, and even South America. Trajectories arriving along the tropical flight segments often remained over water during their 10-day histories, but typically came from the east. Finally, some flights over the eastern portion of the Pacific Basin encountered air from South America, the Caribbean Sea, and even the southeastern United States.

Acknowledgments. This research was sponsored by the NASA Tropospheric Chemistry Program. The PEM-B meteorological team expresses its sincere appreciation to the meteorological staffs at Edwards Air Force Base, California; U.S. National Weather Service in Honolulu and Hilo, Hawaii; Meteo France in Papeete, Tahiti; and the Fiji Meteorological Service in Nadi. These individuals provided valuable insight into local weather conditions. Meteo France, through its regional office in French Polynesia and data distribution center in Toulouse, kindly provided ECMWF gridted data during the flight phase of PEM-TB. Patrick Simon was especially helpful in securing these data for us. We appreciate the support of Joe McNeal, Jim Hoell, Jim Raper, and Richard Bendura in helping with the many scientific, logistical, and managerial matters. The crews and support staff of the DC-8 and P3-B aircraft always were most helpful during the preparations and deployments of PEM-B. We thank Mike Cadena, Erika Harper, and Roy Chesson of the SAIC-GTE Project Office for their assistance during all phases of the project. Finally, Mary Kleb assisted us in summarizing the contents of other manuscripts submitted for this special issue.

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10. Conclusions

The second phase of NASA’s Pacific Exploratory Mission in the Tropics (PEM-B) investigated the atmospheric chemistry of a large portion of the tropical Pacific Basin during February through April 1999. This paper has summarized meteorological conditions over the PEM-B domain. Important circulation systems near the surface included subtropical anticyclones, the Intertropical Convergence Zone (ITCZ), and the South Pacific Convergence Zone (SPCZ). The SPCZ was well defined, stretching from near New Guinea to Tahiti. Conversely, the ITCZ was poorly defined, often exhibiting a double structure with one band of convergence and rising air at ~5°N, and a weaker band near 5°S. There was considerable low-level transport from the northern to the southern hemisphere over the central Pacific. Extensive lightning occurred over the land masses surrounding the Pacific Basin and over the central South Pacific Ocean itself. The eastern subtropical Pacific exhibited widespread sinking motion due to anticyclones in the region. Flow in the middle troposphere over the PEM-B flight area generally was from the east; however, at 300 hPa a clockwise circulation center over the equator provided interhemispheric transport.

PEM-B occurred during a major La Nina event of relatively cold sea surface temperatures in the central equatorial Pacific Ocean, and meteorological conditions during the period were typical of those previously observed during such events. For example, the low-level easterly trade winds were stronger than
European Centre for Medium-Range Weather Forecasts (ECMWF),


(Received September 6, 2000; revised February 15, 2001; accepted March 2, 2001.)