The Christmas Island Wind Profiler: A Prototype VHF Wind-Profiling Radar for the Tropics

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ABSTRACT

After a decade of development, VHF wind profilers are being used for atmospheric research at several locations in the tropical Pacific. A prototype 50-MHz wind profiler was installed on Christmas Island in 1985 and has operated continuously since March 1986 to monitor tropical wind fields in the altitude range 1.8–18 km. This paper presents an overview of the Christmas Island wind profiler and reviews its performance. A survey of sample wind observations and a brief climatology of the observed winds are included.

1. Introduction

Since 1984 the Tropical Dynamics and Climate Program area of NOAA's Aeronomy Laboratory has used wind-profiling radars to study a wide range of dynamical phenomena ranging in scale from turbulence, convection, and gravity waves to planetary-scale equatorial waves and the Hadley and Walker circulations. To examine these dynamical systems, a network of 50-MHz VHF wind-profiling radars was constructed across the equatorial Pacific Ocean basin (Gage et al. 1990). Each wind profiler in the network continuously observes horizontal and vertical motions throughout most of the troposphere from 1.8 to 18 km. In addition to providing a unique dataset for tropical atmospheric research, these tropical VHF wind profilers provide improved upper-air wind observations over the tropical Pacific for routine analysis and forecasting purposes (Gage et al. 1988).

The Christmas Island wind profiler has served as a prototype for the VHF wind profilers that operate throughout the network from Indonesia to Peru. In this paper, we illustrate the utility of the Christmas Island wind profiler for providing wind observations in a data-sparse region of the central equatorial Pacific.

2. The VHF wind profiler at Christmas Island

Christmas Island is located just north of the equator in the Line Islands south of Hawaii, as shown in Fig. 1. It is part of the island nation of Kiribati that extends along the equator in the central Pacific. The weather on Christmas Island is dominated by its location in the equatorial dry zone associated with the cold tongue of equatorial waters extending across the central Pacific. The tongue is maintained by equatorial upwelling and westward advection due to the wind stress exerted by the trade-wind circulation. Substantial rain occurs at Christmas Island only during periods known as El Niño when the trade-wind circulation relaxes and the cold tongue disappears. The wind profiler was placed at Christmas Island to monitor the climatology of tropical wind fields and to observe the natural variability of winds over the central Pacific on the ENSO (El Niño–Southern Oscillation) time scale.

Construction of the 50-MHz wind profiler on Christmas Island presented many logistical challenges. Almost everything used in the construction phase had to be brought to the island. Since island power is very limited, small diesel generators are used to generate power on site. The maintenance of the power system accounts for most of the operating expense of the wind profiler since the profiler itself requires only limited servicing.

The Christmas Island wind profiler comprises a transmitter, a receiver, an antenna, and data processing and controller subsystems. Except for the antenna and feed lines, the wind profiler is housed in the building shown in Fig. 2. The antenna field that can be seen in the background of Fig. 2 comprises phased arrays of dipole elements. The antenna covers an area 100 m × 100 m. The data processing system originally used a Data General NOVA computer. The NOVA computer was replaced by a new PC-based data processing

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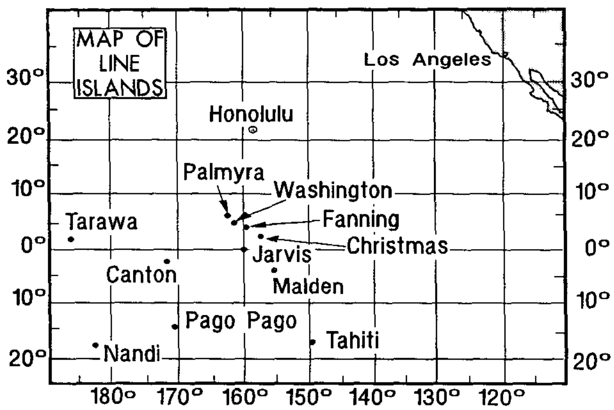

FIG. 1. A map of the Line Islands in the central Pacific.

and controller subsystem in January 1991. The PC-based system, radar receiver, and radar controller units are shown in Fig. 3.

When the Christmas Island wind profiler was first turned on in August 1985, the atmospheric echoes were contaminated by sea echoes. The problem was finally corrected by modifying the wind profiler antenna by moving each alternate string of COCO (coaxial–collinear) elements in the antenna so that a null response was obtained in the vertically polarized signal at the ends of the COCO strings. This arrangement reduced the sea clutter to tolerable levels. Details of the antenna changes are contained in Balsley et al. (1988). Sea echoes before the system was fixed were analyzed to give surface currents as reported by Balsley et al. (1987).

3. Observations of tropical winds using the Christmas Island wind profiler

Wind-profiling radars observe weak backscatter from turbulent irregularities in the atmospheric radio refractive index (see, e.g., Gage 1990; Röttger and Larsen 1990). At lower altitudes the refractivity turbulence is dominated by the contribution of humidity. Above midtropospheric altitudes refractivity turbulence is dominated by turbulence in the thermal field except in deep convection. The intensity of backscattered power depends upon both the magnitude of the gradients of radio refractive index and the intensity of turbulence that acts upon the mean gradients of refractive index. Radar wind profilers are sensitive to the half-wavelength component of the refractivity turbulence.

Wind-profiling Doppler radars measure the radial component of motion in the direction of the radar beam from the Doppler shift of the backscattered power. Most wind profilers operate with several fixed beams. Vertically directed beams are utilized for the measurement of vertical motions. Oblique beams (typically directed 15° off zenith in orthogonal vertical planes) are utilized for the measurement of horizontal motions since vertical motions are typically very small.

FIG. 2. The Christmas Island wind profiler. Shown is the antenna that comprises a phased array of coaxial–collinear elements and the laboratory building that houses the computer and hardware subsystems.

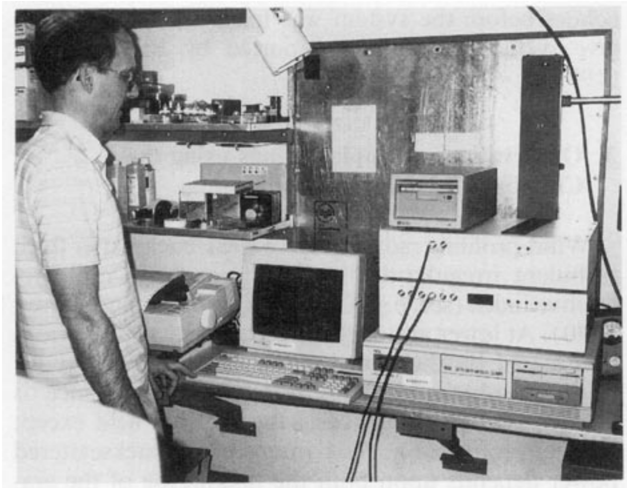

FIG. 3. PC-based radar system at Christmas Island.

At times and places where vertical motions are not small, the measured vertical motions can be used to obtain more accurate measurement of horizontal winds. However, no such correction is made routinely to the oblique measurements of wind at Christmas Island. Unlike VHF wind profilers, UHF wind profilers are relatively much more sensitive to hydrometeors and it is necessary to account for the fall speed of hydrometeors with UHF profilers to obtain accurate wind velocities when hydrometeors dominate the radar returns.

In determining winds from profiler observations, the assumption must be made that the field of motion is uniform over the few kilometers that separate the beams in space. While this assumption is reasonable for average wind profiles obtained under most conditions, it can on occasion break down under conditions of active convection or intense lee-wave activity, when vertical motions are not small and spatial variability is large. These conditions are rare at Christmas Island since Christmas Island is flat and is located in the equatorial dry zone.

The Christmas Island wind profiler, like other Doppler wind profilers, measures line-of-sight winds along three beams. At Christmas Island, one beam is directed vertically and two beams are directed about 14° off zenith in orthogonal vertical planes. In routine operation, orthogonal wind components are sampled every few minutes and processed to yield a consensus mean hourly wind. A consensus is formed by comparing all velocities recorded during the hour and requiring more than half of these to lie within a radial velocity window of specified width. The window for the oblique directions is 2.0 m s^{-1}, and the values within this window are averaged together to form the consensus wind estimate that is assigned to the middle of the hour. At Christmas Island, consensus values are calculated on site. Four times per day hourly averaged Christmas Island wind data are telemetered by means of geostationary satellite (GOES-West) and incorporated onto the Global Telecommunication System (GTS) for worldwide distribution.

Examples of the wind profiles transmitted over satellite and received in our laboratory are contained in Fig. 4. In addition to the hourly winds transmitted by satellite, complete Doppler spectra from nearly 30 heights are recorded every 2–3 min at the profiler site and archived in our laboratory. Average daily wind profiles for zonal and meridional winds deduced from the detailed data are compared in Fig. 4 with the hourly winds transmitted by satellite for 8 June 1987. The daily mean profiles possess a better height coverage and provide a better estimate of the mean daily winds than can be found by simply averaging the four values

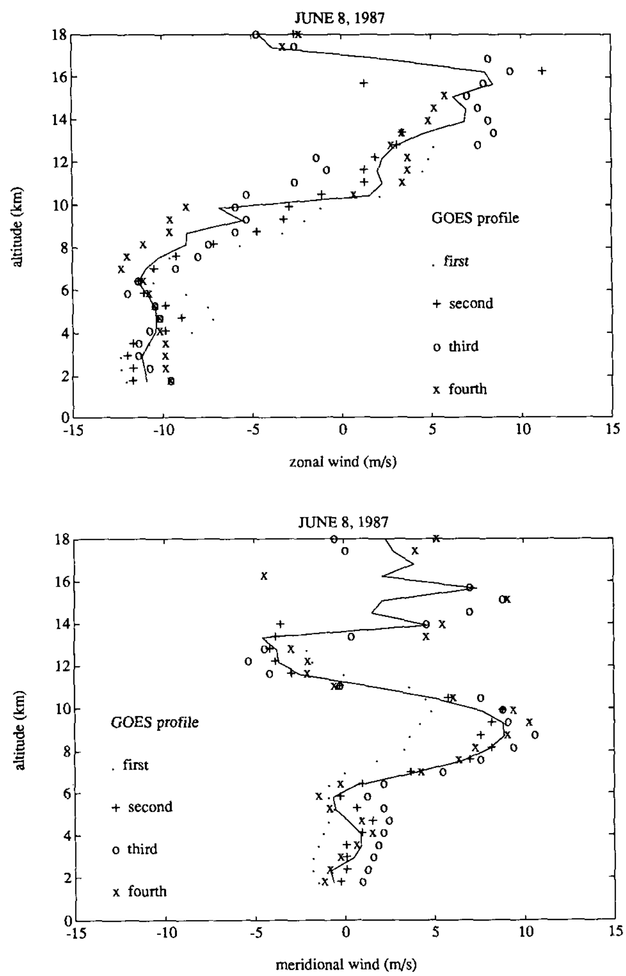

FIG. 4. Sample wind profiles for Christmas Island for 8 June 1987 as transmitted by GOES and daily mean wind profiles deduced from detailed recordings at the Christmas Island wind profiler site. Zonal winds are shown in the top panel and meridional winds are shown in the bottom panel. The symbols indicate hourly values of Christmas Island winds transmitted in near real time by satellite (in order of their observation times: 0000, 0600, 1200, and 1800 UTC).

of hourly winds transmitted by satellite. Note the satellite-transmitted winds are scattered about the daily means as expected. Reanalysis of the Doppler spectra recorded on site also provides an opportunity to apply quality control to the winds in post analysis.

Many studies have been made of the precision of profiler wind measurements. In making intercomparisons with other techniques, a typical standard is winds measured by balloon-tracking systems. The balloon observations yield point measurements along the track of the balloon, which often drifts a considerable distance during a sounding. For this reason temporal and spatial wind variability must be taken into consideration when judging such intercomparisons. In a recent intercomparison of profiler and rawinsonde winds at The Pennsylvania State University, Thomson and Williams (1990) report a root-mean-square difference close to 3 m s^{-1} in wind speeds determined by the two systems. They also intercompared winds determined by more than one profiler and concluded that the inherent accuracy for the profiler wind measurements is better than 1 m s^{-1} and that the larger differences compared to rawinsonde winds are largely due to the influence of spatial and temporal wind variability. These results agree with many other studies, including the definitive work of Strauch et al. (1987).

Intercomparison of 50-MHz profiler winds with a collocated 915-MHz profiler at Christmas Island show horizontal velocity measurement differences less than 1 m s^{-1} rms. Since the oblique beams for the two profilers are pointed at different azimuths and differ substantially in beamwidth and range resolution, different volumes of the atmosphere were sampled by the two profilers. Consequently, a significant fraction of the 1 m s^{-1} measurement difference is likely due to real differences in the wind field rather than measurement errors (Riddle et al. 1991). In the next section we present an evaluation of the performance of the Christmas Island wind profiler that includes comparisons with analyses produced by the National Meteorological Center (NMC) and the European Centre for Medium-Range Weather Forecasts (ECMWF).

4. Performance of the Christmas Island wind profiler

An important criterion for judging the performance of the Christmas Island wind profiler is the percentage of data available. During the period 1986–89, the Christmas Island wind profiler experienced 58 data outages. Most of these data outages were detected by the local site manager and were quickly fixed. Most of the down time occurred within the first year of operation. The median down time was two hours.

An important measure of the performance of any wind profiler is its height coverage. Height coverage is determined by a combination of system performance and the reflectivity of the atmosphere. Radar reflectivity depends on such factors as turbulence intensity, gradients of mean refractive index, atmospheric stability, etc. Instrumental degradation can cause a substantial loss of height coverage, but it is not always easy to distinguish between poor system performance and low atmospheric reflectivity.

A summary comparison of the percent available data versus height during 1986–89 is contained in Fig. 5. Statistics for data rate versus height are plotted separately for the three beam directions during periods when the profiler was operating. The statistics are based on hourly consensus wind calculations. For all practical purposes the height distribution of available data is the same for the two oblique beams. Data availability is virtually 100% up to 10 km. Significant reductions in the amount of available data are evident in all three beams above this level with a rate of data availability of about 55% just below the tropopause. Some recovery is evident above the tropopause, but the data rate drops rapidly above 18 km for the oblique beams and above 21 km for the vertical beam. The vertical beam has better height coverage at 50 MHz because of the anisotropic scattering from the stratosphere (Gage and Green 1978, Röttger and Liu 1978).

Mean data rates as a function of month are shown in Fig. 6 for one of the oblique beams and in Fig. 7 for the vertical beam. In these figures it can be seen that the percentage of data available versus height for the oblique beam was substantially lower in the winter of 1988/89 than in the other seasons. This decrease in percentage of available data coincides with the increased variability in the upper-tropospheric westerlies during La Niña. The naturally occurring high-frequency variability appears to be decreasing the likelihood of a successful calculation of the consensus wind. Shorter consensus time windows, such as a half-hour consensus, should improve the percentage of data available during this period. The percentage of available data in the vertical beam was also reduced during the winter of 1988/89, but not nearly as much as in the oblique beams. Some of the decrease in the amount of available data during this period is likely instrumental resulting from the aging of tubes in the transmitter that need to be replaced periodically.

Since 1987 wind observations from Christmas Island have been used by NMC and ECMWF in their operational analysis and forecast products. Gage et al. (1988) examined the performance of the Christmas Island wind profiler and its impact on NMC and ECMWF analyses by comparing the profiler-observed winds with analyses interpolated to Christmas Island. These comparisons are summarized in Figs. 8 and 9, which contain the statistics for the bias and the root-mean-square difference, respectively, between the observations and the analyses. The change with time of these comparisons from before the profiler winds were incorporated into the analyses to after they were incorporated into the analyses provides a crude indication of the wind profiler impact on the analyses. The change

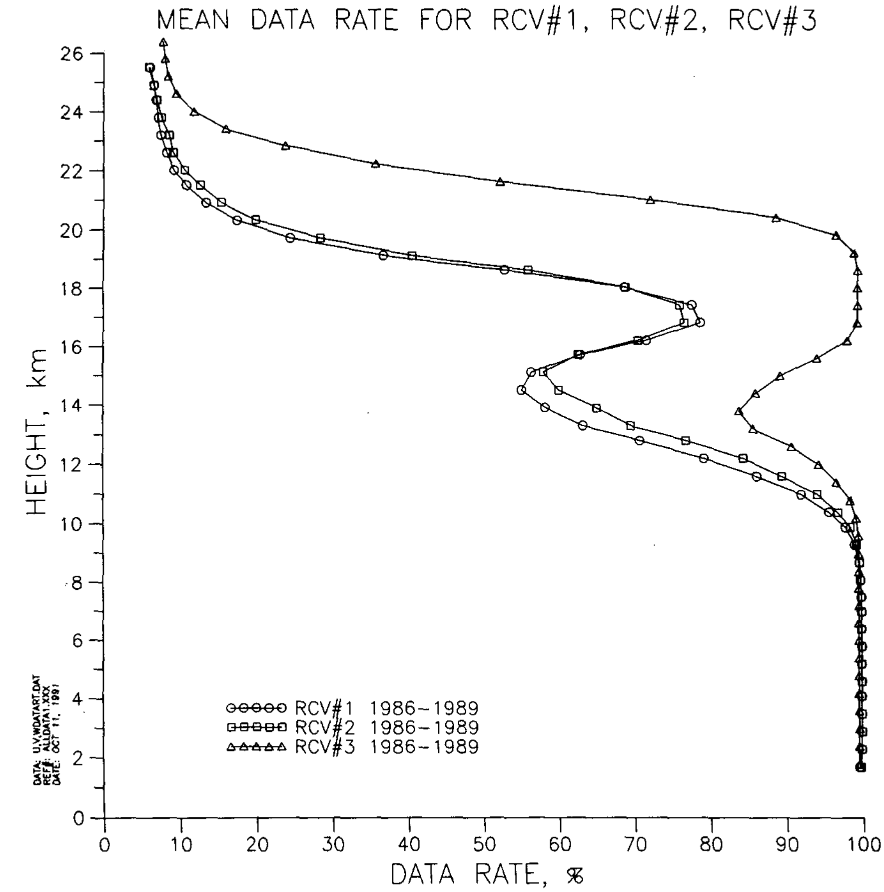

FIG. 5. Percentage of data available from the three beam directions at Christmas Island showing average data rate for the 50-MHz wind profiler during April 1986–November 1989. Receiver 3 is in the vertical direction. The statistics were compiled during periods when the wind profiler was operating.

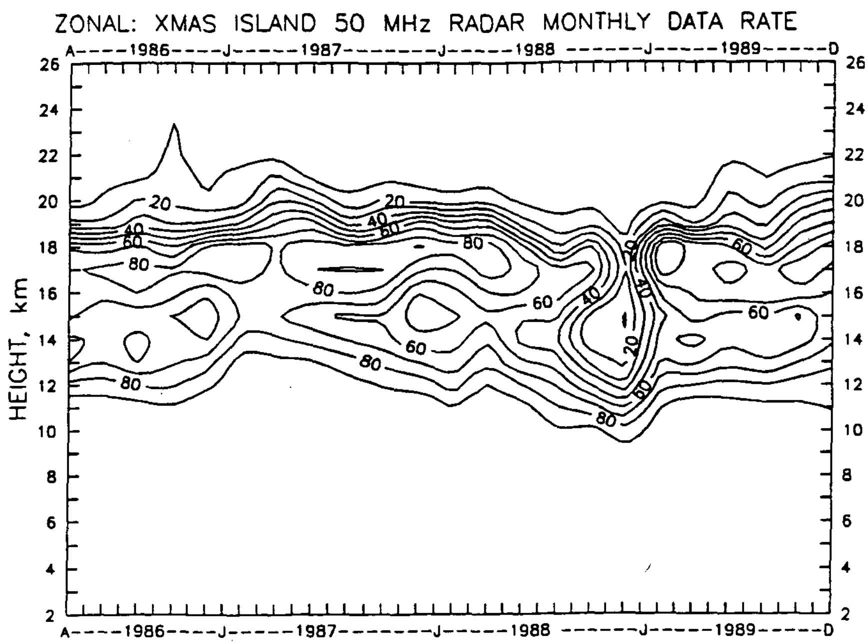

FIG. 6. Percentage of data available from the Christmas Island wind profiler as a function of altitude and time for one of the oblique beams of the profiler (receiver 1).

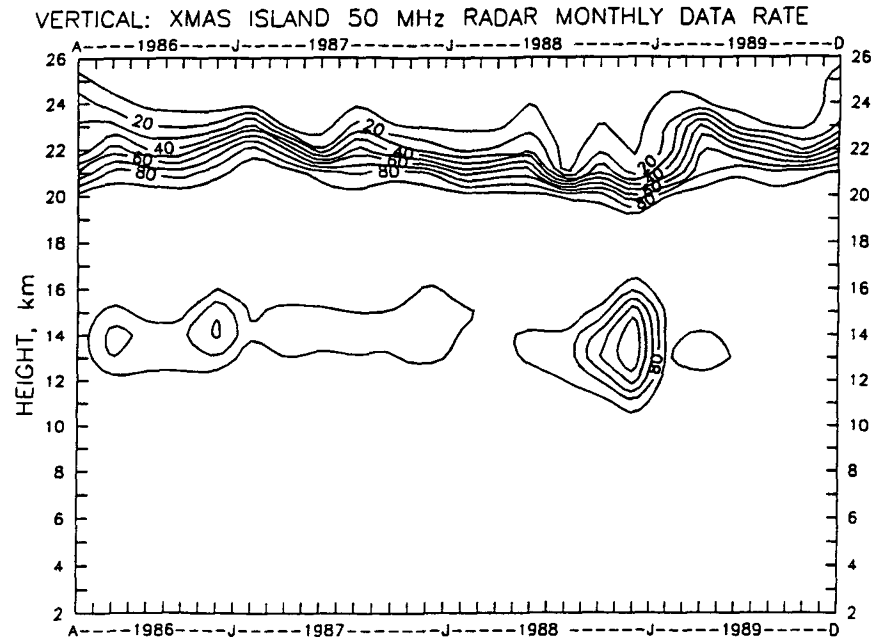

FIG. 7. Percentage of data available from the Christmas Island wind profiler as a function of altitude and time for the vertical beam of the profiler (receiver 3).

for the bias is shown in Fig. 8 and the change for the root-mean-square difference is shown in Fig. 9.

5. A brief climatology of winds and wind variability observed at Christmas Island

Samples of Christmas Island winds are contained in Figs. 10–12. These figures show the wind fields at Christmas Island in different formats summarizing daily and monthly winds. Figure 10 shows a summary time–height cross section of horizontal wind vectors observed on 2 March 1990. In this figure, upper-tropospheric westerlies can be seen above lower tropospheric easterlies. This structure is commonly observed during Northern Hemisphere winter at Christmas Is-

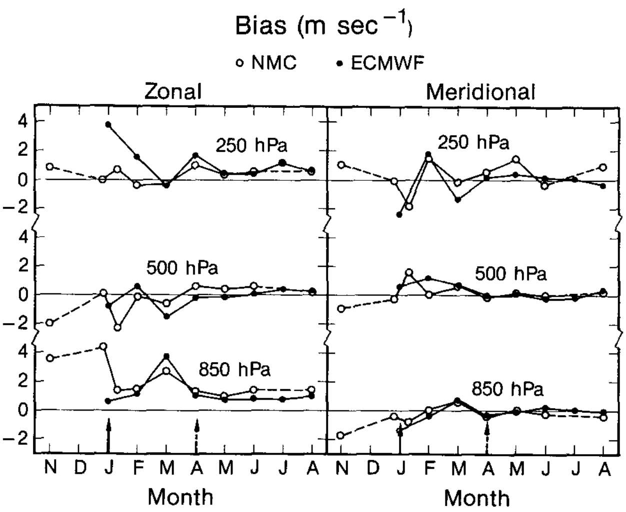

FIG. 8. Time series of monthly bias of Christmas Island winds compared to NMC and ECMWF analyses. The solid arrows indicate the time when the NMC began to use Christmas Island winds in their analyses and the dashed arrows indicate the time when the ECMWF began to use Christmas Island winds in their analyses (after Gage et al. 1988).

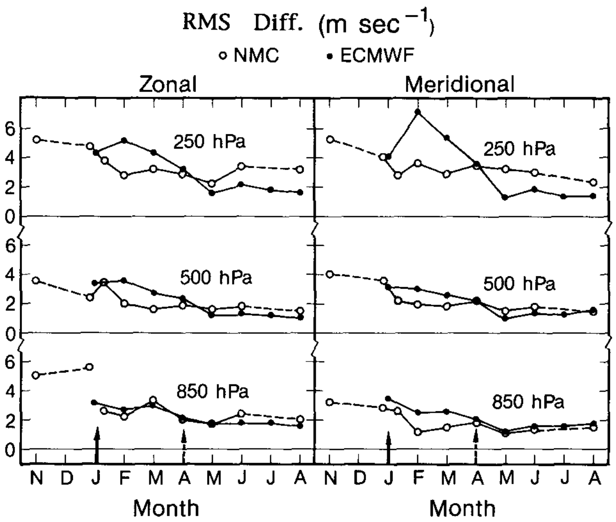

FIG. 9. Time series of monthly root-mean-square difference of Christmas Island winds compared to NMC and ECMWF analyses. The solid arrows indicate the time when NMC began to use the Christmas Island winds in their analyses and the broken arrows indicate the time when the ECMWF began to use the Christmas Island winds in their analyses (after Gage et al. 1988).

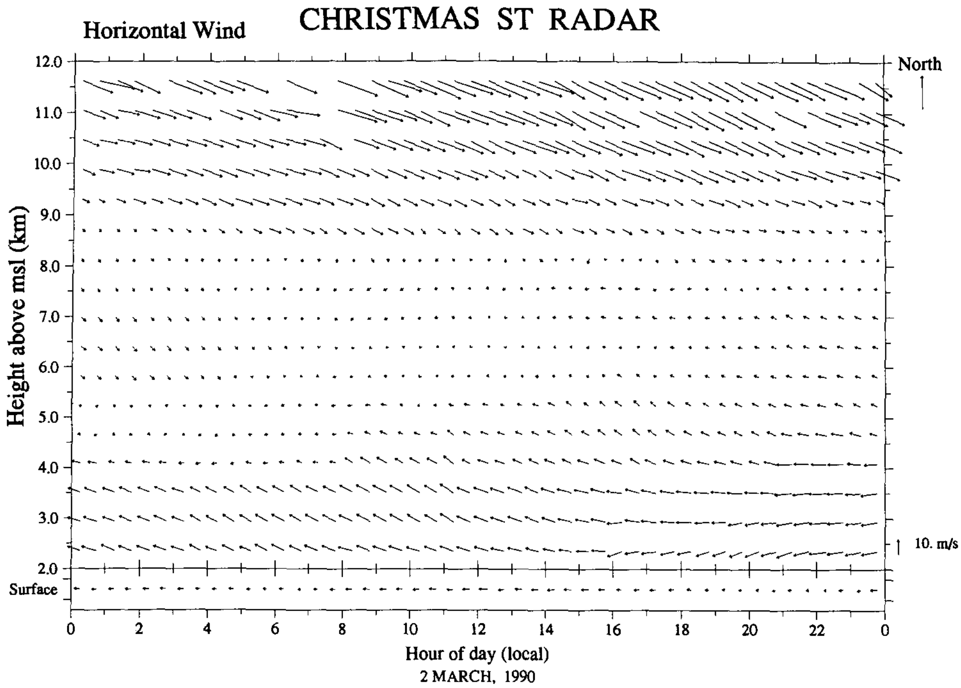

FIG. 10. Sample daily summary of horizontal winds observed at Christmas Island on 2 March 1990.

land. However, these upper-tropospheric westerlies tend to disappear during the warm phase of the Southern Oscillation when the Walker circulation is weak. Wind vectors are plotted in Fig. 10 at half-hourly intervals. With this high temporal resolution, the evolution of winds can be observed in great detail. In par-

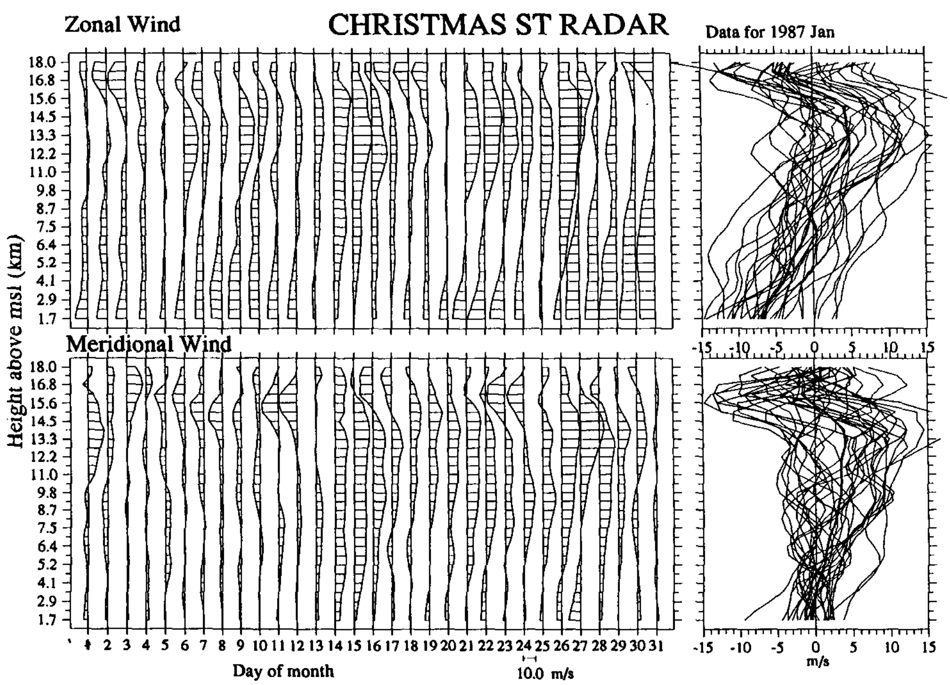

FIG. 11. Monthly summary of vertical profiles of daily averaged zonal and meridional winds observed at Christmas Island during January 1987. Zonal winds are shown in the top panel and meridional winds are shown in the bottom panel. The panels on the right show daily winds in comparison to the monthly mean (heavy solid line).

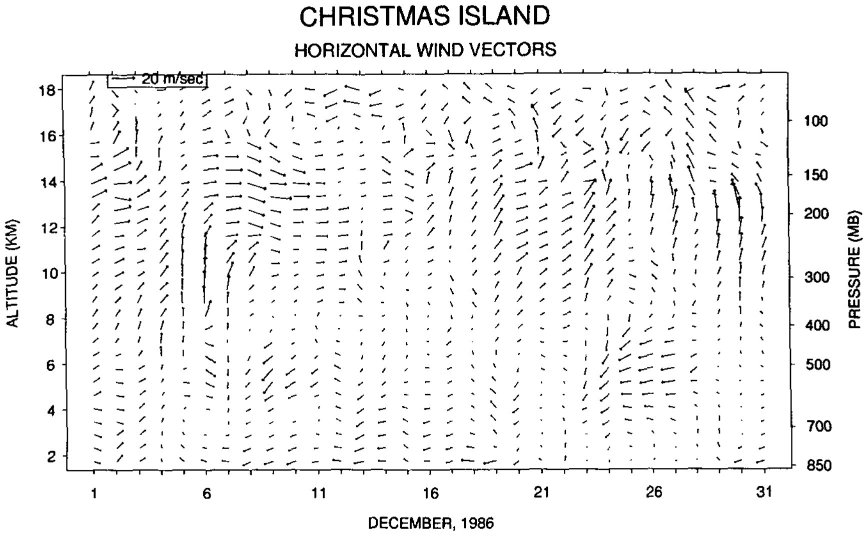

FIG. 12. Monthly summary of horizontal wind vectors observed at Christmas Island during December 1986.

ticular, it is possible to use this capability to resolve the atmospheric tides as has recently been shown by Williams et al. (1992).

Daily vertical profiles of zonal and meridional winds are shown in Fig. 11 for January 1987. This period is unusual because it falls in the middle of the 1986–87 El Niño. The easterly trades in the lower troposphere are weaker than normal as are the upper-tropospheric westerlies. Indeed, examination of detailed day-to-day variability of the observed zonal winds reveals times of lower-tropospheric westerlies and upper-tropospheric easterlies. Also shown in this figure are the vertical profiles of the daily mean winds collapsed on a common scale. This format reveals at a glance the variability of the daily winds about the monthly mean wind profiles. A monthly summary of horizontal wind vectors is contained in Fig. 12 for December 1986. As in Fig. 11, this figure shows substantial variability of the horizontal winds during the 1986–87 El Niño.

There are many ways to summarize the winds observed by the Christmas Island wind profiler. Examples of intraseasonal oscillations have been given by McAfee et al. (1989), and a summary of annual and interannual variability of winds observed at Christmas Island is contained in McAfee et al. (1990). For the purposes of this paper, we summarize the main features of the wind field observed at Christmas Island by using the monthly mean wind deduced from an analysis of the detailed Christmas Island wind data recorded at the site.

The annual variation of tropospheric winds at Christmas Island is shown in Fig. 13. The top panel of Fig. 13 reveals a systematic annual variation with relatively strong upper-tropospheric westerlies during much of the year giving way to weak westerlies and easterlies during the Northern Hemisphere summer. The annual variation in meridional winds observed at

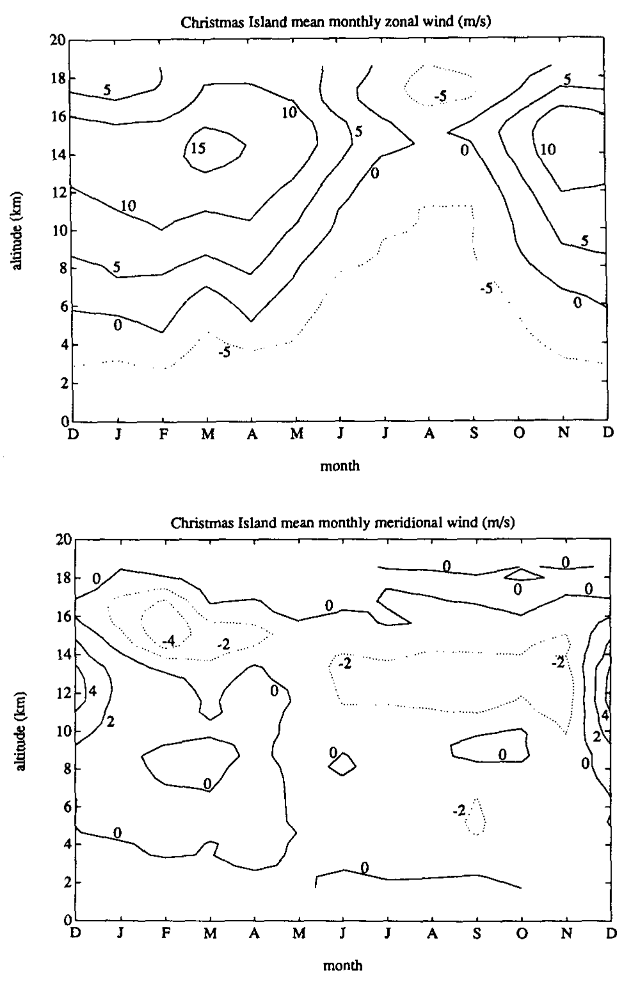

FIG. 13. Annual variation of the mean monthly winds observed at Christmas Island during the period March 1986–November 1989. Zonal winds are shown in the top panel and meridional winds are shown in the bottom panel.

Christmas Island is shown in the bottom panel of Fig. 13. It possesses a much weaker annual cycle. Nevertheless, there are some features in the annual variation of meridional winds at Christmas Island that tend to repeat themselves most years.

Interannual variability of tropospheric winds observed at Christmas Island is shown in Fig. 14. Most of the variability is seen to be related to a modulation of the annual cycle contained in Fig. 13. The top panel shows the zonal winds and the bottom panel shows the meridional winds. The annual cycle in the upper-tropospheric zonal winds is clearly much weaker than normal during the El Niño of 1986–87. In sharp contrast, the most pronounced annual cycle in upper-tropospheric zonal winds is seen to have occurred in the La Niña year of 1988–89. These year-to-year changes are related to the changing phase of the Southern Oscillation. Upper-tropospheric westerlies are strongest at Christmas Island when the Walker circulation is most pronounced during the cold phase (La Niña) of the Southern Oscillation when the contrasts across the Pacific Ocean basin are maximum. Upper-tropospheric westerlies are weakest when the contrasts across the Pacific Ocean basin are weakest as they are during the warm phase of the Southern Oscillation (El Niño).

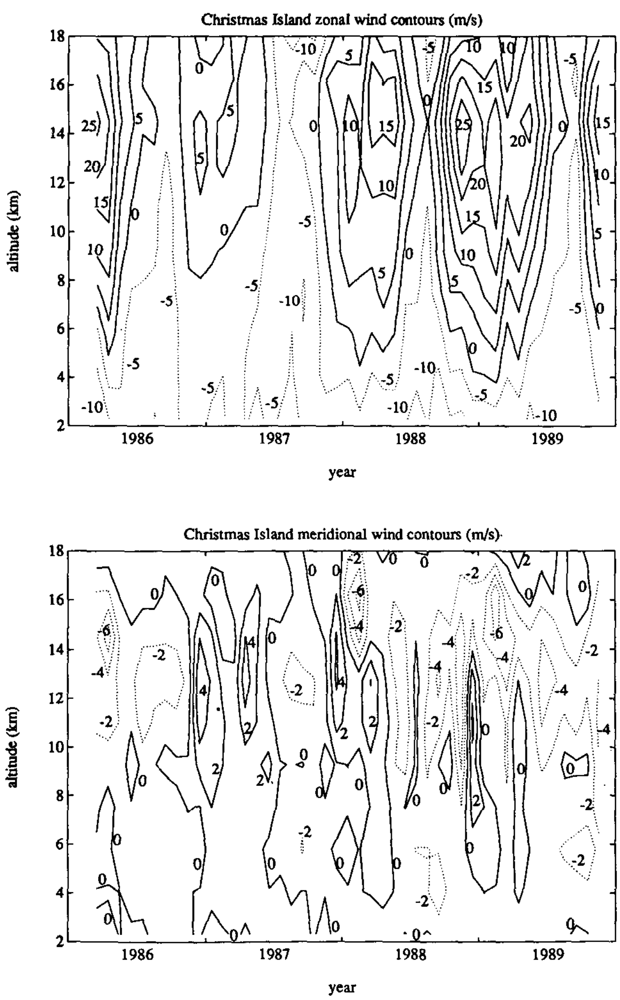

FIG. 14. Contour plots of the mean monthly winds observed at Christmas Island for the period March 1986–November 1989. Zonal winds are shown in the upper panel and meridional winds are shown in the bottom panel.

6. Concluding remarks

The Christmas Island wind profiler has operated reliably through most of the first six years since it began routine operation in March 1986. It can be viewed as a prototype for VHF wind profilers in the tropics. Indeed, VHF wind profilers have subsequently been constructed at Piura, Peru; Saipan; and in Darwin, Australia. The Saipan wind profiler was constructed in 1990 with support from the Office of Naval Research (ONR) and Australian Bureau of Meteorology Research Centre (BMRC) to provide wind observations for the Tropical Cyclone Motion Experiment. The Darwin wind profiler is a joint project of NOAA's Aeronomy Laboratory and the BMRC (Carter et al. 1991). The Pohnpei, Federated States of Micronesia (FSM), 50-MHz VHF radar originally installed as a vertical-only system by the Aeronomy Laboratory in 1984, has been upgraded to provide observations of horizontal as well as vertical winds. The 50-MHz Biak wind profiler in Indonesia commenced operation in March 1992.

The 50-MHz wind profilers have several advantages for tropical applications. Compared to wind profilers that operate at higher frequencies, lower VHF wind profilers are relatively unaffected by the presence of precipitation. Further, because of the enhanced backscatter that occurs from the stable atmosphere, they are ideally suited for observing long-term mean vertical motions in the stratosphere (Gage et al. 1991b). We are currently analyzing long-term mean vertical motions from Christmas Island wind profiler observations in the lower stratosphere, and they seem to show useful results to altitudes of 22 km and possibly higher. The vertical-motion measurements represent a unique capability of the wind-profiling Doppler radars, and they show promise for contributing new information on a variety of dynamical processes in the troposphere and lower stratosphere (Balsley et al. 1991; Gage et al. 1991a).

A significant limitation of the VHF wind profilers is their inability to make observations below about 1.8 km. For this reason the Aeronomy Laboratory has developed a UHF lower-tropospheric wind profiler that can be used in conjunction with the VHF wind profiler to provide complete coverage of tropospheric winds (Ecklund et al. 1988; Ecklund et al. 1990; Ecklund et al. 1991).

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