Long-Term Mean Vertical Motion over the Tropical Pacific: Wind-Profiling Doppler Radar Measurements

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Measurement from Christmas Island (2°N, 157°W) of long-term mean vertical motions in the tropical atmosphere using very-high-frequency wind-profiling Doppler radar show that there is a transition from downward motion in the free troposphere to upward motion in the upper troposphere and lower stratosphere. The observations in the free troposphere are consistent with a balance between adiabatic and diabatic heating and cooling rates in a clear atmosphere. Comparison of the results at Christmas Island during El Niño and non–El Niño conditions with earlier results obtained for stratiform rain conditions over Pohnpei, Federated States of Micronesia, show that cirrus clouds in the vicinity of the tropopause likely play an important role in determining the sense and magnitude of vertical motions in this region. These results have implications for the exchange of mass between the troposphere and stratosphere over the tropics.

Recent developments in atmospheric wind profiling using Doppler radar have made possible the direct measurement of atmospheric vertical motions. This technology is now being applied to observations in the tropics, especially over certain islands in the Pacific Ocean. Previous work (*1*) has focused on vertical motions averaged during periods of convective and stratiform rain over Pohnpei, a volcanic island located in the convectively active western tropical Pacific. The present research is concerned with long-term mean vertical motions over Christmas Island, an essentially flat coral atoll located in the equatorial dry zone of the central Pacific south of Hawaii, where substantial rainfall occurs only during the warm phase of the Southern Oscillation. A wind profiler has been in operation at Christmas Island since early 1986, and in this study we analyzed vertical velocities observed during the period April 1986 to July 1987. These observations reveal a systematic pattern of subsiding downward motion through the free tropical troposphere below about 14 km and ascending motion in the uppermost levels of the troposphere and throughout the lower stratosphere. Adiabatic warming associated with the tropospheric subsidence appears to be in approximate balance with calculated radiative cooling to space in the clear atmosphere, but the ascending motion appears to be somewhat larger than is needed to balance diabatic heating in the lower stratosphere, assuming a clear atmosphere free of ice particles or other aerosols.

The present work builds on the pioneering study of mean vertical motions over the western Pacific reported by Balsley *et al.* (*1*), who used the Pohnpei very-high-frequency radar to measure vertical velocities. These investigators stratified the vertical velocity observations according to rainfall rate and deduced mean motion profiles pertaining to convective precipitation, stratiform precipitation, and relatively clear conditions. The results for stratiform rain are reproduced in Fig. 1. Note the downward velocity evident in the lower stratosphere. This result will be discussed in more detail below where we contrast the Christmas Island results with the earlier observations from Pohnpei. The results from the Pohnpei wind profiler also showed that upward motion through most of the troposphere was related to episodes of rainfall and that during periods of no precipitation vertical motions were downward at all altitudes observed. The "error bars" refer to the standard error of the mean determined from the ratio of the standard deviation of the measured vertical velocities to the square root of the number of independent samples. The standard error is much larger in the vicinity of mesoscale convective systems than under clear conditions.

Vertical velocities in the atmosphere are dominated by short-period internal gravity waves (*2*), with typical root-mean-square amplitudes of 10 to 20 cm s^{-1}, and measurement of the much smaller long-term mean vertical motions requires averaging large numbers of individual measurements. For example, at Christmas Island approximately 200 samples of vertical velocity are obtained every day at each of 34 range gates that cover the altitude range between 1.8 and 22 km. A typical standard deviation of daily averaged vertical velocities about the monthly mean at mid-tropospheric heights is about 1 cm s^{-1}, increasing to larger values between 12 and 15 km, partly because there are fewer samples in this height range and partly because the vertical motions are more variable. Further averaging of the mid-tropospheric daily values allows the determination of monthly means with a standard error of the mean close to 0.2 cm s^{-1}.

In the profiles of monthly mean vertical velocities observed at Christmas Island during 1986 (Fig. 2), there is a remarkable month-to-month consistency; these profiles show systematic downward motion between about 4 and 14 km. Below 4 km there is evidently some upward motion, perhaps associated with convection in the marine

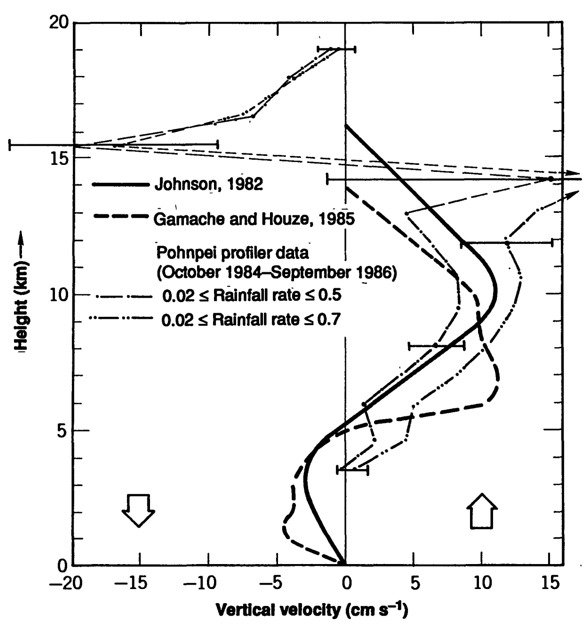

Fig. 1. Height profiles of average vertical velocity observed at Pohnpei between October 1984 and September 1986 for rainfall rates corresponding to stratiform conditions. The shaded area delineates the region between profiles obtained for 0.02 inch (0.5 mm) $hour^{-1}$ ≤ rainfall rate ≤ 0.5 inch (12.7 mm) $hour^{-1}$ and 0.02 inch (0.5 mm) $hour^{-1}$ ≤ rainfall rate ≤ 0.7 inch (17.8 mm) $hour^{-1}$. The Johnson (*11*) profile was obtained by conventional techniques in the south China Sea; the Gamache and Houze (*12*) profile was obtained during GATE [GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment] in the eastern Atlantic [after Balsley *et al.* (*1*)].

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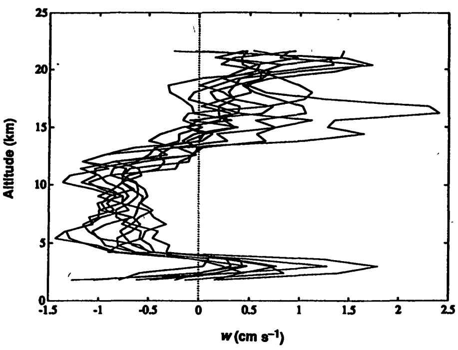

Fig. 2. Height profiles of monthly mean vertical velocities at Christmas Island, April to December 1986.

boundary layer and the trade-wind regime. Above about 14 km, upward motion is also evident in the upper troposphere and lower stratosphere, showing a greater degree of month-to-month variability than the motions in the lower region.

For equilibrium conditions, the downward motions observed over most of the troposphere imply that the adiabatic warming has a magnitude of $-w^*S$, where w^* is the upward vertical velocity, S is the static stability parameter (T/Θ) $(\partial\Theta/\partial z)$, and Θ is the potential temperature (T is temperature and z is height). For an observed value of $w^* = -0.7$ cm s^{-1} and a typical value of S of 3 K km^{-1} in the tropical troposphere (*3*), we deduce adiabatic warming rates of order 2 K day^{-1}, which is of the right magnitude to balance radiative cooling in a clear atmosphere (*4*). Similarly, upward motion in the vicinity of the tropopause and through much of the lower stratosphere implies adiabatic cooling. The observed upward vertical velocity of order 0.3 cm s^{-1} together with a typical value for S of 12 K km^{-1} leads to an inferred adiabatic cooling rate of order 3 K day^{-1}, which is considerably larger than the diabatic heating rates (1 K day^{-1}) calculated for the clear tropical lower stratosphere. A number of recent studies (*5*), however, have shown that diabatic heating rates are substantially modified if ice particles or other aerosols are present in an otherwise clear atmosphere. The presence of thin cirrus either locally generated or originating in distant convective regions is a possible explanation of the large heating rates above 14 km, and cloud effects may also be the explanation of the large and variable upward velocities observed below 4 km.

Another possible explanation for the large inferred heating rates in the lower stratosphere is the influence of vertical motion along sloping isentropic surfaces. Along these surfaces potential temperature is conserved in adiabatic motion. Departures of the motion from isentropic surfaces are associated with diabatic heating or cooling. The arguments made above assume isentropic surfaces that are horizontal so that there is no advective component to the observed vertical motion. In the presence of substantial nonuniform sources of heating and cooling, as would be associated with spatially nonuniform cloud distributions, and with strong winds a significant advective component might be found. Nevertheless, the advective component should usually be small. For example, a very large slope in isentropic surfaces of magnitude 1 km per 1000 km would be required in the presence of 10 m s^{-1} wind to account for 1 cm s^{-1} in vertical motion.

The upward motion in the lower stratosphere over Christmas Island appears to be a robust feature of these observations and should be contrasted with the observations at Pohnpei in the western Pacific that show downward motion in the lower stratosphere even under relatively clear conditions (*1*). If these observations are representative of the

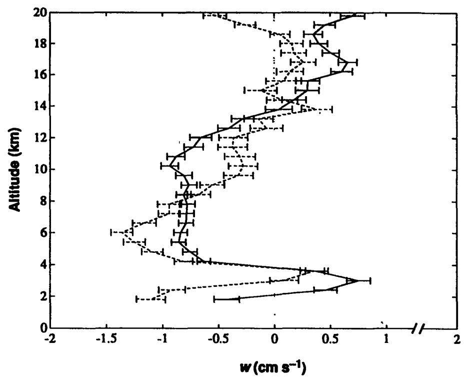

Fig. 4. Height profiles of long-term mean vertical velocities at Christmas Island. Solid curve represents the period April to November 1986 just before the onset of the 1986–1987 El Niño. Dashed curve represents the period during the 1986–1987 El Niño. Error bars represent the standard error of the mean.

central and western Pacific regions, they have important implications for our understanding of the general circulation of the tropical lower stratosphere and for troposphere-stratosphere coupling. For example, they raise the intriguing possibility that upward motion through the tropopause region is more typically found over the central Pacific than over the "stratospheric fountain" region of the western Pacific (*6*). This could occur if radiative effects arising from the different cloud distributions in the two regions act to cool the tropopause region over the western Pacific and warm it over the central Pacific. Furthermore, the observations suggest that the zonal Walker circulation of the tropical Pacific region (*7*), which consists of an upward branch over the convectively active regions and a downward branch over the clear regions, has a mirror-image counterpart in the upper troposphere and lower stratosphere, consisting of a downward branch above the cloudy convective regions and an upward branch over the clear areas, as shown schematically in Fig. 3.

One can test the ideas presented above by comparing the mean vertical motion at Christmas Island between El Niño and non–El Niño conditions. During El Niño events convection moves eastward toward the dateline as can be seen in satellite maps of outgoing long-wave radiation. This means more and thicker high-level cirrus clouds at Christmas Island, which would tend to block the radiative heating process thought to be responsible for the upward motion observed in the lower stratosphere at Christmas Island. Accordingly, we would expect to observe smaller upward velocities and perhaps even downward motion in the lower stratosphere over Christmas Island during El Niño. In the upper troposphere, radiative cooling should be diminished by the pres-

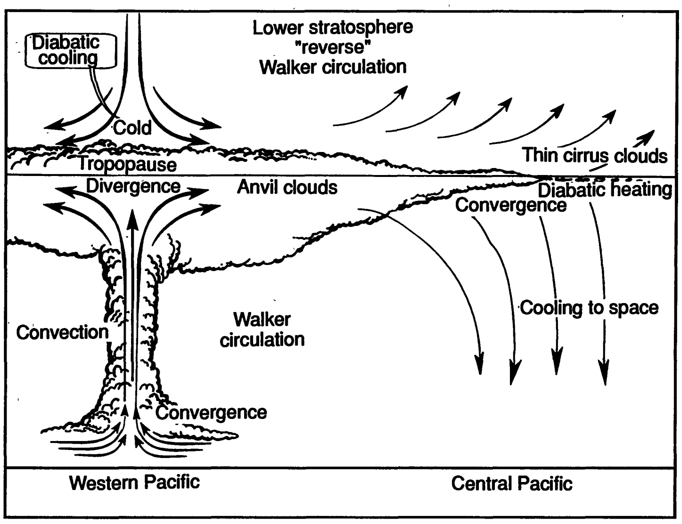

Fig. 3. Schematic circulation in the zonal plane consistent with the wind profiler observations.

ence of thick clouds so that mean vertical motions should be less downward. Diabatic heating at the bottom of thick tropospheric anvils should also give rise to decreased downward motion and possibly even upward motion. At mid-tropospheric heights it is less obvious what to expect during El Niño conditions. On the one hand, the presence of thick clouds should inhibit diabatic cooling and mitigate against downward motion. On the other hand, precipitation from decaying tropospheric anvils would cause diabatic cooling due to evaporation below the clouds, leading to enhanced downward motion there.

Figure 4 shows the mean vertical motions observed at Christmas Island during the period before the 1986–1987 El Niño and during the El Niño. Upward vertical motions above 14 km were observed to be systematically lower during the El Niño, consistent with the idea of reduced diabatic heating. Downward vertical motion is reduced systematically in the upper troposphere, consistent with the idea of reduced cooling to space due to the presence of optically thick clouds; enhanced downward motions around 6 km are consistent with evaporative cooling.

Although we favor a radiative explanation for the vertical motions observed in the upper troposphere and lower stratosphere, dynamical forcing may also play a significant role. In particular, the meridional circulation needed to maintain the stratospheric quasi-biennial oscillation winds in geostrophic balance involves vertical motion near the equator (*8*), with a sign that reverses on the quasi-biennial time scale. This circulation is not expected to penetrate below the tropopause, however.

Tropical networks of wind profilers and integrated sounding systems (*9*) that include wind profilers are currently in an advanced state of development and should be implemented within the next few years. They are expected to provide observations of tropical circulation systems and equatorial waves over a broad range of scales (*10*). Furthermore, profilers by virtue of their ability to resolve small-scale internal waves provide a means for investigating dynamical coupling between the lower and middle atmosphere.

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A Fungal Gene for Antibiotic Resistance on a Dispensable ("B") Chromosome

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A family of cytochrome P-450 (*Pda*) genes in the pathogenic fungus *Nectria haematococca* is responsible for the detoxification of the phytoalexin pisatin, an antimicrobial compound produced by garden pea (*Pisum sativum L.*). The *Pda6* gene was mapped by electrophoretic karyotype analysis to a small meiotically unstable chromosome that is dispensable for normal growth. Such traits are typical of B chromosomes. The strains of *Nectria* studied here have no sequences that are homologous to the *Pda* family other than *Pda6* and therefore demonstrate that unique, functional genes can be found on B chromosomes. Unstable B chromosomes may be one mechanism for generating pathogenic variation in fungi.

THE ABILITY OF THE PLANT PATHOGENIC fungus *Nectria haematococca* MP (mating population) VI to infect pea (*Pisum sativum L.*) is determined in part by whether the fungus can detoxify pisatin, an antibiotic produced by pea (*1*). Detoxification of pisatin is catalyzed by pisatin demethylases, a group of substrate-specific, cytochrome P-450 monooxygenases (*2*) encoded by the *Pda* gene family. Although each *Pda* gene can independently confer pisatin-demethylating ability on the fungus (a trait called Pda$^+$), the genes vary in their inducibility by pisatin and by the amount of resulting enzymatic activity (*3*). Only isolates of *N. haematococca* that rapidly detoxify pisatin have the potential to be aggressive pathogens on pea (*1, 4–6*).

Meiotic events in *N. haematococca* can be studied by the technique of tetrad analysis. The products of meiosis are contained in structures (asci) that allow their recovery as a set. Genetic crossing begins by the joining of a haploid cell from each parent to produce a fusion cell containing two nuclei. This cell multiplies vegetatively inside a maternally produced fruiting body (a perithecium) into a cluster of cells. Asci develop when nuclear fusion and meiosis occur within some of these cells. The four haploid products of meiosis (a tetrad) then divide mitotically, resulting in eight ascospores per ascus. Each tetrad therefore consists of four pairs of sister spores, each pair representing one of the four products of meiosis.

Some crosses of *N. haematococca* produce fewer Pda$^+$ progeny than expected from conventional models of inheritance (*4, 5, 7*). In a cross (cross 272) between two strains that each carried *Pda6* as the only active *Pda* gene (*7*), only asci with 8 Pda$^+$:0 Pda$^-$ segregation were expected. However, many asci from this cross showed 4 Pda$^+$:4 Pda$^-$ segregation (Table 1). The Pda$^-$ condition was not associated with any distinct phenotype or growth pattern in culture. No homology to a cloned *Pda* gene (*Pda-T9*) (*8*) was detected by hybridization to the DNA from these Pda$^-$ progeny (*9*); thus loss of

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