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# The morning glory wave of southern California

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[1] A pulse-like disturbance traveling across the Los Angeles basin was observed on 12 October 2001 with seismographs of the TriNet network. This wave had a period of about 1000 s and a propagation speed of about 10 m/s, much slower than seismic waves. The seismograph data were compared with barograph data, and a good correlation was found so the wave was determined to be atmospheric in origin. It had amplitude of about 1 mbar, but it was not known what process could produce such a wave. Since the initial finding, we have inspected all the TriNet barograph and seismograph data for a period of two and a half years (from January 2000 to August 2002) and found four more similar events. Each of the events has amplitude between 0.8 and 1.3 mbar, a period between 700 and 1400 s, and a propagation speed between 5 and 25 m/s. We conclude that these waves are internal gravity waves trapped in a stable layer formed by a temperature inversion. Some of these waves have large amplitudes and develop into solitary waves (nonlinear internal gravity waves) similar to the spectacular "morning glory" wave observed in Australia. We call these waves the LA morning glory waves. The LA morning glory wave is probably excited by either stormy weather, winds such as the Santa Ana winds, or large teleseismic events. The morning glory wave could contribute to the recently reported excitation of the background free oscillations of the Earth. Additionally, because of its large amplitude it could have important implications for aviation safety, as was suggested earlier for the morning glory waves in Australia. *INDEX TERMS:* 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 7255 Seismology: Surface waves and free oscillations; 7260 Seismology: Theory and modeling; 7299 Seismology: General or miscellaneous; *KEYWORDS:* solitary wave, temperature inversion, smog, LA basin, morning glory

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## 1. Introduction

[2] For many years people living near the Gulf of Carpentaria in Australia have observed spectacular roll clouds. Because they frequently occur in the morning, natives dubbed the strange atmospheric phenomenon the "morning glory." However, the morning glory phenomenon had never achieved such a high degree of regularity anywhere outside of the small area in northern Australia. Despite having been reported to the rest of the world in the 1930s, very few people took any notice of the phenomenon. The scientific community first noticed the morning glory when *Clarke* [1972] published a paper describing its main attributes. *Neal et al.* [1977] performed further studies on the climatology for morning glories. However, the study of morning glories did not gain popularity until *Christie et al.* [1978] gave an in-depth study of the phenomenon classifying it as a solitary wave, an internal, nonlinear gravity wave. Since then, a few investigators have contributed to the understanding of morning glories, including *Clarke et al.* [1981] and *Smith et al.* [1982], and the phenomenon is now generally regarded as relatively well understood.

[3] Similar atmospheric gravity waves have been earlier observed in meteorological data such as wind gauges and barographs. *Gossard and Munk* [1954] reported observations of atmospheric waves with periods of 5–15 min and propagation speeds of about 10 m/s near San Diego. They interpreted these waves as internal gravity waves trapped in a waveguide formed by a temperature inversion over the area. Morning glory-type disturbances have also been sighted in various other places, including in other areas of Australia, the midwestern United States, over the British channel, and in northern Germany [*Christie*, 1992].

[4] In southern California, an unusual long-period wave was observed in 1988 with a TERRAscope (a broadband seismograph network in southern California) station in Pasadena [*Kanamori*, 1989]. However, since the observation was made at only one seismic station (Pasadena) and no high-quality barograph data were available at the time, the wave speed could not be determined and the wave was tentatively attributed to a local slow deformation. No further follow-up studies were made.

[5] On 12 October 2001, a similar pulse-like disturbance with a pulse width of about 1000 s and a propagation speed

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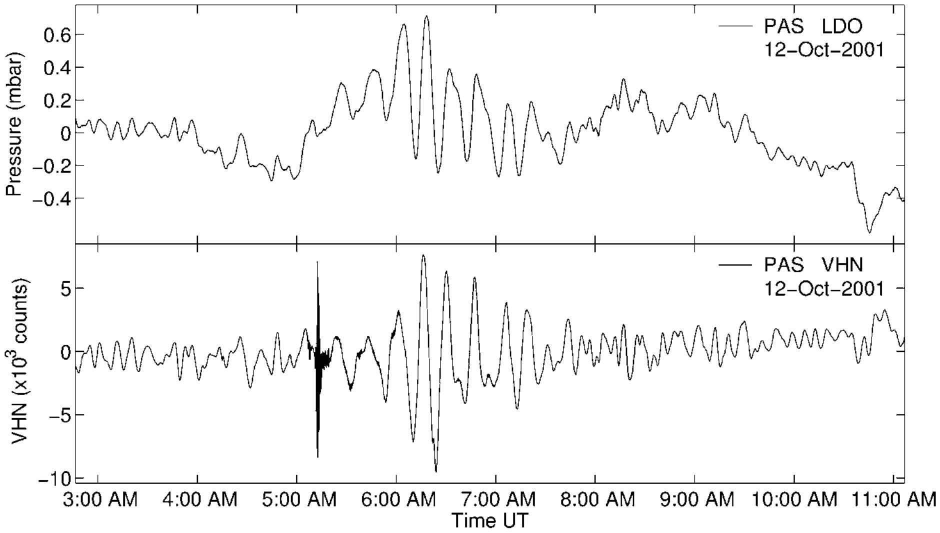

**Figure 1.** (top) Barograph record and (bottom) seismogram (very broadband channel) from station Pasadena for the 12 October 2001 event. The signals are correlated well in the ~1000 s period range. As a further note, there is an earthquake in Figure 1 (bottom) at around 0510 LT. For further information, refer to section 4.2.

of about 10 m/s traveling across the Los Angeles basin was observed (S. Kedar, personal communication, 2001). This wave was recorded with both seismographs and barographs in the Los Angeles (LA) Basin. Figure 1 shows the seismogram and the barograph record of this event recorded at Pasadena. The seismic signal, which is prominent on the horizontal component, correlates well with the barograph record.

[6] The observations that the wave involves pressure changes and that the propagation speed is much slower than any regular seismic waves suggest that this wave is probably of atmospheric origin and is similar to those

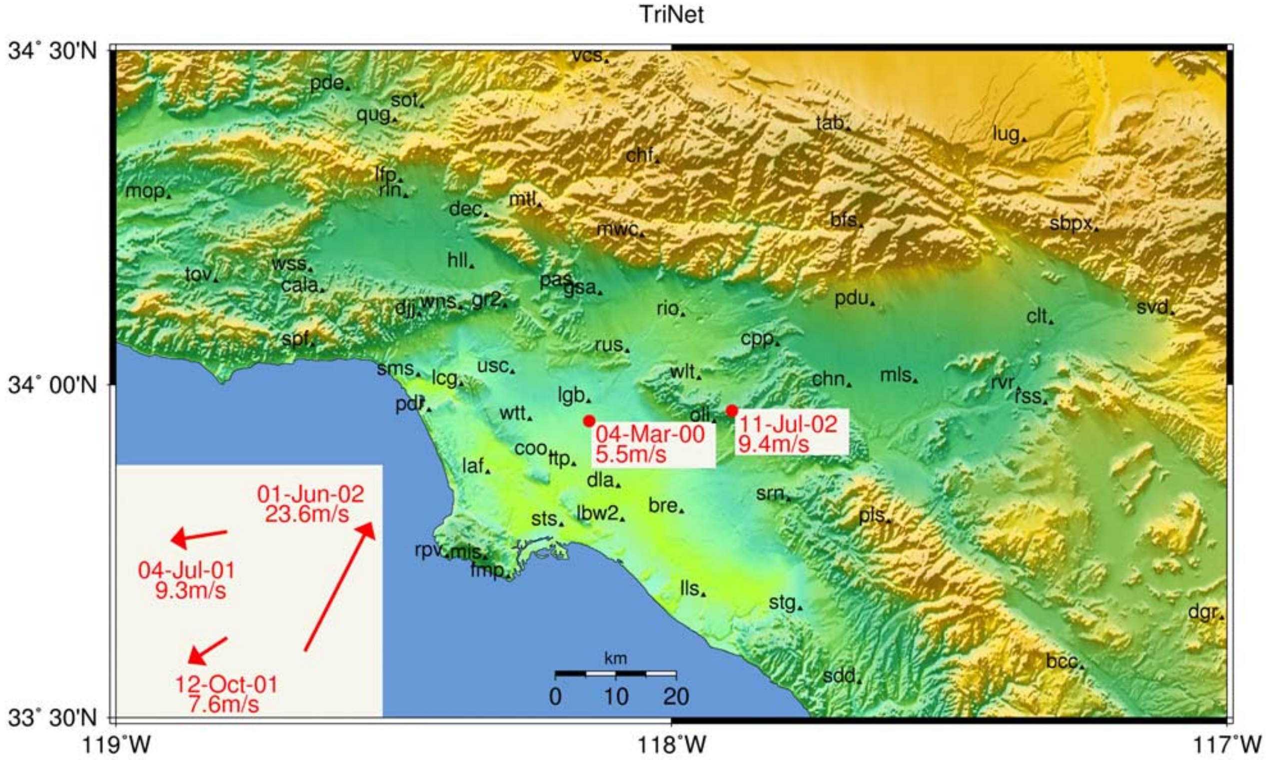

**Figure 2.** Distribution of TriNet stations in the Los Angeles Basin. The propagation direction and azimuth of the morning glory waves are shown in the inset. For the events on 4 March 2000 and 11 July 2002, the speed and location of the origination point are shown on the map.

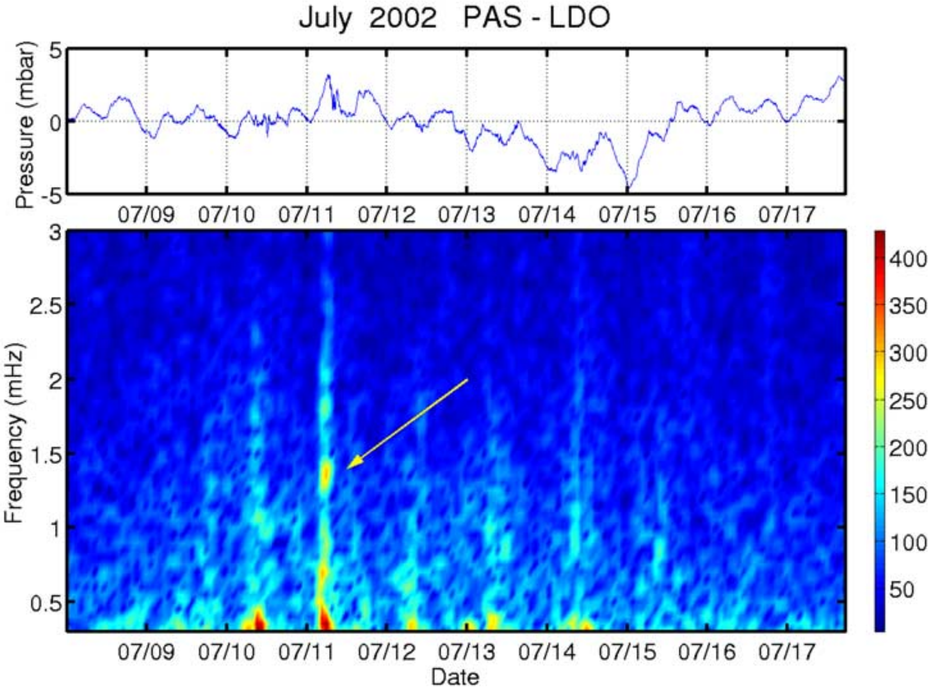

**Figure 3.** Spectrogram of the 11 July 2002 morning glory wave. The original barograph record is shown on top.

observed in San Diego and Australia. In this interpretation, the pressure change recorded on the barograph is the primary signal; the signal recorded with a seismograph is due to local tilt of the ground near the seismograph caused by the pressure changes. Because the tilting is probably caused by complex interactions between the atmosphere and the local structure including the seismograph housing, it is difficult to quantitatively interpret seismic data, but the seismic record can be used to track the propagation of the pressure wave. It should also be noted that because of the complex interactions, the waveform from seismographs does not accurately represent the pressure waveform. The variations in waveform from station to station are interpreted as due to different atmosphere-ground coupling.

[7] This observation, as well as the earlier observation of the slow wave made in 1988, motivated us to investigate this wave more systematically by analyzing seismograph and barograph data now available in southern California from the TriNet network [*Hauksson et al.*, 2001].

## 2. Data Analysis

[8] We examined all of the relevant data available for the period from January 2000 to August 2002. Our primary source of data is from the TriNet seismograph and barograph network in southern California, which we accessed through the SCEC (Southern California Earthquake Center) Data Center as well as from the IRIS (Incorporated Research Institutions for Seismology) Data Center.

[9] The locations of TriNet stations are shown in Figure 2. All of the TriNet stations have a three-component broadband seismograph, but only a few of them have a barograph. Thus we first investigated the barograph records in search of the pressure changes with a characteristic period between 500 and 2500 s. Once the wave was detected, we examined the seismograms to determine the speed and propagation direction.

[10] Because it is not always easy to recognize the wave directly on the barograph time series, we used spectrograms of the barograph record to detect the signal. Figure 3 shows an example of the spectrogram for an event in July 2002. The frequency spectrum of signals at successive time windows, each 20,000 s long and overlapping with the successive window by 5000 s, is given by color code indicated by the color bar at right. Blue denotes small amplitudes whereas red denotes larger amplitudes. The signal for this event is the yellow spot at approximately 0100 LT on 11 July and 1.3 mHz, as indicated by an arrow in Figure 3.

[11] We have systematically examined all the record continuously from January 2000 to August 2002 and found five events which distinctly showed the characteristic spectral pattern on the spectrogram. Figure 4 displays five spectrograms with the characteristic signal and one spectrogram without a signal. Although each of the five spectrograms has unique features, all the spectrograms share the same basic spectral energy peak at around 1 mHz (1,000 s).

[12] Figure 5 shows the filtered barograph record and the horizontal component acceleration record computed from the record at PAS for four of these events (see section 3 for further discussion). In all cases, the waveform from the seismograph correlates very well with that from the barograph. Additionally it should be noted that the signal is seen on the vertical component seismograms (not shown here), although the signal is smaller than on the horizontal component and is thus harder to identify.

[13] Once we identified these waves, we determined the speed and the direction of wave propagation by least

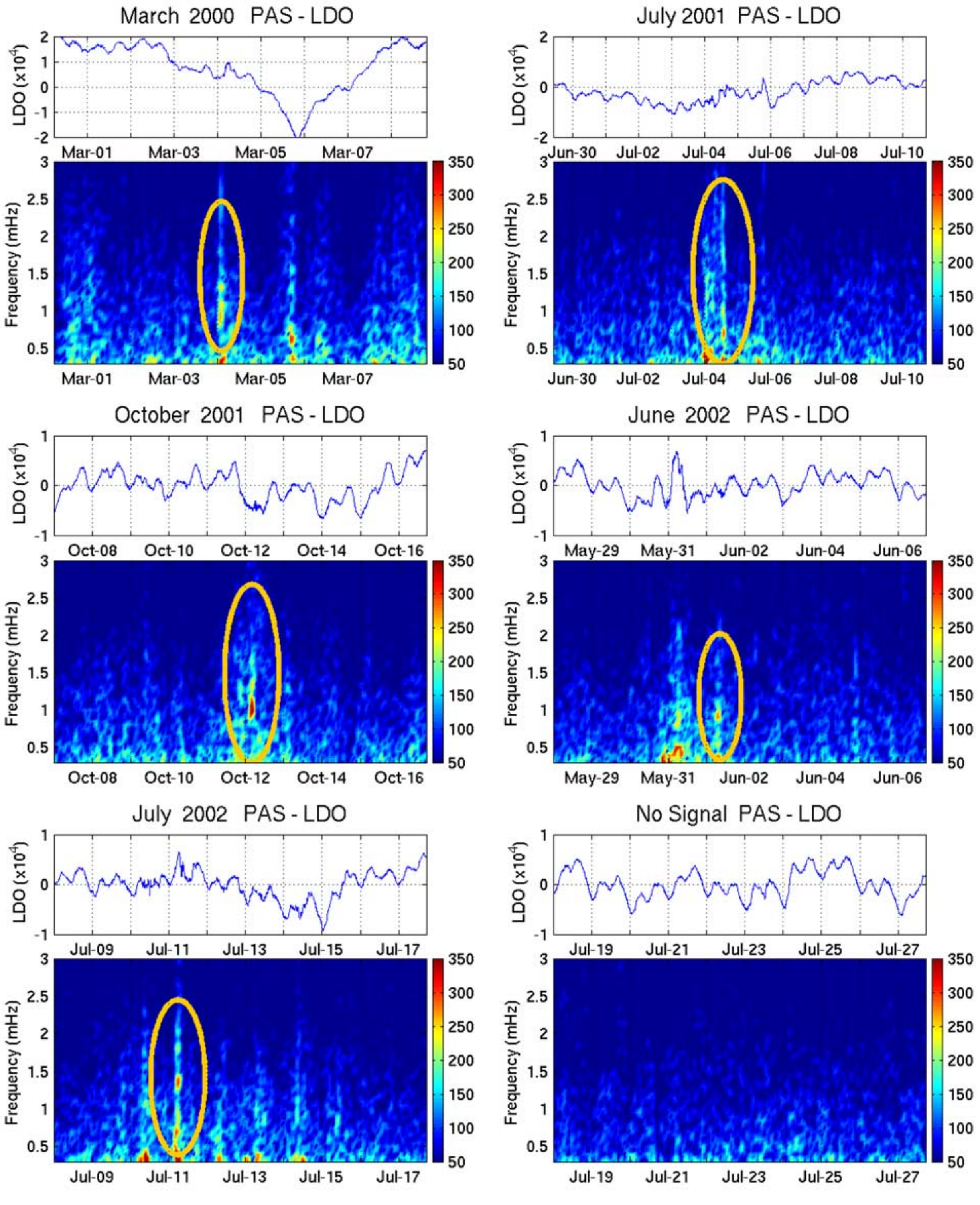

**Figure 4.** Spectrograms of the five morning glory events and one spectrogram without a signal (shown for comparison). Although all five of the spectrograms have unique features, they all share the same basic spectral energy peak at around $10^{-3}$ Hz (1000 s).

squares fitting the arrival times at different stations. Through this method we were able to construct record sections for the events (Figure 6) on which the propagation speed and direction can be visually verified (Figure 2).

[14] With the analysis described above, we identified five events with the distinct spectral characteristics and slow propagation speed. Table 1 lists these events. The event in 1988 mentioned earlier is included, although no barograph

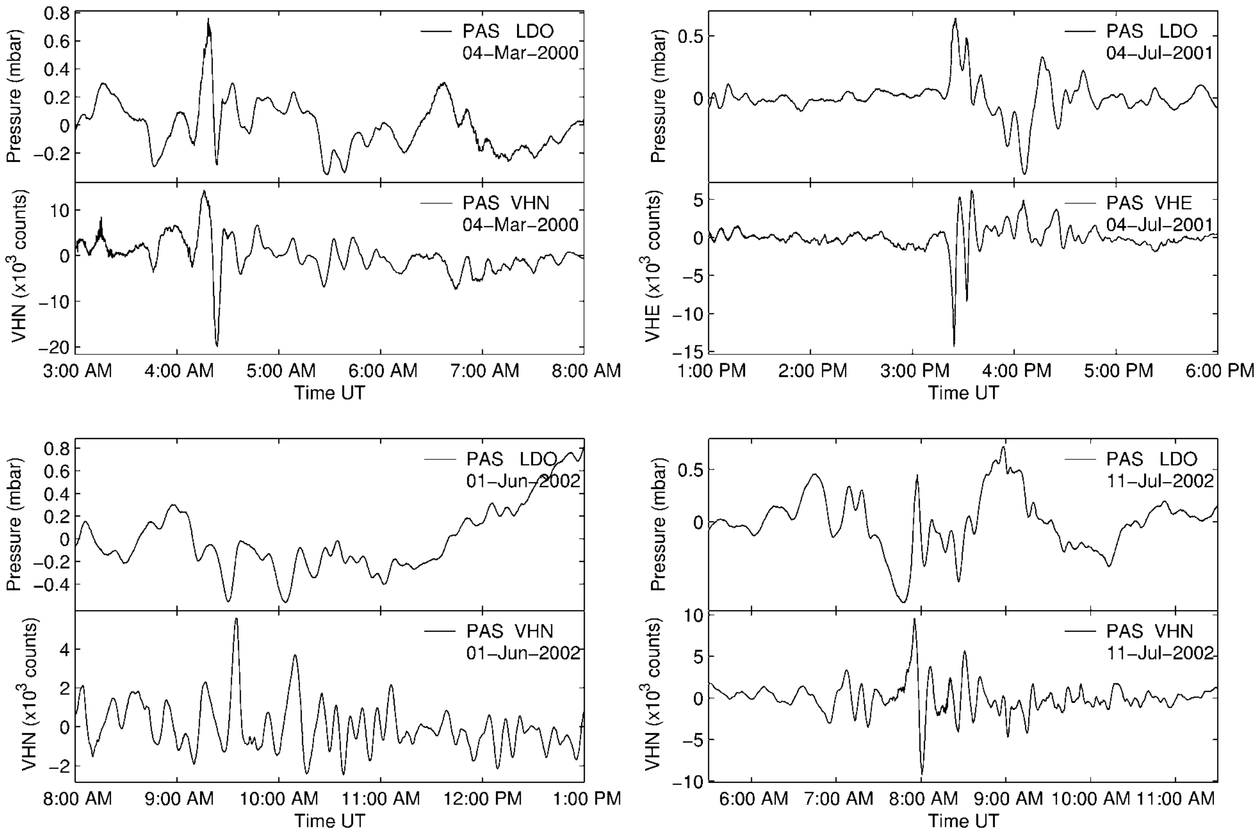

**Figure 5.** Comparison of the barograph records with the broadband seismograms.

data (and only limited seismic data) are available for this event.

## 3. Interpretation

[15] The similarity of the propagation speed and the characteristic period between the waves we observed in the LA Basin and those observed by *Gossard and Munk* [1954] near San Diego, and the morning glory waves observed in Australia [*Christie*, 1992] suggests that the LA Basin waves are similar to those observed in San Diego and Australia. Given this similarity, we hereafter call this wave the LA morning glory wave.

[16] One of the most prominent atmospheric features of the LA Basin is the smog that is nearly always present. Much of the smog is due to the natural temperature inversion that occurs commonly in the basin. In most places, temperature drops with increasing height following an almost adiabatic profile. The LA Basin, which is surrounded by mountains on one side and ocean on the other, is atypical in that the temperature first increases with height before finally decreasing as normal (Figure 7). The typical height of the top of inversion layer is approximately 1 km (see Figure 7). When the condition for temperature inversion prevails, the perturbation $\Delta T$ from the normal temperature is usually about 1% of the background temperature, $T$, (i.e., $\Delta T/T = 0.01$, where $\Delta T$ is the difference between the inversion layer temperature and the surface temperature) and the corresponding relative density perturbation, $\Delta\rho/\rho$, is about $-0.01$. This decrease in density forms a stable layer which acts as a waveguide. This stable layer is characterized by higher Brunt-Väisälä frequencies (see Figure 7). The Brunt-Väisälä frequency $N$ can be calculated from the temperature profile by $N^2 = (g/\Theta)d\Theta/dz$, where $\Theta$ is the potential temperature, $\Theta = T(p_0/p)^{R/\gamma}$, $g$ is the gravity, $p$ is the pressure, $\gamma$ is the specific heat ratio, $R = 287$ J kg$^{-1}$ K$^{-1}$ is the gas constant and $p_0 = 10^5$ Pa is the standard pressure. The LA morning glory wave is probably excited in this waveguide (about 1 km thick) by mechanisms such as a rapid downdraft caused by the Santa Ana type condition or a storm coming into the LA basin (see section 4).

[17] We use a simple two-layered model (i.e., a half-space over a layer with thickness $h$) for interpreting the LA morning glory wave. The pressure change, $\Delta p$, is approximately given by $\Delta p = ga\Delta\rho$ where $a$ is the amplitude of the undulation of the boundary and $g$ is the acceleration of gravity. Then, with $|\Delta\rho| = 0.01\rho = 1.29 \times 10^{-5}$ g/cm$^3$, the observed large (0.5 mbar) pressure perturbation suggests $a \approx 395$ m, a substantial fraction of the layer thickness, $h \approx 1$ km. Thus it is likely that the wave which is initially formed as a linear internal gravity wave, as discussed by *Gossard and Munk* [1954], later develops into a nonlinear wave. When it is fully developed into a nonlinear wave, it becomes a solitary wave as discussed by *Christie et al.* [1978].

[18] Solitary waves have been observed and studied for quite a long time. They were first observed by *Scott-Russell* [1837, 1844]; later both *Boussinesq* [1871] and *Rayleigh*

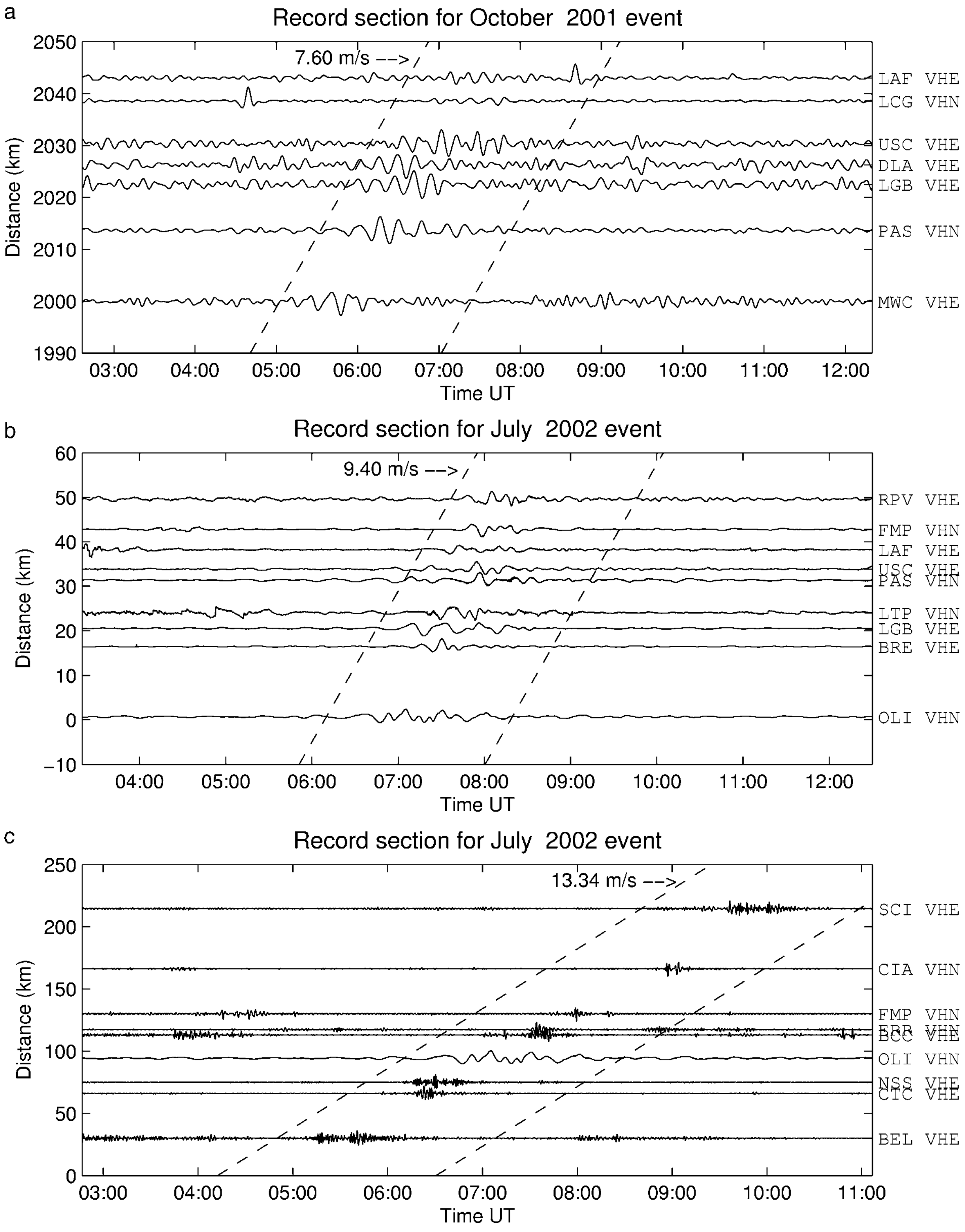

**Figure 6.** Record sections for the (a) 11 October 2001 and (b) 11 July 2002 events. (c) Record section of a high-frequency event which is interpreted as a storm front traveling from the northeast to the Los Angeles Basin. It is not the morning glory wave signal, but it is the precursor to the morning glory wave. The long-period trace is the morning glory wave excited at station OLI upon arrival of the high-frequency wave.

**Table 1.** List of the Morning Glory Events With the Propagation Speed, Direction, and Period[a]

| Origin | | Local | | | | | |
|---|---|---|---|---|---|---|---|
| Date | Time, UT | Date | Time, LT | Speed, m/s | Direction or Source Location[b] | $\Delta p$, Pa | Period, s |
| 19 June 1988 | 0320 | 18 June | 2020 | N/A | N/A | N/A | N/A |
| 4 March 2000 | 0410 | 3 March | 2010 | 5.5 | (33.95, −118.15)[c] | 118.5 | 1200 |
| 4 July 2001 | 1515 | 4 July | 0815 | 9.3 | −99.1 | 88.8 | 800 |
| 12 Oct. 2001 | 0540 | 11 Oct. | 2240 | 7.6 | −123.1 | 88.8 | 880 |
| 1 June 2002 | 0920 | 1 June | 0220 | (23.6)[d] | (27.1)[d] | 54.3 | 1250 |
| 11 July 2002 | 0750 | 11 July | 0050 | 9.4 | (33.96, −117.89)[c] | 113.5 | 800 |

[a] N/A, data necessary to provide the relevant information are not available.

[b] Propagation direction is measured clockwise from north.

[c] Longitude and latitude.

[d] Uncertain and tentative values.

[1876] derived wave solutions for a uniform water layer and gave the wave profile and wave speed by

$$\eta(x) = a\ \mathrm{sech}^2\left[\frac{(3\alpha K)^{1/2}x}{2h}\right] \quad (1)$$

$$c = \sqrt{gh}(1+\alpha)^{1/2} \quad (2)$$

$$\alpha = \frac{a}{h} \quad (3)$$

where $\eta$ is the wave profile, $c$ is the wave speed, $a$ is the maximum amplitude of the wave, $h$ is the undisturbed fluid height, and $K$ is a constant taking the value of 1 in Boussinesq's approximation and $(1+\alpha)^{-1}$ in Rayleigh's solution. This solitary wave solution arises from solving the Korteweg-deVries (KdV) equation:

$$\eta_t + c_0\left(1+\frac{3\eta}{2h}\right)\eta_x + \gamma\eta_{xxx} = 0 \quad (4)$$

where

$$c_0 = \sqrt{gh} \quad (5)$$

$$\gamma = \frac{1}{6}c_0 h^2 \quad (6)$$

The KdV equation, in turn, is an extension of the linearized wave equation to incorporate dispersive effects on the order of $\alpha$ as well as nonlinear effects on the order of $(h/l)^2$, where $l$ is the length scale for waves in the $x$ direction [*Whitham*, 1999].

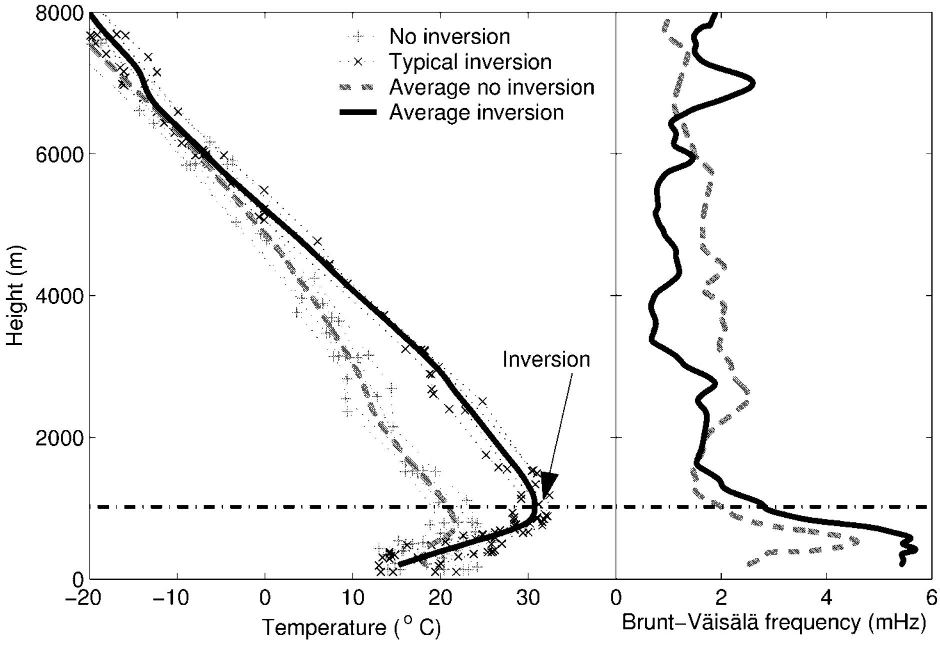

**Figure 7.** (left) Temperature as a function of altitude. The crosses and pluses are the data from locations with and without an inversion layer, respectively. The solid and dotted curves show the average trend. (right) Corresponding Brunt-Väisälä frequency profiles. Data from http://raob.fsl.noaa.gov/.

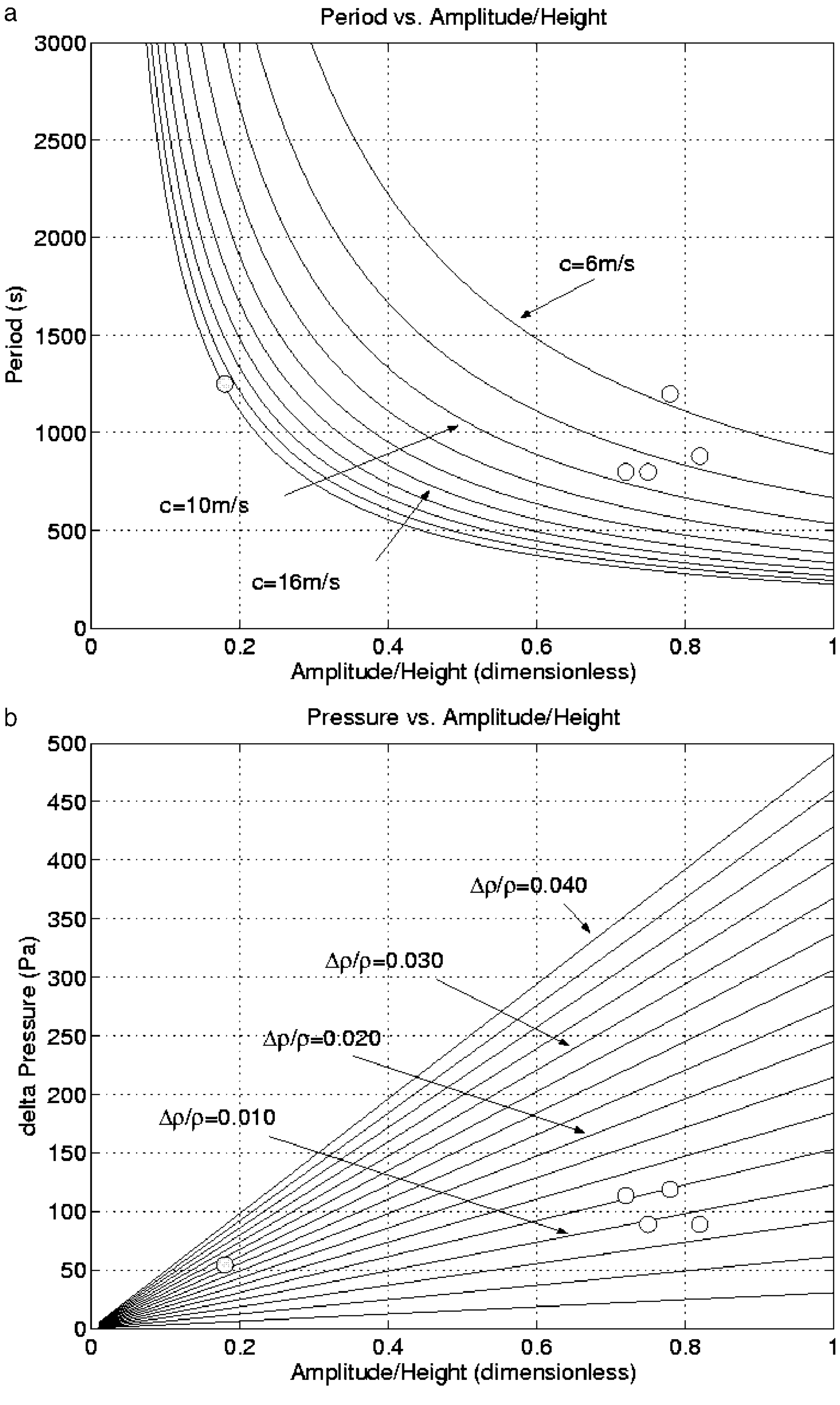

**Figure 8.** (a) Relationship between the period of the morning glory wave and $\alpha = a/h$ (the amplitude normalized by the layer thickness). The four open circles are the relations for the observed events. The gray circle shows the result with $\alpha = 0.2$ which is of marginal significance. The curves show the theoretical relations for a constant wave speed, $c$. (b) Relations between the pressure perturbation, $\Delta p$, and $\alpha$. The curves show the theoretical relations for a constant $\Delta\rho/\rho$.

**Table 2.** List of Earthquakes That Occurred Just Before the Morning Glory Events

| Origin | | | | | | |
|---|---|---|---|---|---|---|
| Date | Time, UT | Latitude | Longitude | Depth, km | $M_w$ | Region |
| 18 June 1988 | 2249:48.4 | 26.75 | −111.02 | 15 | 6.6 | Gulf of California |
| 3 March 2000 | 2222:49.9 | −6.92 | 143.85 | 16 | 6.6 | Papua New Guinea |
| 4 July 2001 | 1209:09.7 | −16.92 | −65.42 | 15 | 6.1 | Bolivia |
| 12 Oct. 2001 | 0502:40.4 | 52.64 | −132.18 | 15 | 6.0 | Queen Charlotte Is. |

[19] The previous discussion with the KdV equation describes a simplification of the full nonlinear wave theory applied to a shallow fluid layer. *Benjamin* [1967] and other investigators have developed more widely applicable solitary wave theories. Benjamin's theory deals with a thin layer beneath an infinitely thick layer. Extending Benjamin's theory further, Christie developed a model for atmospheric solitary waves [*Christie et al.*, 1978]. Following Christie et al.'s two-layer model (a uniform layer with a thickness $h$ overlain by a half-space) for atmospheric solitary waves, we can write the wave speed, $c$, as

$$c = \sqrt{gh\frac{\Delta\rho}{\rho}}\left(1 + \frac{3a}{4h}\right)^{1/2} \tag{7}$$

$$\Delta p = \frac{\Delta\rho}{\rho}\rho g a \tag{8}$$

$$\tau = \frac{16}{3\alpha c}h \tag{9}$$

where the additional parameters are $\tau$, the pulse width (or for multiple oscillations, the time between successive peaks), and $\Delta p$, the pressure change. The measured quantities are $c$, $\Delta p$, and $\tau$; and $\rho$ are taken to be known. The unknowns are therefore $a$, $h$, and $\Delta\rho$. Since we have three unknowns and three equations, we can solve for the unknowns. Note that the hydrostatic model can be used since the wavelength (~10 km) is much longer than the waveguide height (~1 km). As shown in Figure 8a, four of our data points give results for $\alpha$ ranging from 0.6 to 0.9, which are well within the nonlinear regime (i.e., $\alpha \ll 1$ is not satisfied). This suggests that at least some of the LA Basin waves are actually nonlinear solitary waves. Furthermore, we obtain values of $\Delta\rho$ in a range consistent with the hypothesis of the wave being a trapped wave in the temperature inversion layer (Figure 8b). We also note that except for the 4 July 2001 event, the events occurred in the evening to early morning hours (see Table 1). Since inversion layers are typically more common during these times, the findings are consistent with the events being an excitation of such an inversion layer.

[20] Finally, it should be noted that we observe a wide range of 'signals' of which the six listed are the largest in amplitude and therefore the most clearly identified. In fact, there are many instances with significant spectral energy in the regions of interest (between 0.5 and 3 mHz) but which do not develop into well-defined solitary waves. For example, referring to Figure 4, there is energy on 5 March 2000 that does not develop into a well-defined wave. Furthermore, some events such as the 4 July 2001 event started gradually with a small signal (in Figure 4 note the relatively long duration of high energy) that finally developed into a well-defined solitary wave. Thus we interpret low-amplitude signals as atmospheric gravity waves that do not have enough energy to develop completely into solitary waves. For example, the 1 June 2002 event has much smaller amplitude than the other events (see Figure 8) and should therefore be treated as an underdeveloped solitary wave. Because of its small amplitude, fewer stations could be used to determine the wave speed and therefore the speed (as well as other calculated characteristics) is not as well established as for other events. Among the six morning glory waves listed, there is also significant variation in the pulse characteristic. Some of them are more impulsive whereas others are more dispersive (e.g., July 2002 event versus October 2001 event as displayed in Figures 5 and 1, respectively). The more impulsive the event, the more likely they are in the nonlinear regime.

## 4. Excitation Mechanism

[21] Although the existence of the morning glory wave in the LA basin is observationally well established, we have not been able to identify the excitation mechanisms yet. Although no single obvious mechanism has been identified, several mechanisms can be considered. Some of the candidates that we believe may be responsible for excitation are stormy weather, Santa Ana winds, and large teleseismic earthquakes.

### 4.1. Storms and Winds

[22] Data from the 11 July 2002 event show signs of a different atmospheric disturbance in addition to the morning glory wave (Figure 6c). This disturbance shows up on the seismograph records as a high frequency "noise" and travels through California at a relatively well-defined speed. When it reaches the Los Angeles Basin, the morning glory wave appears. Thus the cause and effect relationship seems to be well established. What weather phenomenon causes this high frequency disturbance is not obvious. The weather map for 10 July 2002 indicates monsoonal weather and thus corroborates the suggestion that stormy weather can trigger morning glory events. As for strong winds, we currently do not have enough data to make any definite conclusions. In any case, it is likely that any large weather disturbance, such as storm systems or Santa Ana Winds, would be able to excite morning glory waves in the inversion layer.

### 4.2. Earthquakes

[23] Three out of five morning glory events which we detected by a systematic search for the two and half years occurred within 10 hours after a teleseismic earthquake with a magnitude of 6.0 or greater (see Table 2 and Figure 9).

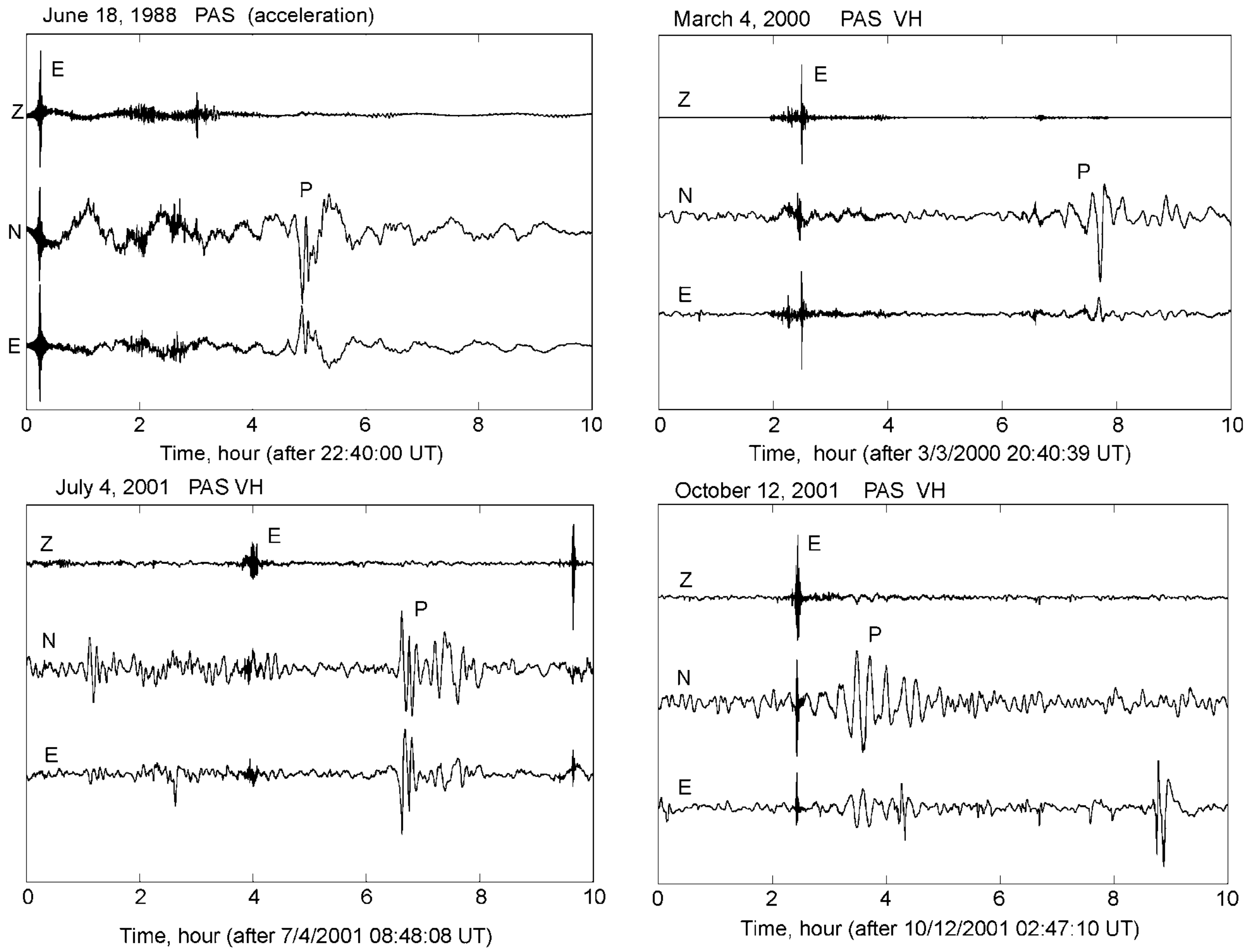

**Figure 9.** Four of the morning glory events which occurred within a few hours of a moderate-magnitude teleseismic earthquake. ”E“ and ”P“ indicate the earthquake and the morning glory wave pressure change, respectively. The time delays between the earthquakes and pressure signals range from 1 to 4 hours.

Although there seems to be no obvious reason that teleseismic events would be correlated with morning glory events because the amplitude of ground motion in the Los Angeles area for these events is on the order of 0.005 cm, the observed correlation is very high. Since magnitude 6.0 earthquakes occur approximately 100 times per year, the probability, $p$, of one randomly occurring within 10 hours of a morning glory event is 0.114. Assuming independence, the probability of three out of five events randomly occurring in such a manner is then ${}_5C_3p^3\ (1-p)^2 = 0.012$. This very low probability suggests that teleseismic events could be somehow partially responsible for morning glory excitations. Small ground motions can be amplified into large-scale motion in the upper atmosphere (ionosphere) [e.g., *Artru et al.*, 2001], but no such amplification is expected in the lower atmosphere. Thus this question remains unresolved at present.

## 5. Consequences of the Los Angeles Morning Glory Wave

[24] Among the possible consequences of the LA morning glory wave both practical and scientific, perhaps the most important are for aviation safety and the excitation of the Earth’s normal modes. After the unfortunate crashes of some commercial airplanes, extensive investigations were made to understand transient and highly energetic atmospheric events. In particular, *Fujita* [1986a, 1986b] has demonstrated that certain “microburst” events can cause airplanes to lose control and crash. The morning glory wave is another such transient, high-energy atmospheric event that is a potential aviation hazard, as has been pointed out by *Christie* [1992].

[25] *Nawa et al.* [1998], *Suda et al.* [1998], *Tanimoto et al.* [1998], and *Kobayashi and Nishida* [1998] showed that the Earth oscillates all the time without any obvious source of excitation. Other studies such as *Ekström*’s [2001] have since shown that these oscillations have a seasonal variation. There is tentative agreement now that the cause of these oscillations is either atmospheric [e.g., *Tanimoto and Um*, 1999] or oceanic in origin but no theory has yet demonstrated a clear cause and effect relationship. It may be likely that numerous processes contribute to the oscillations. The fact that the oscillations occur in the same frequency band as the morning glory events suggests that morning glory waves can be one of the important

contributors to the background oscillations of the Earth. There are many areas in the world that often have inversion layers and thus can develop morning glories. Enough morning glory events around the world could potentially transfer enough energy to the ground to contribute to the excitation of the normal mode oscillations detected. While seasonal variations for morning glories are expected, we currently do not have enough data to determine whether the global morning glory events have a seasonal dependence similar to that of the normal mode oscillations. More global studies are required to further investigate this problem.

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