WAVES AND TURBULENCE OBSERVED OVER TWO CONSECUTIVE VTMX NIGHTS

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1. INTRODUCTION

It is well established that the nighttime planetary boundary layer (PBL) is characterized by intermittent periods of turbulence and wave-like perturbations to the mean flow produced by gravity waves. It has been suggested that gravity waves and turbulence can interact and exchange energy (Fua *et al.* 1982). In the predawn hours of 19 October 2000 during the VTMX experiment in the Great Salt Lake Valley (Doran *et al.*, 2002), wave-like fluctuations in turbulence kinetic energy (TKE) were observed using a sonic anemometer at 8.5 m above ground level (AGL, unless otherwise stated all heights are AGL). An electronic microbarograph located several meters from the sonic anemometer also recorded wave-like fluctuations in surface pressure. Figure 1 shows plots of these data. On the following morning, the PBL mean wind speeds were about half as great, and the pressure perturbations and TKE are plotted in Figure 2. For comparison with Figure 1, Figure 2 is plotted on the same vertical scales; note also that Figure 2 is for the period 13:30 to 14:30. This is because the sonic data from 14:30 to 15:00 are not available. The contrast between Figures 1 and 2 is striking. We propose that the episodes shown in Figure 1 represent a case of wave-turbulence interaction. On the 20th, it appears that wave-turbulence interactions did not occur.

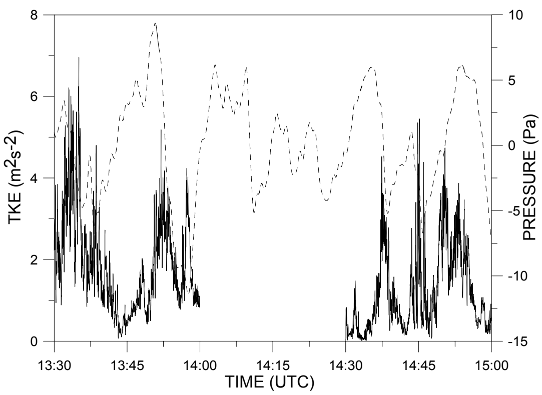

Figure 1 Pressure perturbation (dashed) and TKE (solid) on 19 October 2000; 30-minute gap in TKE due to missing data. Note that mountain daylight time is UTC - 7 hours.

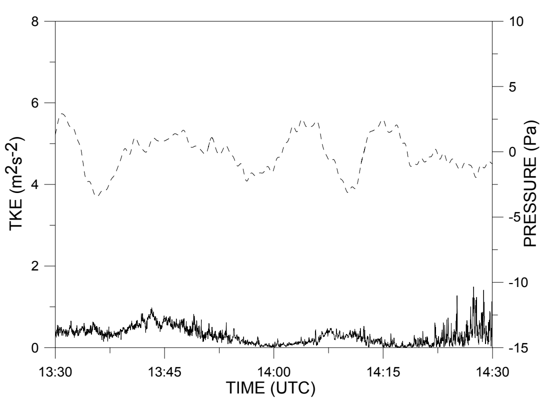

Figure 2 Same as Fig 1 but for 20 October 2000.

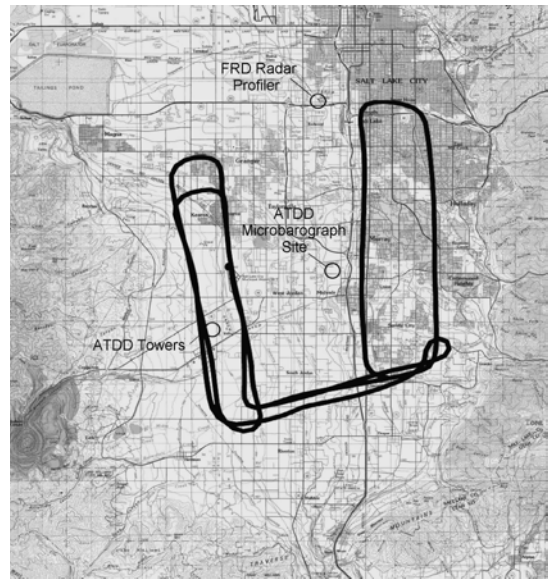

Figure 3 The Salt Lake valley and ATDD instrument sites.

2. THE DATA

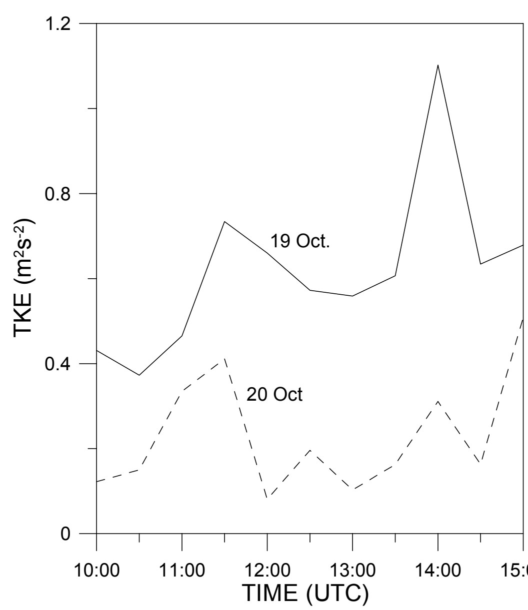

Figure 4 30-minute average TKE measured at the ATDD site.

Data for this study include surface pressure perturbations observed on a horizontal array of six microbarographs, wind speeds, directions, and TKE observed by a sonic anemometer operated by ATDD and located 20 m above the ground surface, the NOAA Mobile Flux Platform mounted on a Long-EZ aircraft (Eckman *et al.* 1999), a sonic anemometer operated by

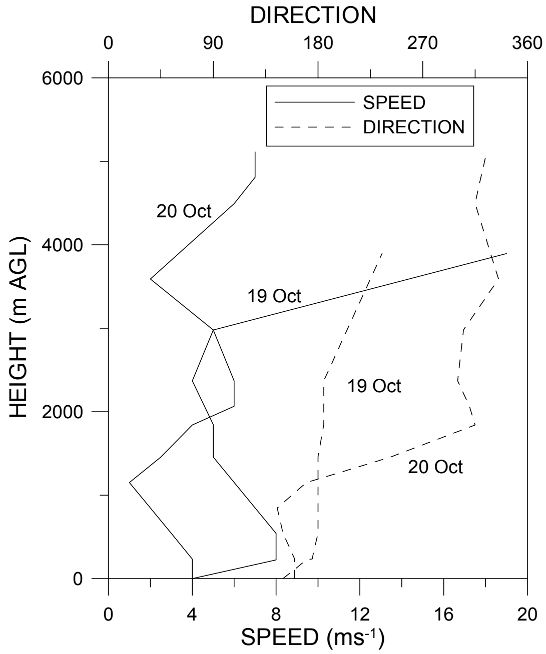

Figure 5 SLC 12:00 soundings on 19 and 20 October**.**

Pacific Northwest National Laboratory (PNNL) , and NWS radiosondes launched from the Salt Lake City International Airport (SLC). The microbarographs were sampled at 1 Hz. We

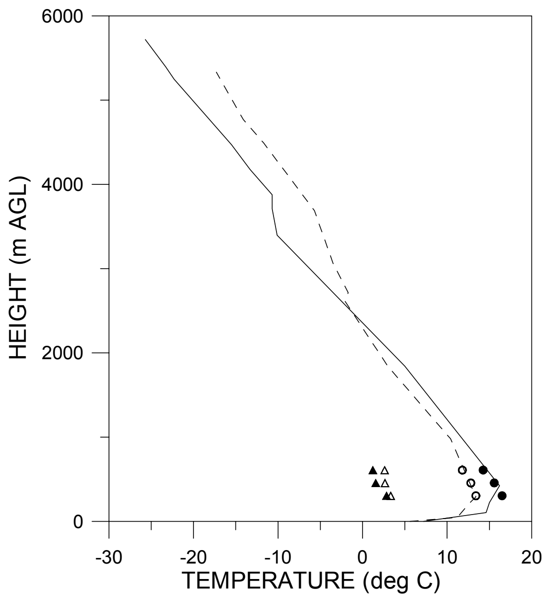

Figure 6 SLC 12:00 temperature soundings on 19 (solid) and 20 (dashed) October. Filled circles are horizontally-averaged temperatures measured by the Long-EZ aircraft on 19 Oct, and open circles are on 20 Oct. Filled triangles are rms temperature×10 for 19 Oct, and open triangles are for 20 Oct.

limit the analysis to those times when the Long-EZ was flying, typically between 10:00 and 15:00 UTC (unless otherwise stated all times are in UTC). The NOAA sonic anemometer was located in a field close to the Midvale elementary school some 4 km SW of Salt Lake City airport #2 (U42). The pressure array was located about 6.3 km east of U42. The PNNL sonic anemometer was located several meters from the microbarograph used in this study.

3. THE OBSERVATIONS

Figure 3 shows the time series of half-hour-averaged turbulence

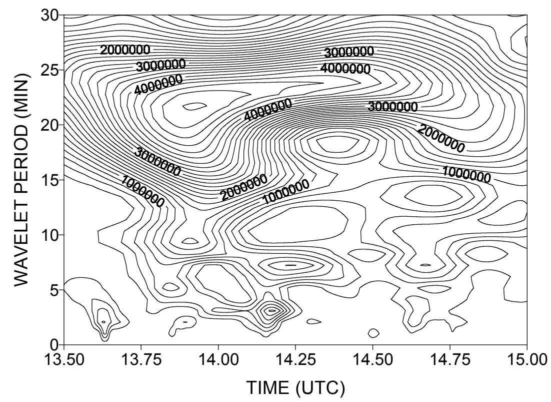

Figure 7 Wavelet analysis for 19 October.

kinetic energy (TKE) at the Midvale sonic anemometer site for the morning hours of 19 and 20 October. Throughout the nights, the TKE was greater during the 19th than the 20th. Although sunrise at these times was 13:44, sunlight did not strike the valley floor until about 14:30. Accordingly, we assume that the TKE shown in Figure 1 and 4 was not convectively generated. Wind profiles for 19 and 20 October 12:00 sounding from SLC airport are shown in Figures 5, and Figure 6 shows the corresponding temperature profiles. On average, the mountains surrounding the Salt Lake Valley have an elevation of about 2000 m. On the 19th, winds were southerly below about 2500 m with a speed jet at about 400 m.

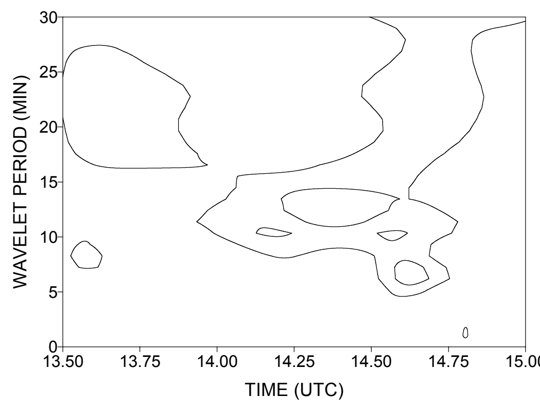

Figure 8 Wavelet analysis for 20 October.

On the 20th, winds were more complex than on the 19th. Speed minima are seen at about 1100 m and 3600m, and a speed maximum is at about 2300 m, and there is about a 180E change in wind direction between about 800 and 1900 m. Temperature profiles and horizontal averages of temperature and rms temperatures obtained from the Long-Ez flights are shown in Figure 5. On the 19th, the ground-based inversion extended up to about 420 m. On the 20th, the ground-based inversion extended up to about 290 m. The Long-EZ measured temperatures along north-south race track flight paths on the eastern side of the Salt Lake Valley. The average temperature along the paths and the accompanying rms temperature are plotted in Figure 6. On the 19th, the area-averaged temperatures differed slightly from the NWS profile; however, on the 20th the

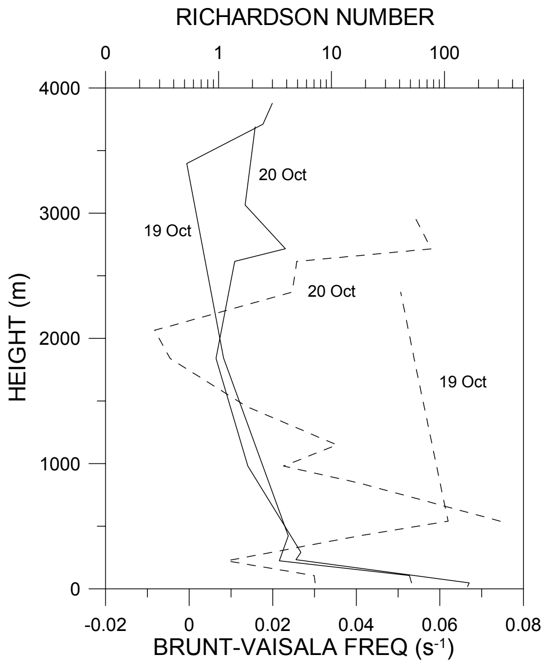

Figure 9 Brunt-Väisälä frequency (solid) and Richardson number (dashed) for 19 and 20 October.

average temperatures agreed well with the NWS profile. The rms temperatures decreased with height on the 19th, but on the 20th the rms values appeared to be constant between about 450 to 600 m.

4. DATA ANALYSIS

Figures 7 and 8 show the wavelet analyses for the 19th and 20th respectively. For these analyses, the Morlet wavelet was used. The contour interval is the same in Figures 7 and 8, and it is clear that much stronger wave-like activity is seen on the 19th than an the 20th. On the 19th, the strongest waves have periods above 15 min. On the 20th, the strongest waves have periods below 15 min. Figure 9 shows vertical profiles of Brunt-Väisälä frequency (N) and Richardson number (Ri) for the 19th and 20th at around 12:00. The values of N for each day were similar; however, the values of Ri are quite different. On the 19th Ri values were less than 10 below about 300 m; however on the 20th Ri was greater than 100 below 300 m. Figure 10 shows the normalized power spectra for the pressure perturbations. The -4/3 slope is predicted from similarity theory, and has been verified by Elliot (1972) and Wilczak *et al.* (1992). For frequencies greater than about 2 Hz, the spectra for both days become flat (fS_f = constant) in agreement with the prediction of Bradshaw (1967). The spectrum of the 20th is similar to but less than that for the 19th above about 0.1 Hz. This difference reflects the results in Figure 4. However, above about 0.15 Hz, the spectrum on the 20th rapidly increases with frequency, and joins the flat region of the 19th. Figure 11 shows the results of beamsteering in the slowness plane. This technique estimates the phase speed and wavelength of a coherent wave as it passes over the sampling array (Nappo, 2002). For a wave with a period of about 22.5 minutes, the beamsteering analysis gives a phase speed of about 1.2 ms^{-1}, a wavelength of about 1620 m,

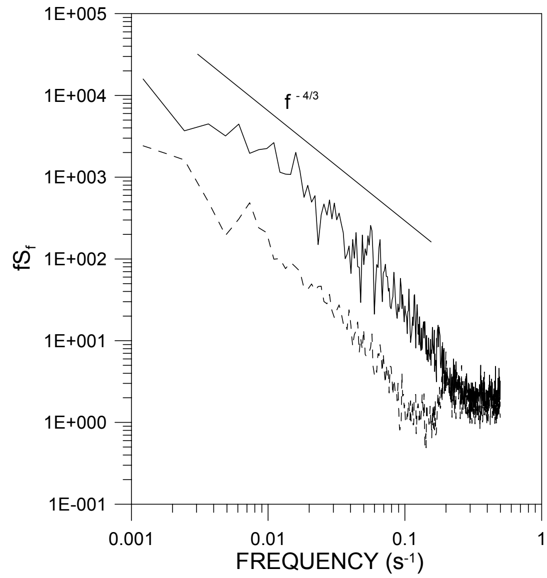

Figure 10 Normalized power spectra for surface pressure fluctuations on 19 October (solid) and 20 October (dashed).

and a direction of about 330E. Beamsteering was not done for 20 October.

5. DISCUSSION

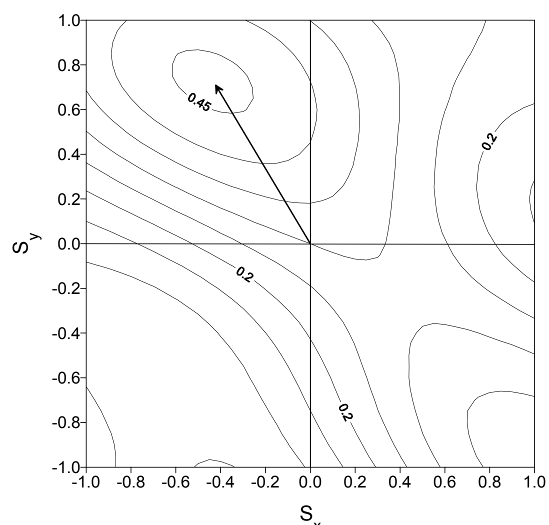

Figure 11 Beamsteering in the slowness plane for 19 October between 13:45 and 14:15.

We have established that on 19 October the energy content in the wave-like structures and TKE was greater than on 20 October. We ask if the events on the 19th are due to wave-turbulence interactions. An accurate analysis of wave-turbulence interactions is beyond the scope of this abstract;

however, we can study the observations to determine if such interactions are not possible. One of the requirements for wave-turbulence interactions is that Ri should be close to but greater than 0.25. From Figure 9 we see that below 500m the smallest value of Ri on the 19th was about 1, but on the 20th Ri was greater than 100 below 500 m, and these points are not plotted. Thus, it is possible that gravity waves could have modulated Ri below its critical value on the 19th, but it is unlikely that this could have occurred on the 20th. The speed jet on the 19th (Figure 5) could provide a duct for a gravity wave (see, for example, Chimonas and Hines, 1968; Nappo, 2002). If the wave is ducted, then the vertical wavelength should scale with the depth of the speed jet. From the linear theory, the vertical wavenumber, m, can be estimated from

$$m^2 = \frac{N^2}{(c-u_0)^2} - k^2$$

where c is the phase speed, u_0 is the background wind speed, and k is the horizontal wavenumber. If we assume average values through the wind duct, then $N = 0.02\ s^{-1}$, $c = 1.2\ ms^{-1}$, $u_0 = 5\ ms^{-1}$, and if the horizontal wavelength is 1620 m, then the vertical wavelength is estimated to be about 1760 m. From Figure 5, we see that this value scales with the depth of the wind duct, and thus it is possible that wave is a ducted gravity wave.

6. CONCLUSION

In the morning hours of 19 October 2000 wave-like oscillations with periods of about 22.5 min were observed in the surface pressure perturbations during the VTMX field campaign in the Great Salt Lake Valley. Similar oscillations were observed in the TKE measured by a sonic anemometer located several meters from the pressure sensor. On the following day, 20 October, such oscillations were not observed, and the levels of TKE and pressure perturbations were much less than on the previous morning. We have postulated that the events on the 19th were the result of wave-turbulence interactions resulting in wave modulation and possible augmentation of the Reynolds stresses. Our analysis suggests the presence of a gravity wave ducted by a speed jet. The wave is estimated to have a period of 22.5 min, a horizontal wavelength of about 1620 m, a phase speed of 1.2 ms^{-1}, and a propagation direction of 330E. Assuming an average wind speed of 5 ms^{-1}, a vertical wavelength of 1760 m is calculated, and this value scales with the depth of the ducting region. We have examined only the possibility of a wave-turbulence interaction. A comprehensive analysis (see, for example, Einaudi and Finnigan, 1981) would require a wave calculation and an explanation of the wave's origin.

ACKNOWLEDGMENTS

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