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Up-gully flow in the great plains region: A mechanism for perturbing the nighttime lower atmosphere?

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[1] Studies using data gathered during CASES-99 show that when the near-surface nighttime wind direction shifts through the "up-gully" direction of a significant gully near the tower, the flow produces a pronounced but localized upward surge of vertical velocity up to at least 55 m. This surge generates an outward propagating wave packet having horizontal and vertical wavelengths on the order of 100–250 m with tilted wave fronts consistent with upward phase propagation. The wave packet is observable (with significant delays) by other sensors out to 850 m. As a working hypothesis we assume that the up-gully flow is constricted and strengthened as it progresses up the narrowing gully. We theorize that, upon exiting the gully, the flow has a pronounced and tightly confined vertical component that in turn produces a packet of internal propagating gravity waves. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 3314 Meteorology and Atmospheric Dynamics: Convective processes. **Citation:** Balsley, B., D. Fritts, R. Frehlich, R. M. Jones, S. Vadas, and R. Coulter, Up-gully flow in the great plains region: A mechanism for perturbing the nighttime lower atmosphere?, *Geophys. Res. Lett.*, *29*(19), 1931, doi:10.1029/2002GL015435, 2002.

1. Introduction

[2] The CASES-99 Campaign in Central Kansas in October, 1999 was designed to document the dynamics of the nighttime stable boundary layer. As such, the campaign included a large variety of *in situ* sensors (aircraft platforms, instrumented towers, microbarographs, and a TLS (kite/balloon) platform) as well as remote sensing instruments (lidars, radars, sodars, and scintillometers). An overview of the experimental plan for CASES-99 is contained in *Poulos et al.* [2002]), with additional information available at http://www.joss.ucar.edu/cases99/.

[3] The present study arose from the fortuitous location of the seven-tower CASES-99 complex near the head of a significant gully. Figure 1 shows a plan view of the tower complex (one 55 m tower centered on two sets of three 10 m towers at radii of 100 m and 300 m. Also shown are the locations of the gully, the CIRES TLS (Tethered Lifting System), and the Argonne National Laboratories (ANL) mini-sodar site.

[4] At its mouth, the gully has a width of about 450 m and a maximum depth of about 10 meters. It narrows to roughly 100 m and rises essentially to the surface 400 m SW of the main tower base. The mean slope of the gully floor is roughly 0.6 degree. The total gully length is of the order of 1000 m, and the mean up-gully direction is approximately 18° East of North.

2. Observations

2.1. Gully Surges

[5] Plots of both the 100-second-average vertical wind magnitude on the main tower and the mean wind direction are shown for four separate 3 hour intervals in Figure 2. For reference, a horizontal line is included to indicate the (198°) wind direction corresponding to flow up the gully. Examination of these four examples shows that, when the wind direction shifts through 198° (all wind directions quoted herein refer to the direction from which the wind is coming), a clear enhancement of the 50 m mean vertical wind can be seen. These enhancements ("surges") range in amplitude from roughly 0.15 m s^{-1} to 0.35 m s^{-1}. In each case, the surge appears to rise relatively slowly over a few minutes and then drop abruptly back to pre-surge levels. The half-width of surges estimated from these four examples is around six minutes.

[6] It is important to point out that the direction changes in the near-surface wind are not gradual (e.g., see the 19 October panel that shows a direction change of better than 100° in less than five minutes). Rather, the up-gully direction appears to be an "attractor" direction for the near-surface wind on occasion. It is also significant that these directional perturbations only occur within 10 meters or so of the surface. Flows at higher heights are relatively unaffected. It therefore appears likely to us that these perturbations are manifestations of local surface wind perturbations that arose near the mouth of the gully and are not directly associated with synoptic scale disturbances.

[7] A near simultaneity of the vertical velocity surge at all levels on the tower is indicated in Figure 3, where the one-hour time history centered on the 12.15 UT surge is shown in the left-hand panel. These results are from three separate levels and have been plotted using 50-second-averaged values to better show details (many other heights are available but have been omitted here for clarity). 100-second-averaged vertical wind profiles at 12.13 UT, 12.15 UT, and 12.17 UT are plotted in the right-hand panel. Examination of both panels shows clearly that, although the velocities in the lowest 10 m are considerably less than those in the upper levels, the upward surge is essentially simultaneous over the entire height range.

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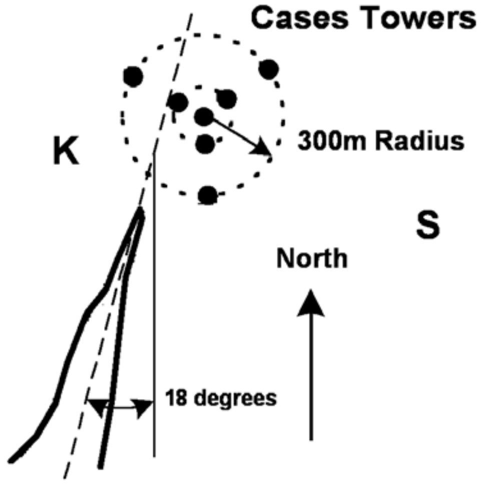

Figure 1. Sketch of the seven-tower CASES-99 complex and its relation to a long gully lying to the SSW. This figure also shows the location of the CIRES TLS (kite/balloon) site (K) and the ANL mini-sodar site (S).

[8] Our preliminary study suggests that up-gully surge occurrences were relatively common events during CASES-99. The total period involved in this study comprised twenty-two 8-hour nighttime data sets gathered between October 5 and October 29. Obvious "surge" events were observed on seven of the data sets (on October 6, 9, 12, 18, 19, 21, and 22), with four other data sets (October 5, 10, 26, and 28) classified as exhibiting possible, albeit more complex, surge patterns. The remaining eleven sets showed no such effect. In the large majority of these latter cases, the near-surface wind direction never exhibited an up-gully flow.

[9] Finally, the horizontal scale of the vertical wind surge estimated using data from the surrounding six towers appears to be in the range of a few hundred meters, with the surge occurring earlier and stronger SSW of the main tower, i.e., near the top end of the gully.

2.2. Wave Packet Observations

[10] Following the gully surge that occurred at 10.5 UT on 21 October (not included in Figure 2), a series of wave-like sinusoidal oscillations in both wind speed and temperature were observed on all four sensors suspended beneath the CIRES TLS situated some 450 m SW of the main tower (see Figure 1). During this period, a kite was employed as a lifting platform instead of a blimp, since the winds aloft were sufficiently strong (approximately 7–8 m s^{-1} at the nominal 80 m kite altitude). The four sensor packages (from bottom to top: Package A, B, C, and D) were separated, respectively, by 4.5 m, 6 m, and 6 m. Among other variables, each package recorded temperature using a coldwire sensor and wind speed fluctuations using a hotwire sensor, both sampled at 200 Hz [see *Frehlich et al.*, 2002 for further details]. Figure 4 shows 100-second-average values of wind speed fluctuations (with mean wind variations subtracted out) on all four sensors during the period 10.5 UT to 10.8 UT. Note that the upper three curves also have been offset vertically for ease in viewing. Examination of this figure shows a close similarity among the fluctuations on all packages. Also apparent, as suggested by the tilted dotted lines, is a systematic decrease (2.4 sec m^{-1}) in the phase pattern with increasing height. Assuming an approximate wave period of 280 seconds, one can estimate the vertical wavelength of the fluctuations to be roughly 110–120 m.

[11] A comparison of wind speed fluctuations obtained from both the TLS and the CASES tower during this period appears in Figure 5. In this figure we have plotted wind speed fluctuations obtained at the 55 m level on the tower, along with the fluctuations observed using TLS Package B, since both measurements were within a few meters of the same altitude (Package B varied in height during this period from 60 m to 55.8 m). Again, the two data sets have been de-trended and offset for viewing ease.

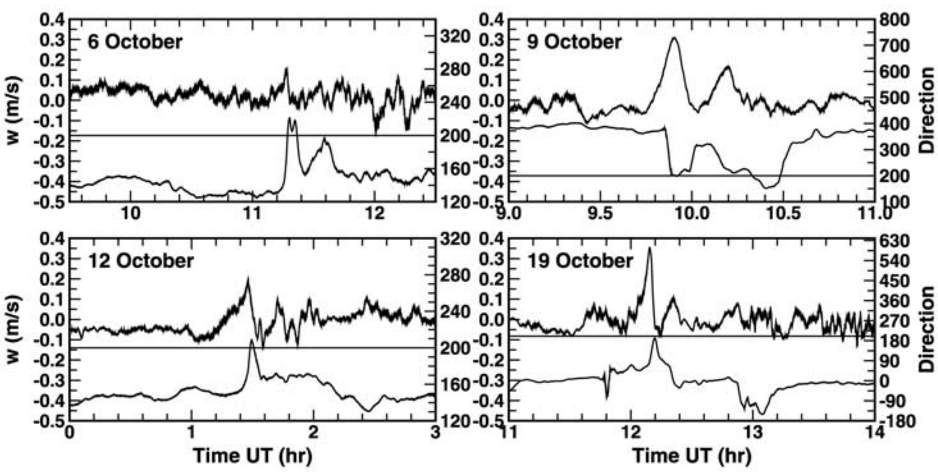

Figure 2. Four examples of 100-second average vertical wind (upper curves) along with the wind direction (lower curves) at the 55 m main tower. The up-gully direction corresponding to a wind direction of 198° and is included as a solid line for reference. Vertical wind values in ms^{-1} are read from the left-hand-side of the figure while the wind direction and the "gully azimuth" in degrees (geographic) are read from the right-hand side. The vertical wind is measured at an altitude of 20, 55, 50, and 20 m for October 6, 9, 12, and 19, respectively. The wind direction is measured at an altitude of 5 m for all dates except October 9 which has an altitude of 1.5 m.

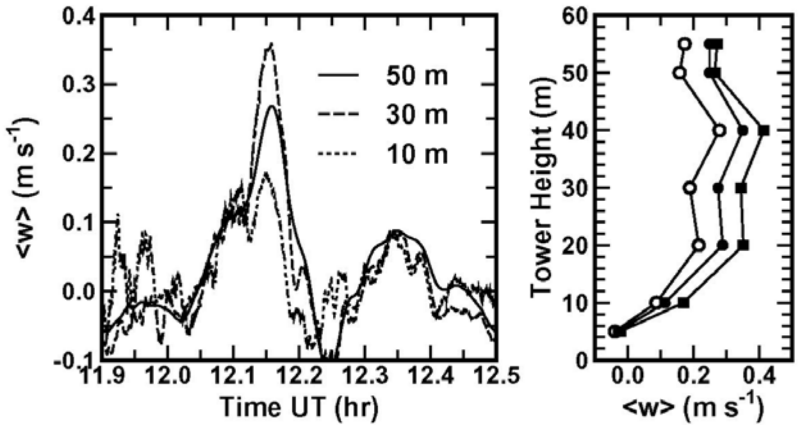

Figure 3. One-hour time history of the 50-second-averaged vertical velocity surge on 19 October (left-hand plot), and 100-second-averaged vertical velocity profiles (right-hand plot) over the entire tower height for 12.13 UT (open circles), 12.15 UT (solid squares), and 12.17 UT (solid circles).

[12] The two curves in Figure 5 clearly are very similar, including the "triple-peak" structure between 10.8 and 10.9 UT. However, while the tower data have been plotted using the time scale shown, the kite data have been advanced by 544 seconds to achieve this apparent match. The quality of the match is evidenced by cross-correlating these two data sets between 10.5–11.0 UT. The result shows a cross-correlation coefficient of 0.63 at a delay (tower data) of 544 seconds. A strong secondary peak in the cross-correlation confirms the dominant period of oscillation to be 280 seconds.

[13] It is possible to estimate the horizontal wavelength of the principle fluctuations and the group velocity of the wave packet along the tower-TLS azimuth for this event. Taking into account the 450 m separation between the tower and the TLS sensor, and the 544-second delay determined above, the resulting wave packet group velocity toward the SW is 0.83 m s^{-1}. Similarly, a horizontal wavelength of 230 m can be deduced using this velocity and the 280 second period. Moreover, since the wind at tower top height was coming from an azimuth of 215° with a mean velocity of 6.6 m s^{-1}, the ($\approx$ upwind) propagation speed in the reference frame of the background wind would be close to 7 m s^{-1}.

[14] Finally, it was possible to examine the stability of the observed atmospheric region containing the wave packet as it passed by the TLS sensors. Using the average temperature and wind speed profiles obtained from the TLS data for the period 10.33–11.27 UT over the height range 54–71 m yielded a buoyancy period of 146 seconds and a stable gradient Richardson number of 0.66. The ratio of buoyancy period to the observed wave period is consistent with the observed horizontal-to-vertical wavelength ratio of 0.52, and corresponds to an internal gravity wave propagating at an elevation angle of 62.5 degrees.

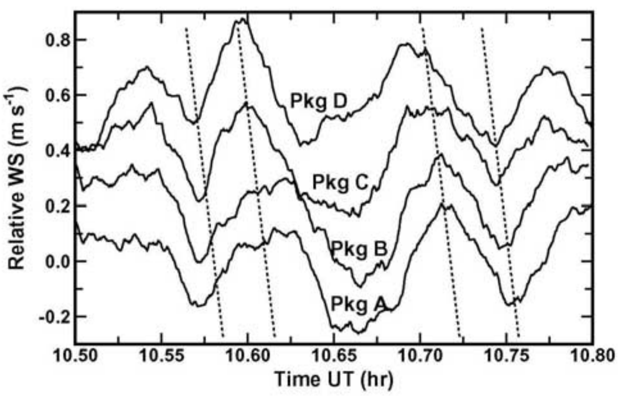

Figure 4. 100-second average values of wind speed fluctuations observed on 21 October 1999 on four separate sensor packages suspended below the TLS at separations indicated in this figure and the text. Downward propagating wave fronts of upward propagating AGWs will appear earlier/later at higher/lower heights in this height-time (time increasing to the right) presentation, as indicated by the dashed lines.

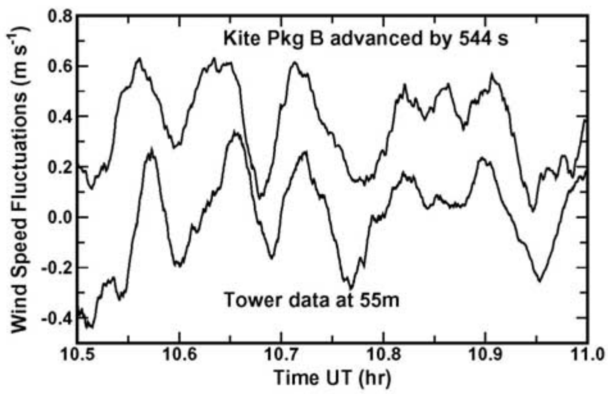

Figure 5. Wind speed fluctuations on 21 October observed at the 55 m level of the CASES tower (bottom curve), and comparable fluctuations observed using sensor package B suspended below the kite at approximately the same altitude (upper curve). The tower data are plotted using the time scale shown. In contrast, the kite data have been advanced in time by 544 seconds.

3. Discussion and Conclusions

[15] The evidence presented herein provides strong support for the idea that surface wind confinement by a reasonably large gully can produce a significant localized vertical velocity surge and associated gravity wave activity well into the nighttime stable boundary layer. The observations outlined above show the initial surge extending up to at least 55 m, and the wave activity up to at least 70 m (based on the highest TLS sensor results). Additional results from the mini-sodar (Figure 1) operating during the same time period suggest that the wave packet observed by the TLS was also present over the sodar some 850 m separated from the tower. It is significant that the sodar echo intensity records suggest that the wave packet observed by the tower and the TLS on 21 October extended to an altitude of at least 150 m. However, although the phase slopes of these echoes with height also showed a vertical wavelength of 100 m and the periods were comparable to those observed, the sodar results are somewhat ambiguous as of this writing because of the presence of a second gully that terminated near the mini-sodar site.

[16] A final comment is in order regarding the results in Figure 2 which suggest that the peaks of the up-gully wind shifts appear to consistently follow—not lead—the upward surges. In the absence of wind direction data near the gully mouth, we assume that the wind direction change measured at the tower lags the corresponding change at the gully mouth.

[17] In summary, it appears likely that up-gully forcing may provide a new mechanism for producing small-scale gravity wave activity throughout the nighttime boundary layer and possibly into the free troposphere. This statement assumes that the underlying topography contains orographic features similar to, or larger than, the gullies involved in the current study. Clearly, the full implications of this mechanism are yet to be determined. Additional work is in progress to establish the ubiquity and the details of gully surges, and will include a theoretical assessment of the wave scales arising from such forcing.

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