Measurement of Cloud Perturbation Pressures Using an Instrumented Aircraft

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ABSTRACT

Vertical accelerations during the early stages of convective cloud formation are often the result of buoyancy and the perturbation vertical pressure gradient forces. Convection modifies the local pressure field surrounding the cloud. Measurement of the cloud perturbation pressure field is challenging over distance scales on the order of the convective elements, since the signals are often small and the turbulent environment complicates the measurement of static pressure. A technique is described that enables detection of the horizontal pressure perturbations associated with evolving convective clouds using global positioning system measurements on an airborne platform. Differential kinematic processing of data from dual-frequency, carrier-phase-tracking GPS receivers on research aircraft with static base station receivers enables the three-dimensional aircraft position to be resolved within decimeters. Vertical positioning and precise measurement of static pressure allow horizontal pressure perturbations to be determined to an accuracy of roughly 10 Pa. Errors in the static pressure measurement, rather than the GPS-derived altitude, are the largest source of error. A field experiment was conducted in May–June 2008 to demonstrate measurement of perturbations in the horizontal pressure field associated with summertime cumulus congestus clouds over the high plains. Observations of growing convective clouds show negative pressure perturbations on the order of 100 Pa near cloud base linked to updraft regions. Growing cumulus show a high degree of variability between subsequent passes that demonstrate that the horizontal pressure fields evolve rapidly along with attendant vertical circulations and cloud microphysical characteristics.

1. Introduction

Convective motions inevitably modulate the ambient pressure field. Conventional thinking regarding early stages of simple convection (e.g., Houze 1993; Bluestein 1993; Markowski and Richardson 2010) suggests that in response to upward accelerations due to buoyancy, horizontal compensating motions must exist beneath and above the rising parcel. Horizontal accelerations and flow toward the cloud base require a local pressure deficit and hence a negative horizontal pressure perturbation. Similarly, a positive pressure perturbation must exist above the rising air mass, such that the vertical gradient of perturbation pressure acts downward and opposes buoyancy. Numerical simulations of large convective systems have been conducted (e.g., Trier et al. 1997) to show net accelerations owing to buoyancy and the vertical perturbation pressure gradient force.

Inherent in the concept of conditional instability is the existence of an energetic barrier that must be overcome before lifted parcels become warmer than their surroundings and begin accelerating upward because of their own buoyancy. This barrier, quantified by the convective inhibition (CIN), can be overcome by heating parcels or by mechanical means in which parcels are forced upward despite their being colder than their surroundings. Parcels do not become warmer than their surroundings until they reach their level of free convection (LFC), which is necessarily higher than the lifting condensation level. In typical summertime convective situations when both CIN and convective available potential energy (CAPE) are both present, clouds tend to form initially after daytime heating and deepening of the convective boundary layer, leading to convective plumes exceeding their convective temperature. As parcels reach their LFC and begin to accelerate upward because of buoyancy, an upward-directed non-hydrostatic pressure gradient must exist beneath. Thus, once convection has begun the updraft below, the LFC will be colder than its surroundings (essentially by definition).
Pressure variations, whether in the form of horizontal gradients or nonhydrostatic perturbations, underlie the dynamics of atmospheric motions. Measurement of cloud pressure perturbations is difficult because of their small magnitude, the transient and often highly turbulent nature of the convective environment, and difficulties inherent in accurately measuring ambient pressure from an aircraft. Measurements of geometric altitude from an aircraft flying at nearly constant pressure can be used to map the height of the isobaric surface above some reference level (generally taken to be sea level). Conversely, ambient pressure measured from an aircraft flying at constant (geometric) altitude can be used to map pressure onto a constant height surface. The slope of the resulting surface can be expressed as a height gradient on an isobaric surface or, conversely and equivalently, as a pressure gradient on a constant altitude surface. This slope is a measure of the horizontal pressure gradient force from which the component of the geostrophic wind normal to the flight track can be computed.

While instrumented aircraft have long been one of the primary tools for investigating atmospheric dynamics, limited options for obtaining pressure-independent estimates of altitude have hindered measurement of horizontal pressure gradients from aircraft and effectively precluded measurement of pressure perturbations. Over distances of a few tens of kilometers or less, inertial navigation system (INS)-derived altitudes, in which vertical accelerations are integrated over short time scales but forced back to pressure altitude over longer scales (e.g., Blanchard 1971), can be used to infer pressure perturbations. LeMone and Tarleton (1986), who investigated pressure variations over cloud-scale distances, estimated the accuracy of their pressure perturbation measurements to be about 20 Pa. In subsequent studies LeMone et al. (1988a,b) presented pressure perturbation measurements for a range of convective clouds. Because errors in INS-derived altitude, unlike those in INS-derived horizontal position of the aircraft. Here, we describe the measurement of pressure perturbations associated with evolving cumulus clouds over horizontal scales ranging from <1 to ~20 km. Such measurements can provide a basis for understanding the fundamentals of convection and a means to test cloud models.

This study focuses on observations collected using the University of Wyoming King Air (UWKA) during the CloudGPS project. This project, conducted during May–June 2008, targeted growing cumulus (Cu). Because of the rapid evolution of these clouds, the horizontal pressure perturbations evolved significantly between successive legs separated by minutes to tens of minutes. Further, as a result of either the short lifetime of the convective cells or their rapid development into large (and frequently electrified) convective complexes, we were able to make, at most, six penetrations through a single cloud. More often, clouds dissipated after only two or three penetrations.

To examine the persistence of horizontal pressure perturbations and demonstrate the use of multiple flight levels within cloud to investigate nonhydrostatic vertical pressure gradients, repeated penetrations through a marine stratocumulus (Sc) drizzle cell sampled off the coast of Northern California in 2006 are also examined. These observations demonstrate that small perturbations (~0.5 m) can be accurately measured in relatively quiescent conditions and how horizontal pressure perturbations measured at different levels can be used to infer nonhydrostatic vertical pressure gradients, which, in turn, are consistent with the observed cloud-scale circulations.

2. Aircraft measurement of the horizontal pressure field

Fundamentally, determination of the height of an isobaric surface requires independent measurements of
the aircraft altitude and the ambient (or static) pressure. On the UWKA the static pressure ports are located on either side of the rear fuselage of the aircraft, just aft of the door. Tubing inside the cabin connects the two static ports to each other and to a pair of redundant Rosemount 1501 hypersonic air data sensor (HADS) pressure sensors. The accuracy of the measured static pressure is examined extensively in Rodi and Leon (2012). Corrections described in Rodi and Leon (2012) have been applied to the static pressures used in this study.

Two GPS receivers, an Ashtech Z-Sensor and a Trimble NetRS, are carried on board the UWKA. Both of these receivers track and record the carrier phase on two frequencies (labeled L1 and L2) in addition to the coarse acquisition (C/A) code broadcast on L1. Postprocessing software utilizing the carrier phase on L1 and L2 provides a position solution with higher spatial resolution than can be obtained from the L1 C/A code alone. Differential corrections of the rover GPS positions are done in post-processing using GrafNav version 8.1 from Waypoint Consulting Inc. The differential processing reduces errors in the aircraft position caused by ionospheric and tropospheric propagation delays, satellite ephemeris errors, and receiver clock errors. Dual-frequency, carrier-phase processing eliminates ionospheric delay errors entirely. Parish et al. (2007) estimated the accuracy of the DGPS-corrected aircraft altitude to be on the order of decimeters.

Since the background vertical pressure gradient exceeds typical horizontal pressure gradients by two orders of magnitude and typical horizontal pressure perturbations by three or more orders of magnitude, even small departures above or below the intended isobaric surface will swamp the horizontal pressure gradients/perturbations that we are trying to measure. Thus, before any meteorological interpretation of the horizontal pressure gradient or pressure perturbations can be attempted, it is critical that pressure be corrected for the inevitable departures of the aircraft from the intended isobaric surface. In this study such a correction is done using an explicit hydrostatic approach. The apparent contradiction of applying a hydrostatic correction to investigate nonhydrostatic pressure perturbations can be resolved by noting that the hydrostatic pressure gradient exceeds the largest nonhydrostatic vertical gradient anticipated by orders of magnitude. For example, to accelerate a neutrally buoyant air parcel to 10 m s\(^{-1}\) within 1 km requires a nonhydrostatic pressure gradient of \(~0.05\) Pa m\(^{-1}\), about 200 times smaller than the hydrostatic pressure gradient.

The height correction for departures from the isobaric surface can be expressed as

$$
\Delta z = \frac{R}{g} T_V \ln \left( \frac{\rho}{\overline{\rho}} \right),
$$

where \(R\) is the gas constant for dry air, \(T_V\) is the mean virtual temperature between the instantaneous flight-level pressure and mean isobaric pressure level, \(g\) is the acceleration due to gravity, \(p\) is the instantaneous static pressure measurement, and \(\overline{\rho}\) is the mean isobaric leg pressure. The resulting isobaric height is simply \(H = z_{\text{dGPS}} + \Delta z\). Following application of the hydrostatic correction, height can be examined on an isobaric surface or, conversely but equivalently, pressure can be examined on a constant height surface.

It is worth noting that \(T_V\), which depends on both temperature and dewpoint temperature, only impacts \(H\) through the height correction. As a result, the accuracy of the final isobaric height is much less sensitive to errors in temperature and humidity than to errors in static pressure or DGPS altitude.

Here \(T_V\) is determined using an average between the instantaneous virtual temperature and the mean virtual temperature of the isobaric leg. Ambient temperature is measured by a Rosemount reverse-flow temperature sensor, while specific humidity is measured using a Cambridge Model 137 C3 chilled mirror. The airframe-relative wind vector is determined from a Rosemount 858 five-hole hemispheric sensor mounted at the tip of a \(~3\)-m-long nose boom. Ground-relative wind components are derived by combining the airframe-relative wind vector with INS-measured aircraft attitude and INS–GPS-derived aircraft velocity.

For clarity we employ the following nomenclature throughout this work: altitude refers to the geometric altitude above sea level determined by the dGPS; height indicates the geometric altitude of a constant pressure surface following correction for departures from the isobaric surface; static pressure indicates ambient pressure measured from on board the aircraft with only corrections for flight conditions having been applied (as discussed in Rodi and Leon 2012); and pressure indicates that corrections for deviations from the constant height surface have been applied. Finally, pressure perturbations (height perturbations) are obtained after the horizontal pressure (height) gradient has been determined and removed.

Figure 1 illustrates the hydrostatic correction process. Data shown in Fig. 1 are taken from a flight leg over the ocean, allowing the DGPS technique to be compared with altimetry methods. From Fig. 1a it is apparent that the raw GPS altitudes for this leg are offset by approximately 20 m from actual heights. Note that the DGPS altitudes follow the general trends in the radar altimeter height signals. The offset of the DGPS altitudes from
Ralt3 is consistent with the displacement between the GPS antenna and radar altimeter on the UWKA.

Figure 1b depicts the DGPS, radar altimeter 1 (RALT1) and RALT3 isobaric heights after correction for UWKA deviations from the mean isobaric surface. Heights show impressive coherence. Slopes of the height surfaces are also consistent; geostrophic wind calculations for the DGPS, RALT3 and RALT1 heights are 10.3, 10.2, and 11.5 m s\(^{-1}\), respectively. The scatter of DGPS-derived height in Fig. 1b is considerably larger than in the DGPS altitudes shown in Fig. 1a as the result of the errors in static pressure being projected into height through the hydrostatic correction process.

Previous studies (e.g., Shapiro and Kennedy 1981) have used \(D\) values, rather than the explicit hydrostatic correction process described here to address departures above or below the intended hydrostatic surface. Here \(D\) values are defined as the difference between geometric altitude and pressure altitude based on the U.S. Standard Atmosphere (Bellamy 1945). Since the U.S. Standard Atmosphere is fundamentally hydrostatic, the use of \(D\) values implicitly amounts to a hydrostatic correction, albeit one using \(T_V\) from the standard atmosphere rather than flight-level measurements.

We believe that use of a hydrostatic correction is preferable to the use of \(D\) values as defined above for two reasons: invocation of pressure altitude not only obscures the underlying physical basis for the correction (which is straightforward) but also implicitly invokes a profile that is likely to be a poor fit to the actual conditions. The original work defining \(D\) values can be traced to Bellamy (1945), who noted that the variation of \(D\) values along an isobaric surface is an alternate definition of the horizontal pressure gradient force. In practice, \(D\) values are computed regardless of deviations from the isobaric surface. Shapiro and Kennedy (1981) note that use of \(D\) values “eliminates the influences of small deviations from constant pressure on the measured height field.” For small departures from an isobaric surface, the \(D\) value approach yields results that are effectively identical to the hydrostatic correction. However, this is the result of \(T_V\) affecting height only through the correction term. For departures from the isobaric surface on the order of tens of meters or more, errors approach the accuracy of the static pressure measurement, particularly where the virtual temperature implicit in the standard atmosphere differs substantially from the actual flight-level virtual temperature. Others, notably LeMone and Tarleton (1986), have defined \(D\) values as departures from the “local” atmospheric profile, thereby alleviating uncertainties associated with the use of a standard atmosphere. Given the ambiguities

![Figure 1. UWKA 10-Hz altitude data (m) collected during east-to-west flight leg from 2243 to 2253 UTC 22 Jun 2006 as part of the DMIMS project illustrating (a) raw (nondifferential) GPS altitudes, altitudes from UWKA radar altimeters RALT1 and RALT3 with RALT1 offset by 6 m for visualization, and differential GPS altitudes; and (b) corrected 10-Hz DGPS, RALT3, and RALT1 heights. RALT3 and RALT1 offset by 4 and 8 m, respectively. Least squares linear fit indicated by dark solid lines.](image-url)
inherent in these definitions of the $D$ value, in addition to the obfuscation of the underlying physics, we advocate the use of a hydrostatic correction approach even over the use of local $D$ values.

Examples of the temperature differences and hence height differences between the $D$ value and hydrostatic correction used here for a typical isobaric leg are illustrated in Fig. 2. This 40-km isobaric leg (mean pressure 533 hPa) was taken from the 17 June 2008 case. Measured temperatures along the leg (Fig. 2a) were warmer than those of the U.S. Standard Atmosphere by 9–13 K. This implies that the actual density is less than that of the U.S. Standard Atmosphere. The $D$ values are thus larger than that observed using a simple hydrostatic correction in which actual temperature is employed. Resulting differences between instantaneous $D$ value and hydrostatic corrections deviate from hydrostatic corrections for deviations along the flight leg are shown in Fig. 2b and range from −3 to 2 m for this leg, corresponding to instantaneous differences in pressure between −0.21 and +0.14 hPa. While such errors are small in an absolute sense, they are potentially significant when examining finescale horizontal pressure perturbations. Further, departures from the intended isobaric surface frequently exceed those shown in Fig. 2 by an order of magnitude or more, resulting in a similar increase in error. It seems appropriate that an aircraft equipped with suitable GPS receivers and recording static pressure should use ambient temperature representative of the environment rather than that inferred from the standard atmosphere to correct for deviations from the selected isobaric surface. LeMone and Tarleton (1986) follow this same principle in their seminal study of cloud perturbation pressure.

To assess the accuracy of the DGPS-corrected aircraft altitude, the DGPS processing was conducted using a variety of base station configurations. GPS base stations at Laramie and Wheatland were deployed during CloudGPS in the summer of 2008. Differential GPS altitudes for the vertical position of the UWKA are obtained using the various base station configurations, providing some indication of the absolute height errors. Examples of the 1-Hz UWKA altitude differences from independent DGPS solutions using Laramie and Wheatland base stations for flights from 17, 19, and 23 June 2008 are shown in Fig. 3. Absolute differences of about 0.2–0.3 m are seen on each day. Some signal dropouts are seen in these records by the vertical lines in Fig. 3; nearly all of these dropouts are associated with aircraft maneuvers during times of relatively sparse satellite coverage.
Data from two Continuously Operating Reference Stations (CORSs), at Medicine Bow and Wheatland, Wyoming, were used to assess the necessity of deploying dedicated GPS base stations for field campaigns where horizontal pressure gradients and pressure perturbations are likely to be of interest. CORS data are archived at 30-s intervals but have been interpolated in GrafNav 8.10 to 10 Hz to match the UWKA and other GPS base station records. Solutions using the CORSs (not shown) yield absolute altitude differences consistently less than 1 m. Based on these results, we conclude that the absolute position errors of the UWKA platform are on the order of decimeters—in agreement with the more qualitative inferences described in Parish et al. (2007). An uncertainty of 0.3 m in vertical position corresponds to an error in pressure of approximately 0.035 hPa near sea level and roughly half that at 500 hPa.

While the absolute accuracy of the DGPS altitude is sufficient for detection of small horizontal pressure signals, the relative position error is critical when resolving horizontal pressure differences. Relative vertical position differences obtained from using various base station configurations are usually better than that shown in Fig. 3. An example of 1-Hz differences of the vertical position from the DGPS Laramie and Wheatland base station solutions for individual flight legs from the 16 June 2008 case is illustrated in Fig. 4. Relative 1-Hz vertical position differences along these legs are typically within 10 cm. These results confirm that the accuracy of DGPS altitudes is more than sufficient to infer horizontal pressure perturbations, provided a favorable satellite constellation—six or more satellites in view—is available. Given a favorable satellite constellation, vertical position errors of the aircraft are no longer the limiting factor in airborne assessment of atmospheric dynamics. Results shown in this paper incorporate differential corrections from the Trimble NetRS on board the UWKA with the University of Wyoming (UW) site as the base station.

The final consideration examined here is the GPS sampling rate required for differential correction pertaining to atmospheric applications. To address this issue, power spectral densities (PSDs) for DGPS altitude and static pressure were computed for a number of flight legs. Figure 5 illustrates the resulting power spectra for 1 h of data collected along isobaric flight legs within the turbulent boundary layer on 23 June 2008. Data were broken up into nine segments, each 409.6 s long. Several key points are apparent from this figure: for low frequencies (below ~0.05 Hz) the pressure and altitude spectra closely track each other, as confirmed by the coherence between the series (not shown). The coherence between the series, which reflects departures from the intended
isobaric surface, reiterates the need to apply a hydrostatic correction. Above \( \sim 0.03 \) Hz the PSD of DGPS altitude drops off rapidly, reflecting both the inertia of the aircraft and declines in the vertical velocity variance. Between 0.1 and 1 Hz, the PSD decreases by more than four orders of magnitude. In contrast, the PSD of pressure decreases only slightly over the same interval and then declines slowly above 1 Hz. As a result of the precipitous drop in the DGPS PSD, there is little or no benefit to recording GPS data at frequencies above 1 Hz. If needed, the aircraft altitude at rates above 1 Hz can be obtained by interpolating the DGPS altitude to the desired rate with essentially no loss in fidelity.

3. Examples of cloud pressure perturbation measurements

Examples shown here document CloudGPS flights conducted to the east of the Laramie Range (Fig. 6), where cumulus congestus frequently developed during the afternoon. Flights were conducted on 11 days during the CloudGPS deployment, with target clouds typically in the cumulus congestus stage. Once a target cloud was identified, isobaric legs were flown near cloud base through the core of the cloud. Individual flight legs were several times the diameter of the cloud in length to capture the ambient horizontal pressure gradient in which the cloud was embedded. During the initial cloud penetration, the flight scientist set a pointer as the aircraft passed through the updraft core. The pointer, which integrates the air relative velocity of the UWKA, was used so that subsequent passes intercepted the cloud at the same relative position. Passes continued until either the clouds became electrified or began to dissipate.

Observations from 3 days are presented to demonstrate the measurement of horizontal pressure perturbations (HPPs) in conjunction with clouds. The first two cases, 17 June and 21 May 2008, were sampled as part of the CloudGPS project; the final case, from 29 June 2006, was taken from the Dynamics and Microphysics of Marine Stratocumulus (DMIMS) project. A similar flight strategy was used for all CloudGPS flights and was intended to sample early convection developing over the elevated terrain of the Laramie Range of eastern Wyoming. Takeoff times, 1820 UTC [1220 local time (LT)] 17 June and 1955 UTC 21 May, were timed so as to catch the start of convection. In each case the UWKA headed north to the region near Laramie Peak, where the cloud penetrations took place. First passes were generally conducted near cloud base. Climb out soundings from both days indicate well-mixed conditions prevailed below 500 hPa. Cloud base was about 620 hPa on 21 May and 540 hPa on 17 June.

a. Isolated cumulus congestus: 17 June 2008

Conditions on 17 June 2008 most closely resembled those envisioned prior to the CloudGPS deployment: isolated convective clouds, sufficiently long lived that multiple passes through cloud could be made as the cloud evolved. As a result of the relative simplicity of
this case, it is used to illustrate the correction process and to investigate the HPPs observed during the evolution of an isolated convective cloud.

Figure 7 shows height data for a single, isobaric flight leg during the 17 June 2008 CloudGPS flight. The UWKA leg was about 40 km in length at a pressure level of 533 hPa. The aircraft penetrated a cumulus congestus roughly 10 km in diameter midway along the leg. Flight level was directed to be near cloud base although significant cloud water was observed, implying that the actual penetration was several hundred meters above the cloud base. Figure 7a illustrates the DGPS altitude of the UWKA along the leg. As is common practice when conducting such legs, the autopilot was activated, allowing the UWKA to maintain a roughly constant pressure level during the leg. As convection is encountered near the 16-km mark in Fig. 7a, more significant altitude deviations result. After hydrostatic correction to correct for aircraft deviations from the isobaric surface, it can be seen that the surface slopes upward to the south (Fig. 7b). A linear fit to the isobaric surface height is applied, the slope of which is proportional to the geostrophic wind perpendicular to the leg. Calculations indicate a mean geostrophic wind normal to the flight track of about 20 m s\(^{-1}\).

To infer the HPP, it is helpful to remove the background horizontal pressure gradient. Winds at flight level were about 19 m s\(^{-1}\) from 286°. Given the south–north orientation of the flight track, this implies that the aircraft was moving roughly normal to the wind along an isobaric surface that was sloping upward toward the south and that the mean winds are close to geostrophic. To determine the HPP along the isobaric surface, the isobaric heights are first detrended to remove the background height gradient. Perturbation heights are converted to pressure using the hydrostatic equation. The resulting HPP is shown in Fig. 7c. A HPP of roughly -0.5 hPa is observed nearly coincident with the updraft core.

Examination of an isolated convective cloud from its initial formation through its congestus stage to monitor the HPP evolution was one of the central goals of CloudGPS. Figure 8 illustrates the cumulus congestus viewed from the UWKA at the start of each of four consecutive legs. Significant shear above the cloud base is evident in Fig. 8. The flight strategy was to approach the cloud at a level near cloud base along an isobaric surface and penetrate the most vigorous part of the cloud. As the aircraft passed through the core of the updraft (as assessed by the flight scientist), a pointer was set to allow the aircraft to return to the same cloud-relative position for subsequent passes. New growth continued to develop on the upshear side (i.e., west of the updraft core). The initial updraft core appeared to weaken after several passes. Six passes, each about 40 km in length, were made to document the HPP associated with this cloud along with the background pressure gradient. Lifetime of the convective growth for this cloud was about 40 min. Voice notes indicate that the cloud dissipated rapidly after precipitation was first encountered during the fifth leg, approximately 30 min after the updraft core was first sampled. Here, our focus is on the 20-km section containing the convection for the first four legs.

Figure 9 illustrates the Wyoming Cloud Radar (WCR) reflectivity and UWKA measurements of key variables along legs 1 and 2 at the 533-hPa level conducted along a general heading of 350°/170° with north to the left. Radar reflectivity from the WCR for the first two passes shows only weak returns, despite the fact that the cloud displayed impressive new growth. Voice notes (T. Drew 2008, personal communication) from the second pass suggested the cloud development was like “an atomic bomb [that] just went off.” The low radar reflectivity observed by the WCR during legs 1 and 2 is consistent with sampling the early stages of the cloud life cycle before precipitation had time to develop.

Liquid water content (LWC) gradually increases from the edge to the core of the cloud with a sharp boundary
seen on the northern side of the cloud for both legs 1 and 2. During this time, the cloud diameter is about 6 km. Given that the LWC is in excess of 1 g kg$^{-1}$, the flight level must have been several hundred meters above cloud base. Measurement of virtual potential temperature shows that the cloud is 1–2 K warmer than the adjacent environment, not surprising given the initial growth stage of the cloud that was sampled. Other measures of temperature, such as from the reverse flow probe (not shown), also show an increase in temperature associated with the cloud. Signals of both the LWC and virtual potential temperature are closely coupled.

Updrafts of about 10 m s$^{-1}$ were observed for both legs. For the first leg, a downdraft–updraft couplet is seen on the north edge of the cloud. Within a span of just a few kilometers, vertical velocities shift from nearly a 3 m s$^{-1}$ downdraft to about a 10 m s$^{-1}$ updraft. Note the sharp edge of the vertical velocity trace matches both the LWC and temperature signal for the first leg, leaving no doubt of the warm nature of the updraft. The same sharp feature in the vertical velocity trace can be identified for the second pass as well, collocated with the LWC spike and virtual potential temperature increase. Updrafts show a gradual decrease to the south in both profiles. Note that the updraft profile as measured by the UWKA evolves considerably in the approximately 6 min between sampling of the updraft cores. Voice records from the flight indicated that new growth was present, and the secondary updraft maximum at a position of 5 km on the distance scale for leg 2 may reflect that. Updraft velocities increased slightly from leg 1 to leg 2 with a maximum of about 12 m s$^{-1}$.

As the convective cloud was penetrated, the magnitudes of both horizontal wind components decrease. These changes are consistent with a decrease in vertical transport of lower momentum air from below. Directional changes during both passes were consistent with veering with height such as would be observed through warm-air advection but also through simple friction considerations in which boundary layer air is transported upward. Changes in the wind speed are more consistent with the vertical transport of lower momentum air from below rather than accelerations in response to the HPP field.

Examination of HPPs indicates that lower pressure was detected near cloud base as the UWKA penetrated the cloud with magnitudes roughly proportional to the intensity of the updraft. Negative HPPs of about 0.6 hPa
were found near the updraft core. Positive HPPs of 0.4 hPa were seen associated with the downdrafts during leg 1. In general, the HPPs slightly above cloud base are inversely correlated to the vertical velocity.

Figure 10 illustrates UWKA measurements from the third and fourth passes of the same cloud, again spaced such that the updraft cores are sampled 6–8 min apart. WCR reflectivity indicates pronounced changes in the cloud in the short duration between legs 2 and 3 and that the cloud has become glaciated by the third leg. At the point of penetration, maximum LWC amounts had decreased from the previous pass to less than 1 g kg$^{-1}$ and the core was only about 5 km in width. Note that the maximum LWC for both legs 3 and 4 is found just to the north of the reflectivity maximum, consistent with visual inspection and voice notes indicating new convective development apparent on the north side of the cloud. The development of new growth made it difficult to identify the original updraft core. Voice notes indicate that flight scientists were confident that the original updraft core was sampled in leg 3, but that new growth was probably sampled during leg 4. Virtual potential temperature measurements reveal that the cloud continues to be slightly warmer than the environment, although not as pronounced as seen during the first two passes.

Consistent with the position of the LWC maximum was a main updraft core with maximum values about 10 m s$^{-1}$ for both legs 3 and 4, again most pronounced on the north side of the cloud. Horizontal winds shown in Fig. 10 are also influenced by the convection, and again the change is especially apparent on the north side of the cloud. During a 6-km cloud segment, both horizontal components of the wind show a decrease of nearly 10 m s$^{-1}$. Winds within the updraft core are about 13 m s$^{-1}$ from 185°, consistent with the near-surface wind during this flight. The geostrophic wind component along the track as determined from the slope of the isobaric surface was 12.1 m s$^{-1}$. Since the heading for this leg was 171°, a geostrophic wind of 18 m s$^{-1}$ would be expected. Thus, although the slope is in the correct sense, the magnitude of the geostrophic wind is considerably greater than the observed wind. It seems that convection perturbs the ambient pressure field.

**FIG. 9.** WCR reflectivity and UWKA measurements for successive passes on 17 Jun 2008 at (left) 2003–2006 UTC and (right) 2009–2012 UTC. Each column shows (from top to bottom) radar reflectivity (dBZ), liquid water content (g kg$^{-1}$) and virtual potential temperature (K), horizontal wind components $u$ and $v$ and vertical velocity $w$ (m s$^{-1}$), and the horizontal pressure perturbations (hPa).
Negative HPPs are associated with the updraft cores for legs 3 and 4, but the magnitudes of the maximum perturbations have decreased considerably from legs 1 and 2 with values less than 0.5 hPa. Significant downdrafts have developed on the south side of the cloud during leg 4, although little evidence of positive HPPs is seen. Results of the HPP calculations and measured variables from the UWKA platform reveal a rapidly changing convective cloud but with clearly defined negative HPPs near cloud base that are especially prominent throughout the early growth stages.

b. Convective cloud band: 21 May 2008

Convective activity on 21 May 2008 was far more complex and severe than the isolated cumulus sampled on 17 June. Bands of convection in eastern Wyoming developed rapidly after takeoff. Although clouds with significant updrafts were encountered during the 21 May case, widespread convection made it difficult to identify isolated individual cells. Rapid development of cells from cumulus congestus into severe convection made repeat passes difficult.

An example of the convection is illustrated in Fig. 11, taken at 2132 UTC. The UWKA sampled this cloud with reciprocal passes near cloud base. As can be seen from Fig. 11, a line of convection was present with the initial UWKA penetration near what was perceived to be the most vigorous growth. A pointer was again set when the maximum updraft was seen so as to allow the next pass...
to sample the same convective element. Cloud base was well defined for the two passes shown with no precipitation apparent. Owing to uncertainties in ambient wind conditions and the rapid development of the clouds and the proximity to nearby convection, understanding the dynamics of this complex system is difficult. The intensity of the updrafts suggested that detectable HPPs should be evident for these legs.

Figure 12 depicts the radar reflectivity from the WCR and coincident UWKA measurements for two consecutive passes, 2129–2139 and 2140–2150 UTC 21 May 2008. The flight tracks were made along the 620-hPa surface that was estimated to be at cloud base on headings of 83° and 271°, respectively. Mean winds during these legs were about 13 m s⁻¹ from 165° and thus the UWKA track was nearly orthogonal to the isobaric height contours and wind. Calculation of the isobaric slope from the legs (not shown) indicated a cross-track geostrophic wind of about 11 m s⁻¹, close to the ambient wind, suggesting that quasigeostrophic conditions prevailed.

Radar reflectivity for the legs is shown in the top panels of Fig. 12 with west shown to the left on the distance scale, which is relative to the pointer. Maximum radar reflectivities were +10 dBZₑ for the first leg and +20 dBZₑ about 10 min later during the second leg, confirming that precipitation had already developed. Reflectivity patterns indicate a similarity between legs that provides some confirmation that flight legs passed through the same core region of the cloud. LWC measurements were used as an indicator of proximity to cloud base. UWKA measurements from both legs indicated LWC values of about 0.2 g kg⁻¹, indicating a flight level a few hundred meters above cloud base. Virtual potential temperatures indicate that for this case, the cloud was colder than the surrounding environment by about 2 K, consistent with the flight level being several hundred meters below the LFC.

Components of motion along the flight legs are illustrated in the third panel of Fig. 12. Vertical velocity measurements reveal maximum updraft velocities of nearly 15 m s⁻¹ for the first pass and about 9 m s⁻¹ for the second leg. In each case the updrafts are colder than the ambient environment. Measurement of cold updrafts during severe weather has been noted previously by Marwitz (1974), who concluded that the vertical perturbation pressure gradient was necessary to explain the acceleration of negatively buoyant air into the
updraft. Large changes in the updraft profiles between legs indicate in part the rapidly changing convective environment but may also reflect some uncertainty in the relative position where the UWKA intercepted the convection. It is clear from both passes that the main updraft core is situated upwind of the zone of maximum reflectivity.

Horizontal motion components shown in Fig. 12 are significantly modulated by the convection. Observations indicate that updrafts are coincident with an increasing west-to-east component of motion and a decreasing south-to-north component of motion. Wind directions thus shift from the ambient southerly flow to a more westerly flow within the updraft. It is also apparent that changes in the magnitude of the horizontal wind components are not in phase with each other or the vertical velocity field. Such wind changes are thought to be either the result of the transfer of lower momentum air by the updraft or the modification of the motion field through accelerations induced by the HPP field.

HPPs along both legs in Fig. 12 show negative values near cloud base that are associated with updrafts. Magnitudes of the HPPs are relatively large, with values approaching 2 hPa for the first leg and nearly 1 hPa for the second leg. HPPs are not in phase with updrafts on each leg but rather are situated east of the updraft in each case, indicating an upwind direction along the leg. It appears as though the $x$ component of motion is in phase with the HPP in each case (although the $y$ component is not) and suggests a possible link between the changes in the motion field as a response to the HPP field. Simple calculations based on the steady $x$ equation of motion without Coriolis influences suggest that the observed changes in the $x$ component of motion are consistent with the observed HPP field.

c. Marine stratocumulus “drizzle cell”: 29 June 2006

The rapid evolution and short lifetimes of the convective clouds sampled during CloudGPS severely limited what could be inferred from perturbation pressures measured from a single aircraft. Here, we examine a single, persistent mesoscale structure (drizzle cell) embedded within a marine stratocumulus layer off the Northern California coast. These observations were collected during
the DMIMS project, which took place during May–June 2006 with the UWKA based out of Arcata, California. Data presented here were collected during the second UWKA flight on 29 June 2006. Larger-scale organization was dominated by a vortex southwest of Cape Mendocino that developed following the cessation of the 23–26 June 2006 coastally trapped wind reversal (Parish et al. 2008; Rahn and Parish 2007, 2010). The marine boundary layer (MBL) was anomalously deep (>1 km) for the northeast Pacific stratocumulus region (e.g., Leon et al. 2008)—conditions more representative of the deeper MBL observed near the Azores and in the southeast Pacific stratocumulus region (Albrecht et al. 1995; Bretherton et al. 2004).

Repeated penetrations through a single drizzle cell provide an opportunity to examine the vertical structure of the HPPs and the time evolution of the cell. Nine flight legs were conducted over the course of 80 min. The target cell was identified by the flight scientist and the pointer set on the initial pass, about 150 m above the top of the MBL. The UWKA then descended into the MBL and flew a pair of legs across the cell at 920 m, 50–75 m below cloud top. The aircraft proceeded to conduct three legs below the cell at an altitude of 100 m before ascending to conduct an additional pair of legs near cloud base (620 m). These were followed by a pair of in-cloud legs at 770 m, a final near-surface pass below the cell (100 m), and a pass above the cell at the beginning of the ferry back to Arcata.

WCR reflectivity cross sections for this sequence of legs are shown in Fig. 13. It was expected that the horizontal pressure perturbations associated with this cloud would be small, owing to the weak forcing in the marine environment. Maximum updraft velocities were seen on the second pass at the 620-m level, where values reached nearly 5 m s\(^{-1}\), although updrafts on the second pass were only about half that value. Updrafts at other levels were weak, with maximum values of 1–2 m s\(^{-1}\). The radar reflectivity cross sections shown in Fig. 13 demonstrate that while the cell evolved considerably during the sampling time, this evolution appears to be continuous and is clearly the same feature.

Figure 14 shows HPPs for nine legs within the MBL. Distances shown in Fig. 14 are with respect to the pointer. The legs conducted at the 100-m level show negative HPPs of about 0.1 hPa, associated with the updraft region of the cloud for the first two passes, but increasing to about 0.2 hPa for the third pass. Maximum HPPs at the 620-m level for the two passes were about 0.2 hPa. The pattern of HPPs changes near the top of the cloud. Little detectable pressure perturbation was seen at 770 and by 910 m a clearly defined positive horizontal perturbation was observed on both legs. HPP traces throughout the period reveal nonsteady conditions, yet it appears that negative HPPs are found in the lower to middle sections of the cloud with positive HPPs near the top of the cloud. This is consistent with the observed circulations: horizontal convergence near the surface is driven by the negative HPP. An upward-directed nonhydrostatic vertical pressure gradient would be needed to lift negatively buoyant parcels into the cloud layer, while the downward-directed gradient in the upper part of the cloud is consistent with the observed divergence from the center of the cell near cloud top.

4. Summary

Differential processing of raw data collected by an airborne GPS platform with GPS data from a fixed base station provides a means by which the vertical position of the aircraft can be detected to within a decimeter or so. Combined with accurate measurement of static pressure, heights along an isobaric surface or, equivalently, horizontal variations of pressure can be detected along a flight track. An application of this technique has been used to infer horizontal pressure perturbations
associated with convective clouds during a field project in the late spring of 2008. Flights conducted near cloud base indicate negative horizontal pressure perturbations on the order of 1 hPa. The magnitude of the pressure perturbation appears linked to the intensity of the updraft. Rapid changes in the cloud dynamics were observed for high plains congestus that limited the ability to sample clouds at various levels to examine vertical changes in the horizontal pressure perturbations. Accurate measurement of the vertical position of the aircraft was for many years the fundamental challenge in measuring horizontal pressure perturbations. Results from this study show that through differential processing, the vertical position is known to within a decimeter and is no longer the limiting factor in measurements of horizontal pressure perturbations; rather, the fundamental limitation in detecting horizontal pressure perturbations is the accuracy with which static pressure is measured, especially in the turbulent environment through which the aircraft flies. Future studies will focus on marine convective clouds for which lifetimes can be significantly longer to permit more flight legs to be conducted.

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REFERENCES