Estimating Sensible and Latent Heat Fluxes Using the Integral Method from in situ Aircraft Measurements

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ABSTRACT

In September 2009, several Aerosonde unmanned aerial vehicles (UAVs) were flown from McMurdo Station to Terra Nova Bay, Antarctica, with the purpose of collecting three-dimensional measurements of the atmospheric boundary layer (ABL) overlying a polynya. Temperature, pressure, wind speed, and relative humidity measurements collected by the UAVs were used to calculate sensible and latent heat fluxes (SHF and LHF, respectively) during three flights. Fluxes were calculated over the depth of the ABL using the integral method, in which only measurements of the mean atmospheric state (no transfer coefficients) were used. The initial flux estimates assumed that the observations were Lagrangian. Subsequent fluxes were estimated using a robust and innovative methodology that included modifications to incorporate adiabatic and non-Lagrangian processes as well as the heat content below flight level. The SHF ranged from 12 to 485 W m\(^{-2}\), while the LHF ranged from 56 to 152 W m\(^{-2}\). The importance of properly measuring the variables used to calculate the adiabatic and non-Lagrangian processes is discussed. Uncertainty in the flux estimates is assessed both by varying the calculation methodology and by accounting for observational errors. The SHF proved to be most sensitive to the temperature measurements, while the LHF was most sensitive to relative humidity. All of the flux estimates are sensitive to the depth of the boundary layer over which the values are calculated. This manuscript highlights these sensitivities for future field campaigns to demonstrate the measurements most important for accurate flux estimates.

1. Introduction

The coastal landscape of Antarctica is dominated by fierce winds that originate over the continental interior, introducing cold, dry air to a relatively warmer and moister atmospheric boundary layer (ABL) at the outlet of glacial valleys. Coastal polynyas are formed when this strong off-continental flow pushes ice offshore, leaving an area of open water or thin sea ice adjacent to the coast. In Terra Nova Bay (TNB), located in the western Ross Sea (Fig. 1), strong flow that can be greater than 40 m s\(^{-1}\) (Bromwich 1989; Hauser et al. 2002; Knuth and Cassano 2011) produces a polynya that is a dominant feature throughout the winter months. As cold and dry air is advected over the polynya, the ensuing large ocean–atmosphere temperature and humidity differences can lead to large sensible and latent heat fluxes (SHF and LHF, respectively). This modification of the near-surface air above the polynya in TNB has been shown to enhance mesocyclone development, sea ice production, and Antarctic Bottom Water (Budillon et al. 2003; Carrasco et al. 2003; Petrelli et al. 2008; Orsi and Wiederwohl 2009).

To understand the conditions within the ABL over the polynya and to quantify air–sea interactions in TNB from observational data, several unmanned aerial vehicles (UAV) were flown over TNB in September 2009 to collect information on the three-dimensional state of the atmosphere (Cassano et al. 2010; Knuth et al. 2013). Using the data collected during these flights, sensible and latent heat fluxes are calculated to quantify air–sea interactions in the region.

A methodology to calculate the heat fluxes is described, where only mean atmospheric state data from the UAV are utilized and a bulk transfer coefficient is not used. This method initially considers a Lagrangian approach to estimating the fluxes with corrections to incorporate other processes considered. The purpose of

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this paper is to describe this method while highlighting the sensitivity of the necessary corrections on estimating the fluxes. Understanding this sensitivity will be critical for other researchers flying scientific missions to ensure the data most sensitive to the flux estimations are observed well. Section 2 describes the UAV flights, section 3 discusses the methodology used to calculate the fluxes, section 4 describes the results and uncertainty, and section 5 provides a summary.

2. Aerosonde flights

In 2009, 16 Aerosonde UAV missions were flown from McMurdo Station, Antarctica, with 8 missions to TNB (Cassano et al. 2010; Knuth et al. 2013). The UAV had a wingspan of 3 m, a weight of 15 kg, and a payload capacity of 2–5 kg. The aircraft had a range of over 1000 km and flew at approximately 150–3000 m altitude during the flights. The flights were flown as low as possible to ensure the most accurate flux estimates but not below 150 m because of concerns about icebergs as well as inaccuracies in the global positioning system (GPS) data.

The UAV carried several instruments on board, including temperature, pressure, and relative humidity sensors that recorded data with a 10-s temporal resolution (Knuth et al. 2013). Wind speed measurements were made using a combination of airspeed calculated by the onboard pitot tube and ground speed observations from the GPS. Specific humidity was calculated from the relative humidity and pressure measurements.
On days when the flight mission was to estimate the turbulent fluxes over the polynya, the UAV flew north from McMurdo toward TNB along the coast. Once over the Drygalski Ice Tongue (DIT), the UAV would descend to ~150–240 m, and a roughly south–north coastline parallel flight leg across TNB was flown to find the location of maximum wind speed (the downslope wind jet) (Fig. 2). The UAV was then flown downwind within the jet, accomplishing two goals: 1) to sample the area with the strongest air–sea fluxes and 2) to document the downstream evolution of the ABL. Along this approximately west–east cross section, vertical profiles were
collected approximately every 20 km (Fig. 2). The UAV ascended and descended within the profiles by spiraling with a 1-km width; however, not all profiles contained useable data within each ascent or descent.

Of the 16 UAV flights, 3 flights—on 18, 23, and 25 September—were used to calculate heat fluxes as part of this study. Three profiles were collected on 23 and 25 September [profiles 1–3 (P1–3)], where leg 1 uses data between profiles 1 and 2, and leg 2 between profiles 2 and 3 (Fig. 2). On 18 September, four profiles were collected, but only the farthest downstream pair—profiles 3 and 4 (corresponding to leg 3)—is used in this study. Using the data from these flights, a methodology for calculating the heat fluxes as part of this study. Three profiles were collected on 23 and 25 September—were used to calculate heat fluxes as part of this study. The necessary observations to quantify these terms are not available for these flights.

Equation (1) is modified by multiplying by $\rho dz$, the mass per unit area of the column of interest, to put the equation in terms of watts per square meter such that

$$\rho \Delta z Q_s = \frac{c_p \Delta T \Delta z - \Delta \rho \Delta z}{\Delta t},$$  \hspace{1cm} (2)

where $\Delta t$ is the time it takes the air parcel to travel between the upwind and downwind profiles by spiraling with a 1-km width; however, not all profiles contained useable data within each ascent or descent.

### 3. Flux calculation methodology and corrections

The methodology described below uses atmospheric data (temperature, pressure, wind speed, and moisture) to estimate changes in the energy present in the atmosphere over the UAV flight path via the integral method. The general approach, described in section 3a, uses methods similar to those of Kottmeier and Engelbart (1992) and Serreze et al. (1999), as well as those in the ocean community to estimate carbon dioxide flux through inverse modeling (Tarantola 1987; Enting et al. 1993; Bouquet et al. 1999). However, the methodology outlined in this work provides a much more extensive analysis of the non-Lagrangian correction methods (outlined in section 3c), making this work unique and innovative. Clouds are not considered in this work, as there were no clouds present during the UAV flights.

#### a. SHF formulation

Using a Lagrangian approach, the heat fluxes are estimated by examining changes in the state of an air parcel along a UAV flight path. An estimation of the SHF can be found from the thermodynamic energy equation (TEE) written in finite difference form:

$$Q_s = c_p \frac{\Delta T}{\Delta t} - \frac{1}{\rho} \frac{\Delta \rho}{\Delta t},$$  \hspace{1cm} (1)

where $c_p$ is the specific heat of dry air at constant pressure (1004 $J \text{ kg}^{-1} \text{ K}^{-1}$), $T$ is the air temperature (K), $t$ is the time it takes the air parcel to travel between concurrent profiles, $\rho$ is the density of the air (kg m$^{-3}$), and $p$ is the pressure (Pa). The density is calculated using virtual temperature and pressure from the UAV data. Term $c_p(\Delta T/\Delta t)$ is proportional to the time rate of change of temperature and $(1/\rho)(\Delta \rho/\Delta t)$ is the adiabatic term, which are both estimated from the UAV observations. It is assumed that changes in $Q_s$, the diabatic heating term (J kg$^{-1}$ s$^{-1}$), are only due to surface fluxes from the polynya into the air parcel. All other diabatic processes, such as entrainment, subsidence, and radiation, are assumed to be negligible as part of this study. While neglecting these processes may impact the results, the necessary observations to quantify these terms are not available for these flights.

Equation (1) is modified by multiplying by $\rho dz$, the mass per unit area of the column of interest, to put the equation in terms of watts per square meter such that

$$\rho \Delta z Q_s = \frac{c_p \Delta T \Delta z - \Delta \rho \Delta z}{\Delta t},$$  \hspace{1cm} (2)

where $z$ is the UAV height (m) at some point in the ABL profile. The term on the lhs is the SHF in units of watts per square meter, while the rhs represents the change in heat content (HC) adjusted by adiabatic processes over the ABL over time. For these calculations the air parcel is assumed to extend over the depth of the ABL, since this is the portion of the atmosphere directly influenced by the surface. The depth of the ABL is estimated from the UAV-observed potential temperature profiles along the flight path.

Considering the change in HC throughout the depth of the ABL at a single point in time and (for the moment) neglecting adiabatic processes, the rhs becomes

$$HC = \sum c_p \rho T \Delta z,$$  \hspace{1cm} (3)

where the HC is being summed over the depth of the ABL (UAV flight level to the ABL top). This term represents the amount of energy present over the entire depth of the ABL within each profile measured along the UAV flight path. The SHF (W m$^{-2}$) is then calculated by examining the change in HC over the amount of time $\Delta t$ it takes the air parcel to travel between the upstream and downstream profiles, or

$$\text{SHF} = \frac{HC_{\text{down}} - HC_{\text{up}}}{\Delta t}.$$  \hspace{1cm} (4)

Because the SHF in Eq. (4) is valid between two concurrent profiles, there is one value estimated for each flight leg. For example, if a flight leg has three profiles, then there will be two SHF values—one valid between profiles 1 and 2, and one valid between profiles 2 and 3.

Equations (3) and (4) are critical to this study, as these indicate how changes in the atmospheric state will alter the HC of the air parcel, which will in turn be used to estimate the SHF. The derivation of these equations assumes the observations are exactly Lagrangian and neglect adiabatic changes in temperature between pairs.
of profiles. We will use this simplest estimate of the SHF as a baseline for comparing more realistic flux estimates that include processes such as adiabatic temperature changes and the non-Lagrangian nature of the observations. To account for this, the HC estimated in Eq. (3) will be altered for each process that influences the SHF, and corrections to the purely uncorrected HC [given in Eq. (3)] will be made to estimate a new flux. Each of these corrections (described below) will be compared to the uncorrected SHF to estimate the relative impact of each correction on the SHF.

b. Adiabatic processes

As shown in Eq. (1), as the air parcel travels from the upstream to the downstream profile, changes in the temperature of the column occur because of both diabatic and adiabatic processes. When calculating the SHF, only diabatic changes in temperature should be considered and adiabatic changes removed. To account for and remove changes in the temperature due to adiabatic processes, Poisson’s equation, derived from the TEE, can be used to estimate the adiabatic temperature of the air parcel:

\[ T_{adb} = T_{1obs} \left( \frac{p_2}{p_1} \right)^{R/c_p}, \]

where \( T_{adb} \) is the adiabatic temperature the upstream air column would have if it were moved downstream at the new pressure \( p_2 \). Term \( T_{1obs} \) is the UAV-observed mean temperature of the upstream air column; \( p_1 \) and \( p_2 \) are the average pressures of the upstream and downstream columns, respectively; and \( R \) is the gas constant for dry air (287 J kg\(^{-1}\) K\(^{-1}\)). Then, to estimate the diabatic temperature of the downstream air column, we use

\[ T_{2dia} = T_{2obs} - (T_{adb} - T_{1obs}), \]

where \( T_{2obs} \) is the UAV-obtained mean temperature of the downstream air column, and the term in parentheses on the rhs is the adiabatic temperature change experienced as the air parcel moves from the upstream to the downstream profile location.

Finally, to estimate an SHF that excludes adiabatic processes, the temperature in Eq. (6) is used to estimate the downstream HC, so that Eq. (3) now becomes

\[ HC_{down} = \sum c_p \rho T_{2dia} \Delta z \]

and Eq. (4) is used to estimate the SHF.

c. Non-Lagrangian processes

The above-mentioned formulations describe fluxes that use a Lagrangian approach, assuming the UAV measures the same air parcel at the location of the downstream profile as it did at the upstream. In reality, the UAV does not fly at the same speed as the air parcel, and this non-Lagrangian nature of the observations needs to be accounted for in the flux estimations within the TEE. Non-Lagrangian processes will be used to correct the temperature and pressure variables to consider the conditions that should have been measured if the UAV had followed the air parcel. This correction can consider two perspectives: time and space, with both perspectives separated into two distinct methodologies. Because of a lack of data, the time perspective cannot be considered for the 2009 flights and is not discussed further. However, both space perspectives are considered below. Both perspectives are equally viable but differ in the observations used to implement them.

SPACE PERSPECTIVE

The first space perspective considers a scenario where the air parcel and UAV start at profile 1 (P1) at the same time but at some later time are not collocated. The second space perspective considers a scenario where the air parcel and UAV are at P2 at the same time and are not collocated at the initial time. Each method should provide similar answers, and both are described below.

Figure 3a is a schematic illustrating the first space perspective scenario. P1 and P2 are separated by a distance \( \Delta x \), and both the UAV and air parcel are located at P1 \((x_{u,1} = x_{p,1})\) at the initial time \((t_{u,1} = t_{p,1})\). As the parcel and UAV move toward P2, they travel at different speeds. In the example illustrated in Fig. 3, top, the UAV travels slower than the air parcel. Therefore, when \( t_{p2} = t_{u2} \) and the UAV is located at P2, the air parcel is located at some point downstream, and \( x_{u,2} \neq x_{p,2} \). This space mismatch needs to be corrected with (in terms of temperature)

\[ T_{corr} = \frac{\partial T}{\partial x} \Delta x, \]

where \( \partial T/\partial x \) is the temperature gradient found from the difference in the mean column temperatures at the start and end of the flight path, and \( \Delta x \) is the difference in space \((x_{p,2} - x_{u,2})\) between the air parcel location and the UAV location (P2).

The bottom panel in Fig. 3 is a schematic illustrating the second space perspective scenario where the UAV and air parcel are located at P2 \((x_{u,2} = x_{p,2})\) at the same time \((t_{u,2} = t_{p,2})\). Because the air parcel and UAV travel at different speeds, they must have originated at different locations upstream. In the example illustrated in Fig. 3, bottom, the air parcel, located at P1 at \( t_{u,1} \), travels faster than the UAV. At this same time, the UAV is located some distance downstream of P1, so that...
x_{u,1} \neq x_{p,1}. This space mismatch, much like the equal P1 scenario described in Fig. 3, top, is also corrected with Eq. (8).

An SHF that accounts for the non-Lagrangian processes illustrated in Fig. 3, top, can be estimated by altering the downstream HC in Eq. (3) such that
\[ HC_{\text{down}} = \sum c_p \rho T_{2L_G} \Delta z, \] (9)
where $T_{2L_G}$ is the downstream air column temperature that incorporates only Lagrangian processes. This temperature is found by adjusting the observed downstream temperature by the non-Lagrangian temperature given by Eq. (8). Equation (4) is then applied to estimate the SHF. Alternately, a correction for the upstream HC can be applied based on the case illustrated in Fig. 3, bottom.

In the space correction detailed above, the estimated temperature gradient based on the UAV measurements is considered instantaneous over the amount of time it takes the air parcel to fly to the downstream profile. An adjustment to the temperature gradient that considers changes over time should also be considered. However, an appropriate correction would need to consider data from a local automatic weather station (AWS) site, and these data are not viable for the 2009 flights. Therefore, for the final SHF (and LHF) calculations, a correction to the estimated $\partial T/\partial x$ for changes due to time along the flight path is not considered.

d. Changes in the atmosphere below flight level

The flux estimates described above neglect changes in the HC in the atmosphere below flight level, which likely underestimates the fluxes described previously. To account for this, we estimate the change in HC below the flight level by modifying Eq. (3) to give
\[ \Delta HC = \sum c_p \rho \Delta T \Delta z, \] (10)
where the summation is evaluated over the depth of the layer between the lowest UAV flight level and the surface, and $\Delta T$ is the change in temperature between pairs of profiles and includes the non-Lagrangian and adiabatic corrections described previously. Since observations of the temperature below flight level are not available, we assume that $\Delta T$ below the UAV flight level is the same as that found between the flight level and ABL top. Given that the ABL is usually well mixed, this is a reasonable assumption. The additional HC calculated with Eq. (10) is added to the previously estimated HC value from flight level to the top of the ABL and a new SHF is calculated. This SHF is the final, fully corrected flux (final flux).

The above-mentioned discussion highlights several adjustments to the uncorrected flux necessary for providing the most accurate estimate of the SHF. In this study, the following fluxes will be discussed: uncorrected flux, adiabatic only (described in section 3b), space only (section 3c), space adiabatic (for both described scenarios), and the final flux estimate. The final fluxes adjust temperatures to account for both adiabatic and non-Lagrangian processes, as well as the HC below flight level.

e. Latent heat fluxes

Calculation of the LHF will follow a similar formulation to the SHF. The water vapor conservation equation ($J \text{ kg}^{-1} \text{s}^{-1}$) in finite difference form is
\[ Q_l = L_v \frac{\Delta q}{\Delta t}, \] (11)
where $L_v$ is the latent heat of vaporization at 0°C ($2.5 \times 10^6 \text{ J kg}^{-1}$) and $q$ is the specific humidity. Equation (11) is converted to units of watts per square meter by

![Fig. 3. Schematic of the space perspectives of the non-Lagrangian approach to the heat flux calculations. The circle represents the air parcel, and the plane outline represents the UAV. P1 and P2 are shown, $x$ indicates distance, $t$ indicates time, $u$ represents the UAV, and $p$ represents the parcel. The “1” and “2” subscripts indicate two different points in space or time. (top) Shown is the equal P1 space perspective and (bottom) the equal P2 space perspective.](image-url)
multiplying both sides by the mass per unit area of the column \((\rho \Delta z)\). The diabatic moisture term with respect to latent heating \(Q_l\) incorporates surface fluxes, entrainment, and any latent heat release due to changes in phase, but we will assume that all changes to \(Q_l\) are due to surface fluxes.

Following on the methods of calculating the SHF, it is also useful to define the latent heat content (LHC) of the air parcel in each profile within the ABL to be

\[
LHC = \sum \rho L_v q \Delta z.
\]  

(12)

The LHF is then calculated by considering the difference in LHC measured within each profile along the UAV flight path over the amount of time \(\delta t\) it takes the air parcel to travel between the upstream and downstream profiles:

\[
LHF = \frac{LHC_{\text{down}} - LHC_{\text{up}}}{\delta t}.
\]  

(13)

Equations (11)–(13) yield the uncorrected LHF for this study.

To make the most accurate estimate of the LHF, non-Lagrangian corrections similar to the SHF must be applied. Following on the space perspective subsection of section 3c, the space-only correction to the specific humidity data is

\[
q_{\text{corr}} = -\frac{\partial q}{\partial x} \delta x,
\]  

(14)

where the terms in the equation are as listed above. Equation (12) is then modified to become

\[
LHC = \int \rho L_v q_{21G} \Delta z,
\]  

(15)

and Eq. (13) is used to estimate the LHF that incorporates non-Lagrangian processes. The correction to account for the LHC below flight level is implemented in a manner similar to what was described in section 3d.

4. Results

a. ABL selection

The top of the ABL was determined to be the point at which the upstream and downstream potential temperature profiles are no longer clearly distinguishable from each other. This criterion was used because we expect that the surface fluxes experienced by an air parcel will modify the atmospheric state in the lowest portion of the profile, while conditions above the influence of the surface fluxes should remain relatively constant between pairs of profiles. However, some flight days displayed clear features, such as inversions, capped mixed layers, or changes in mixing ratio, which indicate the presence of a convective ABL (CBL), and in these instances the ABL height is chosen accordingly.

On 18 September (Fig. 4), the top of the ABL was defined at 457 m. Below this point, the lapse rate in the downstream profile (profile 4) is decreasing dry adiabatically, whereas above the lapse rate shifts to a positive value. The specific humidity profiles also support an ABL depth of 457 m as a shift in the profiles from decreasing specific humidity to a more well-mixed value is apparent, particularly in profile 4. Given the complexity of the ABL profiles, alternative ABL heights (and impacts on flux estimates) are explored in section 4d.

On leg 1 on 23 September (Fig. 5), an ABL height of 720 m was determined. Above this point, the upstream and downstream profiles are similar, while below 720 m the downstream profile (profile 2) is clearly warmer throughout the layer than the upstream profile (profile 1). In profile 2, the layer between 420 and 720 m exhibits sharp spikes in the potential temperature, where the colder temperatures show conditions similar to profile 1, and the warmer temperatures similar to profile 2. We suspect that these spikes are not noise but an example of the UAV sampling the convective plumes of the ABL alongside the conditions in the profile that are not yet impacted by convection. This indicates the top of the ABL on this day is not at one level but varies vertically over this 300-m distance. The specific humidity profiles also show a clearly moister ABL in the downstream profile below 720 m with little difference above this height.

The height of the ABL for leg 2 on 23 September (Fig. 6) was determined to be at 540 m. This flight leg exhibited most clearly the characteristics of a CBL, with a well-mixed layer present from flight level to 540 m in the downstream profile (profile 3). This layer is topped by a capping inversion at 540 m that extends to 600 m. The specific humidity profiles also are well mixed in this layer with a rapid decrease in specific humidity above 540 m, consistent with the ABL top being located at this height.

On 25 September, an ABL depth of 240 m was determined for leg 1 (Fig. 7), with profile 2 being warmer than profile 1. Above this level, the two profiles exhibit similar characteristics to approximately 525 m, above which another air mass is likely impacting conditions within the profiles. The specific humidity profiles also show clearly distinct values below 240 m, although the values do not appear well mixed until approximately 280 m.

For leg 2 on 25 September, the two profiles exhibit similar characteristics throughout the entire depth of the UAV profile (Fig. 8). However, a nearly well-mixed
layer topped by a capping inversion in profile 3 shows that the ABL top is likely at 250 m on this day. The specific humidity profiles support this contention. The downstream profile shows nearly constant specific humidity up to 250 m with a rapid drop above this height, consistent with an ABL depth of 250 m.

b. Sensible heat fluxes

From the methods described in section 3, five variations of SHF have been calculated—the uncorrected, adiabatic-only, space-only, space-adiabatic, and final fluxes for the P1 and P2 scenarios. This section will briefly
examine the uncorrected fluxes and then describe each correction made to understand how the addition of other processes change the original, uncorrected flux estimate.

The estimates of the SHF are influenced by the temperature difference between the two profiles, the depth of the ABL, and the amount of time it takes the air parcel to travel between profiles (which is influenced by the wind speed) (Table 1). A larger temperature difference indicates a larger amount of energy being added to the air parcel as it moves downstream, which will lead to

FIG. 5. The upstream (blue) and downstream (red) (top) potential temperature, (bottom left) temperature, and (bottom right) specific humidity profiles for leg 1 on 23 Sep. The black horizontal line represents the best estimate of the ABL height.
a larger SHF. A deeper ABL will also yield a larger flux because of a greater amount of mass being heated in the air column. An increased wind speed will yield a faster air parcel travel time that will also increase the flux.

Examining the uncorrected fluxes for each flight day (Table 1) shows a range of SHF between −1 and 331 W m$^{-2}$, with the largest flux occurring in leg 1 on 23 September and the smallest on leg 2 on 25 September.

FIG. 6. The upstream (blue) and downstream (red) (top) potential temperature, (bottom left) temperature, and (bottom right) specific humidity profiles for leg 2 on 23 Sep. The black horizontal line represents the best estimate of the ABL height.
Despite leg 1 on 23 September having a higher SHF than all other flight days, leg 1 on 25 September exhibits the strongest wind speed and the largest difference in temperature between the upstream and downstream profiles (Table 1). This seeming disparity occurs because of the depth of the ABL over which the HC is calculated—the ABL depth on 23 September is over 475 m greater than on 25 September (Table 1). As such, the difference in HC per unit meter between the two concurrent profiles is over $6.6 \times 10^5 \text{ J m}^{-2}$ greater.
on 23 September than 25 September, leading to a larger SHF being estimated on 23 September.

The adiabatic-only correction will decrease (increase) the flux because of an increase (decrease) in pressure along the flight path. An increase in pressure downwind will lead to a heating of the air parcel due to adiabatic effects. Because adiabatic heating needs to be removed to estimate an accurate diabatic SHF, this increase in pressure will act to decrease the flux. The opposite is true for a decrease in pressure downwind.

In Table 1, $\Delta P$ describes the difference in pressure between the downstream and upstream profiles ($\Delta P = P_{\text{down}} - P_{\text{up}}$).
shows that on most flight legs, pressures increased downwind (positive $\Delta P$) and that the adiabatic-only correction was negative, leading to a decrease in the uncorrected flux. On leg 2 on 25 September, however, the pressure decreased, leading to a positive adiabatic-only correction.

The adiabatic-only corrections for all five flight legs ranged from $-34$ to $26$ W m$^{-2}$. Considering only the relative magnitude of the corrections, the largest magnitude correction was on leg 1 on 23 September ($34$ W m$^{-2}$) (Table 1), and the smallest ($1$ W m$^{-2}$) on leg 2 on 23 September (Table 1). The adiabatic correction had the largest relative impact on leg 2 on 25 September, altering the uncorrected fluxes by 26%. The pressure change was also largest on this flight leg. The adiabatic correction had the smallest relative difference on leg 2 on 23 September, where the adiabatic correction changed the uncorrected flux 0% (Table 1).

The space-only correction depends on two main factors: the temperature gradient along the flight leg ($\partial T/\partial x$), and the space difference $\delta x$ between the UAV and air parcel locations (see the space perspectives subsection in section 3c). A positive temperature gradient indicates an increasing temperature with increasing distance downwind. A positive $\delta x$ indicates a situation where the UAV is farther downstream than the air parcel—in other words, the UAV is flying faster than the air parcel. It is the product of these terms, as given in Eq. (8), that controls whether the space-only correction will be positive or negative, and thus act to increase or decrease the uncorrected flux.

The space-only corrections for the P1 equal scenario ranged from $-1$ to $81$ W m$^{-2}$ (Table 1), with the correction term on leg 1 on 23 September being the largest, and leg 2 on 25 September the smallest. The space-only correction had the largest impact on 18 September, however, adjusting the uncorrected fluxes by 151%. On leg 1 on 25 September, the relative impact of the space correction altered the uncorrected fluxes by half that of 18 September, and the other 3 days had a relatively small adjustment. For all flight days, the $T_{corr}$ term is positive, indicating an increase in the uncorrected flux. The space corrections for the P2 equal scenario are nearly identical to the P1 equal scenario, with values ranging from $-1$ to 83 W m$^{-2}$, and the relative impacts ranging from 1% to

Table 1. Values for average wind speed over the ABL (WS), various ABL depths, temperature difference between pairs of profiles ($\Delta T$), estimated sensible heat flux (SHF), pressure difference between pairs of profiles ($\Delta P$), change in SHF from uncorrected value ($\Delta$SHF), and the correction to the observed temperature ($T_{corr}$) for flight legs on 18, 23, and 25 Sep 2009. Percent difference comparing the correction to the uncorrected flux is given in parentheses.

<table>
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<th>18 Sep leg 3</th>
<th>23 Sep leg 1</th>
<th>23 Sep leg 2</th>
<th>25 Sep leg 1</th>
<th>25 Sep leg 2</th>
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<td>0.6</td>
<td>0.4</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Delta P$ (Pa)</td>
<td>45</td>
<td>90</td>
<td>3</td>
<td>101</td>
<td>-146</td>
</tr>
<tr>
<td>SHF (W m$^{-2}$)</td>
<td>44</td>
<td>297</td>
<td>120</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>$\Delta$SHF (W m$^{-2}$)</td>
<td>-5 (-10%)</td>
<td>-34 (-10%)</td>
<td>-1 (0%)</td>
<td>-5 (-7%)</td>
<td>26 (26%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space-only correction—P1 equal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T$ (K)</td>
<td>0.9</td>
<td>0.8</td>
<td>0.4</td>
<td>1.9</td>
<td>0</td>
</tr>
<tr>
<td>SHF (W m$^{-2}$)</td>
<td>123</td>
<td>412</td>
<td>129</td>
<td>128</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta$SHF (W m$^{-2}$)</td>
<td>74 (151%)</td>
<td>81 (24%)</td>
<td>8 (7%)</td>
<td>53 (71%)</td>
<td>-1 (1%)</td>
</tr>
<tr>
<td>Space-only correction—P2 equal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHF (W m$^{-2}$)</td>
<td>124</td>
<td>414</td>
<td>129</td>
<td>128</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta$SHF (W m$^{-2}$)</td>
<td>75 (153%)</td>
<td>83 (25%)</td>
<td>8 (7%)</td>
<td>53 (71%)</td>
<td>-1 (1%)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space-adiabatic correction—P1 equal</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>$\Delta T$ (K)</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
<td>1.8</td>
<td>0</td>
</tr>
<tr>
<td>SHF (W m$^{-2}$)</td>
<td>111</td>
<td>371</td>
<td>128</td>
<td>120</td>
<td>11</td>
</tr>
<tr>
<td>$\Delta$SHF (W m$^{-2}$)</td>
<td>62 (126%)</td>
<td>40 (12%)</td>
<td>7 (6%)</td>
<td>45 (60%)</td>
<td>12 (12%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final correction—P1 equal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHF (W m$^{-2}$)</td>
<td>232</td>
<td>472</td>
<td>185</td>
<td>385</td>
<td>12</td>
</tr>
<tr>
<td>$\Delta$SHF (W m$^{-2}$)</td>
<td>183 (373%)</td>
<td>141 (43%)</td>
<td>64 (53%)</td>
<td>310 (413%)</td>
<td>13 (13%)</td>
</tr>
</tbody>
</table>
Perhaps the most important result from the space-only corrections described above is the similarity of both the P1 and P2 space-only fluxes, showing the robustness of this methodology. Each perspective is a different approach to an equally scientifically viable method, which should, and does, provide similar answers. For the P1 and P2 equal scenarios, the space-only fluxes vary by at most 2 W m\(^{-2}\), which is well within the uncertainty of the fluxes because of observational uncertainty (see below). Because of this, the remaining discussion in the text assessing individual corrections (such as the space-adiabatic correction and incorporating the HC and LHC below flight level) will only include a discussion of the P1 estimates. The final range of fluxes given at the end of this study, however, will include both the P1 and P2 estimates.

The space-adiabatic correction incorporates both the space-only and adiabatic corrections and uses the terms that impact each individual correction to adjust the uncorrected flux. The relative strengths of each correction term will determine how much the uncorrected flux is adjusted. Over all flight legs but leg 2 on 25 September, the space-only correction is larger than the adiabatic correction, indicating that the non-Lagrangian term is more important than the adiabatic term on these flight legs for correcting the fluxes. The space-adiabatic correction terms for both the P1 and P2 equal scenarios are nearly identical, with the P1 equal scenario ranging from 7 to 62 W m\(^{-2}\) and the P2 equal scenario ranging from 7 to 63 W m\(^{-2}\). For both scenarios, the largest correction term is on 18 September and the smallest on leg 2 on 23 September. The largest and smallest impacts on the uncorrected flux occurred on these days at 126%–129% and 6%, respectively.

The final corrected fluxes, which include the space-only, adiabatic, and HC below flight-level corrections, range from 12 to 472 W m\(^{-2}\) (Table 1). Incorporating the ABL HC below the flight level has a large impact on the fluxes for most of the flight legs. The largest impacts are on leg 1 on 25 and 18 September, where this correction changes the uncorrected flux by 413% and 373%, respectively. This is a ~350% and ~250% change, respectively from the space-adiabatic correction (Table 1). These large corrections from incorporating the HC below flight level are because the depth of the ABL below the flight level (160 and 237 m, respectively) is a large percentage of the total ABL depth (236 and 457 m, respectively) (Table 1). The ABL depth is also small on leg 1 on 25 September (250 m), but the changes in the atmospheric variables between the two profiles are comparatively smaller, and so the addition of the HC from below flight level does not have as large of an impact.

c. Latent heat fluxes

Similar to the SHF, the estimates of the LHF are influenced by the specific humidity difference between the two profiles, the depth of the ABL, and the amount of time it takes the air parcel to travel between profiles (which is influenced by the wind speed) (Table 2). A
larger specific humidity difference indicates a larger amount of moisture being added to the air parcel as it moves downstream, which will lead to a larger increase in the amount of LHC in the column and thus larger LHF. The uncorrected LHF estimates range from 11 to 98 W m\(^{-2}\) for each of the five flight legs, with the largest flux occurring on leg 2 on 25 September, and the smallest on leg 1 on 25 September (Table 2). The largest difference in specific humidity between concurrent profiles occurs in leg 2 on 25 September, with the smallest occurring on 18 September (Table 2). The difference in LHF between 18 September and leg 1 on 25 September is only 8 W m\(^{-2}\), with the smaller ABL depth on 25 September leading to a smaller flux despite a slightly higher wind speed and specific humidity difference.

The space-only LHF correction depends on two main factors: the specific humidity gradient downwind (\(\Delta q/\Delta x\)), and \(\Delta x\) (see the space perspectives section in section 3c), where the product of these terms given by \(q_{\text{corr}}\) [Eq. (14)] determines whether this correction will increase (positive \(q_{\text{corr}}\)) or decrease (negative \(q_{\text{corr}}\)) the uncorrected LHF. The space-only LHF corrections for the P1 equal scenario range from \(-47\) to \(27\) W m\(^{-2}\), with the largest flux correction on 18 September and the smallest on leg 2 on 25 September (Table 2). The smallest magnitude flux correction, 4 W m\(^{-2}\), occurred on leg 2 on 23 September. The space-only correction also had the largest relative impact on 18 September, when the space-only correction adjusted the uncorrected LHF by 142% compared to only 6% on leg 2 on 23 September, which had the smallest relative impact. Four of the five flights showed a positive \(q_{\text{corr}}\) value, leading to an increase in the uncorrected flux (Table 2). Leg 2 on 25 September had the only negative \(q_{\text{corr}}\) term, which led to a decrease in the uncorrected flux. The P2 equal scenario showed similar results, with the space-only correction ranging from \(-55\) to \(37\) W m\(^{-2}\). Again, the largest relative impact on the uncorrected flux (195%) occurred on 18 September, and the smallest (7%) occurred on leg 2 on 23 September. The space correction also reduced the uncorrected flux on leg 2 on 25 September.

Again, because the space-only P1 and P2 LHF are so similar, the correction incorporating the LHC below flight level is applied only to the space-only P1 corrected fluxes. These final fluxes are the best estimate of the LHF and vary from 56 to 151 W m\(^{-2}\) (Table 2). The largest correction terms come on 18 September and on leg 1 on 25 September at 416% and 409%, respectively, which is an increase of 274% and 336% from the space-only corrected fluxes. On 18 September and on leg 1 on 25 September, the depth of the ABL below the flight level (237 and 164 m, respectively) is large relative to the total depth of the ABL (457 and 250 m, respectively) and is the reason for the large correction on these flight legs.

d. Uncertainty

There are three main areas of uncertainty associated with estimating the fluxes as described above. This uncertainty comes from using time or space corrections for the non-Lagrangian nature of the UAV observations, from measurement uncertainty (instrument errors) and from the choice of ABL depth. As discussed above, the time versus space will not be considered here, but the other two uncertainties are detailed below. Since it has been shown above that the P1 and P2 equal methods provide very similar flux estimates, only the P1 equal method fluxes will be discussed below when assessing the remaining two of these uncertainties.

All instruments operate with a certain degree of uncertainty. It is important to assess how this uncertainty impacts the calculated fluxes. To do this, we randomly perturbed the UAV observations of temperature, pressure, relative humidity, and wind speed within the degree of uncertainty of each instrument. The uncertainty was based on specifications provided by each manufacturer, with accuracies of ±0.1°C for temperature [Vaisala humidity measurement module (HMM) 213], ±0.3 hPa for pressure (Vaisala PTB110), and ±3% for relative humidity (Vaisala HMM213). Because of the way the wind speed is measured, there is no manufacturer-specified uncertainty, but McGeer and Holland (1993) and Holland et al. (1992) found Aerosonde to have a wind speed accuracy within ±1 m s\(^{-1}\). Koer et al. (2011) found the UAV (not an Aerosonde) in their study to be accurate to within ±0.7 m s\(^{-1}\). A value of ±1 m s\(^{-1}\) was used in our assessment of instrument uncertainty.

Five combinations of perturbations of the measured atmospheric variables were tested. The first involved perturbing all four variables within each instrument’s degree of uncertainty. This most closely follows reality when the UAV collects measurements. The remaining four combinations involved only perturbing one of the atmospheric variables at a time while leaving the remaining three unchanged (i.e., as measured by the UAV). Testing these individual perturbations allows an examination of the sensitivity of each measurement on the calculated flux. Each flux was calculated 500 times using random perturbations, and an average flux and standard deviation across all trials was found. This average flux and standard deviation were then compared to the unperturbed SHF and LHF to determine the uncertainty.

Table 3 shows values of the SHF and LHF for all flight legs for each of the five instrument uncertainty combinations. The average fluxes for the uncertainty calculations show that for all combinations, both the SHF and LHF do not vary by more than 2 W m\(^{-2}\) from the final
best estimate flux values. Most flight days had a standard deviation within 5–15 W m\(^{-2}\) for the SHF and less than 5 W m\(^{-2}\) for the LHF. On 18 September, the standard deviation was over 30 W m\(^{-2}\) for the SHF and this was primarily due to sensitivity to the imposed pressure errors on this leg. The standard deviations also show that the perturbed SHF is least sensitive to changes in relative humidity, and generally most sensitive to changes in temperature and pressure, which is consistent with the way the flux is calculated. The LHF is most sensitive to changes in relative humidity, which is also consistent with how this flux is estimated.

Because the fluxes are sensitive to the selection of ABL depth, it is important to assess the uncertainty in the fluxes due to different ABL heights by choosing other scientifically reasonable heights to calculate the fluxes. Changes in the fluxes when changing the ABL depth will result from two effects—the positive or negative change in the heat (moisture) content due to increasing or decreasing the mass of air being warmed (moistened) as the ABL depth changes and changes in the atmospheric conditions within that ABL depth, which will alter the heat and moisture content. For example, a deeper ABL with the same atmospheric conditions will give a larger flux because of the greater atmospheric mass and thus heat and moisture content within the layer. If the change in ABL depth alters the atmospheric conditions within the layer, then the flux will increase or decrease depending on whether the change in the atmospheric variables increases or decreases the temperature (moisture) difference between pairs of profiles. The individual sensitivity of each effect to the final flux estimation will vary for each case. Alternative selections for the ABL depth outlined in section 4a and the impact of changing the height of the ABL on the best estimates of the SHF and LHF (space adiabatic and space only) are assessed below.

On 18 September (Fig. 4), the top of the ABL could be 625 m. Above this point, the potential temperatures in both the upstream (profile 3) and downstream (profile 4) profiles are very similar, whereas below this level the upstream profile is generally colder than the downstream. This layer is unlikely to be the top of the ABL because of the distinctness of the dry-adiabatic layer below, but an assessment of this ABL height can still be made. The increase in the depth of the ABL from 457 to 625 m yields an SHF of 212 W m\(^{-2}\) and an LHF of 82 W m\(^{-2}\). This decreases

<table>
<thead>
<tr>
<th>Best estimate SHF</th>
<th>Sensible heat flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Sep leg 3</td>
<td>232</td>
</tr>
<tr>
<td>23 Sep leg 1</td>
<td>472</td>
</tr>
<tr>
<td>23 Sep leg 2</td>
<td>185</td>
</tr>
<tr>
<td>25 Sep leg 1</td>
<td>385</td>
</tr>
<tr>
<td>25 Sep leg 2</td>
<td>12</td>
</tr>
<tr>
<td>SHF (all)</td>
<td>230 ± 33</td>
</tr>
<tr>
<td>SHF (T only)</td>
<td>232 ± 10</td>
</tr>
<tr>
<td>SHF (p only)</td>
<td>234 ± 32</td>
</tr>
<tr>
<td>SHF (RH only)</td>
<td>232 ± 0</td>
</tr>
<tr>
<td>SHF (WS only)</td>
<td>232 ± 0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Best estimate LHF</th>
<th>Latent heat flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Sep leg 3</td>
<td>98 ± 5</td>
</tr>
<tr>
<td>23 Sep leg 1</td>
<td>151</td>
</tr>
<tr>
<td>23 Sep leg 2</td>
<td>100</td>
</tr>
<tr>
<td>25 Sep leg 1</td>
<td>56</td>
</tr>
<tr>
<td>25 Sep leg 2</td>
<td>130</td>
</tr>
<tr>
<td>LHF (all)</td>
<td>98 ± 0.6</td>
</tr>
<tr>
<td>LHF (T only)</td>
<td>98 ± 0.3</td>
</tr>
<tr>
<td>LHF (p only)</td>
<td>98 ± 5</td>
</tr>
<tr>
<td>LHF (RH only)</td>
<td>98 ± 0.3</td>
</tr>
<tr>
<td>LHF (WS only)</td>
<td>98 ± 0.3</td>
</tr>
</tbody>
</table>

On leg 1 on 23 September, it is possible to consider an ABL top of approximately 280 m (Fig. 5). Below this level is the presence of a mixed layer, with a capping inversion at the top of this layer. Calculating the flux with an ABL top of 280 m on this day yields an SHF of 337 W m\(^{-2}\) and an LHF of 82 W m\(^{-2}\). This decreases
the fluxes by 135 and 69 W m$^{-2}$ (−29% and −46%), respectively. Despite an increase in the temperature difference, wind speed, and specific humidity difference, the SHF and LHF still decrease, which is solely due to a decrease in the ABL top. This ABL height was not chosen over the 720-m level because there is a warming between 280 and 720 m that is unexplained if we assume the ABL top is at 280 m.

For leg 2 on 23 September, an ABL height of 500 m could be chosen as the level above which the downstream profile becomes colder than the upstream profile (Fig. 6). This could indicate that surface processes are no longer controlling the atmosphere at this point because the atmosphere should continue warming throughout the ABL. The clear well-mixed layer on this flight leg, however, yields the 540-m level to be the appropriate ABL height rather than at 500 m. When the SHF and LHF are calculated using 500 m as an ABL top, the fluxes become 207 and 93 W m$^{-2}$, respectively, increasing the SHF by 22 W m$^{-2}$ and decreasing the LHF by 7 W m$^{-2}$ (12% and −7%, respectively). The wind speed change was negligible, but the temperature difference increased by 0.1 K, while the specific humidity difference decreased very slightly. Because there was only a 40-m difference in ABL height between the two cases, the fluxes were most sensitive to the changes in atmospheric conditions on this flight leg.

For legs 1 and 2 on 25 September, no other scientifically reasonable values could be chosen for the ABL height outside of that selected for this study (Figs. 7–8). On leg 1, the location of both an inversion and where the two profiles exhibit similar characteristics is at 240 m.

The areas of uncertainty described above aid our understanding of the accuracy of the SHF and LHF estimated as part of this work. Final estimates of the fluxes for the UAV flights in September 2009 with error bars based on the uncertainty assessment described above are provided in Table 4. The values in Table 4 include the uncertainty from both the P1 and P2 space corrections (see section 4b).

<table>
<thead>
<tr>
<th>Date</th>
<th>SHF (W m$^{-2}$)</th>
<th>LHF (W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Sep leg 3</td>
<td>209–231 ±33</td>
<td>98–112 ±5</td>
</tr>
<tr>
<td>23 Sep leg 1</td>
<td>472–485 ±13</td>
<td>151–152 ±4</td>
</tr>
<tr>
<td>23 Sep leg 2</td>
<td>176–185 ±11</td>
<td>100–101 ±4</td>
</tr>
<tr>
<td>25 Sep leg 1</td>
<td>370–385 ±6</td>
<td>56–58 ±2</td>
</tr>
<tr>
<td>25 Sep leg 2</td>
<td>12–30 ±6</td>
<td>117–130 ±3</td>
</tr>
</tbody>
</table>

One of the main goals of this work is to highlight sensitivities in the UAV observations that are important to the methodology used in estimating the fluxes. This will enable future field campaigns to better design and implement measurement collection. The methodology discussed here requires a few key measurements to accurately estimate the SHF and LHF. First, accurate...
collection of profile data within and higher than the atmospheric ABL is critical. Second, the data need to be corrected considering adiabatic (for SHF) and non-Lagrangian processes (for both SHF and LHF), as well as for the HC and LHC below flight level, and this work has shown that it is imperative to acquire accurate measurements of the atmospheric variables included in these calculations. To minimize the correction due to the unsampled HC and LHC below flight level, ensuring flight data as close to the surface as possible is necessary. Missing from this study were appropriate measurements of changes in the atmosphere over time, such as from a nearby AWS or from the UAV data itself, which will be included in future field campaigns.

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REFERENCES


