Alexander Tall Tower! A Study of the Boundary Layer on the Ross Ice Shelf, Antarctica

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ABSTRACT

Because of the harsh weather conditions on the Antarctic continent, year-round observations of the low-level boundary layer must be obtained via automated data acquisition systems. Alexander Tall Tower! is an automatic weather station on the Ross Ice Shelf in Antarctica and has been operational since February 2011. At 30 m tall, this station has six levels of instruments to collect environmental data, including temperature, wind speed and direction, relative humidity, and pressure. Data are collected at 30-, 15-, 7.5-, 4-, 2-, and 1-m levels above the snow surface. This study identifies short-term trends and provides an improved description of the lowest portion of the boundary layer over this portion of the Ross Ice Shelf for the February 2011–January 2014 period. Observations indicate two separate initiations of the winter season occur annually, caused by synoptic-scale anomalies. Sensible and latent heat flux estimates are computed using Monin–Obukhov similarity theory and vertical profiles of potential air temperature and wind speed. Over the three years, the monthly mean sensible heat flux ranges between 1 and 39 W m$^{-2}$ (toward the surface) and the monthly mean latent heat flux ranges between $-8$ and 0 W m$^{-2}$. Net heat fluxes directed toward the surface occur most of the year, indicating an atmospheric sink of energy.

1. Introduction

Studying the Antarctic atmosphere is difficult because of its challenging climate and sparse observational network, with the lowest near-surface meteorological observation density of any other region. The Antarctic Meteorological Research Center (AMRC) at the University of Wisconsin–Madison has installed dozens of automatic weather stations (AWS) over the past few decades, most of which are nominally 3 m tall (Lazzara et al. 2012b). Most recently, Costanza et al. (2016) studied the climatology of the Ross Ice Shelf using more than a dozen of these stations. Over the past few decades, more stations and better technology have filled in some of the gaps in the Antarctic observational record.

In February 2011, AMRC installed Alexander Tall Tower! (ATT), a 30-m-tall AWS located on the Ross Ice Shelf at 79.023°S, 170.699°E (see Fig. 1). The surface elevation at the tower site is 55 m. There are six observational levels over the 30-m height of the tower that...
FIG. 1. (a) Map showing the location and (b) photograph of ATT on the Ross Ice Shelf in West Antarctica. Both images can be found online (http://amrc.ssec.wisc.edu).
allow for analysis of the lower portion of the boundary layer in this region. Table 1 describes the location of the sensors on the tower, and Fig. 2 illustrates this in schematic form. In total, there are six temperature sensors, four aerovanes, two wind anemometers, two relative humidity sensors, a net shortwave and net longwave radiation sensor, a pressure sensor, and an acoustic depth gauge (to measure snow depth). The heights of each tower level listed in Table 1 are approximate, as snow accumulation and drift can slightly affect these; however, efforts are made to restore these heights when the site is visited every year or two. These approximate heights above ground level (AGL) are used in all computations and figures in this study. The average height of each level over this period of study is slightly different as a result of snow accumulation: levels 1–4 were 0.25 m lower, level 5 was 0.17 m lower, and level 6 was 0.15 m lower. Having multiple levels of observation allows for computation of the sensible and latent heat fluxes. A biannual winter phenomenon is identified in these monthly means, similar to work done by Costanza et al. (2016) using AWS data on the Ross Ice Shelf and Lazzara et al. (2012a) using Amundsen–Scott South Pole Station data. Temperature and pressure data from the West Antarctic Ice Sheet display this interannual variability as well, indicating that it may not be a local phenomenon (Reusch and Alley 2004). Section 2 details the findings of previous studies that have calculated turbulent heat fluxes in the Antarctic. Section 3 describes the data from the tower. Section 4 explains the method for computing heat flux estimates. Section 5 presents the results of monthly averaging and heat flux estimates, and discusses the apparent second initiation of winter earlier in the year. Last, section 6 contains concluding remarks.

### Table 1. List of observations, the approximate height (m) of each level above the snow surface, instruments, and the manufacturer’s stated accuracy of the instruments. See Fig. 2 for a visual representation of this table. Numbers in parentheses in the approximate heights column are the average height of the instrument over the period studied, February 2011–January 2014.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Approx heights (m)</th>
<th>Level</th>
<th>Instrument</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>30 (29.75)</td>
<td>1</td>
<td>R. M. Young platinum resistance temperature</td>
<td>±0.3°C</td>
</tr>
<tr>
<td></td>
<td>15 (14.75)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.5 (7.25)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 (3.75)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 (1.83)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 (0.85)</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>30 (29.75)</td>
<td>1</td>
<td>R. M. Young aerovane</td>
<td>±0.3 m s&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wind speed only</td>
<td>2 (1.34)</td>
<td>5</td>
<td>R. M. Young Wind Sentry cup anemometer</td>
<td>±0.5 m s&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>30 (29.75)</td>
<td>1</td>
<td>Vaisala HMP45C-L humidity</td>
<td>±2% (0%–90%)</td>
</tr>
<tr>
<td></td>
<td>7.5 (7.25)</td>
<td>3</td>
<td>Paroscientific model 215 A pressure sensor</td>
<td>±3% (90%–100%)</td>
</tr>
<tr>
<td>Pressure</td>
<td>3 (2.3)</td>
<td>—</td>
<td>Campbell Scientific acoustic depth gauge</td>
<td>±0.05 hPa</td>
</tr>
<tr>
<td>Snow depth</td>
<td>4 (3.2)</td>
<td>Just below level 4</td>
<td>Campbell Scientific acoustic depth gauge</td>
<td>±1 cm or 0.4% of distance to target (whichever is greatest)</td>
</tr>
<tr>
<td>Net shortwave and longwave radiation</td>
<td>30 (29.75)</td>
<td>1</td>
<td>Kipp and Zonen CNR2-L net longwave and shortwave radiation</td>
<td>&lt;10% (in daily totals)</td>
</tr>
</tbody>
</table>

2. Background

Computing turbulent heat fluxes with similarity theory has been used in several different regions of Antarctica. These fluxes, while not large in magnitude, can vary based on local environmental conditions, such as specific wind regimes (high plateau vs proximity to the coast). Near-surface measurements across ice shelves, however, are relatively unvarying as a result of the flatness and uniformity of the surface. Consequently, turbulent heat flux estimates would not vary much.
across the ice shelf either. However, this homogeneity does not necessarily mean that these flux estimates can be ascribed to larger surrounding regions, as wind speeds greatly affect these estimates and change across the ice shelf.

Halley is a research station on the Brunt Ice Shelf of Antarctica, where multiple studies have estimated turbulent fluxes. King (1990) used field campaign measurements from Halley and determined that above 5 m, the temperature and wind profiles cannot be described by similarity theory. Cassano et al. (2001) used tower measurements (and direct eddy covariance calculations) to calculate the fluxes at Halley and compared those with seven model surface layer parameterizations (based on Monin–Obukhov similarity theory). Their results showed that models tend to underestimate the magnitude of the downward sensible heat flux, contrasting the results of even earlier studies by King and Connolley (1997) and Hines et al. (1999).

Van As et al. (2005a) used field campaign measurements to quantify the diurnal cycle of turbulent heat fluxes at Kohnen station in Dronning Maud Land, located on the East Antarctic plateau 500 km from the coast. Other studies in Dronning Maud Land specifically attempt to identify differences in turbulent heat fluxes caused by environmental conditions. van den Broeke et al. (2005) calculated sensible heat flux estimates over a 4-yr period for four AWS in Dronning Maud Land, Antarctica, including two in the katabatic wind zone (one coastal, one inland). The sensible heat flux was found to be highest in katabatic wind zones, especially under clear-sky conditions. A follow-up study by van den Broeke et al. (2006) calculated the diurnal cycle of both sensible and latent heat fluxes at the same four sites during the austral summer and identified a nighttime supply of heat to the surface from the sensible heat flux and a daytime loss of heat from the surface as a result of sublimation (latent heat flux). In the katabatic wind zones, the nocturnal sensible heat flux was enhanced and nighttime radiative heat loss was greatest at the interior AWS (van den Broeke et al. 2004; van den Broeke et al. 2006).

Stearns and Weidner (1993) used the AMRC AWS network to compute monthly mean sensible and latent heat flux estimates. Several stations from different Antarctic regions were studied, including at a site on the Ross Ice Shelf where ATT is located. The monthly mean sensible heat flux estimates were less negative (from atmosphere to surface, the opposite convention used in this study) closer to the Transantarctic Mountains, though the latent heat flux estimates appeared unaffected by this proximity (Stearns and Weidner 1993). Pavolonis et al. (2004) later used these heat flux estimates as validation.
for a satellite product. The results in the current study are computed using the same methodology as Stearns and Weidner (1993), which makes use of Monin and Obukhov (1954) similarity theory as well as wind speed and temperature profiles as described in Lettau (1979). Sensible and latent heat fluxes are nonnegligible when determining net energy flux in Antarctica. To estimate the surface energy budget, the net shortwave and longwave radiation are also required. Data from the radiometer (on level 1) indicated that the sensor might have tilted as a result of snow accumulation, and thus they could not be utilized in this climatology, so the results below discuss only the turbulent flux contributions to the surface energy budget. Estimates of the latent and sensible heat fluxes are made at the tower site using observations from levels 3, 4, and 6.

3. Data

The instruments at ATT record measurements every 10 s. The data used in this study are from a memory card collected from the tower in January 2014. A few studies have been published using this same data in different manners (Cassano et al. 2016; Wille et al. 2016; Nigro et al. 2017). The raw measurements were processed according to the World Meteorological Organization (WMO) standards of averaging data over time intervals to reduce uncertainties in instantaneous data (WMO 2012). Temperature, relative humidity, and pressure are averaged over a 1-min period, and the wind speed and wind direction are averaged over a 2-min period. The wind speed and direction averages in this study are result values. For example, the temperature measurement for 0000 UTC is taken as the mean of data from 2359:10 to 0000:00 UTC, and the wind speed measurement is the resultant of wind speeds from 2358:10 to 0000:00 UTC. This was done at 10-min intervals, which were then quality controlled following procedures outlined in Lazzara et al. (2012b). Data greater than 3 standard deviations from the mean are flagged using a computer program, and data are manually removed when thought to be unrealistic. The relative humidity data presented are with respect to water, the WMO (2012) standard for automatic weather stations. All data presented in the following sections are monthly means from February 2011 to January 2014. Quality-controlled instantaneous scalar wind data were provided by the University of Colorado Boulder. The quality control (QC) was performed for the first two years of available data, February 2011–January 2013, at 10-min intervals. This is compared with the quality-controlled resultant wind in section 5.

An example of the quality-controlled averaged data (available at ftp://amrc.ssec.wisc.edu/pub/aws/iridium/AlexanderTallTower) is presented in Fig. 3. These quality-controlled plotted data are from the period 20–22 September 2011, which is when the lowest four levels of the tower observed the lowest temperatures, including the lowest observed temperature over the 3-yr period (see Table 1). Figure 3a shows how the temperature (°C) at each level varies throughout the month. Figure 3b displays the wind speeds (m s⁻¹). In each figure, the black dotted line marks the time at which the temperature was lowest. The high resolution of these data can be used to study weather events, and the multilevel instrumentation can describe the boundary layer quite well. For example, higher wind speeds in the early hours on 21 September are paired with relatively uniform temperatures in the vertical profile as a result of mixing. When the temperature drops very low, however, there is a larger spread among the many layers, with the lowest temperature being the closest observation to the surface. These lower, spread-out temperatures occurred during lower wind speeds, indicating a less well-mixed boundary layer. These vertical profiles allow the following turbulent heat flux estimates to be computed. An exhaustive analysis of the diurnal cycle using ATT data was performed in Cassano et al. (2016).

4. Methods

To illustrate the advantage of a multilevel tower and to bolster the information gained from several observations per level, the turbulent heat fluxes are computed. Estimating the sensible and latent heat fluxes using similarity theory requires many instruments on ATT. King (1990) found that the surface layer at Halley (on the Brunt Ice Shelf) could be as shallow as 5 m AGL, and thus similarity theory no longer applies to wind and temperature profiles above this height. Surface flux estimates are made using levels 3, 4, and 6 (7.5, 4, and 1 m, respectively) on the tower. The level-3 (or 7.5 m) relative humidity sensor is used with the level-4 temperature and wind sensors to compute the latent heat flux. Level 3 has the lowest (height) relative humidity sensor, level 4 has the lowest wind anemometer, and level 6 is the closest temperature reading to the surface. Using these data reduces the error of surface temperature estimates when using a temperature profile.

a. Profiles for wind speed and temperature

The temperature and wind speed profiles are found using the Monin–Obukhov (Monin and Obukhov 1954) nondimensional height. A more in-depth description of these computed profiles and the stability functions can be found in Lettau (1979). The stability functions from Lettau (1979) were primarily chosen to replicate the work in Stearns and Weidner (1993). There are other vertical profiles that are valid for use in Antarctica and were compared at Dome C, Antarctica, in Vignon et al. (2017).
Vignon et al. (2017) found the Lettau (1979) profiles did not markedly underestimate the stability function for $\theta$. The turbulent scales of wind speed (or friction velocity $u^*$) and temperature $\theta^*$ are approximated using the bulk method.

The horizontal wind speed profile is

$$u(z) = \frac{u^* \left[ \ln \left( \frac{z}{z_0} \right) - \psi(z) \right]}{k},$$

where $u(z)$ is the horizontal wind speed at 4 m, $z$ is 4 m, $z_0$ is the surface roughness, $u^*$ is the turbulent scale of wind speed, $k$ is the von Kármán constant (0.4), and $\psi(z)$ is the wind profile departure from logarithmic. The surface roughness may vary regionally as a result of snow mass transport and wind speeds (Amory et al. 2015). In Stearns and Weidner (1993), $z_0$ was assumed to be 0.5 mm for the entire network of stations. Van den Broeke et al. (2005) determined surface roughness to be approximately 0.16 mm in a katabatic wind zone as a result of stronger sublimation in the summer and small sastrugi. The Ross Ice Shelf area around ATT is a katabatic-driven wind zone (Bromwich 1989a,b; Bromwich et al. 1992; Parish et al. 2006; Nigro and Cassano 2014) with sastrugi, and thus these estimates

![Figure 3](https://example.com/figure3.png)

**FIG. 3.** Example of the available quality-controlled (a) temperature and (b) wind speed data from AMRC every 10 min. The minimum temperature over the 3-yr period occurred on 21 Sept 2011 at 1 m AGL (vertical black line).
use a constant surface roughness of $z_0 = 0.16 \text{ mm}$, consistent with the value used by van den Broeke et al. (2005).

The temperature profile is

$$\theta(z) - \theta(z_0) = -\frac{\theta^* \ln(z/z_0) - \Psi(z)}{k},$$

(2)

where $\theta(z)$ is the potential air temperature at 4 m, $\theta(z_0)$ is the potential air temperature at the surface, $\Psi(z)$ is the temperature profile departure from logarithmic, and the turbulent scale of potential temperature is

$$\theta^* = \frac{Q_0}{\rho C_p u^*}.$$

(3)

Term $Q_0$ is the sensible heat flux to air, $\rho$ is the air density (found using the ideal gas law and the observed pressure, relative humidity, and temperature), and $C_p$ is the specific heat of air at constant pressure (taken to be $1004.67 \text{ J kg}^{-1} \text{C}^{-1}$).

b. Sensible heat flux estimates

First, the equation for the wind profile is rearranged to solve for $u^*$, giving

$$u^* = \frac{u(z)k}{\ln(z/z_0) - \psi(z)},$$

(4)

and it is solved initially with $\psi(z)$ equal to zero. The height $z = 4 \text{ m}$ because that is the height at which the wind speeds are measured. We then solve for the sensible heat flux $Q_0$ by combining Eqs. (2) and (3) to give

$$Q_0 = \frac{\rho C_p u^* k [T(z_2) - T(z_1)]}{\ln(z_2/z_1) - \Psi(z_2) + \Psi(z_1)},$$

(5)

where $z_2$ and $z_1$ are levels 4 and 6 (4 and 1 m, respectively). As in Stearns and Weidner (1993), we replace the potential temperature difference with the air temperature difference. For the first iteration of calculating $Q_0$, $\Psi(z_2) = \Psi(z_1) = 0$.

After computing the first values for $u^*$ and $Q_0$, the Monin and Obukhov (1954) nondimensional height $\zeta$ is computed. This is done at both levels to find the temperature profile departures from logarithmic at each level, to be used in Eq. (5), where

$$\zeta = \frac{-g k z Q_0}{\rho C_p T_0 u^* k^3}.$$  

(6)

The surface temperature $T_0$ is found with Eq. (2) by substituting $T$ in for $\theta$ and solving for $T_0$. In this study, we use the level-6 (1 m) temperature to solve for the surface temperature.

Then, the departures from logarithmic are calculated (where $z = \text{level 4} = 4 \text{ m}$). To remain consistent with Stearns and Weidner (1993), the stability functions from Lettau (1979) are used. If $\zeta < 0$, then the stability functions are

$$\phi_h = (1 - 22.5 \zeta)^{-1/3}$$

(7)

for $\theta$ and

$$\phi_u = (1 - 15 \zeta)^{-1/4}$$

(8)

for momentum. If $\zeta > 0$, then

$$\phi_h = (1 + 5 \zeta)^{1/2}$$

(9)

and

$$\phi_a = (1 + 5 \zeta)^{3/4}$$

(10)

(Letttau 1979). Once the departures from logarithmic for both temperature profiles and the wind profile (computed from the 4-m level only) have been computed, the second iteration of $u^*$ is computed and then $Q_0$ can be computed. New values of $Q_0$ are calculated iteratively until there is less than a 0.01 W m$^{-2}$ difference between two successive values of $Q_0$. On average, only one or two iterations is required, and the maximum number of iterations done is 7.

If the surface temperature is computed [using Eq. (2), described above] to be above freezing, then the heat flux is rejected based on the assumption that a snow-covered surface will not be above freezing (Stearns and Weidner 1993). Values of $Q_0$ are positive when the flux is downward from the atmosphere to the surface.

c. Latent heat flux estimates

Using the calculated $u^*$ and surface temperature $[\theta(z_0)]$, the saturation vapor pressure is estimated for both the surface and level 4 (4 m) using

$$e_s = \frac{611.2 \times \exp \left[ \frac{17.67 \theta(z_0)}{243.5 + \theta(z_0)} \right]}$$

(11)

Next, the vapor pressure at level 3 is computed as the product of the measured relative humidity at level 3 and the computed saturated vapor pressure. In other words, the relative humidity at level 3 is assumed to be the same as observed at level 4, and is used in these calculations. It is assumed that the near-surface air is saturated, and thus the surface vapor pressure is set equal to the surface saturation vapor pressure. Using the pressure measurements, the specific humidity is estimated at both the surface and level 4:

$$q = \varepsilon e / \rho,$$

(12)

where $\varepsilon = 0.622$. Finally, the latent heat flux is estimated using
Maximum and minimum temperatures, wind speeds, and pressure over the 3 yr as well as the month in which these measurements were taken. Level 1 is the top of the tower (30 m). Minimum wind speed is not reported, as it is 0.0 m s$^{-1}$ during calm conditions. Maximum temperature, wind speed, and minimum temperature observed across all levels are highlighted in boldface type.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature 1</td>
<td>1.4°C (2130 UTC 27 Dec 2012)</td>
<td>−54.0°C (0940 UTC 12 Aug 2012)</td>
</tr>
<tr>
<td>Temperature 2</td>
<td>−0.1°C (0330, 0520 UTC 26 Dec 2011)</td>
<td>−54.3°C (1000, 1050, 1100 UTC 12 Aug 2012)</td>
</tr>
<tr>
<td>Temperature 3</td>
<td>−0.1°C (0330 UTC 26 Dec 2011)</td>
<td>−55.1°C (1520 UTC 21 Sep 2011)</td>
</tr>
<tr>
<td>Temperature 4</td>
<td>0.0°C (0330 UTC 26 Dec 2011)</td>
<td>−55.7°C (1500 UTC 21 Sep 2011)</td>
</tr>
<tr>
<td>Temperature 5</td>
<td>0.8°C (2300 UTC 27 Dec 2013, 0630 UTC 31 Dec 2013)</td>
<td>−56.4°C (1510 UTC 21 Sep 2011)</td>
</tr>
<tr>
<td>Temperature 6</td>
<td>0.2°C (0330 UTC 27 Dec 2011)</td>
<td>−57.3°C (1430 UTC 21 Sep 2011)</td>
</tr>
<tr>
<td>Wind speed 1</td>
<td>29.6 m s$^{-1}$ (0330 UTC 27 Dec 2011)</td>
<td>—</td>
</tr>
<tr>
<td>Wind speed 2</td>
<td>27.5 m s$^{-1}$ (0250 UTC 9 Aug 2013)</td>
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</tr>
<tr>
<td>Wind speed 3</td>
<td>25.1 m s$^{-1}$ (0250 UTC 9 Aug 2013)</td>
<td>—</td>
</tr>
<tr>
<td>Wind speed 4</td>
<td>23.1 m s$^{-1}$ (0250 UTC 9 Aug 2013)</td>
<td>—</td>
</tr>
<tr>
<td>Pressure</td>
<td>1020.3 hPa (1630, 1640 UTC 2 Aug 2011)</td>
<td>945.8 hPa (0940, 0950, 1000 UTC 23 Aug 2011)</td>
</tr>
</tbody>
</table>

5. Results and discussion

The three years of meteorological data from Alexander Tall Tower! provide a picture of local conditions and add to the surrounding network of automatic weather station data. The monthly mean of measured temperature, relative humidity, resultant and scalar wind speeds, and pressure are displayed and discussed. Additionally, the absolute humidity is computed and presented as a monthly mean. Last, the sensible and latent heat flux estimates are also presented as monthly means.

a. Temperature

Maximum and minimum measurements over the 3-yr period are listed in Table 2. Figure 4a shows the mean monthly temperatures measured at the tower for the 2011–14 period. The maximum temperature is almost always below freezing, with the most notable exception being the maximum temperature observed at the top level on 27 December 2012 (1.4°C). The minimum temperature recorded was −57.3°C at 1430 UTC 21 September 2011, at level 6, the lowest level of the tower. The maximum temperatures all occur in December, while the minimum temperatures occur during August or September. In the monthly mean there is a persistent inversion year-round (Fig. 4a) as a result of net radiative heat loss, which is characteristic of the Antarctic. Cassano et al. (2016), using ATT data from February 2011 to January 2013, found inversions over the depth of the 30-m tower that exceeded 25°C. The reduced range of temperatures over the depth of the tower during the austral summer, seen in Fig. 4a, is due to decreased net radiative heat loss (more insolation), which weakens the inversion (Phillpot and Zillman 1970), while the winter months have a greater range of temperatures as a result of greater radiative loss at this time of year.

During the month of May, there is an increase in monthly mean temperature, which is evident in the minute-averaged data as well. Figure 4b illustrates the monthly mean temperature at level 1 (30 m) for each year. The monthly means in May do not vary from the 3-yr mean much, although the 2011 winter is seemingly more muted. This phenomenon in May can be attributed to the circumpolar trough being closer to the pole during the autumn months, which slows or reverses the progression of the winter season (van Loon 1967; van den Broeke 2000). The break in the winter season as a result of this circulation anomaly is also apparent in wind speeds and pressure. Lazzara et al. (2012a) and Costanza et al. (2016) referred to the two decreases of temperature (seen in April and June surrounding the May temperature increase) as two separate winter seasons. Here, it is referred to as two winter regimes.

b. Humidity

Monthly mean relative humidity measured at levels 1 and 3 are plotted in Fig. 5a. Monthly mean absolute humidity is plotted in Fig. 5b. On average, relative humidity is always higher at lower heights on the tower, where the temperatures are lower. Relative humidity is highest in the austral summer and lowest in the winter. However, it is an important caveat that the relative humidity data illustrated here and available through AMRC are measured with respect to water. There is a local
maximum in the relative humidity in May, when, thus far, there has been a local maximum in temperature and wind speeds and a local minimum in pressures for 2011 and 2012, possibly as a result of the aforementioned early winter synoptic anomaly. The absolute humidity, shown in Fig. 5b, is computed using the relative humidity, the ideal gas law, and Eq. (11). The absolute humidity is highest in the austral summer, with a local maximum in monthly averages during the month of May. The discrepancies between levels 1 and 3 are minimal, indicating that vertically atmospheric moisture content does not vary much. This is justification for using the relative humidity at level 3 (7.5 m) to compute the sensible and latent heat flux estimates.

Fig. 4. (a) Monthly mean temperatures at ATT from February 2011 to January 2014. Inversion conditions are observed year-round with the highest temperatures at 30 m. The amount of data missing or dropped during QC from each level is 4.60% (30 m), 4.55% (15 m), 4.69% (7.5 m), 4.98% (4 m), 5.18% (2 m), and 4.88% (1 m). (b) Monthly means of level-1 temperatures for each individual year.

Fig. 5. Monthly mean (a) relative humidity and (b) absolute humidity at ATT from February 2011 to January 2014. The amount of data missing or dropped during QC from each level is 4.64% (30 m) and 4.36% (7.5 m).

c. Winds

Monthly resultant wind speeds are shown in Fig. 6a and monthly scalar wind speeds in Fig. 6b. The maximum resultant wind speeds are given in Table 2. The level-5 (2 m) wind speeds were not included, as they were measured with a cup anemometer and there is no wind direction observed at that level. Figure 6a shows that the resultant wind speed over the 30-m depth of observations increases with altitude, as expected from similarity theory, and increases sharply in February and decreases sharply in December. The maximum resultant (2 min) wind speeds all occur at the same time (0250 UTC) on 9 August 2013, indicating a strong wind event that extended to at least 30 m in the boundary layer. In Fig. 6a, the maximum monthly resultant wind speeds for all four levels occur in May, which was previously noted to have an increase in
monthly averaged temperatures. Again, this indicates the pause in the winter season.

The monthly mean of the scalar wind, Fig. 6b, consists of one less year than the resultant wind data and stops in January 2013. The scalar wind appears to be consistently higher than the resultant windspeeds throughout the year, but it shows an annual trend of increased wind speeds during the austral winter and decreased wind speeds in the austral summer. The constancy, defined as the ratio of the scalar wind to the resultant wind, was computed for each level at each time step. The average constancy over the two years for each level was 83% at level 1, 84% at levels 2 and 3, and 90% at level 4. The constancy increases with decreasing altitude, indicating more directionally consistent winds at lower levels. Annually, the constancy is highest during the austral winter for all levels and lowest during the austral summer.

d. Pressure

Figure 7 shows the monthly mean pressures measured at approximately 3 m above ground. Instead of averaging all months together, as the interannual variability is large, it is plotted as a time series. The month of June exhibits a local maximum in pressure, with especially higher mean pressure in 2012 and 2013, possibly indicative of the end of the early winter pause. Both the maximum and minimum pressure were recorded in August 2011, with a pressure of 1020.3 hPa at 1630 and 1640 UTC 2 August and 945.8 hPa from 0940 to 1000 UTC 23 August, respectively. It is important to denote that these are 1-min averages of pressures and not the 10-s instantaneous values. There is a sharp increase in average pressure from May to June each year, and a sharp decrease between June and July. This same pattern marking the two winter regimes was found at South Pole Station (Lazzara et al. 2012a) and is again caused by the circumpolar trough moving toward the pole in autumn (van Loon 1967; van den Broeke 2000).

e. Heat fluxes

For the heat flux estimates, the assumptions made are similar to those made in Stearns and Weidner (1993); eddy diffusivities for momentum and moisture are assumed to be equal, and the latent heat flux is zero when the wind speed is zero. If inversion conditions cannot be determined as a result of QC removal of data from one or both levels, then the heat flux estimate is not made. When the surface temperature is computed [using Eq. (2)] to be above 0°C, this is assumed to be physically unrealistic, as a
snow surface cannot have a temperature above the melting point, and no heat flux is calculated. A positive surface temperature was computed fewer than 1600 times, which is approximately 0.977% of the data. This corresponds to 10.7 days of data removed, which was found to occur during the austral summer. When the level-4 wind speed is less than 3 m s\(^{-2}\) and the vertical air temperature difference is larger than 0°C (inversion conditions), the computation for sensible heat flux will not always converge to a solution. In this case, the sensible and latent heat fluxes are not computed, approximately 16.8% of the time. As previously reported, data from January 2013 were removed from these estimates, as there were many missing data points from the QC of data, which caused biases in the monthly mean.

### f. Sensible heat flux

The sensible heat flux estimates are plotted in Fig. 8, with positive values indicating a downward flux from the atmosphere to the surface. An annual pattern is identified with the heat flux close to 0 W m\(^{-2}\), although still downward, in the summer months (December and January) and a maximum downward flux in the winter months (June–August). This annual shape inversely matches that of the temperatures in Fig. 4a, as the lower sensible heat flux estimates during austral summer are caused by more insolation. The larger downward flux in winter is also consistent with the stronger inversion conditions seen in Fig. 4a.

The closest AWS to ATT that Stearns and Weidner (1993) computed heat flux estimates for was Schwerdtfeger, during the period 1985–90 (excluding 1987). The monthly sensible heat flux estimates at Schwerdtfeger were between −42 and −2 W m\(^{-2}\) (opposite sign convention as this study). By comparison, the ATT monthly sensible heat flux estimates were within 1 and 39 W m\(^{-2}\). The annual mean sensible heat flux estimates at ATT, for the three years of this study, are between approximately 19 and 23 W m\(^{-2}\). van den Broeke et al. (2005) calculated annual mean sensible heat fluxes in katabatic wind zones as being 22–24 W m\(^{-2}\) toward the surface. Van As et al. (2005a) found a daily mean sensible heat flux of 8 W m\(^{-2}\) (toward the surface) in Dronning Maud Land, a katabatic wind zone, in January and February 2002. These studies agree that on average in these katabatic wind zones, the sensible heat flux is toward the surface, just as was computed for ATT.

The observed inversion conditions agree with a sensible heat flux toward the surface, as the near-surface air is cooled by this flux. In January and December, where the temperatures are highest annually, the 1-min averaged sensible heat flux estimates are the smallest magnitude, which is reflected in the smaller temperature gradient during these months—the atmosphere is well mixed in these conditions. The greater-magnitude sensible heat flux estimates during nonsummer months are caused by large vertical temperature gradients and high wind speeds, which Stearns and Weidner (1993) attribute to katabatic flow from Byrd Glacier. Several satellite analyses support that katabatic flow originating from Byrd Glacier as well as Marie Byrd Land propagates through the vicinity of tall tower during nonsummer months (Bromwich 1989a,b; Bromwich et al. 1992).

### g. Latent heat flux

The latent heat flux estimates are plotted in Fig. 9, and the monthly means are much smaller in magnitude in comparison with the sensible heat flux estimates for every season other than austral summer. The annual mean latent heat flux estimates are between −2 and −4 W m\(^{-2}\). In December, the latent heat flux estimates are greatest in magnitude, like the sensible heat flux estimates at this time of year. The larger magnitude of the upward moisture flux during the austral summer increases the absolute humidity of the air, as evidenced in Fig. 5b.

Stearns and Weidner (1993) computed monthly latent heat flux estimates of between −1 and 11 W m\(^{-2}\) at Schwerdtfeger site (again, the opposite sign convention), whereas the ATT monthly latent heat flux estimates are between −8 and 0 W m\(^{-2}\). Van As et al. (2005b) computed the daily latent heat flux to range from −4 to 0 W m\(^{-2}\) during January and February 2002 in Dronning Maud Land, which is in a katabatic wind zone. There is
agreement that averaging the latent heat flux over longer periods results in sublimation over deposition. Before averaging, the maximum amplitude of the latent heat flux at Dronning Maud Land is 2 W m\(^{-2}\) (van As et al. 2005a); in this study, during the same period, the maximum amplitude is 10 W m\(^{-2}\). In both cases the maximum amplitude is directed to the surface (deposition).

**h. Flux discussion**

Both the monthly mean sensible and latent heat flux estimates have an annual cycle, though of opposite sign. The sensible heat flux, on average, is directed toward the surface throughout the year with the largest flux occurring during winter months. The latent heat flux, on average, is directed toward the atmosphere throughout the year, with the largest flux occurring during the summer months. The positive heat flux estimates indicate a sink of atmospheric energy in the Antarctic, while the negative heat flux estimates would indicate a source of energy. These computed heat flux estimates are comparable in both magnitude and direction to those computed in Antarctic katabatic wind zones (Stearns and Weidner 1993; van den Broeke et al. 2005; van As et al. 2005a,b).

To further test the estimation of the turbulent heat fluxes, Table 3 shows the annual range of monthly mean sensible and latent heat fluxes using four different stability correction functions. For stable conditions the correction functions used are from Holtslag and De Bruin (1988), Grachev et al. (2007), King and Anderson (1994), and Högström (1996). For unstable cases, the stability functions from Högström (1996) were used; this combination of stable and unstable functions was done in Vignon et al. (2017). The annual range of turbulent heat fluxes varies little, with the largest difference being the lower sensible heat flux maximum when using the Högström (1996) stability correction functions. Future studies, which will include more tall towers (exceeding the standard 3-m height) in Antarctica, will further investigate the turbulent heat fluxes and the manner in which they can be estimated in these remote locations.

**6. Conclusions**

Alexander Tall Tower! has had a relatively short lifetime as an Antarctic AWS, but it is providing consistent and beneficial data. Observations of meteorological conditions at the six tower levels provide details of the lower boundary layer in this otherwise unobserved region. The presence of two winter regimes annually, caused by circulation anomalies, is evident in these observations. Using the multiple levels of instrumentation, sensible and latent heat flux estimates were calculated over three years. Positive sensible heat flux estimates ranging from 1 to 39 W m\(^{-2}\) (monthly mean) indicate a cooling atmosphere, and negative latent heat flux estimates ranging from –8 to 0 W m\(^{-2}\) indicate sublimation of snow. The latent heat flux estimates are smaller in magnitude when compared with the sensible heat flux estimates, though both have an apparent annual cycle. The positive sensible heat flux estimates are large as a result of large temperature gradients and higher wind speeds forced by katabatic flow and support the strong inversion conditions noted in the monthly mean temperatures. Similar magnitude and direction of these fluxes were found using multiple different stability correction functions. Future estimations of turbulent fluxes will further investigate different models of stability and will use measurements from multiple tall towers.

These heat fluxes are an important component of the atmospheric energy budget, given that Antarctica acts as a global heat sink. To produce the most accurate estimates, the conditions of the tower itself must be well known. Observational data are prone to error when instruments are damaged or the tower is tilted or buried. Installing

**TABLE 3.** Annual range of monthly mean sensible and latent heat flux estimates (W m\(^{-2}\)) based on the stability functions used. For Holtslag and De Bruin (1988), Grachev et al. (2007), and King and Anderson (1994), the Högström (1996) unstable stability functions were used, as was done in Vignon et al. (2017).

<table>
<thead>
<tr>
<th>Stability function</th>
<th>Sensible</th>
<th>Latent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lettau (1979)</td>
<td>1.81–38.5</td>
<td>From −7.86 to −0.76</td>
</tr>
<tr>
<td>Högström (1996)</td>
<td>2.18–35.7</td>
<td>From −7.35 to −0.80</td>
</tr>
<tr>
<td>Holtslag and De Bruin (1988)</td>
<td>2.51–38.5</td>
<td>From −7.26 to −0.69</td>
</tr>
<tr>
<td>Grachev et al. (2007)</td>
<td>2.67–39.6</td>
<td>From −7.22 to −0.64</td>
</tr>
<tr>
<td>King and Anderson (1994)</td>
<td>2.43–36.9</td>
<td>From −7.25 to −0.71</td>
</tr>
</tbody>
</table>

**FIG. 9.** As in Fig. 8, but for latent heat flux estimates. Missing data points are 26.4% of the total timeline.
more tall towers in the Antarctic would allow for more heat flux estimates to be computed and would create a broader picture of the energy budget in this region. Future work includes comparisons between turbulent heat flux estimates from multiple tall towers, as well as comparisons with the Antarctic Mesoscale Prediction System (AMPS) fluxes, and incorporation of radiation flux data to perform a surface energy balance analysis. In addition, more towers could confirm the dual-winter regime phenomenon that is unique to the Antarctic. This could affect travel in this region and thus is an important feature to document and understand. Greater temporal and spatial coverage would allow further analysis of the consequences of this phenomenon in Antarctic weather and climate.

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