Characteristics of turbulence in the lower atmosphere at Halley IV station, Antarctica

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Abstract

A study of turbulent processes taking place in the stably stratified boundary layer overlying an Antarctic ice-shelf is presented. The ice-shelf is regarded as a flat, homogeneous surface. Turbulent measurements were made by the British Antarctic Survey from their meteorological station at Halley, Antarctica. Instrumentation included a 32 m mast supporting three ultrasonic thermo-anemometers, platinum resistance thermometers and other meteorological instruments. Mechanical and thermal properties of boundary layer turbulence are investigated, and parameters such as friction velocity and turbulent exchange coefficients are calculated and their dependence on the gradient Richardson number and local stability parameter, \( z/\Lambda \), is discussed. It is shown that the friction velocity is a key parameter controlling the turbulent characteristics in this particular boundary layer. Strong surface-based thermal inversions of up to 10\(^\circ\)C over the lowest 30 m are often observed. The relationships between the inversion strength and turbulent parameters are studied and their influence on near-surface mixing is assessed. It is shown that in the very strongly stratified boundary layer stability functions for heat and momentum may reach a constant value at fairly low-levels, suggesting that \( z \)-less scalings are applicable under such conditions. The implications for numerical modelling of the stable boundary layer are discussed and the need for further observational studies is highlighted. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The atmospheric boundary layer (ABL) is that portion of the atmosphere closest to the earth’s surface. Processes such as the dispersion of pollutants and the transfer of heat,
momentum and moisture are directly influenced by its meteorological and dynamical properties. The degree of stratification is one of the key factors affecting turbulent transfer in the ABL. Turbulent transfer and mixing tend to be inhibited in stably stratified regions of the atmosphere (Morgan and Bornstein, 1977; Kondo et al., 1978; Howell and Sun, 1999; Cuxart et al., 2000). Smedman (1991) pointed out that the main difficulties in understanding the stable boundary layer arise from the suppression of vertical transfer. This leads to intermittency of turbulence, particularly within the surface layer. It is difficult to identify and scale all of the key processes governing the evolution of an ABL under strongly stratified conditions. Antarctica is a natural laboratory for the study of the stable ABL since during the months of winter darkness observations can be made which are free from the effects of diurnal variations. Strong surface-based inversions lasting for several days are commonplace in Antarctica as the surface energy balance is dominated by radiative cooling (King et al., 1996). Such conditions are not often observed in midlatitudes (Yagüe and Cano, 1994a). King (1990) studied the failure of surface layer similarity theory at very low heights over an Antarctic ice-shelf, and suggested that the stability of the overlying atmosphere restricts the depth of the turbulent boundary layer and the length scales of turbulence in this layer. It was found that high Richardson numbers (up to 10) are reached resulting in very low levels of heat and momentum transfer (Yagüe and Cano, 1994b). Another problem which arises in the study of the ABL is that of expressing the turbulent parameters in terms of surface fluxes. If this is not possible, then local-scaling hypotheses can be used to evaluate turbulent parameters (Nieuwstadt, 1984a; Yagüe and Redondo, 1995).

It is often assumed that the variation with height of vertical turbulent fluxes over the lowest few tens of metres in the stable ABL is negligible and this has formed the basis of traditional theoretical formulations for stability functions. However, several studies have suggested that heat fluxes at lower levels are systematically greater than those at higher levels (Haugen et al., 1971; Kondo et al., 1978). Thus, computed stability functions are sensitive to the height at which the fluxes are calculated. This may explain the variations in stability functions computed using data from different sites. Howell and Sun (1999) studied surface layer fluxes using data from a meteorological tower deployed in the Microfronts experiment which took place in Kansas, USA, during March 1995. They calculated stability functions for values of \( z/\Lambda \) up to 10, where \( z \) is the observational height and \( \Lambda \) is the local Obukhov length. Consideration was given to the possibility of inaccurate estimation of the stability functions arising from the flux sampling error, particularly under very stable conditions.

Observational studies of the ABL over an ice-covered surface, for example, a glacier or an ice-shelf, provide important information for climate models. Turbulent exchange of heat, momentum and moisture through melt influence directly the mass balance of an ice sheet. Furthermore, in the stable boundary layer, the surface layer (where fluxes of momentum and heat are roughly constant with height) over an ice sheet can be extremely shallow, even less than 5 m (King, 1990; Yagüe and Redondo, 1995). This implies that ideally numerical models of the boundary layer over ice should incorporate fine vertical resolution near the ground. Estimation of radiative and turbulent fluxes is aided by a good understanding of surface layer characteristics. Forrer and Rotach (1997) examined turbulence measurements from a 30 m tower in the stably stratified boundary layer over the Greenland ice sheet. They found that for strong inversion conditions local-scaling hypotheses were superior to
surface layer scalings for modelling the non-dimensional gradients of wind speed ($\phi_m$) and temperature ($\phi_h$). Yagüe and Cano (1994b) showed that the vertical momentum flux tended to exhibit a greater degree of variation with height than the corresponding heat flux in the stably stratified ABL overlying the brunt ice-shelf, Antarctica.

In this work we attempt to identify the main mechanisms influencing turbulent transfer in the stably stratified lower atmosphere at Halley. The eddy transfer coefficients of heat and momentum characterise turbulent transfer. Yagüe and Cano (1994b) studied the dependence of the eddy transfer coefficients on the gradient Richardson number, the value of which depends on the combined effects of inversion strength and wind shear. Here, we extend the study of Yagüe and Cano (1994b) by examining separately the mechanical and thermal properties of boundary layer turbulence. The stability parameter $z/\Lambda$ has also been used and compared to the gradient Richardson number, $R_i$. A description of the data set available for this study can be found in Section 2. The turbulent and stability parameters used to evaluate the characteristics of the Antarctic boundary layer are defined in Section 3. The main results are presented in Section 4 and the conclusions are summarised in Section 5.

2. Data and location

During the austral winter of 1986, the British Antarctic Survey made a series of boundary layer observations from their meteorological station at Halley IV station, Antarctica ($76.5^\circ$S, $26.7^\circ$W). The project was called the Stable Antarctic Boundary Layer Experiment (STABLE). Its aim were to investigate the properties of waves and turbulence in the stably stratified ABL. Further details can be found in King and Anderson (1988) and King (1990). Halley is located towards the seaward edge of the brunt ice shelf. Inland there is a uniform fetch of about 40 km between the observing station and the irregular terrain where the ice-shelf meets the continental plateau at the hinge line. Thus, the topography at the observational site can be regarded as flat and homogeneous, with a roughness length of $z_0 = (1.1 \pm 0.1) \times 10^{-4}$ m measured for near-neutral conditions.

The data used in this work were obtained from a 32 m meteorological mast supporting three sonic thermo-anemometers at nominal heights of 5, 17 and 32 m, and platinum resistance thermometers which measured temperature differences between 2–4, 4–8, 8–16 and 16–32 m. An ultrasonic thermo-anemometer at 5 m supplied the absolute temperature at this level. In addition, three cup anemometers were deployed at 2, 8 and 24 m. The sampling rate for the ultrasonic thermo-anemometers had to be limited to 5 Hz in order to keep a synchronous processing of the two machines involved in the data logging; however, this rate should be sufficient for the calculation of turbulence statistics (King and Anderson, 1988). The resistance thermometers and the cup anemometers were sampled at 1 Hz. All the variables, as well as the covariances of velocity and temperature, were averaged over 10 min, which is a compromise between obtaining stable turbulence statistics and excluding the effects of large-scale motions or trends. In order to reduce statistical scatter, this data set was further processed by calculating 1 h averages. Data used in this study were compiled from March to August 1986 which includes the three month period of winter darkness.
3. Turbulent parameters

The following turbulent and stability parameters have been calculated from the data.

1. The eddy transfer coefficient for momentum, $K_m$:

$$K_m = -\frac{\overline{u'w'}}{\overline{(U/\partial z)}},$$  

(1)

where $u'$ and $w'$ are the fluctuating horizontal and vertical components of the velocity, $U$ is the background wind speed and an overbar denotes the average value, $z$ denotes height above the ground. By relating the turbulent momentum flux to the vertical mean wind shear, $K_m$ quantifies the level of mechanical turbulence present in the boundary layer.

2. The eddy transfer coefficient for heat, $K_h$:

$$K_h = -\frac{\overline{\theta'w'}}{\overline{(\partial\theta/\partial z)}},$$  

(2)

which gives the ratio of the turbulent heat flux to the gradient of mean temperature, and hence measures the level of thermal turbulence present in the boundary layer. Here $\theta$ denotes temperature.

3. The friction velocity, $U_*$, is defined by:

$$U_* = \left(\overline{(u'w')}^2 + \overline{(v'w')}^2\right)^{1/4},$$  

(3)

and is an important scaling variable and gives a measurement of the shear stress in the boundary layer.

4. The stability parameter $z/L$, where $L$, the Obukhov length is defined as:

$$L = -\frac{T_0 \overline{u^3}}{k g \overline{\theta'w'}},$$  

(4)

where $k$ is the von Karman constant, $g$ the acceleration due to gravity and $T_0$ is a reference temperature. When $L$ is evaluated using local turbulent fluxes instead of the surface fluxes, it is referred to as the local Obukhov length, $\Lambda$.

5. The gradient Richardson number, $R_i$, can also be used as a stability parameter (Rees, 1991; Cuxart et al., 2000). It is defined as:

$$R_i = \frac{(g/\theta_0)(\partial\theta/\partial z)}{(\partial U/\partial z)^2 + U^2(\partial\alpha/\partial z)^2},$$  

(5)

where $\alpha$ is the wind direction. In order to evaluate the gradient of the mean potential temperature and wind speed, log-linear profiles were fitted to both variables using a least-squares procedure (Nieuwstadt, 1984b). This procedure has been widely used in the literature on stable boundary layers (King, 1990; Yagüe and Cano, 1994b; Howell and Sun, 1999; Cuxart et al., 2000). Measurements of $\theta$ were available at heights of 2, 4, 5, 8, 16 and 32 m. Wind speed measurements from sonic anemometers at 5, 17
and 32 m were supplemented by readings from cup anemometers deployed at 2, 8 and 24 m. Observations from the cup anemometers were discarded when the wind speed was less than 5 m s\(^{-1}\) in order to avoid problems due to riming. The gradient of the mean wind direction has been evaluated from fitting a linear profile to the corresponding data at 5, 8, 17 and 32 m. The method adopted for estimating these parameters from the data is discussed in detail in Yagüe and Redondo (1995). The terms in Eqs. (1) and (2) representing gradients of wind speed and potential temperature were also evaluated by fitting log-linear profiles to observations using a least-squares procedure.

6. The gradients of mean wind and potential temperature in their dimensionless forms (\(\phi_m\), \(\phi_h\)) are defined by:

\[
\phi_m = \frac{K_m}{U_*} \frac{\partial U}{\partial z} \quad (6)
\]

\[
\phi_h = \frac{K_h}{\theta_*} \frac{\partial \theta}{\partial z} \quad (7)
\]

where \(\theta_* = \frac{(-\theta' w')}{U_*}\). \(\phi_m\) and \(\phi_h\) have been calculated from observations made at Halley for a wide range of thermal stabilities. Stability functions derived from the STABLE datasets have been compared with those obtained from studies undertaken at other sites. The gradient Richardson number, \(Ri\) and \(z/L\) are directly related by the equation (Arya, 1988, p. 160)

\[
Ri = \frac{z}{L} \frac{\phi_h}{\phi_m^2}. \quad (8)
\]

Thus, if the stability functions \(\phi_m\) and \(\phi_h\) are known as functions of \(z/L\) (or \(z/A\)), then the functional form of \(Ri(z/L)\) can be determined.

The parameters \(K_m\), \(K_h\), \(U_*\), \(z/L\), \(Ri\), \(\phi_m\) and \(\phi_h\), have all been calculated at 5, 17 and 32 m, so a local-scaling approach has been used. Also, an inversion strength has been defined as the temperature difference between heights of 32 and 2 m (\(\Delta T_{32-2}\)).

4. Results and discussion

Log–log plots have been used to present the results as several parameters exhibit a range of values extending over several orders of magnitude. In order to aid interpretation and to improve convergence of statistics, results have been grouped into the following intervals:

- \(z/L\): (0.0–0.05), (0.05–0.1), (0.1–0.2), (0.2–0.3), (0.3–0.5), (0.5–0.7), (0.7–1.0), (1.0–3.0), (3.0–6.0) and (6.0–10.0);
- \(U_*\): (0.01–0.05), (0.05–0.1), (0.1–0.2), (0.2–0.3), (0.3–0.4) and (>0.4) m s\(^{-1}\);
- \(\Delta T_{32-2}\): (0.01–0.1), (0.1–0.5), (0.5–1.0), (1.0–2.0), (2.0–4.0), (4.0–6.0), (6.0–8.0) and (>8.0)°C;
- \(U\): (3.5–5.0), (5.0–6.5), (8.0–9.5) and (>9.5) m s\(^{-1}\);
- \(Ri\): (0.0–0.01), (0.01–0.05), (0.05–0.075), (0.075–0.1), (0.1–0.15), (0.15–0.25), (0.25–0.5) and (0.5–10).
A total of 502 data points (hours) have been used at 5 m, 518 points at 17 m, and 408 points at 32 m.

4.1. Dependence of turbulent transfer on $z/\Lambda$, $U_*$ and $\Delta T_{32-2}$

Yagüe and Cano (1994b) studied the relationships between turbulent transfer and the gradient Richardson number, $Ri$. $Ri$ is a stability parameter that incorporates the combined effects of background stratification and wind shear. In the present work we aim to highlight the separate contributions to turbulence of mechanical and thermal effects. In Figs. 1–5, results are plotted as geometrical mean values, together with corresponding error bars (standard deviation). The number of observational results contributing to the mean are also shown for the first occurrence of the variable represented by the abscissa.

First of all we will investigate the variations of turbulent transfer with the local stability parameter $z/\Lambda$. Plots of $K_m$, $K_h$, $U_*$ and $U$ against $z/\Lambda$ are shown in Fig. 1. For this

![Fig. 1.](image-url)
plot all flux values have been calculated using data from the 5 m sonic anemometer. It can be observed that turbulent transfer is closely controlled by the stability parameter $z/\Lambda$, although the scatter is markedly greater for $K_h$ than it is for $K_m$. This increased scatter may be attributed to the fact that observational procedures tend to result in larger errors in estimated temperature gradients than in corresponding gradients of wind velocity (Duynkerke, 1999). From Fig. 1(a), it is observed that the eddy transfer coefficient for momentum tends to decrease more sharply at lower values of $z/\Lambda$ than the eddy transfer coefficient for heat. This indicates that $K_h$ is not as susceptible as $K_m$ to changes in stability for $z/\Lambda < 0.2$, and so the transfer of heat is maintained for this range of stabilities whilst the transfer of momentum starts to be restricted as $z/\Lambda \to 0.2$. The scatter obtained using $z/\Lambda$ as stability parameter is smaller compared to that obtained when $Ri$ is used (see Yagüe and Cano, 1994b). This could in part be explained by the shared-variable problem (the two variables whose relationship is being analysed have a shared-variable, for example, $U_*$ in $K_m$ and $z/\Lambda$). This problem of shared variables is thought to be reduced when using $Ri$ as a stability parameter.
parameter as its value is evaluated directly from the temperature and wind gradients without using the turbulent fluxes of momentum or heat at all. However, the expected scatter can be larger. From Fig. 1(d), it can be observed that the 5 m wind speed attains an approximately constant value of around 3 m s\(^{-1}\) for values of \(z/\Lambda > 0.7\). This indicates that the 5 m wind speed is not controlled by the underlying stability for \(z/\Lambda > 0.7\).

The relationships between the eddy transfer coefficients of momentum and heat and the friction velocity are shown in Fig. 2(a) and (b), and those between the eddy transfer coefficients and the inversion strength are plotted in Fig. 2(c) and (d). As for Fig. 1, all fluxes have been calculated using observations from the 5 m sonic anemometer. The temperature inversion strength is taken to be the temperature difference between heights of 32 and 2 m, \(\Delta T_{32-2}\). \(K_m\) and \(K_h\) both decrease in value as the friction velocity is reduced, however, \(K_m\) starts to decrease at higher values of \(U_\ast\) than \(K_h\). This suggests that \(K_m\) is more sensitive than \(K_h\) to changes in wind shear for values of \(U_\ast > 0.1\) m s\(^{-1}\). Again the error bars indicate that there is less scatter in the estimates of \(K_m\) than in those for \(K_h\). For the lowest values of \(U_\ast\) turbulent transfer takes place close to molecular scales (around \(10^{-4}\) m\(^2\) s\(^{-1}\)). Such

![Fig. 3. (a) \(U_\ast\) evaluated from observations at 5 m plotted against the 5 m wind speed, \(U\); (b) \(U_\ast\); (c) \(U\) plotted against \(\Delta T_{32-2}\).](image-url)
small values are not found at midlatitudes. At such scales laminar flow is approached, which gives an idea of the very strong inhibition of turbulence. From Fig. 2(c) and (d) it may be deduced that as the inversion strength develops, eddy turbulent transfer begins to weaken and that increases in the temperature gradient in excess of 1°C over the lowest 30 m are associated with a sharp decrease in the coefficients of eddy turbulent transfer for both heat and momentum. The decrease in $K_m$ is noted at smaller temperature gradients than for the case of $K_h$. Thus, the onset of a period of stable stratification initially has a greater effect on momentum transfer than on heat transfer. From Fig. 2 we can therefore deduce that both $U_*$ and $\Delta T_{32-2}$ are important controlling parameters for turbulent transfer.

At 5 m a high correlation exists between the friction velocity and the wind speed. $U_*$ is almost perfectly controlled by the wind speed at 5 m and scattering is small (except in very stable conditions) as can be seen in Fig. 3(a). The relationships of $U_*$ and $U$ with

![Fig. 4. (a) $\phi_m$ and (b) $\phi_h$ plotted against $R_i$. (c) $\phi_m$ and (d) $\phi_h$ plotted against $z/\Lambda$. All fluxes were calculated using observations from the 5 m sonic anemometer. The functional relationships between $\phi_m$ and $\phi_h$ with $z/\Lambda$ found from the studies of Businger et al. (1971), King (1990) and Duynkerke (1999) are also shown in parts (c) and (d), respectively.](image-url)
ΔT_{32−2} are presented in Fig. 3(b) and (c), respectively. Friction velocity decreases with increasing inversion strength, so these two controlling parameters of turbulent transfer are highly correlated. However, the correspondence between wind speed and inversion strength at 5 m is not so clear. There is a general decrease in wind speed with increasing values of ΔT_{32−2}, but the results are quite scattered and for temperature gradients in excess of 4°C over the lowest 30 m, the wind speed is roughly constant, which implies that for a certain level of inversion strength the wind speed is independent of the temperature gradient.

4.2. Dimensionless wind and temperature gradients (ϕ_m and ϕ_h)

One of the main results from the Monin–Obukhov (M–O) surface layer similarity theory is that the dimensionless wind and temperature gradients (ϕ_m and ϕ_h) can be expressed as functions of only one parameter (z/L), and this functional dependence has been evaluated.

![Graphs showing dimensionless wind and temperature gradients](image_url)
from atmospheric field data by different authors (Hogstrom, 1988). For weak to moderate stably stratified boundary layers (i.e. $0.01 < z/L < 0.5$, for example) with continuous turbulence, these relationships work well, but when the stability is strong the fluxes are not constant with height and the theory fails. Nieuwstadt (1984a) demonstrated that under such conditions it is more appropriate to use local-scaling whereby M–O theory is modified to incorporate turbulent fluxes evaluated at each height rather than using surface fluxes.

The behaviour of $\phi_m$ and $\phi_h$ versus the two stability parameters $Ri$ and $z/\Lambda$ at 5 m can be seen in Fig. 4. The $\phi_m$ and $\phi_h$ are calculated from Eqs. (6) and (7), where the gradients of wind and temperature are derived from the log-linear profiles fitted to the data, as explained in Section 3. The functional relationships between $\phi_m$ and $\phi_h$ with $z/\Lambda$ found from the studies of Businger et al. (1971), King (1990) and Duynkerke (1999) are also shown for comparison. The scatter in both $\phi_m$ and $\phi_h$ is much greater when results are plotted against $Ri$ than when they are plotted against $z/\Lambda$. This could again be explained by the shared-variable problem. However, the general behaviour is that $\phi_m$ and $\phi_h$ increase with stability and at certain level of stratification ($Ri > 0.25$ or $z/\Lambda > 1$) their values tend to level off. From a study of turbulence measurements from the stably stratified boundary layer over the Greenland ice sheet, Forrer and Rotach (1997) also found that under strong inversion conditions the stability functions for heat and momentum tended to approach a constant value at some levels. Howell and Sun (1999) showed that the stability function for momentum levelled off at 10 m under conditions of moderate stability (i.e. $z/L = 0.5$). The stability functions can be considered as the inverse of the dimensionless eddy transfer coefficients for heat and momentum ($K_m$ and $K_h$) if $kz U_s$ is used to scale the coefficients, as $K_m/(kz U_s) = \phi_m^{-1}$ and $K_h/(kz U_s) = \phi_h^{-1}$. Comparing, for example, Fig. 1(b) with Fig. 4(d) it is observed that although the turbulent heat transfer coefficient decreases continuously at high stabilities, the dimensionless form ($\phi_h$) tends to level off which is a consequence of the local-scaling. This can be interpreted as a $z$-less approach (Wyngaard, 1973), which is a consequence of the limiting behaviour of local-scaling for large values of $z/\Lambda$: stable stratification inhibits the vertical motion in the ABL and thus the length scale of turbulence is reduced. When the stratification is very strong, the length scale is much smaller than the height above the surface (i.e. $\Lambda \ll z$, or $z/\Lambda \rightarrow \infty$). A common interpretation of this phenomenon is that the turbulence does not feel the presence of ground and thus dependence on $z$ is removed. Hence dimensionless quantities approach constant limits for large values of $z/\Lambda$ (Nieuwstadt, 1984a). Howell and Sun (1999) showed that the general behaviour of the stability functions does not change using fluxes calculated with a 10 min cut-off time scale instead of a variable cut-off scale, so the results of the present work are compatible with their study. The $\phi_m$ and $\phi_h$ are plotted against $U_s$ in Fig. 5(a) and (b) and their dependence on $\Delta T_{32-2}$ is illustrated in Fig. 5(c) and (d). Under near-neutral conditions (i.e. small values of $\Delta T_{32-2}$ and large values of $U_s$), in agreement with M–O theory, $\phi_m$ approaches a value of 1.0, with very little scatter in the results. However, corresponding values of $\phi_h$ are quite scattered and values even greater than 1.0 are reached for the largest friction velocities, where the temperature gradients may be poorly defined. For very stable conditions (which are usually associated with high values of inversion strength or small values of friction velocity) the tendency of $\phi_m$ and $\phi_h$ to a constant value is not observed and there is a greater degree of scatter in the results.
4.3. Variation of turbulent parameters with height

In order to study how turbulent properties may change with height, \(K_m, K_h\) and \(U^*\) have been evaluated at 17 and 32 m in addition to 5 m. These results are shown in Figs. 6–8. Similarities in behaviour are observed across all three heights. However, some specific distinctions are found. From Fig. 6a it can be seen that the friction velocity, \(U^*\), attains its maximum value when near-neutral conditions are reached. The relationship between wind speed, \(U\), at 5, 17 and 32 m and inversion strength is shown in Fig. 6b. It can be observed that as the temperature inversion increases, the wind speed at 5 m falls off to a roughly constant level. However, high values of \(U\) at 17 and 32 m remain. This result suggests that wind speed at high levels does not control the formation of the inversion near the surface. Strong winds prevalent at 17 and 32 m may be associated with a low-level of turbulent activity at 5 m, which is indicative of a decoupling between the near-surface flow and that aloft.

In Fig. 7, \(K_m\) and \(K_h\) have been plotted against \(U^*\) and \(\Delta T_{32-2}\). Under near-neutral conditions (corresponding to \(U^* > 0.1 \text{ m s}^{-1}\) and \(\Delta T_{32-2} < 1^\circ \text{C}\)), \(K_h\) is seen to increase with height. Brost and Wyngaard (1978) and Wittich and Roth (1984) found that \(K_m\) and \(K_h\) both increased with height under near-neutral conditions. In the present study the change in \(K_m\) associated with \(z\) is less clear. For the strongest temperature stability range considered, \(\Delta T_{32-2} = 10^\circ \text{C}\), relatively larger values of \(K_m\) are found at the two higher levels than at 5 m (Fig. 7c). This feature is not observed in \(K_h\) (Fig. 7d). This could be explained by the existence of internal gravity waves in the boundary layer overlying the brunt ice-shelf, which have been widely reported in the literature (Rees and Mobbs, 1988; Rees et al., 2000). Such waves are prevalent in regions where the local gradient Richardson number is greater than 0.25, which is the theoretical critical value for the onset of turbulence. Near the surface (around 5 m), the wind shear is often sufficiently large that the Richardson number becomes subcritical and the gravity wave signature is then dominated by shear-generated turbulent eddies. At 17 and 32 m, the Richardson number is usually
Fig. 7. (a) $K_m$ and (b) $K_h$ evaluated at 5, 17 and 32 m plotted against $U^*$. (c) $K_m$ and (d) $K_h$ plotted against $\Delta T_{32,2}$.

Values of $\phi_m$ and $\phi_h$ as functions of $Ri$ and $z/\Lambda$ for the three sonic heights are shown in Fig. 8. When gradient Richardson number is the chosen stability parameter (Fig. 8(a) and (b)), an increase of the stability functions with height is found. For values of $Ri < 0.25$, $\phi_m \approx \phi_h$. However, a marked difference is observed when $Ri > 0.25$ when $\phi_h$ is of $O(10)$ larger than $\phi_m$ at all three measurement heights. This indicates different behaviour in the mixing of heat compared to that of momentum. This concept will be analysed further in the next subsection. In Fig. 8(c) and (d) $\phi_m$ and $\phi_h$ are shown versus $z/\Lambda$. For values of $z/\Lambda < 0.5$, $\phi_m$ increases gradually with height. However, for $z/\Lambda > 0.5$, the values of $\phi_m$ at 17 and 32 m are slightly smaller than at the 5 m level. In the stability regime $z/\Lambda > 1.0$, $\phi_h$ is approximately constant throughout the depth of the boundary layer, suggesting that a $z$-less scaling is appropriate (Fig. 8(c) and (d)).
4.4. The relationship between $Ri$ and $z/\Lambda$

We have described the dependence of turbulent parameters, calculated from the Halley data, on the stability parameters $Ri$ and $z/\Lambda$. Recent models of the stable ABL have assumed the existence of a functional relationship between these two different measures of stability, i.e. $Ri = Ri(z/\Lambda)$ (Nieuwstadt, 1984a). If these two stability parameters are directly related, then analyses based on local scalings would be equivalent to studies where turbulent parameters have been calculated as functions of the gradient Richardson number (Kondo et al., 1978; Ueda et al., 1981; Yagüe and Cano, 1994b). The functional relationship between $Ri$ and $z/\Lambda$ given in Eq. (8) has been found to be a good approximation to observational data obtained in a number of field campaigns. However, in the present study, we have already highlighted some major differences in the trends observed depending on which stability parameter is used. In Fig. 9 the relationship between $Ri$ and $z/\Lambda$ is shown using data from 5, 17 and 32 m, respectively. The functional forms using Eq. (8) with the expressions for $\phi_m$ and $\phi_h$ found by Businger et al. (1971), King (1990) and Duynkerke (1999) are also plotted for comparison. Businger et al. (1971) evaluated $\phi_m$ and $\phi_h$ from
Fig. 9. $R_i$ plotted against $z/\Lambda$ at: (a) 5 m; (b) 17 m; (c) 32 m. Observational results calculated from the Halley data set are indicated by a ($\times$), (□) or (△), respectively. Standard deviations are also shown. Continuous and dashed lines illustrate the functional relationship $R_i = (z/\Lambda)(\phi_h/(\phi_m))^2$, where the values of $\phi_h$ and $\phi_m$ have been taken from the works of Businger et al. (1971), King (1990) and Duynkerke (1999).

surface fluxes and found that $\phi_m = 1 + 4.7\zeta$ and $\phi_h = 0.74 + 4.7\zeta$, where $\zeta = z/L$. King (1990) used local scalings to obtain stability functions from the Halley data sets for neutral to moderately stable conditions ($0 \leq z/\Lambda \leq 2.0$). Different functional forms for $\phi_m$ and $\phi_h$ were found at 5, 17 and 32 m. Although the scatter in the values of $R_i$ calculated for each stability range is relatively large, it can be said that the functional forms for $R_i = R_i(z/\Lambda)$ predicted by Eq. (8) follow the behaviour of the data reasonably well at heights of 17 and 32 m. As might be expected, King’s formula is the best fit to the observations. However, at the lowest 5 m level, King’s formula systematically underestimates $R_i$ for all stability ranges considered. This suggests that Eq. (8) does not ideally parameterise $R_i$ in this regime. We attempt to explain this discrepancy by considering, at each level, the limiting value of $R_i$ as $z/\Lambda \to \infty$. At 5 m $R_i$ is roughly constant for $z/\Lambda > 0.1$. This limiting value of $R_i$ as $z/\Lambda \to \infty$ can be considered as a critical Richardson number for the transition from a stable boundary layer with continuous turbulence to a strongly stably stratified boundary layer with sporadic turbulence (Nieuwstadt, 1984b). At the higher levels of 17 and 32 m,
**4.5. The inverse Prandtl number**

Finally, we investigate the effect of stability on another dimensionless number, the inverse Prandtl number, $K_h/K_m$. The dependence of the inverse Prandtl number on $Ri$, $z/Λ$, $U_∗$ and $ΔT_{32−2}$ is shown in Fig. 10. Yagüe and Cano (1994b) showed (with a reduced Halley data set and slightly different intervals of Richardson number) how the inverse Prandtl number

![Diagram](image-url)

Fig. 10. The inverse Prandtl number, $K_h/K_m$, plotted against: (a) $Ri$; (b) $z/Λ$; (c) $U_∗$; (d) $ΔT_{32−2}$, at heights of 5, 17 and 32 m.
decreases as the Richardson number increases. This illustrated the difference between the turbulent mixing of momentum and heat. In many situations, this difference is ignored, and for simplicity it is assumed that $K_h = K_m$. From Fig. 10(a) it can be seen that $K_h/K_m < 1$ for values of $Ri > 0.15$. However, when $K_h/K_m$ is related to $z/\Lambda$, no clear dependence is established (Fig. 10(b)). For values of $z/\Lambda > 1$ there are more points where $K_h$ is less than $K_m$, and the opposite happens when $z/\Lambda < 1$, but this difference is not statistically significant. The inverse Prandtl number can be related to the stability functions as $K_h/K_m = \phi_m/\phi_h$ (Arya, 1988), so for large values of $\zeta$ (strong stability) $K_h/K_m$ tends to $a/b$ where $a$ is the slope of the stability function ($\phi_m$) in stable conditions, and $b$ the corresponding slope for $\phi_h$. In many occasions $a$ and $b$ are equal or very close (see Hogstrom, 1988) so from this analysis a value close to 1.0 is found for the inverse Prandtl number. Howell and Sun (1999) highlighted the uncertainty in the behaviour of the Prandtl number for $z/\Lambda > 1$. $K_h/K_m < 1$ for values of $U_0$ < 0.1 m s$^{-1}$ and for $\Delta T_{32-2}$ > 4$^\circ$C. This supports the idea that under strongly stable conditions at Halley, mixing of heat is inhibited to a greater extent compared to that of momentum. The lack of a continuous turbulence regime, and the role played by internal waves in this situation of sporadic turbulence could account for the more efficient transfer of momentum compared to that of heat (Kondo et al., 1978; Yagüe and Cano, 1994b).

5. Concluding remarks

Turbulent transfer is an important topic in studies of the atmospheric boundary layer, and may exhibit complex features when the ABL is strongly stably stratified. Then, the lack of stationarity, due to intermittency of turbulence, the presence of internal gravity waves, decoupling of the near-surface flow, etc. makes it difficult to parameterise the dynamical properties of the ABL. In this work we have analysed the behaviour of turbulent transfer in the stable boundary layer for a wide range of stabilities, including very stable conditions which frequently occur in Antarctica, but which are rarely observed midlatitudes. The main results of this work can be summarised as follows:

- the eddy transfer coefficients of heat and momentum show a significant decrease of several orders of magnitude as stability increases. This decrease in $K_m$ is first noted at weaker stabilities than for the case of $K_h$;
- dimensionless gradients of wind and temperature ($\phi_m$ and $\phi_h$) are found to increase with stability but at certain level of stratification ($Ri > 0.25$ or $z/\Lambda > 1.0$) their values tend to level off, indicating a $z$-less behaviour, which is a consequence of local-scaling in the limit of strong stability;
- when turbulent transfer is evaluated at different heights (5, 17 and 32 m), a similar variation is presented, but the eddy transfer coefficient for momentum at 5 m is much smaller than at higher levels for strong stratification. This is likely to be due to the presence of internal gravity waves, which have been documented in previous studies of the ABL at Halley. The $\phi_m$ and $\phi_h$ do not present any significant difference with height for $z/\Lambda > 0.5$, thus displaying a $z$-less scaling across all three levels;
- although the stability parameters $Ri$ and $z/\Lambda$ are related via local-scaling hypotheses, the scatter in observed values is large. The critical Richardson number at 5 m is significantly lower than that at 17 and 32 m;
• the inverse Prandtl number \((K_h/K_m)\) tends to decrease as \(Ri\) increases, and attains values less than 1.0 when \(Ri > 0.1\). However, when representing this ratio versus \(z/\Lambda\), \(K_m\) is not statistically different from \(K_h\).

It has been shown that the depth of the stable ABL may be shallow, particularly under strong inversion conditions. Stability functions for heat and momentum transfer may approach constant values at relatively low levels. Under such conditions \(z\)-less scalings are more appropriate than surface layer scalings. This highlights the need for numerical models of the stable ABL to incorporate a fine grid mesh over the lowest few tens of metres above the ground. However, it is important to be aware that in the very stable ABL errors may accrue in the flux calculations due to an inadequate sampling frequency. For this study turbulent fluctuations were sampled at a rate of 5 Hz. It is possible that higher frequency turbulent fluctuations not resolved at this sampling rate (for heights very close to the ground) could contribute significantly to the total flux. Further discussion on the difficulties of making measurements of turbulent fluxes in the stable ABL can be found in Mahrt (1999). The findings of this paper add support to the need for a comprehensive observational study of turbulence in the stable ABL over several different sites where strict attention is paid to standardisation of the data sampling and analysis procedures.

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References


