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Nonstationarity of turbulent heat fluxes at Summit, Greenland

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Abstract Turbulence data collected over a total of 25 days during two summers are used to describe processes responsible for the nonstationarity of turbulent sensible heat fluxes at Summit, Greenland. A stationarity test shows that about 40% of the data are classified as nonstationary. Three main factors are explored to account for the large fraction of nonstationary runs: (1) intermittency of turbulence in stable conditions, (2) changes in net all-wave radiation in response to cloud forcing, and (3) diurnal trends in stability. A classification procedure that accounts for the intermittent nature of turbulence shows that during stable, nonstationary conditions 50% of the total sensible heat flux is realized in 22% of the sampling time. Intermittency often occurs at Summit during periods characterized by weak and irregular horizontal winds in combination with strong stability. Rapid changes in net all-wave radiation in response to cloud forcing results in nonstationarity during unstable conditions. Between 0930–1130 and 1900–1930 UTC turbulent heat fluxes are not only small in magnitude but also typically change sign, with nonstationarity during these periods often as high as 65%. These results should help resolve some of the present uncertainties in obtaining reliable fluxes at this site, in particular under stable atmospheric conditions.

Keywords Greenland ice sheet · Intermittency · Nonstationarity · Sensible heat fluxes

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1 Introduction

Motivated by the need to quantify the impact of snow photochemistry on the composition of the surface snow and overlying atmosphere at Summit, a region near the highest point on the Greenland ice sheet, an integrated program of field research took place during summers in 2000 and 2001 (Bottenheim et al. 2002). An understanding of present-day snow photochemical and atmospheric boundary-layer (ABL) processes is necessary to determine the origins of many atmospheric species in ice cores. During the field campaign vertical gradients of oxidized nitrogen compounds, organics and oxygenated organics very close to the surface were obtained. Eddy correlation data collected at 1 and 2 m above the surface allowed fluxes of some chemical species to be determined (Dassau et al. 2002; Honrath et al. 2002; Jacobi et al. 2002), as well as allowing the energy balance of the ABL for a short period in summer to be described (Cullen and Steffen 2001). An issue that has not yet been addressed is that closer examination of the turbulent sensible heat flux (H) data obtained from the eddy correlation measurements show that about 40% of all 30-min averaging intervals fail to pass a stationarity test. Understanding the physical causes behind this is necessary in order to properly measure and interpret other turbulent flux measurements over this and other semi-permanent atmospherically stable sites. It is also relevant to those interested in the origins of atmospheric species in snow or glacial ice in connection with ice-core studies.

The issue of nonstationarity in the stable to very stable ABL is closely linked to studies describing the occurrences of intermittent turbulence (Lykossov and Wamser 1995; Howell and Sun 1999; Marht 1999; Coulter and Doran 2002; Doran 2004), where intermittency is characterized by brief episodes of turbulence with intervening periods of relatively weak or small fluctuations of motion. There has been much interest in examining the mechanisms responsible for turbulent bursts or events that are typical of intermittent turbulence (Poulos et al. 2002; Poulos and Burns 2003; Sun et al. 2002; Van de Wiel et al. 2002, 2003; Blanken et al. 2003; Nakamura and Mahrt 2005) but because of their complexity common features of turbulent bursts or events over a variety of sites and circumstances have been limited (Doran 2004). Because well-defined and isolated intermittent turbulent events are relatively rare in atmospheric records (Nakamura and Mahrt 2005), the identification of such events is not straightforward. Problems associated with the classification of intermittent turbulence during stable conditions, using runs that fail tests of stationarity at Summit, are examined in this study.

While the ABL is typically stable throughout the course of a day in summer over melting surfaces along the margins of the Greenland ice sheet (Forrer and Rotach 1997), the stratification of the ABL over dry snow sites such as Summit has a diurnal trend in stability. Stable conditions that prevail during periods when the sun is close to the horizon are replaced by unstable conditions during high solar insolation (Munger et al. 1999; Albert and Hawley 2000; Cullen and Steffen 2001), which has also been observed over both snow and ice in Antarctica (Wendler et al. 1988; Stearns and Weidner 1993; Bintanja and Van den Broeke 1995a, b; Mastrantonio et al. 1999; Van den Broeke et al. 2005; Van As et al. 2005). On the interior plateau of Dronning Maud Land, Antarctica Van den Broeke et al. (2005) show that low temperatures limit sublimation and, in the absence of other heat sinks, surface temperatures rise rapidly during periods of high insolation in summer resulting in convective conditions. We explore in this study the consequences of a diurnal trend in stability at Summit, with a focus on whether times series of H are more likely to be nonstationary during the transition from one stability regime to the other.

Given the diurnal structure of the ABL at Summit in summer this study describes the occurrences of nonstationarity of H in both stable and unstable conditions. First, intermittent turbulence is characterized so as to better understand one way in which the nonstationarity of H can occur during stable conditions. This first description of intermittent turbulence over the Greenland ice sheet should lead to more robust methods to understand processes responsible for its occurrence. Second, occurrences of nonstationarity of H during conditions that are not (very) stable are examined. Two case studies are used to investigate the nonstationarity of H as a function of, (1) cloud forcing during periods of high insolation in unstable conditions, and (2) diurnal trends in stability. Given the interest in snow photochemistry for ice-core interpretation, and ongoing studies of the ABL at Summit, these results should help resolve some of the present uncertainties of obtaining reliable fluxes at this site, in particular under stable atmospheric conditions. These results should also be of benefit to the larger community interested in measuring and modelling ABL processes over the Greenland ice sheet.

2 Site description and instrumentation

The turbulence data used in this analysis were obtained during two intensive measurement periods (summer) June 21–July 6, 2000 and June 16–June 24, 2001 at Summit, Greenland (72.58°N, 38.51°W, 3203 m.a.s.l.). Summit is situated in the upper zone of the accumulation area, the dry snow zone, which accounts for 41% of the ice-sheet surface and 45% of the accumulation area (Ohmura et al. 1999). The surface of the ice sheet in the vicinity of Summit is smooth and homogenous, with average surface slopes less than 0.005°. During the summer months the sun never sets at Summit, with the midnight sun 5° above the horizon at the summer solstice. Descriptive statistics of some basic meteorological variables in both stable and unstable conditions during the two summers are shown in Table 1. One of the most important characteristics of the ABL at Summit in summer is that unstable (or near-neutral) conditions typically occur between 1000 and 1900 UTC, or for about 40% of the day, which has been demonstrated using both eddy correlation measurements and vertical gradients from profiles of temperature (Cullen and Steffen 2001).

Two three-dimensional sonic anemometers (Campbell Scientific Inc. (CSI), CSAT3) with fine wire thermocouples (CSI FW05) were deployed on a tower at two levels, 1 and 2 m above the snow surface, to provide supplementary data for investigations into photochemical processes at and very near the air–snow interface. The instruments were sampled at 50 Hz using a CR5000 data logger (CSI) connected directly to a laptop computer, which transferred data directly to an external storage device (2 GB Iomega Jazz Drive). The fluxes of different chemical species calculated from profile measurements very near the surface (e.g. Honrath et al. 2002; Jacobi et al. 2002) used eddy diffusivities obtained from sonic anemometer data. Corrections applied to compensate for flux loss due to the proximity of the sonic anemometers to the surface are discussed in the following section.

Supporting instruments included a Kipp and Zonen (KZ) four component pyrano-pyradiometer housed in a heated ventilation unit (KZ CV2) for downward and upward broad-band shortwave radiation flux (CM21, spectral range 305–2800 nm) and

Table 1 Mean and standard deviation (parenthesis) of horizontal wind speed (u), air temperature (t), and friction velocity (u_*) at 2 m above the surface

	Stable stratification	**Unstable stratification**
Horizontal wind speed ($m\,s^{-1}$)	3.2 (1.6)	4.0 (2.2)
Air temperature (°C)	−17.7 (4.7)	−13.4 (2.6)
Friction velocity ($m\,s^{-1}$)	0.13 (0.07)	0.19 (0.09)
Stability (z/L)	0.19 (0.2)	−0.10 (0.19)
Surface roughness (m)	$1.84 \times 10^{-4} (2 \times 10^{-4})$	$2.89 \times 10^{-4} (2 \times 10^{-4})$

Stability is expressed as the ratio z/L, where z is equal to 2 m, and L is the Obukhov length. The aerodynamic roughness length for momentum (z_{ov}) is in m. The method to calculate z_{ov} is the same as that used by Van den Broeke et al. (2005). Statistics are calculated from 30-min periods classified as stationary (the run test used is explained in the text): (1) 322 runs are stable and (2) 342 are unstable

downward and upward broadband longwave radiation flux (CG4, spectral range 4.5–42 μm). The instruments were mounted on a separate tower at a height of 1.8 m and sampled at 1 Hz, and averaged every 10 min in 2000 and 1 min in 2001 using a CR10X data logger (CSI). Instrument uncertainty is estimated to be $\pm 5\,W\,m^{-2}$ for daily totals. More detailed information on the performance of this instrument over an ice-sheet surface can be found in Van den Broeke et al. (2004).

Profiles of air temperature, humidity and horizontal wind speed were measured at 0.5, 1.0 and 2.0 m above the snow surface on a third tower. Ventilated radiation shields (Met One, 077 motor aspirated shields) housed Met One T200 (temperature) and 083D (relative humidity) instruments, while naturally ventilated shields (Campbell Scientific Inc. (CSI), 41002 12-plate Gill radiation shield) housed Vaisala HMP45C temperature and relative humidity probes. Additional measurements included wind direction, surface height and barometric pressure. All instruments had sampling intervals of 5 s and data were averaged every 10 min using a CR10X data logger (CSI). The relative accuracy of the instruments obtained from calibrations made on-site was in almost all cases greater than the absolute accuracy stated by the instruments' manufacturers. Humidity measurements were rescaled to account for saturation with respect to ice rather than liquid water using the approach described by Box and Steffen (2001), which relies on the method proposed by Anderson (1994). The sign convention employed is that all fluxes (radiative and turbulent) are positive as a gain to the surface and negative as a loss.

3 Turbulence data treatment

It is important to consider appropriate time intervals for the analysis of the mean and higher-order moments from a time series of turbulence data. If flux calculations for an energy balance are the primary goal, an averaging time between 10 and 60 min is typically chosen. The averaging time is usually determined as a trade off between data availability and estimates of the statistical uncertainty due to averaging time (e.g. Wyngaard 1973; Finnigan et al. 2003). Two steps are taken to determine a suitable integration period for this study: (1) a simple estimate of the statistical uncertainty due to averaging time (Lumley and Panofsky, 1964, pp. 35–38) is calculated, and (2) changes in the variance of H over different averaging windows is assessed. Significantly, the variance in H in this study decreases as window size increases and becomes increasingly stable at or above 10 min. As statistical uncertainty due to averaging time in H is estimated to be less than 10% over integration periods of 30 min, increasing as averaging intervals are decreased, 30-min sampling periods are considered the most suitable for this study. The total number of 30-min runs available from the two brief measurement periods using this sampling interval is 1080. Though 30-min averages are chosen as the primary averaging interval, different time windows are also used in this study.

Block averaging with preceding linear detrending is used to calculate the sensible heat flux H over all averaging intervals; no other high-pass or low-pass filtering of the turbulence data is performed unless otherwise stated. Sonic (speed of sound) temperature is corrected for the effects of specific humidity (Schotanus et al. 1983), which results in less than a 1% increase in H. A coordinate rotation of the velocity time series is applied to all chosen averaging intervals, which results in individual wind vectors being rotated into the mean wind direction in such a way that mean vertical (w) and lateral wind (v) are equal to zero (Kaimal and Finnigan 1994; Forrer and Rotach 1997). The effect of this rotation on the magnitude of H is small, on average less than 3%.

Flux loss resulting from limitations imposed by the physical size of the eddy correlation instruments is corrected using a procedure proposed by Moore (1986). This method employs spectral transfer functions that account for pathlength averaging and sensor separation (Moore 1986; Moncrieff et al. 1997). Given the proximity of the instruments to the surface the largest correction is linked to the pathlength of the CSAT3s, which at 0.115 m is over 10% of the measurement height of the lower sonic anemometer. The correction procedure is also sensitive to stability, with flux losses approaching 18% during very stable conditions at 1 m above the surface (Fig. 1). The flux loss over a range of stabilities at 2 m above the surface is between 2 and 11% (Fig. 1). The portion attributable to sensor separation is negligible and is only important if auxiliary measurements such as water vapour are included (e.g. Forrer and Rotach 1997). Even though the main results in this study do not depend critically on the above corrections, values of H at 2 m above the surface are only used in the following analyses.

4 Procedure to identify nonstationary runs

One of the important assumptions of Monin–Obukhov (MO) similarity theory is stationarity of key variables in the atmosphere, but such conditions cannot be expected to prevail on the top of the Greenland ice sheet, which is characterized by low wind speeds and a diurnal trend in stability in summer. Issues related to nonstationarity are not well understood and have only recently received more attention (e.g. Gluhovsky and Agee 1994; Dias and Brutsaert 1996; Dias et al. 2004; Mahrt 1999; McNaughton and Laubach 1998). The issue of nonstationarity is closely linked to integral time scales, which are often assumed to have the same order of magnitude for all turbulence variables, but Dias et al. (2004) have shown that this is not always the case.

A number of methods have been used to identify nonstationarity in turbulence datasets, and such methods often involve dividing a time series into non-overlapping sub-intervals, the data of which are then assumed to be approximately independent (Gluhovsky and Agee 1994; Forrer and Rotach 1997; Vickers and Mahrt 1997; Mahrt 1998; Dias et al. 2004). If data from a specified interval (e.g. a 30-min averaging

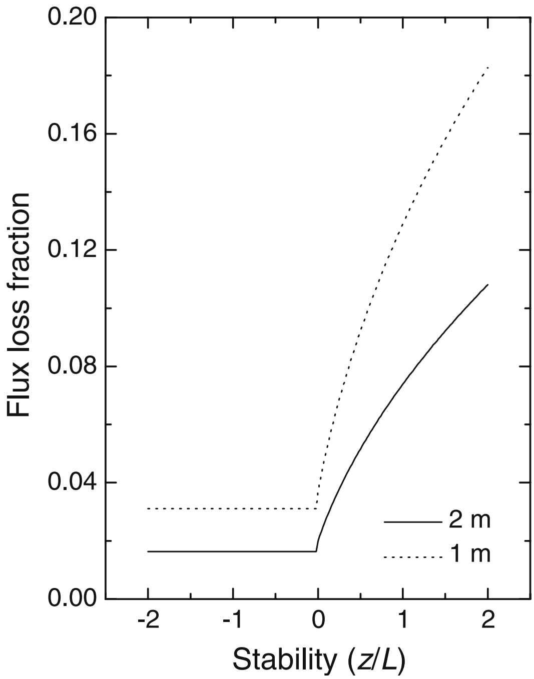


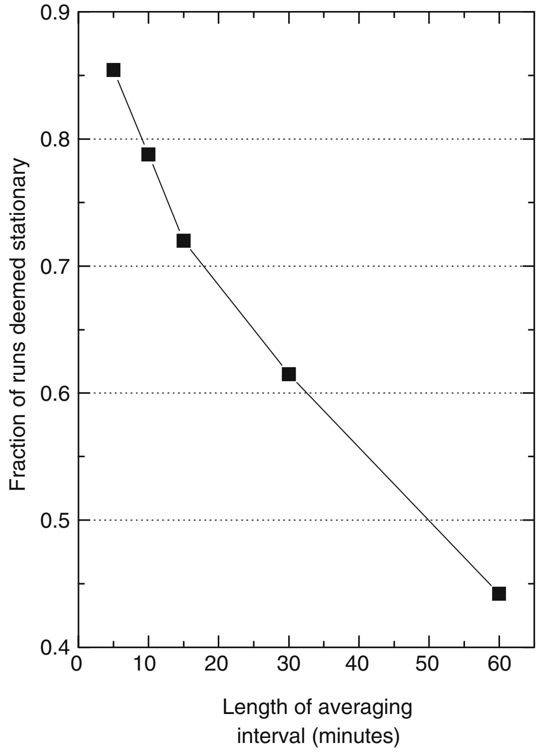
Fig. 1 Fraction of loss estimates of H over the range of stabilities expected at Summit for CSAT3 sonic anemometers mounted at 1 and 2 m above the surface

period) are nonstationary it is expected that the statistical properties of a sequence of shorter time intervals within the sample record will vary significantly. The word "significantly" in this case means larger variations than would be expected due to statistical sampling variations. If this view is accepted, random data can be tested for stationarity by investigating the behaviour of individual sample records rather than an ensemble of sample records.

A nonparametric procedure, the "run test", is used here to evaluate stationarity. The run test is useful for evaluating statistical independence and underlying trends (Bendat and Piersol 1966), and has recently been compared to the "reverse arrangement test" by Dias et al. (2004). Following a similar approach to Forrer and Rotach (1997), who used the procedure to evaluate turbulence data collected on the western margin of the Greenland ice sheet, each 30-min averaging period is divided into 40 sub-intervals. The mean values of H for each segment are then compared to the median value (H_m) of all 40 sub-intervals and classified into two categories (either $H < H_m$ or $H_m \leq H$). The number of changes between these two categories in a sequence of observations indicates whether or not the results are independent random observations. A Student's t-test can be performed on the hypothesis that the means of the segments are not independent random observations by comparing the number of counts to known probabilities of runs of random data (e.g. Bendat and Piersol 1966, p. 170). Based on the 1080 30-min runs available from the two measurement periods, and performing the test at the $\alpha = 0.05$ level of significance, 39% of all observations are deemed nonstationary (416 averaging periods). If partitioned by stability, the number of runs that are nonstationary in stable (unstable) conditions is 43 (33) %.

Changes to the averaging interval and number of sub-intervals within each interval were made to assess the sensitivity of the run test. The number of runs classified

Fig. 2 The sensitivity of the length of averaging interval, ranging from 5 to 60 min, on the fraction of runs deemed stationary. Each averaging period is divided into 40 sub-segments



as stationary are sensitive to the length of the averaging period (Fig. 2), though the number of sub-intervals chosen within an averaging period (not shown) is less important. Figure 2 shows that the number of runs classified as stationary increases as the length of the averaging period decreases (while the number of sub-intervals, 40, is kept constant). This result favours reducing averaging intervals to avoid issues of nonstationarity at Summit. For any chosen averaging interval between 5 and 60 min the results of the run test do not differ if 40 or 60 sub-intervals are used, but outside of this range results do vary. An increase (decrease) in the number of sub-intervals results in fewer (more) runs being classified as stationary.

The number of runs classified as nonstationary using the run test, despite showing some sensitivity, are large at Summit compared to other datasets we have obtained over the Greenland ice sheet and glaciers on high mountains at lower latitudes. One reason for this is the small magnitude of H at Summit, which often leads to a change in sign of H during nonstationary runs. To further account for the high number of nonstationary runs it is useful to consider the diurnal variability of nonstationary cases with stability and wind speed (Fig. 3). Nonstationarity is most common during periods that are characterized by stable conditions and during a transition from one stability regime to the other (50–60% of all runs on average). The highest wind speeds tend to coincide with unstable conditions, and importantly, have the lowest nonstationary percentages ($< 20\%$). We will demonstrate in the following sections that the above ABL conditions (Fig. 3) lead to the high number of nonstationary runs at this location.

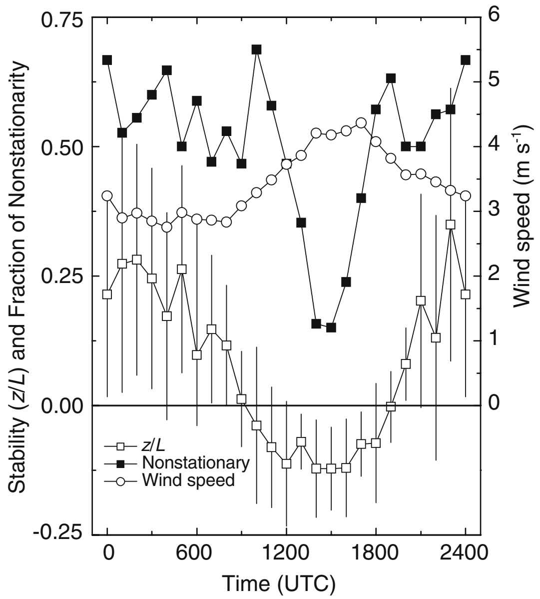


Fig. 3 Mean diurnal variation of stability, wind speed and fraction of nonstationary cases for all runs in both field seasons. The vertical lines show the uncertainty (1 standard deviation) of z/L

5 Intermittent turbulence in stable conditions

Turbulence is often weak and intermittent in the stable ABL at Summit, which leads to runs being classified as nonstationary. However, intermittent turbulence, defined as extended periods with little or no turbulent activity separated by brief periods of greater activity (Doran 2004), is not easy to characterize, as not all events are well-defined (Nakamura and Mahrt 2005). To obtain a sense of what we regard as intermittent turbulence at Summit, Fig. 4 shows five different 30-min runs of vertical velocity, w, obtained from the sonic anemometer data. Panels (a) through (c) show relatively well-defined events, while (d) and (e) are less straightforward with respect to defining specific patches of turbulence. Despite differences in the nature of the turbulent events in each of these runs they all share one thing in common: they are not classified as stationary using the run test.

The challenge of trying to establish a procedure to appropriately characterize intermittent turbulence has resulted in a number of different methods being proposed (e.g. Kondo et al. 1978; Howell and Sun 1999; Coulter and Doran 2002; Doran 2004; Nakamura and Mahrt 2005). To better understand why some runs in stable conditions at Summit are nonstationary we modified the Coulter and Doran (2002) method in such a way to allow us to assess intermittency in each 30-min averaging interval. To define turbulent events we calculated fluxes over 30-s intervals for each 30-min period (60 segments) and ordered them from largest to smallest according to their magnitudes. The proportion of individual 30-s fluxes that accounted for 50% of the total accumulated flux for each 30-min period is the intermittency fraction (IF), and, similarly to Coulter and Doran (2002), the maximum value of an IF fraction using this approach is 0.50. A low fraction case is a 30-min interval that has a high degree of intermittency.

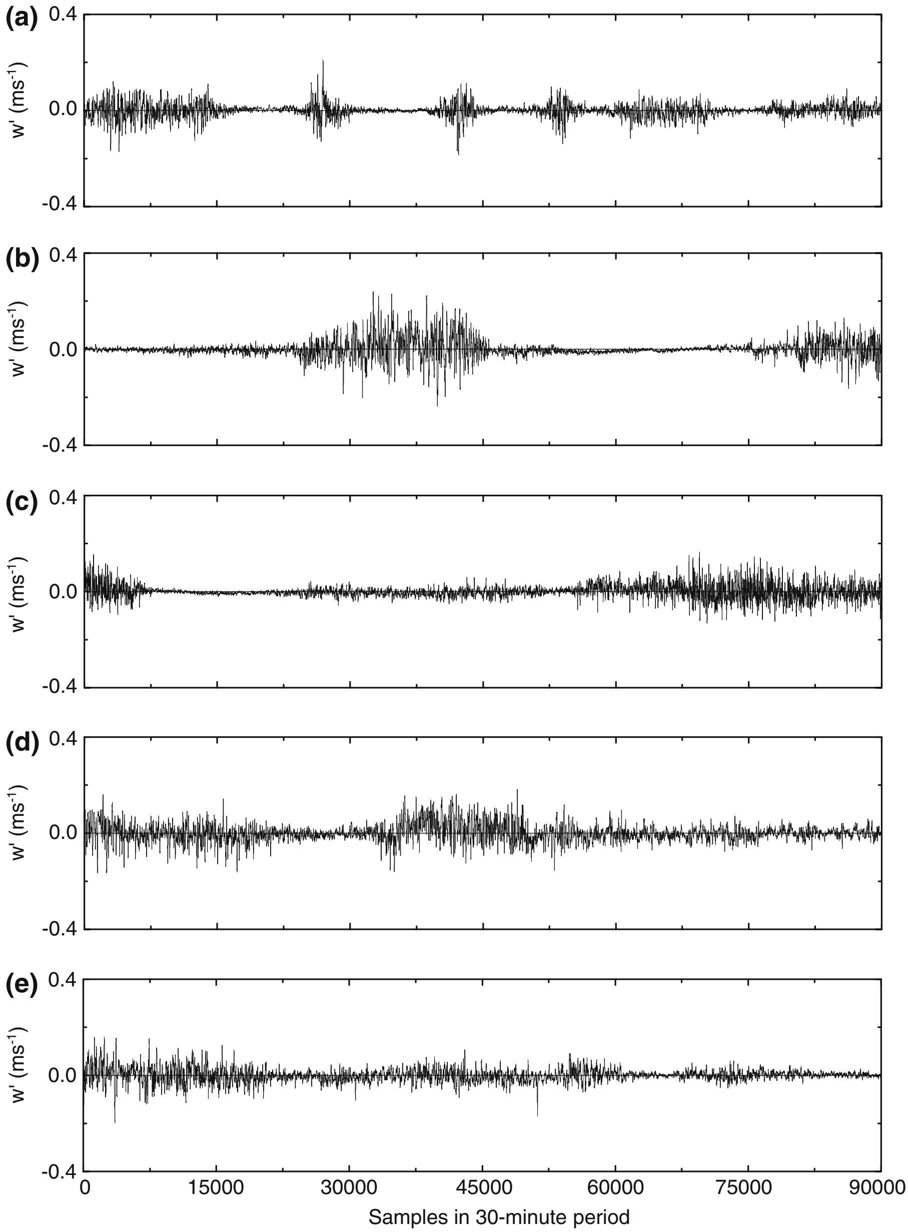


Fig. 4 Time series of linearly detrended vertical velocity (w) sampled at 50 Hz but smoothed here with a 50-point running mean. Cases (**a**) through (**c**) show runs (45, 101 and 167) that are characterized by quite well-defined intermittent turbulence, while (**d**) and (**e**) show runs (162 and 216) that have less defined "intermittent events"

The normalized mean cumulative fractions of runs classified as stationary (322 runs) and nonstationary (246 runs) in stable conditions compared to the cumulative 30-s intervals required to achieve that fraction are shown in Fig. 5. The cumulative fractions for the five case studies shown in Fig. 4 are also included in Fig. 5. The ensemble IF for stable, stationary conditions is 0.34, which is at the point where the

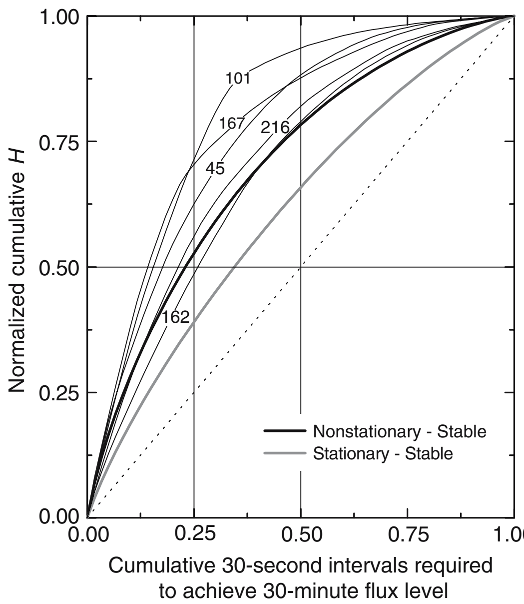


Fig. 5 Cumulative normalized fraction of an ensemble 30-min interval of H as a function of number of seconds (normalized) within the interval. The dashed line running through the centre of the figure from each corner is the value that H would take if continuously turbulent. The bold black (grey) line is the mean value for all stable nonstationary (stationary) runs. The thin labeled black lines show the case study runs from Fig. 4

bold grey curve intercepts the 0.50 value on the y-axis (Fig. 5). On average, 50% of the total flux in stable, nonstationary conditions is realized in 22% of the total sampling time. Intermittency thus appears to be a more important characteristic of turbulence in stable, nonstationary runs than stationary runs at Summit. The IF values of the case study runs (Fig. 5), which range from 0.15 to 0.27 (Table 2), support this conclusion.

The number of runs that have IF values below 0.20 account for about one third (31%) of all nonstationary cases in stable conditions. Features that are typical of intermittent turbulence, episodes of turbulent activity separated by quiet periods, are easily identified by visually inspecting runs that have IF values below 0.20. The stable, nonstationary runs that have IF values between 0.20 and 0.30 also show features typical of intermittent behaviour but are less defined by weak and patchy turbulence, as observed in Fig. 4d–e. Given that 78% of all stable, nonstationary runs have IF values below 0.30, intermittency appears to be one important way in which nonstationarity can occur. Though we do not fully understand the mechanisms that trigger intermittent turbulence at Summit, Fig. 6 shows there is a linear dependence of IF on wind speed, with a correlation coefficient of 0.85 observed in stable conditions ($z/L < 1$). Low wind speeds in very stable conditions lead to small IF values. Such conditions are common when the sun is closest to the horizon at Summit during the summer months. Thus, the mechanisms that trigger intermittent turbulence are more likely to occur when winds are weak and irregular at Summit, which is more common at this site than at lower elevations on the Greenland ice sheet.

While the purpose here is to demonstrate that intermittency is an important part of stable ABL processes at Summit, especially during runs that are defined as nonstationary, care must be taken when comparing intermittency fractions determined here with those in other studies. For example, if nonstationarity is not taken into account and 12-h periods are used to determine IF values, where 1-min fluxes within this interval are ordered according to their magnitudes, intermittency fractions are smaller and compare well to those calculated by Coulter and Doran (2002), who used

Table 2 Descriptive statistics for each case study run (defined as 30-min interval). All runs are classified as nonstationary

	run 45	run 101	run 167	run 162	run 216
hour (UTC)	2300	0130	0000	2130	0130
horizontal wind speed (m s^{-1})	2.1	1.78	1.89	1.33	1.81
z/L	0.39	0.49	1.23	0.28	1.48
H over 30-min run	0.92	3.17	8.07	2.20	4.59
σ_w over 30-min run	0.053	0.059	0.063	0.057	0.050
IF	0.183	0.167	0.150	0.267	0.217
$f_{\text{turb}}(H)$	0.25	0.33	0.22	0.31	0.27

The methods to calculate IF and $f_{\text{turb}}(H)$ are given in the text

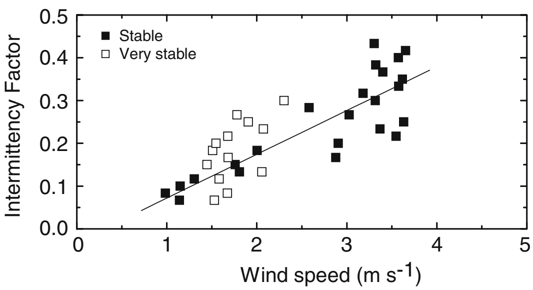


Fig. 6 The dependence of intermittency fraction (IF) on horizontal wind speed at 2 m above the surface during stable conditions. Each value is a binned wind speed for a given intermittency fraction. Stable cases (black squares) are all stable cases below $z/L = 1$, while very stable cases (white squares) are those for $z/L > 1$. The solid line is a linear fit to the stable cases

this approach. If 30-min periods are maintained but the number of fluxes calculated within the interval increased, IF values also decrease in magnitude.

As noted by Doran (2004) the disadvantage of using an approach that depends on an intermittency fraction is that if a sampling period has a turbulence level that is high, then the intervals identified as the quiescent portions of that period may still have significant turbulence. The opposite may also be as likely, where a run may have low overall turbulence and a period that is identified as having turbulent bursts may show very little actual turbulence. To avoid this issue a flux threshold can be assigned to each interval and events can be characterized as those periods exceeding the value of the threshold (Doran 2004). Table 2 shows turbulent event fractions (f_{turb}) calculated using a flux threshold of 0.005 (K m s^{-1}) for the five case studies (30-min runs). Even though the flux threshold for H is very small, the fraction of events exceeding this magnitude only ranges between 0.22 and 0.33 (Table 2).

If all stable f_{turb} data are plotted against flux magnitude (not shown), then a linear decrease in f_{turb} values as average fluxes tend toward zero is also observed, as demonstrated by Doran (2004). One limitation of using a flux threshold is that it may not necessarily identify a turbulent event but only show that a certain level of turbulent activity has been exceeded. However, Doran (2004) argues that if event thresholds are changed, the relationship between f_{turb} and average fluxes is retained, which supports using this approach to characterize intermittent turbulence.

Rather than defining a certain "threshold" of turbulent activity at Summit it seems as logical to characterize the duration of "quiet" periods to help explain the occurrences of nonstationarity. The duration of quiescent periods with little or no turbulent activity can undoubtedly be expressed in a number of ways (e.g. values below an event threshold) but for our purposes here we have chosen a simpler approach. We use the standard deviation of the vertical wind component (σ_w) over an averaging interval as an indicator of whether turbulent activity is suppressed. For example, 22% of all nonstationary runs at Summit have a mean value of σ_w below 0.05 m s^{-1}, and of those 98% have IF values below 0.30. If the σ_w threshold is increased to 0.1 m s^{-1}, then 50% of all nonstationary runs are accounted for and IF values below 0.30 remain high (90%). Thus, if σ_w is below 0.05 m s^{-1} over the duration of an averaging period at Summit, it is very likely that turbulence will be characterized by extended quiescent periods and intermittency of turbulence is likely. We recommend using a σ_w threshold as a first approach in determining the likelihood of intermittency in an environment such as Summit.

6 Occurrences of nonstationarity in unstable conditions

One third of all runs in unstable conditions at Summit are nonstationary, and even though this proportion is smaller than in stable conditions (43%) it is still surprisingly large and warrants further explanation. Figure 7 shows the fraction of nonstationary runs in both stable and unstable conditions as a function of horizontal wind speed. Clearly, there is a tendency for a large proportion of runs to be nonstationary at low wind speeds in stable conditions (as discussed in the previous section). In contrast, the peak in nonstationarity in unstable conditions is at higher wind speeds. The highest wind speeds were associated with synoptic conditions in 2001 that brought variable cloud cover over the Summit region. Rather than the high wind speeds being the cause for the peak in nonstationarity of H we believe that changes in radiation fluxes at the surface controlled by the variability in cloud cover are responsible.

To demonstrate the cloud forcing effect, Fig. 8 shows an unstable 30-min averaging period (run 746) characterized by high wind speed conditions (7.5 m s^{-1}) and broken, low level stratus cloud cover. The net all-wave radiation receipt at the surface is controlled primarily by variability in longwave incoming radiation (Fig. 8a), which is indicative of variability in cloud cover aloft. Changes in net all-wave radiation in response to the cloud forcing is responsible for the variability in H over the same interval (Fig. 8b). Fluctuations in H over this short time interval result in the run being classified as nonstationary. Interestingly, the net radiative effect of clouds is positive at Summit during all hours of the day (Starkweather 2004). The effect is largest in the afternoon, when a 100% change in cloud cover yields a 40 W m^{-2} increase in the net all-wave radiation flux at the surface. We propose that this forcing during unstable conditions at Summit can also lead to nonstationarity in H.

As shown in Fig. 3, a large proportion of runs are classified as nonstationary during the transition from one stability regime to the other. Because the ABL at Summit has a distinct diurnal trend in summer it is to be expected that issues related to nonstationarity of H should arise. Figure 9 shows a typical transition from stable to unstable conditions in response to changes in the net all-wave radiation; while the mean flux (H) over the 30-min run is −1.25 W m^{-2}, Fig. 9 clearly shows the transition from stable to unstable conditions. The increase in net-all wave radiation (white circles) during this time is responsible for the change in the sign of H (change in stability of the ABL) (Fig. 9). Not surprisingly, the distinct trend in the time series of H over the averaging interval resulted in the run failing our test of stationarity.

The number of runs that have a change of sign in H (change in direction) within an averaging interval if partitioned into 60-s sub-intervals is 309, or 29% of the total number of available runs. The percentage of changes in the sign of H for all runs is

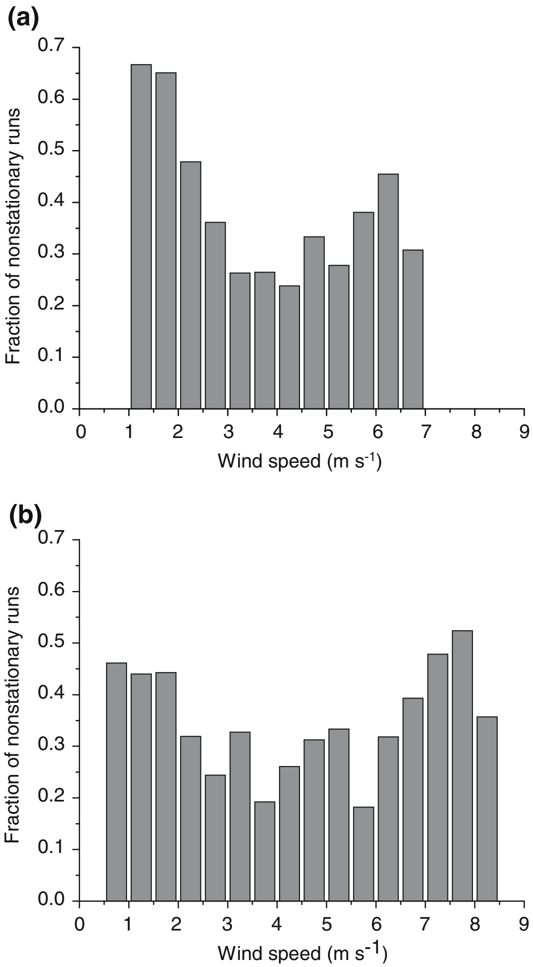


Fig. 7 Bins of wind speed versus fraction of nonstationary runs in (**a**) stable and (**b**) unstable conditions. Each wind speed bin is of length 0.5 m s^{-1}

quite high not only because of the diurnal trend in stability, but at nighttime (when the sun is close to the horizon) at Summit, the magnitude of H can be very close to zero, which results in some brief occurrences of small heat transfer away from the surface (negative H). Periods when there is a greater than 50% chance of a change in sign of H are between 0930–1130 and 1900–1930 UTC. The fraction of cases that are nonstationary during these periods is on average 0.65. Thus, the occurrence of nonstationarity runs is high during transition periods. At these times, values of H are not only very small (positive and negative values of H cancel) but also often have a trend (change in sign) that leads to nonstationarity.

7 Conclusions

In this study we have described several ways in which nonstationarity can occur at Summit, Greenland. We felt that this step was necessary in order for others to properly measure and interpret turbulent flux measurements at this site or at other similar

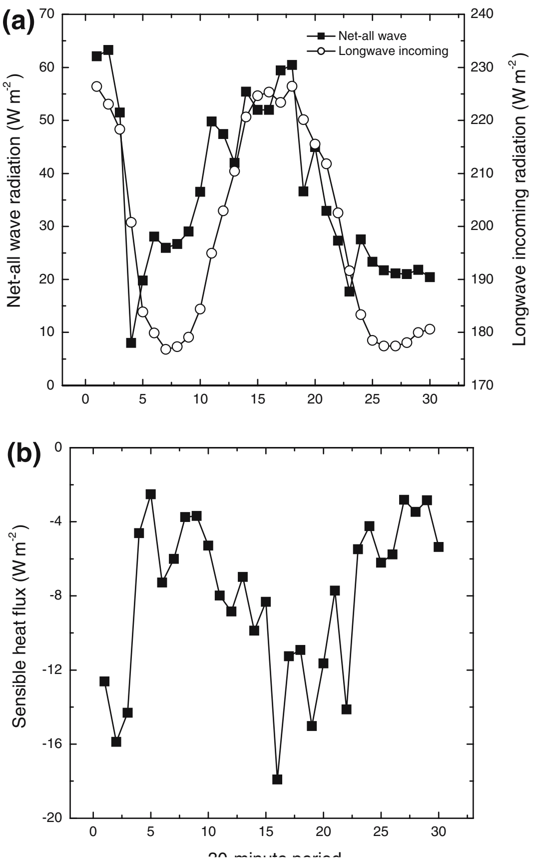


Fig. 8 A 30-min run on June 17, 2001 at 1730 UTC showing 1-min averages of (**a**) net-all wave and longwave incoming radiation and (**b**) *H*

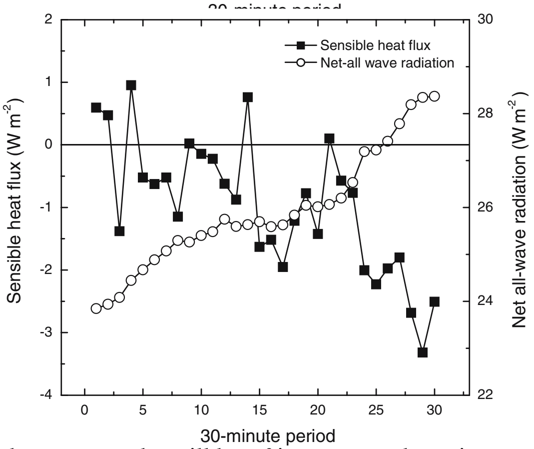


Fig. 9 An example of a change in sign of *H* (black squares) over a 30-min averaging interval (June 18, 2001–1100 UTC). The change from a stable to unstable atmosphere is typical of the morning at Summit

locations. In particular, we hope that our results will be of interest to those interested in calculating fluxes of chemical species at Summit. By identifying some of the unique characteristics of the ABL at this site, problems associated with the interpretation of photochemical processes may be more easily overcome. The main findings described in this study are as follows:

1. A stationarity test applied to all available runs shows that about 40% of the data are classified as nonstationary. However, the fraction of runs classified as nonsta-

tionary is sensitive to the length of the averaging interval chosen. The main factors contributing to the high number of nonstationary runs are: (1) intermittency of turbulence in stable conditions, (2) changes in net all-wave radiation receipt in response to cloud forcing, and (3) diurnal trends in stability.

2. A classification procedure that accounts for the intermittent nature of turbulence shows that during nonstationary runs 50% of the total flux is realized in 22% of the sampling time in stable conditions. A linear dependence of the intermittency fraction on wind speed is found, which suggests that the mechanisms that generate intermittent turbulence coincide with weak and irregular winds at Summit.
3. A flux threshold can also be used as a method to determine the duration of intermittent events. An even simpler approach is to use the standard deviation of the vertical wind component (σ_w), and it is likely that turbulence will be characterized by extended quiescent periods, separated by turbulent activity, if σ_w is below $0.05\,\mathrm{m\,s^{-1}}$ over an entire averaging interval at Summit.
4. Rapid changes in net all-wave radiation in response to cloud forcing result in variability in H within small time intervals (minutes), and fluctuations in H over small time scales in response to this cloud forcing result in nonstationarity. The number of nonstationarity runs is also high during transition periods from one stability to the other. Changes in the sign of H are most common between 0930–1130 and 1900–1930 UTC, with nonstationarity of runs during these periods typically as high as 65%.

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