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Transition to Turbulence in Shear above the Tropopause

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[1] Airborne measurements were conducted above the UK during May and June 2000 in order to investigate turbulence and mixing in the tropopause region. Measurements of temperature frequently exhibited a periodic series of ramps that resembled a sawtooth pattern. These repeating structures were only observed in or near patches of intense shear-generated turbulence associated with the jet-stream. In each observed case the temperature ramps had the same orientation with respect to the wind shear. The temperature increased gradually in the direction of the shear, dropped suddenly, and the pattern repeated with wavelengths of about 1 to 1.2 km. Numerical simulation was applied to demonstrate that the observed temperature ramps are a signature of growing Kelvin-Helmholtz waves that are just beginning to overturn in transition to turbulence. The fluctuations in wind became increasingly three-dimensional along the direction of the shear with coherent oscillations that are consistent with the shear-aligned vortices found in laboratory experiments and numerical simulations. *INDEX TERMS:* 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 3379 Meteorology and Atmospheric Dynamics: Turbulence; 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Whiteway, J. A., G. P. Klaassen, N. G. Bradshaw, and J. Hacker (2004), Transition to Turbulence in Shear above the Tropopause, *Geophys. Res. Lett.*, *31*, L02118, doi:10.1029/2003GL018509.

1. Introduction

[2] Air in the tropopause region is mixed by a variety of dynamical processes that range in scale from thousands of kilometres to millimetres: from planetary waves to small-scale turbulence. This mixing plays a substantial role in determining the chemical composition of the upper troposphere and lower stratosphere. For example, sub-tropical tropospheric air with low ozone content is transported laterally into the mid-latitude stratosphere by planetary wave breaking [*Chen*, 1995] and irreversible mixing is ultimately achieved through small-scale turbulence. The rate at which mixing is achieved depends on the amount of irreversible small-scale turbulence and this influences the impact of chemical reactions between species that have different origins [e.g., *Thuburn and Tan*, 1997; *Balluch and Haynes*, 1997]. An accurate quantification of the mixing is required to understand and predict changes in ozone within the lower stratosphere, and this will require advancement in our understanding of the various dynamical processes and their interaction over a broad range of scales.

[3] During May and June 2000, an airborne measurement campaign was conducted over the UK to observe the nature of mixing in the tropopause region. This has provided insight into the dynamics of mixing over the full range of scales involved. For example, large-scale filamentation, associated with planetary wave breaking, was observed between sub-tropical and polar air masses in the flight of 5 June 2000 [*Bradshaw et al.*, 2002]. On the following day, a flight through the same meteorological pattern observed evidence for substantial mixing by small-scale turbulence at the tropopause [*Pavelin et al.*, 2002]. Here we report on an intriguing observation in the latter flight: the temperature exhibited a striking series of ramps forming a sawtooth pattern within and near patches of intense shear generated turbulence. These coherent structures have scales in the energy input range of turbulence and are likely associated with motions in the process of transition to turbulence.

[4] Temperature sawtooth patterns, or ramps, are already known to be a common characteristic of turbulence in the atmospheric boundary layer [e.g., *Antonia et al.*, 1979] and also in the laboratory [e.g., *Gibson et al.*, 1977]. The temperature ramps in the boundary layer have mainly been associated with convection [e.g., *Williams and Hacker*, 1992], and there have been no previous reports of temperature ramps in other regions of the atmosphere. Here we present high-resolution measurements in shear-generated turbulence just above the tropopause. Temperature ramps are found in this turbulence that have a much more coherent pattern than the previously reported observations in the boundary layer. Numerical simulation is applied here to show that the observed ramp patterns are a signature of Kelvin-Helmholtz waves developing in the transition to turbulence.

2. Measurements

[5] The measurements were carried out using the Grob G520T 'Egrett' high altitude research aircraft. This is a former reconnaissance aircraft that is now operated for atmospheric research by Airborne Research Australia (http://ara.es.flinders.edu.au). It has the unique ability to fly at heights of up to 15 km at a relatively slow airspeed of 100 m/s. This study makes use of measurements with a turbulence measurement system on-board the Egrett. Temperature was measured with a Rosemount PT50 platinum-wire at a 20 Hz sampling rate (5 m horizontal resolution).

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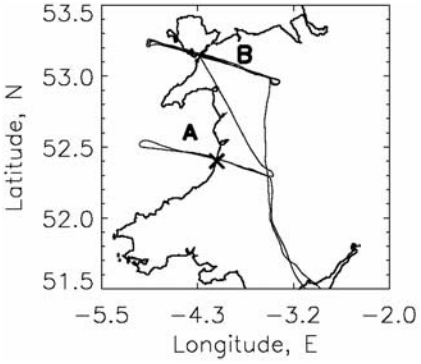

Figure 1. Egrett flight track above Wales on 6 June 2000. Flight track-A corresponds to the measurements shown in Figures 2 and 3.

Wind velocity was measured with two separate turbulence probes installed under either wing of the aircraft. One was a standard 5-hole Rosemount probe and the other was a recently developed BAT probe [*Hacker and Crawford*, 1999; *Crawford and Dobosy*, 1992]. The BAT probe measurements are being presented in this paper. Correction for aircraft velocity and orientation made use of on-board GPS receivers and high-frequency accelerometers [*Crawford and Dobosy*, 1997]. The wind was measured accurately to within 10 cm/s in the horizontal and 15 cm/s in the vertical. Wind measurements were acquired at a rate of 55 samples per second, corresponding to a horizontal resolution of about 2 m. Such a capability for resolving both waves and turbulence within the stratosphere is unprecedented.

[6] On June 6, 2000 the Egrett made several horizontal flight legs above Wales at heights ranging from 9 to 13 km along the tracks shown in Figure 1. This study is concerned with flight leg-A, above mid-Wales and Cardigan Bay, where a patch of intense turbulence was encountered. The flight direction was oriented parallel to the wind, which was dominated by a strong jet stream. Figure 2 shows the vertical profiles of temperature and horizontal wind measured on a vertical ascent parallel to flight leg-A. A shear layer with Richardson number (Ri) less than 1/4 was encountered at a height of 11.4 km and the Egrett then proceeded to conduct a horizontal flight leg at this level.

[7] Figure 3a shows the measurements of potential temperature, wind, and turbulent kinetic energy along flight leg-A. The wind was toward the southeast, decreasing with height, and the vertical shear is orientated from right to left in Figure 3, along the flight track, as indicated by the bold arrow. A patch of intense turbulence was encountered between the distances of 50 and 70 km while there was moderate turbulence throughout the remainder of this flight leg. Figure 3b focuses on the 50 to 58 km region where the turbulence is developing. The measured temperature exhibits a striking series of ramps that resemble a sawtooth pattern. Temperature increases gradually over a distance of about 1 km in the direction of shear, falls rapidly within 200 m, and then the pattern repeats. Neither of the three wind components exhibits a similar pattern. The only consistent correlation is with the zonal wind component - the one with the dominant shear. There is a peak in the zonal wind where the temperature has a minimum. There appears to be no direct correlation between the temperature ramps and the vertical wind. Similar patterns were observed on several different flights that encountered intense turbulence.

3. Discussion

[8] The turbulence observed here was generated in a stably stratified shear layer with Richardson number less than 1/4 over a vertical width of about 100–300 m (Figure 2). The transition to turbulence involved a sawtooth wave pattern in temperature with a wavelength of 1.0 to 1.2 km. The most well-known process for the transition to turbulence in such conditions is the Kelvin-Helmholtz (K-H) instability [e.g., *Thorpe*, 1969; *Browning et al.*, 1973; *Drazin and Reid*, 1981]. This involves the development of unstable waves that break into turbulence by overturning. In what follows, we will demonstrate that when these waves are in the early stages of overturning the perturbation in temperature along a line through the middle of the shear layer will exhibit a sawtooth pattern.

[9] We performed simulations of K-H waves using a 2-dimensional numerical model similar to that of *Klaassen and Peltier* [1985a]. Figure 4 shows the simulated temperature perturbation along a horizontal line through the middle of a shear layer where K-H waves are starting to overturn. This clearly bears a strong resemblance to the measurements shown in Figure 3. Temperature increases gradually in the direction of shear, drops quickly, and this would repeat in a series of ramps that form a sawtooth pattern. The gradual temperature ramp occurs where the wave is just starting to overturn. Here the potential temperature surfaces are bending over to form a horizontal gradient. This region will become the central core of the K-H billow. The temperature then abruptly drops while crossing the region of concentrated temperature gradient where the temperature surfaces are sloping upward in the direction of shear - the braids. The pattern would repeat in adjacent K-H wavelengths.

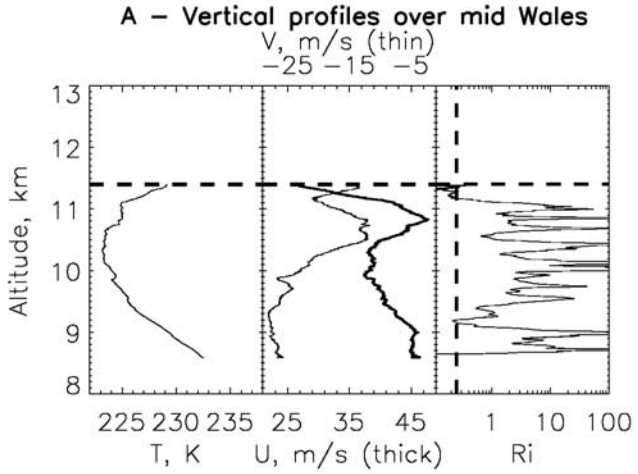

Figure 2. Temperature, wind and derived Richardson number profiles measured on the Egrett as it ascended above mid-Wales along flight track-A in Figure 1. The horizontal dashed line shows the height of the Egrett in the flight leg shown in Figure 3. The vertical dashed line indicates a Richardson number of 1/4.

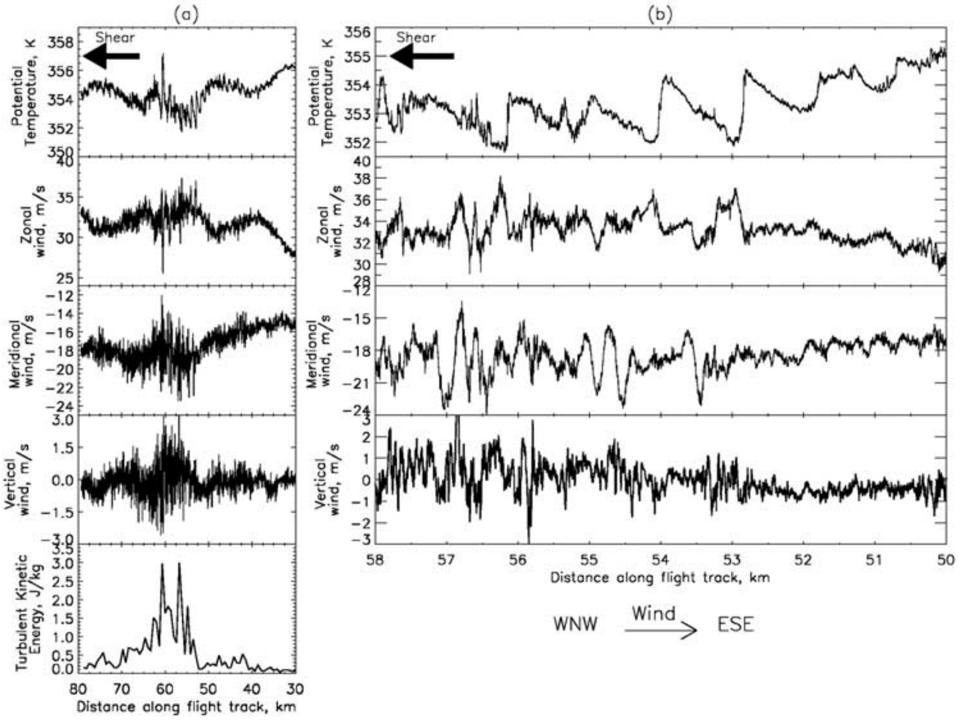

Figure 3. (a) Measurements along flight leg-A (height 11.4 km) of temperature, wind, and the turbulent kinetic energy (calculated as half the sum of the variance in the three wind components, using 1 km averaging windows). (b) An expanded view of the portion of the flight where there were clear sawtooth patterns observed in temperature. The wind direction is from left to right, while the vertical shear is in the opposite direction (wind decreasing with height), as indicated by the arrows.

[10] It is straightforward to explain why the peaks in zonal wind are observed to correspond with minimum temperature. This is the position of maximum upward displacement and the wave has transported faster moving air upward. The observed correlation between horizontal wind and temperature is not as direct as in the simulation. This could be because the vertical profiles of horizontal wind and temperature used in the simulation were different from what the Egrett was flying through. It was not possible to measure the vertical profile of wind while flying horizontally but it is likely that the shear changed substantially along the horizontal flight track. Note the changes in each wind component along the flight track in Figure 3a. The difference could also be due to the lack of 3-dimensional turbulent structures in the 2-dimensional simulation.

[11] The meridional wind did not have any correlation with the temperature ramps and this is likely because there was not as much shear in this component. Nearby radar and radiosonde measurements at different times showed that the shear in the meridional wind component was much smaller than in the zonal component. This is not obvious in Figure 2 because the vertical ascent stopped at the height of the shear layer and at a different location.

[12] It was initially puzzling that the observed vertical velocity exhibited no obvious features corresponding to the sawtooth structures in temperature and horizontal velocity; e.g., one would expect the overturning motion in the billow core to induce upward motion in the right part of the billow core, and downward in the left. The reason for this lack of observed correlation was determined by running several simulations with different Richardson numbers. It was found that with weak stratification ($Ri < 0.1$) the KH waves induced large perturbations in the vertical velocity that would have been observed. However, stronger stratification ($Ri > 0.2$) gives a flattened billow, in which the vertical velocity is suppressed. This is the case for the simulation shown in Figure 4; the value $Ri = 0.22$ is consistent with our best estimate that the minimum Richardson number of the shear layer lies in the range $0.2 < Ri < 0.25$. The billow grows and overturns slowly, so the temperature sawtooths persist for a much longer time than they do at lower values of Ri. This explains why the observed vertical wind perturbation associated with the KH wave is very weak, and is masked by turbulence in the measurements. This turbulence could be associated with instability in the statically unstable region of the wave, or it could be fossil turbulence left over from previous events.

[13] Recent investigations of Kelvin-Helmholtz instability have found that the transition to turbulence involves vortices that are elongated along the direction of shear and wrap around the overturning billows. This was originally anticipated by *Klaassen and Peltier* [1985b], and has since been demonstrated in both the laboratory [*Thorpe*, 1985; *Showalter et al.*, 1994] and numerical simulations [e.g., *Palmer et al.*, 1996]. We would expect to see this process manifested in the airborne measurements as three-dimensional motion developing along the direction of shear, initially as coherent oscillations of the cross-shear component of the wind. Assuming that the flight path does not cut a substantial angle across the shear-aligned vortices for the

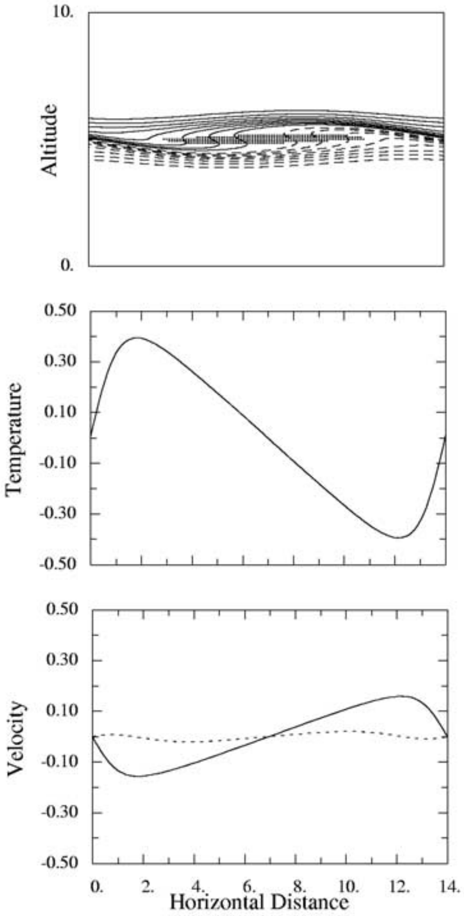

Figure 4. Top: Potential temperature contours from a numerical simulation of an overturning K-H wave with minimum Richardson number 0.22. The shading indicates the statically unstable region at the core of the billow. Middle: Variation of the temperature along a horizontal path through the middle of the K-H wave. Bottom: Variation of the horizontal (solid) and vertical (dashed) velocity along the same horizontal path. Lengths are scaled by the half-depth of the shear layer; potential temperature is scaled by half the potential temperature difference across the layer; velocities are scaled by half the horizontal velocity difference.

present case, oscillations would be observed first in the meridional wind component. The measurements shown in Figure 3b are consistent with this. There were oscillations in the meridional wind component with a wavelength of about 400 m at distances of around 53.5 km, 54.5 km, and 57.0 km. Oscillations with a similar scale were also found in the sawtooth patterns observed in other Egrett flights.

4. Conclusions

[14] High-resolution airborne measurements have been used to investigate the transition to turbulence in shear above the tropopause. It has been found that the measured temperature exhibits a sawtooth wave pattern near the edge of a patch of intense turbulence. We have interpreted this as being caused by Kelvin-Helmholtz waves. Numerical simulation was applied to demonstrate that a sawtooth structure would be induced when the waves are starting to overturn. The airborne measurements also indicate the development of three-dimensional motions that are consistent with the shear-aligned vortices found in laboratory experiments and numerical simulations of Kelvin-Helmhotz instability.

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