Break-up of a stratospheric streamer observed by MST radar

By G. VAUGHAN* and R. M. WORTHINGTON
University of Wales, Aberystwyth, UK

(Received 25 August 1999; revised 29 December 1999)

SUMMARY

The break-up of a stratospheric streamer over the British Isles is described, using satellite, Mesosphere–Stratosphere–Troposphere (MST) radar and in situ observations together with European Centre for Medium-Range Weather Forecasts analyses. The streamer started as a thin ribbon of high potential vorticity to the west of the British Isles. As this was strained by the background flow it broke up into a series of mesoscale vortices. MST radar and ozonesonde observations delineated a tropopause fold to the west of the initial streamer, taking the form of a thin layer of stratospheric air embedded in a deep layer of descending upper-tropospheric air. The fold appears to have been mixed out by small-scale turbulence as the streamer broke up. This break-up also generated strong inertia-gravity waves, which broke just above the tropopause introducing extensive mixing to the lowermost stratosphere. One of the mesoscale vortices returned over the MST radar, showing a very indistinct tropopause typical of a synoptic-scale cut-off low. This vortex was also responsible for the development of a rain band on its eastern flank, which brought significant rainfall to the British Isles at a time when the synoptic flow pattern was strongly anticyclonic.

KEYWORDS: Atmospheric dynamics Potential vorticity Tropopause

1. INTRODUCTION

When stratospheric air is transferred into the troposphere, it brings with it high ozone and potential-vorticity (PV) values and very low humidity. Each of these properties has significant effects in the troposphere: ozone is an essential ingredient of tropospheric chemistry (through production of O(^1D) and hence OH); both water and ozone are radiatively active gases; and dry, PV-rich air intruding into fronts can result in severe weather, e.g. squall lines (Browning and Golding 1995), frontal rain-band intensification (Browning and Roberts 1994), severe surface winds (Browning and Reynolds 1994) and cyclogenesis (Gronas and Kvansto 1995). Although the overall flux of stratospheric air into the troposphere is now believed to be controlled by the wave-induced meridional circulation in the mid-stratosphere (Holton et al. 1995), the dynamics at tropopause level control the occurrence and intensity of individual exchange events. Crucial to an improved understanding of such events is better observation of the vertical and horizontal structure of stratospheric intrusions into the troposphere, for comparison with models. We report here on a case-study using a Very High Frequency (VHF) radar, which measured winds, echo power and turbulence during the passage of an intrusion, with a height resolution of 300 m.

Stratospheric intrusions are usually defined as incursions of stratospheric air to altitudes normally considered tropospheric. This definition includes distortions of the tropopause, when basins or streamers of stratospheric air are drawn isentropically off the polar reservoir by baroclinic processes (e.g. Appenzeller et al. 1996), as well as tropopause folds, where a tongue of stratospheric air extends downwards into the troposphere (Danielsen 1968; Keyser and Shapiro 1986; Danielsen et al. 1987; Browell et al. 1987). Folds are found along the flanks of a typical intrusion, and promote mixing of stratospheric and tropospheric air through the increased area of the interface and the often turbulent nature of upper-level fronts (Shapiro 1980; Kennedy and Shapiro 1980; Pepler et al. 1998). They form in the frontal zone beneath a jet stream, typically one flowing in a southward or south-eastward direction along the flank of an upper-air

* Corresponding author: Department of Physics, University of Wales, Aberystwyth, Ceredigion SY23 3BZ, UK.

1751
trough (e.g. Vaughan et al. 1994). Ageostrophic motion at the jet entrance forces ozone-rich, high-PV air into the frontal zone, some of which transfers into the troposphere and some of which returns to the lower stratosphere at the jet exit as the direction of the ageostrophic circulation reverses.

The distribution of tropopause folds is well documented in the literature (e.g. Van Haver et al. 1996; Beekmann et al. 1997; Elbern et al. 1998), but less attention has been paid to the fate of the stratospheric air once transferred into the troposphere. Filamentation and mixing breaks up the coherent laminae emerging from folds, leaving patches and streamers of air which gradually acquire tropospheric chemical and dynamical signatures. This does not happen immediately: ozonesonde profiles in midlatitudes in winter reveal a plethora of dry, ozone-rich layers, usually about 0.5–1.5 km thick. Since chemical production of ozone in the troposphere is largely dormant in winter, all of these layers must have originated in the stratosphere. Some are clearly linked to jet streams (and hence tropopause folds), but many are not (Beekmann et al. 1994; Oltmans et al. 1996). Some of the latter display the anomalous PV expected of their source region: away from the jet stream this is evident as enhanced static stability. However, there is no clear relationship between static stability and ozone mixing ratio in these layers, and extremely dry, ozone-rich air may be found with tropospheric values of PV (Bithell et al. 2000). This implies that stratospheric air within the troposphere loses its dynamical characteristics (PV) more quickly than its chemical characteristics (O₃, H₂O).

Stratospheric intrusions can be observed on upper-tropospheric PV charts or in satellite water vapour images (Appenzeller and Davies 1992). The low-tropopause characteristic of the non-folded part of an intrusion presents a column of very dry air to the satellite sensor at altitudes above about 5 km. The radiation sensed by the satellite therefore passes unhindered from the warm lower troposphere, making a streamer appear dark on a (negative) infrared image. Appenzeller and Davies showed how the superior horizontal resolution of the satellite image captures details of the roll-up of a streamer that conventional meteorological analysis cannot represent. Using such images, Appenzeller et al. (1996) described the typical evolution of an intrusion in the northern hemisphere through the formation of a ‘y’ shape, with the shorter branch connecting to the stratospheric reservoir and the longer typically aligned with a cold front. They presented two basic paradigms for its subsequent evolution (see also Thorncroft et al. (1993)):

(i) the longer branch of the y is stretched by background anticyclonic shear into a ribbon of high PV extending south or south-westwards from the main polar PV reservoir. The ribbon is initially stable (Dritschel et al. 1991) because of the background shear but eventually rolls up into separate mesoscale and synoptic-scale vortices in which stratospheric and tropospheric air are horizontally mixed.

(ii) the north-east tip of the y rolls up cyclonically to form a large-scale vortex above a surface cyclone.

A detailed study of the break-up of a type (i) intrusion was presented by Browning (1993), based on satellite images and UK Meteorological Office Unified Model products. In this case a strip of high PV at tropopause level, roughly 500 km wide, broke up into three mesoscale vortices about 900 km apart. The model was able to represent this event correctly, even though it occurred over the Atlantic, well away from the conventional observing network. One of the mesoscale vortices tracked towards the British Isles and eventually developed some high cloud on its eastern flank. Anticyclonic conditions prevailed on the synoptic scale, and the mesoscale vortex developed no
significant precipitation. In this paper we report on a very similar event which occurred between 7 and 9 March 1997, also during anticyclonic conditions, but which did result in precipitation. In this case the streamer passed over the Mesosphere–Stratosphere–Troposphere (MST) radar at Aberystwyth, Wales (52.4°N, 4.0°W) (Slater et al. 1991), giving a detailed view of its internal structure and associated mixing. As in Browning’s (1993) case, an operational model (in this case from the European Centre for Medium-Range Weather Forecasts (ECMWF)) captured the overall development of the streamer very well, and for this reason we focus here on the small-scale and mesoscale structure of the intrusion and the inertia-gravity waves that accompanied it.

2. SYNOPTIC DEVELOPMENT OF THE STREAMER

At 00 GMT 7 March 1997 the synoptic pattern was dominated by a deep low (955 mb) over Iceland, with high pressure over continental Europe and at 40°N, 40°W. A weak front extended from the Icelandic low south towards north-west Ireland and then south-westwards towards the Azores. During the 7th the low moved north-eastwards over the Norwegian Sea and the front moved eastwards and weakened. By 00 GMT on the 8th high pressure extended from the Azores towards Ireland. This anticyclone was centred over the British Isles at 12 GMT on the 8th and moved slowly eastwards, being centred over Germany and Denmark by 12 GMT on the 9th. The predominantly anticyclonic flow over the British Isles at 12 GMT on the 8th is illustrated by the 700 mb chart shown in Fig. 1.

Also shown in Fig. 1 is a cyclonic feature between Spain and the Azores, which corresponds to a cut-off low at 300 mb. This low cut off from a trough which extended south-westwards behind the front on 7 March. The 300 mb chart for 8 March also shows a shallow low over southern England which moved slightly westward over the following 24 hours. In fact, as will now be shown, the cut-off low west of Portugal and the shallow low over England were part of a stratospheric intrusion which was breaking up into
Figure 2. Meteosat water vapour images for the period 7–9 March 1997, showing the evolution of the streamer. Dark shades denote high temperatures, i.e. dry air around 400 mb. Times are: (a) 06 on the 7th, (b) 18 on the 7th, (c) 06 on the 8th, (d) 18 on the 8th, (e) 06 on the 9th and (f) 18 on the 9th. All times are GMT.
independent vortices and bringing significant rainfall to the British Isles during a period of anticyclonic weather.

An overview of the development of the streamer is given in Fig. 2, which shows Meteosat water vapour images for 7–9 March 1997. The dark shades denote dry bands on the images. Initially (06 GMT on the 7th) a dry region was located at the tip of the 300 mb trough north-west of the Azores, behind the surface front. Over the subsequent 12 hours the dry region extended to the north-west, developing a very sharp eastern boundary about 300 km behind the surface front. This boundary passed over Aberystwyth about 0230 GMT on the 8th. By 06 GMT on the 8th the cut-off low had developed west of Portugal, and a clear spiral structure is seen in the streamer there. At this time the streamer extended as far as Norway and a wave began to appear over southwest England. Its wavelength of 900 km closely matched that described by Browning (1993). Over the next 12 hours this developed into a vortex, which stopped moving eastwards and began to move back towards Aberystwyth. By 06 GMT on the 9th three secondary vortices were clearly evident along 50°N between 15°W and 10°E, with the central one of these passing directly over Aberystwyth between 07 and 21 GMT on the 9th before tracking north to Scotland and ultimately over the North Sea to Sweden on the 10th. The vertical structure of the streamer on 8 March (before its fragmentation) is illustrated by a cross-section of specific humidity from the ECMWF analysis at 18 GMT 8 March, taken along the latitude of Aberystwyth, 52°N (Fig. 3). This shows an intrusion of very dry air in a tongue sloping westwards with depth—a tropopause fold.

The streamer corresponded to a ribbon of high PV extending from the polar reservoir to lower latitudes. This is illustrated for the 310 K surface in Fig. 4. The trough on 7 March is initially represented as a fairly broad tongue of stratospheric PV (~800 km wide) extending southwards at 25°W. At this time, only the tip of the tongue appears as a distinctive feature on the Meteosat water vapour. During the 7th the trough thinned and became aligned with the developing Meteosat streamer, the dark band corresponding
well to the ribbon of PV >1 PV unit (PVU). Its width at this time was ~500 km, again similar to that described by Browning (1993). Subsequent development saw the streamer fragment, leaving two remnants—one in the cut-off low west of Portugal, which persisted until 00 GMT on the 9th, and the other over the British Isles, which persisted until the early hours of the 10th. The development was similar at 320 K (not shown), except that on this surface the three small vortices around 50°N all appeared as more distinctive PV anomalies. During 9 and 10 March the westernmost small vortex weakened and moved eastward, being absorbed by the central vortex early on the 10th. The central vortex did not weaken (central PV remained in excess of 2 PVU at 310
and 4 PVU at 320 K) while moving northward to Scotland on the 9th and then rapidly eastward to reach Sweden by 18 GMT 10 March. The easternmost vortex initially moved westward to 0° longitude, then swivelled slowly northward to lie over the south-eastern tip of England by 12 GMT on the 10th.

The central vortex, which developed over the British Isles, caused widespread precipitation over the west of the country, as discussed later.

3. Structure of the intrusion on 8 March 1997 at Aberystwyth

Detailed profiles of the streamer as it passed Aberystwyth were measured by the MST radar, by radiosondes at Aberporth (40 km south-west of Aberystwyth) and by an ozonesonde launched from Aberystwyth at 1715 GMT on the 8th. The profile from the latter is shown in Fig. 5. At this time the leading edge of the streamer was over central England so the sonde was launched into its trailing edge (Fig. 2(d)). The sonde showed a remarkable structure: an extremely dry layer extending from 2.0 to 4.2 km, within which there was a thin layer of elevated ozone concentration extending from 3.0 to 3.4 km. Its extreme dryness, high ozone and high static stability mark this out as being a layer of stratospheric origin embedded in a deeper layer of tropospheric air.

Because of its anomalous static stability, the evolution of the stratospheric layer over Aberystwyth can be followed using the MST radar. The vertical echo power from a VHF radar is a function of the static stability and humidity gradient (see the appendix), with a negative-going humidity gradient reinforcing the effects of static stability, and a positive-going layer detracting from it. The vertical power measured by the radar is shown in Fig. 6(a), and a labelled summary of the salient features is given in Fig. 6(b). They can be identified as features on the radiosonde profile as follows:

L1 (2 km): base of dry layer; high stability and negative humidity gradient
L2 (3 km): stratospheric layer; very high stability
L3 (3.8 km): high stability layer within the dry layer, not stratospheric (no ozone excess)
L4 (4.2 km): top of dry layer; low stability and positive humidity gradient (power maximum up to 1000 GMT, minimum thereafter (see below for discussion of power maximum))
L5 (~5 km): high stability
L6 (6.8 km): stable, negative-going humidity
L7 (11 km): tropopause—increased stability
L8 (12–13 km): stable layer in the stratosphere.

The three layers L1, L4 and L2 therefore define the lower and upper boundary of the very dry layer and the position of the stratospheric layer as the intrusion passed over Aberystwyth. Confirmation of this analysis is obtained from the radiosondes launched at Aberporth on this day (Fig. 7): the stratospheric layer appeared on the first two soundings at 3.8 and 2.8 km respectively as a stable layer accompanying a decrease in absolute humidity. At 1715 GMT the layer at 3 km matches the ozonesonde and MST radar, but by 23 GMT the profile is different: the stable layer at 3 km marks the top of the low-level moist layer, and there is no second stable layer in the dry air.

The vertical echo power is shown again in Fig. 8(a), this time for the two days 8–9 March, together with other parameters measured by the radar. The wind speed (Fig. 8(b)) shows the passage of a sloping minimum-wind line between 01 and 04 GMT on the 8th, denoted by the ‘Z’ on Fig. 6(b), as the wind rotated sharply from south-westerly to north-easterly. This minimum-wind line merged with L2 at 04 GMT,
consistent with the passage of a PV anomaly which sloped down to the west from the axis of the streamer. At 10 km, along the streamer axis, the PV anomaly corresponded to a maximum in absolute vorticity, where the wind shear was greatest. As it descended, excess shear vorticity was replaced by excess static stability, as observed by the sondes. The radar was able to observe both the wind and static stability structure, and therefore tracked the entire PV anomaly as it advected over the site.
Figure 6. Vertical echo power measured by the MST radar on 8 March 1997: (a) actual measurement (dB) and (b) labelled sketch of salient features referred to in the text.
Figure 7. Absolute humidity (full line) and static stability (dashed line) measurements from the radiosondes launched from Aberporth (52.1°N, 4.6°W) at (a) 0515, (b) 1115, (c) 1715 and (d) 2315 GMT on 8 March 1997.
As the horizontal wind-shear anomaly was replaced by the stability anomaly, a strong vertical wind shear of up to 40 m s\(^{-1}\) km\(^{-1}\) appeared across the layer of stratospheric air (Fig. 8(c)). (Even stronger wind shear is seen at the tropopause, around 11–12 km, associated with the inertia-gravity waves prominent in the lower stratosphere at this time—see section 5.) This layer of wind shear can be tracked right through to 09 GMT on the 9th, and shows how the PV anomaly moved first away and then back towards Aberystwyth as the vortex over south-west England developed and moved northward (Fig. 2). The wind shear coincided with the layer of high power until 20 GMT on the 8th, after which the power feature merged into a general increase of power below 4 km. This indicates that after this time the wind shear corresponded to the top of the low-level moist layer.

The Aberystwyth radar can detect turbulence in two ways (Pepler et al. 1998): broadening of the vertical echo spectra and isotropy of the echoes around the vertical direction. The spectral width (corrected for beam broadening as described by Pepler et al.)
is shown in Fig. 8(d). Until 20 GMT on the 8th the stratospheric layer was marked by anisotropic echoes and narrow spectra, with sporadic turbulence around 04–06 GMT. However, an extensive layer of turbulence was seen at the position of L4—the interface between the descending dry air and the surrounding troposphere. Indeed, this layer corresponded to a maximum in power at this time because of the enhanced turbulent scatter. At 20 GMT the stratospheric layer became turbulent, which would cause it to mix with the surrounding tropospheric air. The 2315 GMT radiosonde from Aberporth, as previously noted, did not show a dry stable layer at 3.8 km (the altitude of the windshear maximum).

The combined radar and sonde measurements therefore show that the trailing edge of the streamer took the form of a tropopause fold—a layer of stratospheric air extending down into the troposphere. This layer was narrow—about 600 m in the radiosonde stability at 0530 GMT and 400 m in the ozone at 1730 GMT. It descended to about 3 km altitude by around 14 GMT, and ascended thereafter as the intrusion began to move back towards Aberystwyth. Either side of this layer was a much deeper layer of very dry air—4 km deep at 0515 and 2.5 km deep at 1730 GMT. The stratospheric layer exhibited little turbulence before 20 GMT, despite the sharp vertical wind shear across it, but the descending upper edge of the dry layer was turbulent between 04 and 08 GMT. After 20 GMT there is no evidence in the radiosonde or radar power profiles of the stratospheric layer, despite the fact that the intrusion was by then moving back towards Aberystwyth—the sonde humidity at 23 GMT, for instance, was generally >100 g kg⁻¹ in the dry air, in contrast to 50 g kg⁻¹ or less earlier in the day. The only remaining trace of the tropopause fold after 20 GMT on the 8th was the layer of enhanced wind shear.

4. Passage of the Mesoscale Vortex over Aberystwyth

During 9 March the secondary vortex which formed on the streamer over south-west England tracked northwards over the radar. During the first eight hours, the wind shear previously associated with the stratospheric layer was co-located with the inversion at the top of the low-level moist air. The Aberporth ascent at 05 GMT showed a layer of dry air between 4 and 5 km with low stability, corresponding to low power on the radar profile. No very dry, stable layers are evident in this profile—confirming that no stratospheric layer was observed, despite the return of the intrusion towards west Wales.

As the vortex reached Aberystwyth (08 GMT) the layer of high power at 11–12 km denoting the radar tropopause disappeared, and the troposphere showed a general monotonic decrease in radar power with height reminiscent of a cut-off low (Vaughan et al. 1995). This reflects the thermal structure of the vortex, confirmed by the 1115 GMT Aberporth sounding: extremely dry air above 2.8 km and anomalously high static stability from 5 km to the tropopause at 11.5 km. On the radar power profile the transition from moist boundary-layer air to the dry air of the vortex is clearly seen to fluctuate wildly in height and even to fold over at ~14 GMT. There is some evidence of a wind-shear anomaly associated with this boundary. In such a cut-off low the thermal tropopause is often very indefinite (Price and Vaughan 1994) and the ozone tropopause, generally found several kilometres below its thermal counterpart, is a much better indication of the boundary between stratospheric and tropospheric air (Bethan et al. 1996).

The core of the vortex (minimum-wind line) passed Aberystwyth at 15 GMT 9 March 1997. The radar winds imply that the vortex was sloping downwards to the east—in the opposite sense to the fold encountered on the previous day. Sloping layers in the echo power after this time look at first glance like those on the 8th—but they do not coincide either with a layer of wind shear or the height of a particular isentropic surface. They do
Figure 9. (a) Full and (b) perturbation wind vectors for 8–9 March 1997, the latter derived from the full winds using a 5 km high-pass vertical filter to remove the synoptic-scale structure. Note the pronounced inertia-gravity waves in the lower stratosphere, identified by clockwise rotation of the vectors with height. Time as on Fig. 8.

not therefore represent tropopause fold-like structures, although a layer of very dry (but not stable) air seen at Aberporth at 2315 GMT testifies to the interleaving of different air masses by the intrusion.

5. TURBULENCE AT THE TROPOPAUSE AND INERTIA-GRAVITY WAVE ACTIVITY

Although the spectral-width profiles show mixing between stratospheric and tropospheric air in the fold on the 8th and possibly on the edge of the vortex on the 9th, by far the most extensive patches of turbulence on these days were found just above the tropopause. Layers of wind shear, stronger than 35 m s\(^{-1}\) km\(^{-1}\), were seen near 11–12 km altitude, and were associated with a layer of turbulence, sometimes several hundred metres thick, persisting for more than a day with varying intensity. The turbulence is occurring in the region of steep increase in ozone concentration at the base of the stratosphere (Fig. 5). The wind shear causing it comprises a superposition of the background synoptic-scale wind shear and pronounced inertia-gravity wave activity, as evidenced by the sloping layers in the horizontal wind (Thomas et al. 1992). At certain phases of the wave, the horizontal wind almost becomes zero. Full and perturbation horizontal wind vectors are plotted in Fig. 9. The perturbation wind vector is seen to rotate clockwise with increasing height, as expected for inertia-gravity waves in the northern hemisphere propagating energy upwards (e.g. Thompson 1978); the vector length is longest at those phases of the wave where the vector points near north-west or south-east, implying that this is the direction of the horizontal wave vector (Thomas et al. 1992, 1999). This direction is transverse to the background wind direction in the troposphere, and to the alignment of the streamer.
The generation of gravity waves by a PV streamer has been studied theoretically, using the shallow-water equations, by Ford (1994). He found that the break-up of a strip of high PV into discrete vortices generated gravity waves of long horizontal wavelength (i.e. inertia-gravity waves) propagating away from the disintegrating streamer in the transverse direction. A direct comparison between the present results and Ford’s idealized model is not possible, both because of the simplifications of the model and because his results concentrated on the far-field gravity waves (whereas the MST radar measurements are very close to the streamer), but it is worth pointing out that on 7 March, when the streamer was approaching Aberystwyth relatively intact, the radar saw very little inertia-gravity wave activity and no turbulence at the tropopause.

6. **Significant weather associated with the intrusion**

The streamer passed over the British Isles during a period of anticyclonic weather, but its break-up, as we have seen, caused the development of a mesoscale cyclonic vortex in the mid and upper troposphere. This in turn induced a rain band on its northern and
eastern side which first appeared on The Met. Office weather radars around 12 GMT 9 March. Cloud and precipitation on the eastern side have long been recognized as typical features of a cut-off low or cold pool (e.g. Palmen and Newton 1969, p. 284), but most reported observations have been for synoptic-scale vortices much bigger than the present one (an exception is the case described by Hill and Browning (1987)). It is clear that convergence occurred in the confluence at the south-eastern and eastern edge of the vortex, between the circulation of the vortex itself and the overall synoptic (anticyclonic) flow.

The extent and development of the rain band is shown in Fig. 10. When compared with the NOAA* satellite visible image at 1714 GMT (Fig. 11), when the vortex core was near Aberystwyth, the rain is seen to be formed in a cloud band extending north from Somerset and curling westwards over mid and north Wales, north of the vortex core. As the vortex tracked northwards the rain followed, continuing to show up on the radar images until it disappeared to the east of Scotland on 10 March.

* National Oceanic and Atmospheric Administration.
7. CONCLUSIONS

This study of a disintegrating stratospheric streamer has revealed a number of novel features:

(i) The pronounced tropopause fold west of the streamer, along the 300 K isentropic surface, on 7 and 8 March 1997. This observation confirms the overall structure of a ribbon intrusion described by Appenzeller et al. (1996), with the added observation that the stratospheric layer was thin (~600 m depth) and embedded in a much deeper layer of dry air that had descended from the upper troposphere. With the aid of the MST radar we can follow the passage of this fold over Aberystwyth—the stratospheric air was marked by a narrow layer of enhanced vertical wind shear which could be tracked back to the horizontal wind shear that marked the core of the streamer.

(ii) The evolution of the fold late on 8 March gave rise to considerable turbulent mixing, further demonstrating the power of the MST radar for observations of this type.

(iii) Meteosat images show that the intrusion broke up into three small vortices near the British Isles on 8 March, with the larger of the three returning over Aberystwyth on the 9th. In marked contrast to the clear fold on the 8th, the returning fold was much less distinct—indeed it could only be identified by continuity of the line of enhanced wind shear from the previous day.

(iv) The passage of the core of the mesoscale intrusion over Aberystwyth on 9 March was accompanied by very dry air above the boundary layer and an indistinct tropopause—the latter being consistent with radar observations in synoptic-scale cut-off lows. As well as turbulent patches around the flank of the vortex, the MST radar power showed a convoluted pattern to the top of the boundary layer.

(v) Theory suggests that a streamer breaking up into vortices should generate inertia-gravity waves. This is amply demonstrated in this case, with breaking gravity waves engendering strong turbulence above the tropopause on 8 and 9 March. Indeed, it is at this height that the turbulence generated by the streamer was strongest. This means that streamers can promote mixing of stratospheric and tropospheric air at tropopause level, not simply by direct mixing of filaments but by the indirect mechanism of inertia-gravity waves. Note that inertia-gravity waves were first observed by the radar on the 8th—they were not present on the 7th when the streamer was still intact. While this may simply be a result of the inertia-gravity waves not having reached the radar yet on the 7th, it is also consistent with theory in that the inertia-gravity waves are mainly a product of the streamer breaking up (Ford 1994).

(vi) As well as its profound influence on the deformation of the tropopause and subsequent mixing, the breaking streamer was responsible for significant rainfall over the western side of the British Isles in a period of anticyclonic weather when rain would not normally be expected. Total rainfall on 8 March exceeded 8 mm over Avon and eastern Wales, with totals exceeding 2 mm experienced from Lancashire up to the Firth of Tay in Scotland.

ACKNOWLEDGEMENTS

We thank the Director, ECMWF, for access to meteorological analyses and the Natural Environment Research Council (NERC), British Atmospheric Data Centre and the Norwegian Institute for Air Research for supply of data. The MST radar is a NERC national facility, and this work was supported by a NERC grant. We also thank The Met. Office for provision of rainfall radar data, and the NERC satellite station, Dundee, for
Fig. 11. Dr H. Wernli, of the Eidgenossiche Technische Hochschule (Zurich), kindly provided the images for Fig. 2.

APPENDIX

Interpretation of MST radar vertical echo power profiles

The vertical echo power measured by a VHF radar (the Aberystwyth radar uses 46.5 MHz) is related to the vertical gradient of potential refractivity, \( M \) (Ottersten 1969):

\[
\text{Power} \propto M^2,
\]

where

\[
M \propto \frac{p}{T} \left\{ \frac{1}{\theta} \frac{\partial \theta}{\partial z} \left( 1 + 15600 \frac{q}{T} \right) - \frac{7800}{T} \frac{\partial q}{\partial z} \right\}
\]

where \( q \) is specific humidity (kg kg\(^{-1}\)), \( \theta \) is potential temperature and \( T \) is temperature (K), \( z \) is altitude (m) and \( p \) is pressure (Pa). Power then is enhanced in statically stable regions and in regions of negative humidity gradient—such as the lower boundary of a stratospheric air mass intruding into the troposphere. At a positive humidity gradient the stability and humidity terms act in opposite ways so such regions can exhibit a positive or negative (or no) power anomaly. Thus the MST radar is an excellent tool for identifying the base of a dry layer and (in dry air) stable layers, but does not identify so well the top of a dry layer.

The derivation of this relationship essentially relies on a similarity argument—that structure in the atmosphere on the scale of the radar wavelength (6 m) is a function of the large-scale gradients of \( q \) and \( \theta \). It has been tested for the Aberystwyth radar by Vaughan et al. (1995), who found it to be valid in the stratosphere, at least in a statistical sense. In the troposphere, the full relation is found to work well at low relative humidity (Warthon and Vaughan 1998) although it overpredicts the echo power in saturated conditions.

REFERENCES


<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Title</th>
<th>Journal/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Kennedy, P. J. and Shapiro, M. A.</td>
<td>Further encounters with clear-air turbulence in research aircraft.</td>
<td>J. Atmos. Sci., 37, 986–993</td>
</tr>
<tr>
<td>1969</td>
<td>Ottersten, H.</td>
<td>Mean vertical gradient of potential refractive index in turbulent mixing and radar detection of CAT.</td>
<td>Radio Sci., 4, 1247–1249</td>
</tr>
</tbody>
</table>
Van Haver, P., De Muur, D., Beekmann, M. and Mancier, C.
Vaughan, G., Price, J. D. and Howells, A.
Vaughan, G., Howells, A. and Price, J. D.
Worthington, R. M. and Vaughan, G.

1995  Use of MST radars to probe the mesoscale structure of the tropopause. Tellus, 47A, 759–765
1998  ‘Effects of humidity, precipitation and severe convection on VHF vertical-beam echoes’. Pp. 69–72 in Proceedings of the 8th workshop on technical and scientific aspects of MST radar, Bangalore, India. SCOSTEP secretariat, NOAA, Boulder, USA