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Classifying fronts in data from a VHF wind-profiling radar

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Abstract

Many fronts over the UK do not fit the traditional conceptual model of a single maximum of vertical shear of the horizontal wind sloped over the cold air. A 2-year climatology of 296 cold, warm, and occluded fronts from a mesosphere–stratosphere–troposphere radar near Aberystwyth, Wales, reveals that 74% of warm fronts were associated with multiple linear bands representing maxima of vertical wind shear, radar return signal power, or both. In contrast, 51% of cold fronts lacked any such maxima. Similarly, the warm frontal segments of occluded fronts exhibited more banding than the cold frontal segments. Copyright © 2011 Royal Meteorological Society

Keywords: **MST radar; cold fronts; warm fronts; occluded fronts; wind shear**

1. Introduction

Fronts are often depicted as sloping boundaries between warm and cold air extending throughout the troposphere (Bjerknes, 1935; Bjerknes and Palmén, 1937). In particular, warm fronts are gently sloped, and cold fronts are steeply sloped (Bjerknes, 1919). Iconic images of fronts are etched in our consciousness, particularly for cold fronts (Sanders, 1955; Browning and Harrold, 1970; Shapiro, 1984; Bond and Shapiro, 1991). Yet, previous observational research has shown that frontal structures may differ from these iconic images. For example, wind shifts may precede the temperature gradient and wind shift associated with the front (Miles, 1962; Schultz *et al.*, 1997; Hutchinson and Bluestein, 1998; Sanders, 1999a, 1999b; Schultz, 2004, 2005, 2008; Schultz and Roebber, 2008) and cold fronts may tilt forward with height (Parker, 1999; Schultz and Steenburgh, 1999; Stoelinga *et al.*, 2002). In addition, Bergeron (1937) proposed that cold fronts could be manifest either as rearward-sloping anafronts or forward-sloping katafronts, concepts further developed by Miles (1962), Browning and Monk (1982), and Browning (1986, 1990, 1999). This variety of frontal structure has not been well documented in the literature, however. Although Sansom (1951) studied 50 UK cold fronts to understand the differences between anafronts and katafronts, warm and occluded fronts remain largely unaddressed (Keyser, 1986; Kemppi and Sinclair, 2011).

As one step in remedying this situation, a preliminary experiment was performed. Given the continuously-monitoring, Natural Environment Research Council mesosphere–stratosphere–troposphere (MST) wind-profiling radar near Aberystwyth, Wales, and operational surface analyses, could fronts be identified in the radar data? If so, could their variability be described? We would expect some success with this approach as VHF radars have previously been used to identify mid and upper tropospheric fronts (Neiman and Shapiro, 1989; Neiman *et al.*, 1992, 1998, 2001; Spencer *et al.*, 1996; Browning *et al.*, 1998; Lucas *et al.*, 2001; Pavelin *et al.*, 2003). Indeed, Lucas *et al.* (2001) automated an algorithm to detect fronts in data from a VHF wind profiler, but the signal-to-noise ratio of the Aberystwyth radar is significantly better than for the radar they used. Furthermore, we employ a simpler, manual approach to detecting fronts.

2. The MST radar

The MST radar (Vaughan, 2002; http://mst.nerc.ac.uk/), in Capel Dewi, Aberystwyth, Wales (52.4 °N, 4.0 °W), has been in continuous operation since 1997 and profiles the atmosphere every 2 min from heights of 2 km above the ground to the lower stratosphere. VHF radiation with a frequency of 46.5 MHz is scattered by clear air rather than particles; return signal power comes from variations in refractive index on the scale of about 3 m, or half the radar wavelength. Such scattering can result from active turbulence, but

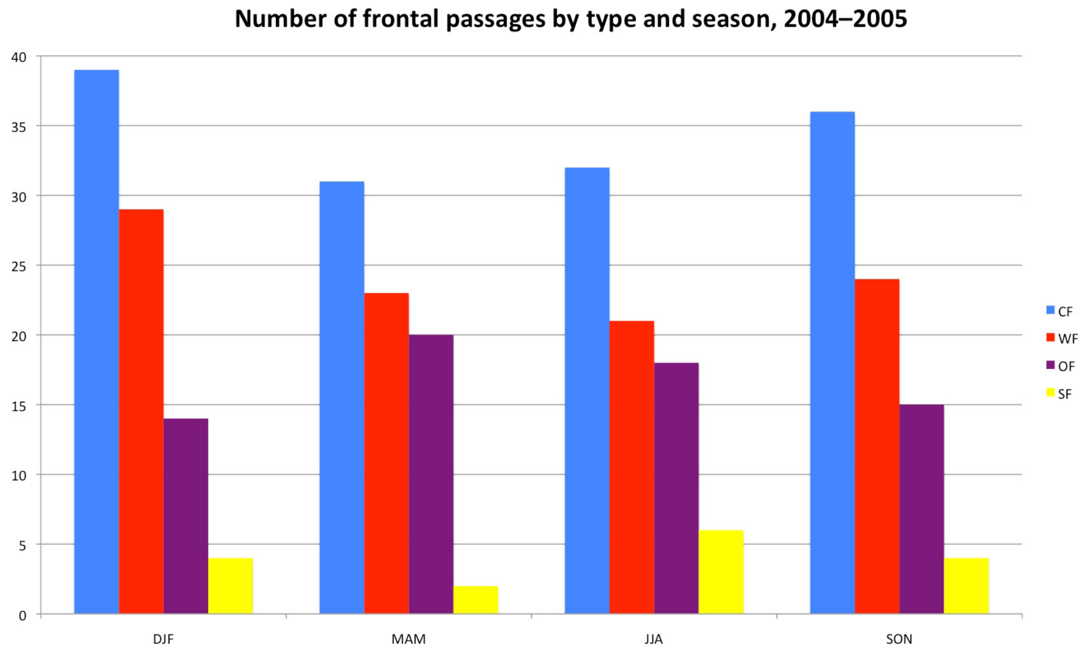

Figure 1. Number of frontal passages by type [cold front (CF), warm front (WF), occluded front (OF), stationary front (SF)] and by season [December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON)].

is more commonly Fresnel scattering (Gage *et al.*, 1981), which is best understood as reflection from a stack of thin sheets with sharp vertical gradients in refractive index. Both types of scattering lead to return signal power proportional to the square of the vertical gradient of refractive index (Gage and Balsley, 1980), related to vertical gradients in potential temperature or absolute humidity. The strong stability gradient across the tropopause may be readily detected as a layer of enhanced return signal power (Gage and Green, 1979; Vaughan *et al.*, 1995), whereas returns from the lower troposphere are dominated by humidity gradients (Vaughan and Worthington, 2000). The radar imagery used for this study was taken from quick-look plots stored at the British Atmospheric Data Centre[1] and processed with the original operational data analysis scheme for the radar (Slater *et al.*, 1992). Data for 2004–2005 were chosen because the quality of radar data has deteriorated over time (leading to a refurbishment programme in 2011 to restore performance), and archived Deutscher Wetterdienst (DWD) surface analyses were available from http://www.wetter3.de for 2004 onwards.

3. Methods

Surface analyses at 0000, 0600, 1200, and 1800 UTC were examined for any frontal passages. A frontal passage was included in the climatology if a cold, warm, or occluded front in the DWD analyses moved over Aberystwyth or a stationary front was over the area. For some cases, slow-moving fronts would retrograde in consecutive analyses. On such occasions, the time of the first passage over Aberystwyth was used. For other cases, a front might have changed type between consecutive charts. In these cases, the front type when closest to Aberystwyth was selected.

The resulting data set comprised 318 fronts: 138 (43%) cold fronts, 97 (31%) warm fronts, 67 (21%) occluded fronts, and 16 (5%) stationary fronts. All frontal types occur year-round, showing a weak dependence upon season (Figure 1). With this list of cases in hand, the corresponding daily quick-look plots of the MST radar data were examined. MST radar data were available for all fronts except four occluded and two warm fronts. The 16 stationary fronts were not analysed further because they were few in number and the radar time series could not be interpreted as a frontal passage. Thus, the final data set consisted of 296 cold, warm, and occluded fronts.

4. Classification scheme

Two caveats deserve mention. First, because the radar does not sample below 2 km, fronts in the DWD analyses, especially shallow ones, may not appear in the radar data. (Further discussion of the signatures of the fronts in radar data occurs in conjunction with Figure 5). Second, the slopes and structures of these fronts in the time–height cross sections (Figures 2 and 3) depend upon the speed and orientation of the fronts, and so may not be representative of a snapshot in time of the front.

[1] Natural Environment Research Council, Aberystwyth Radar Facility, (Hooper, D.). The NERC Mesosphere–Stratosphere–Troposphere (MST) radar facility at Aberystwyth, [Internet]. NCAS British Atmospheric Data Centre, 2006. Available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_MST

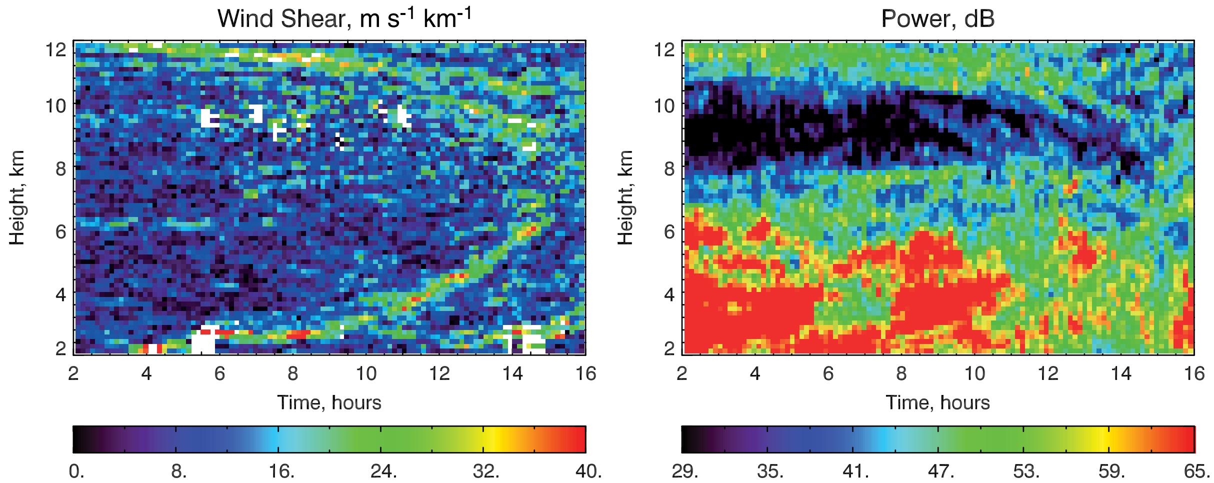

Figure 2. MST radar plot from 4 April 2005, showing the passage of a cold front with a single band. The cold front was analysed on DWD charts to pass at 0000 UTC. Note band of high vertical wind shear ascending with time after 0800 UTC, corresponding to a less distinct pattern in the signal power return. The data in this figure were processed with the signal-processing scheme of Hooper *et al.* (1998).

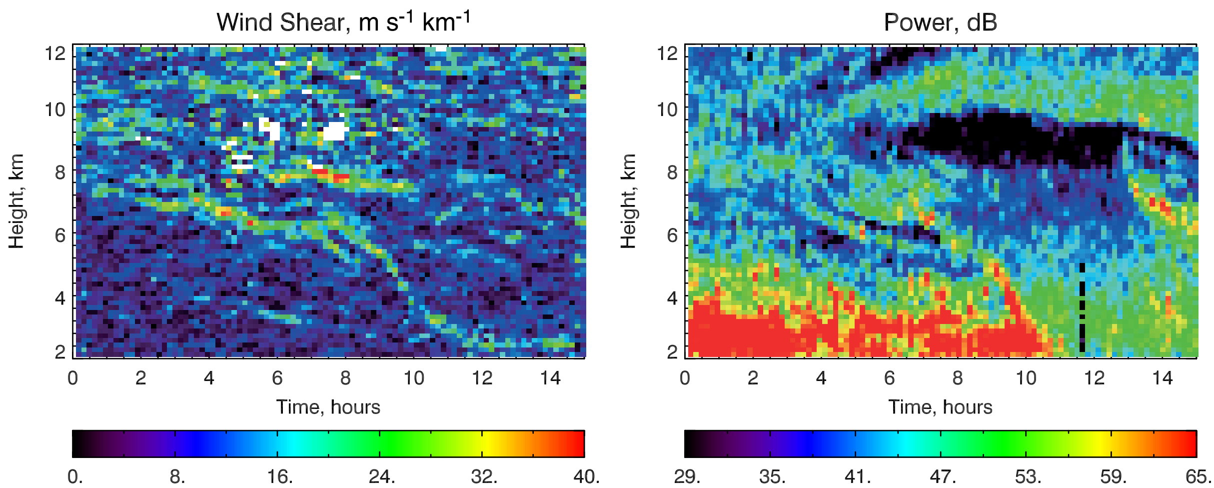

Figure 3. MST radar plot from 28 September 2005 showing the passage of a warm front with multiple bands. The warm front was analysed in DWD charts to pass at 1200 UTC. Multiple bands can be seen in shear and power prior to and during the passage of the surface warm front.

Taking into account these two caveats, we relied primarily upon two quantities from the MST radar data: vertical shear of the horizontal wind vector (hereafter known as 'shear') and radar return signal power (hereafter known as 'power'). Shear is useful for identifying fronts in MST radar data (Reid and Vaughan, 2004) due to the thermal-wind relationship between the horizontal temperature gradient and vertical shear of the horizontal wind. Fronts are associated with a local maximum of shear, as might be expected below a jet streak – typically $\sim$30 m s^{-1} km^{-1} for the fronts in this article. As discussed previously, power is related to the refractive index, which is a function of vertical gradients in potential temperature and absolute humidity. Because fronts are often associated with precipitation, structures in the power field below 5 km may be poorly defined (Vaughan and Worthington, 2000). A local maximum in power is more strongly marked along the tropopause and lines of wind shear associated with upper-level fronts often descend into the troposphere (Reid and Vaughan, 2004).

In this study, fronts commonly exhibited a sloping maximum in vertical wind shear and power aligned in a linear band. For example, the cold front in Figure 2 displays a band in shear and power, sloping upward from left to right. Cold fronts slope upward from left to right in these figures because the cold air deepened over time as the fronts moved eastward over Aberystwyth. Thus, fronts in time–height cross sections with time moving from left to right exhibit a structure reversed from its typical depiction (i.e. cold fronts sloping upward to the left and warm fronts sloping upward to the right). Note the fairly thick layer of enhanced wind shear (about 1 km thick), coinciding with a narrow band of enhanced power in Figure 2. In this case, the power maximum is embedded in a belt of low power below 5 km and can be followed to about

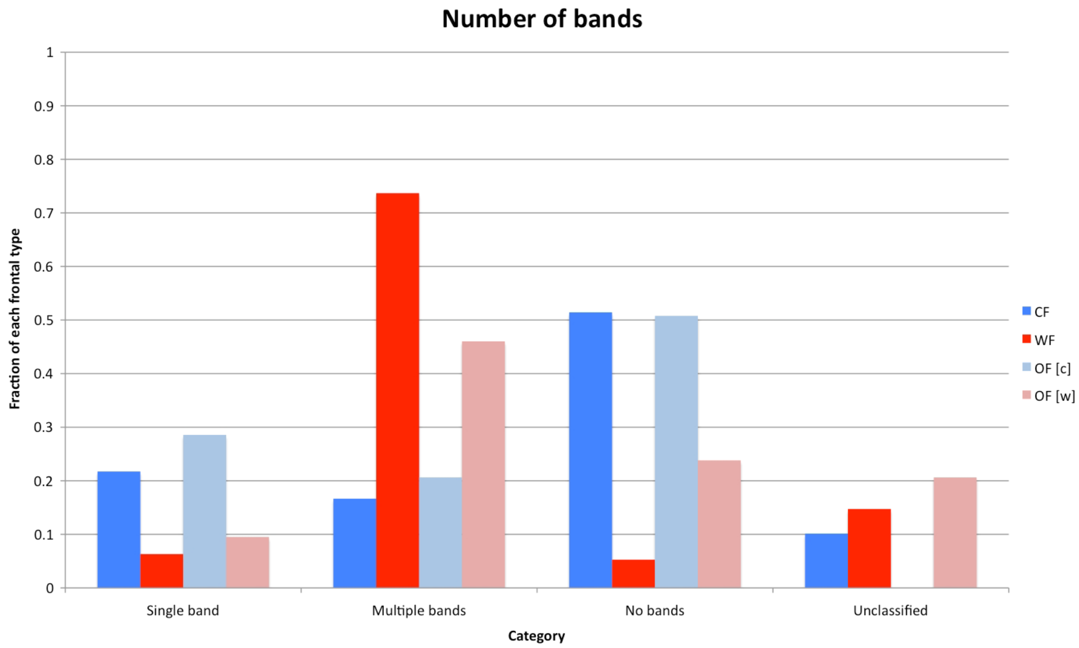

Figure 4. Frontal passages in 2004–2005 classified by the number of bands and by type of front: cold fronts (CF), warm fronts (WF), cold frontal segment of occluded fronts (OF [c]), and warm frontal segment of occluded fronts (OF [w]).

3.5 km; more typically, only the shear banding may be traced below 5 km.

Often multiple bands were present. For example, the warm front in Figure 3 displays several bands in shear and power, sloping downward from left to right. Warm fronts slope downward in these figures because the prefrontal cold air became shallower as the warm front approached Aberystwyth. The shear layers for warm fronts are typically narrower and the power anomalies more pronounced than those for cold fronts (at around the radar resolution of 300 m). Warm fronts and tropopause folds appeared similar in the radar cross-section, and referring to a synoptic analysis was essential for discriminating between the two.

Fronts were classified by whether a single band was present, multiple bands were present, or bands were absent (Figure 4). A fourth class (unclassified) accounted for situations that did not easily fit into any of these three classes. These situations might be where a shallow cold air mass was surmounted by an upper-level front, or a lower tropospheric warm front was poorly defined. In such situations, lower tropospheric bands associated with the cold front often failed to reach above 5 km or upper tropospheric bands associated with an upper-level front often failed to extend below 5 km. Only 10% of cold fronts and 15% of warm fronts fit into this unclassified category (Figure 4).

Bands were also classified by whether they appeared in both echo power and shear, only in power or shear, or neither in power nor shear (Figure 5). (The latter cases are those designated as 'bands not present' in Figure 4). Bands in shear and power were only marked as belonging to a front when they descended with time (warm front) or ascended with time (cold front). Specifically, horizontal bands in power were excluded if they could not be confidently attributed to a front (e.g. standing waves, tropopause, and other humidity gradients).

Occluded fronts often showed similar signatures to both cold and warm fronts. Consequently, occluded fronts were analyzed for their component warm and cold fronts (the occluded portion of the front was usually not observed or was below the 2 km minimum height). Both these warm frontal and cold frontal segments were classified separately (Figures 4 and 5).

Seventy-four percent of warm fronts had multiple bands (Figure 4) and 86% of warm front bands were apparent in both power and shear (Figure 5). By contrast, 51% of cold fronts had no bands, usually owing to noisy shear fields associated with convection (identified through rapid and large variations in vertical wind). The characteristics of both warm frontal and cold frontal segments of occluded fronts were similar to those of warm fronts and cold fronts, respectively (Figures 4 and 5).

5. Discussion

At first glance, these results of strong warm frontal signatures in the UK seem to contradict the conventional wisdom that warm fronts at the diffluent end of storm tracks are weak and stubby, as discussed by Schultz *et al.* (1998) and Schultz and Vaughan (2011). Because the radar does not directly measure temperature gradient and because data from the lowest 2 km is unavailable, an explicit test of this conventional wisdom using this data set is not possible.

In contrast, that many cold fronts had no signatures is consistent with Miles (1962) who found that five of his nine cold fronts had no shear zone or shear

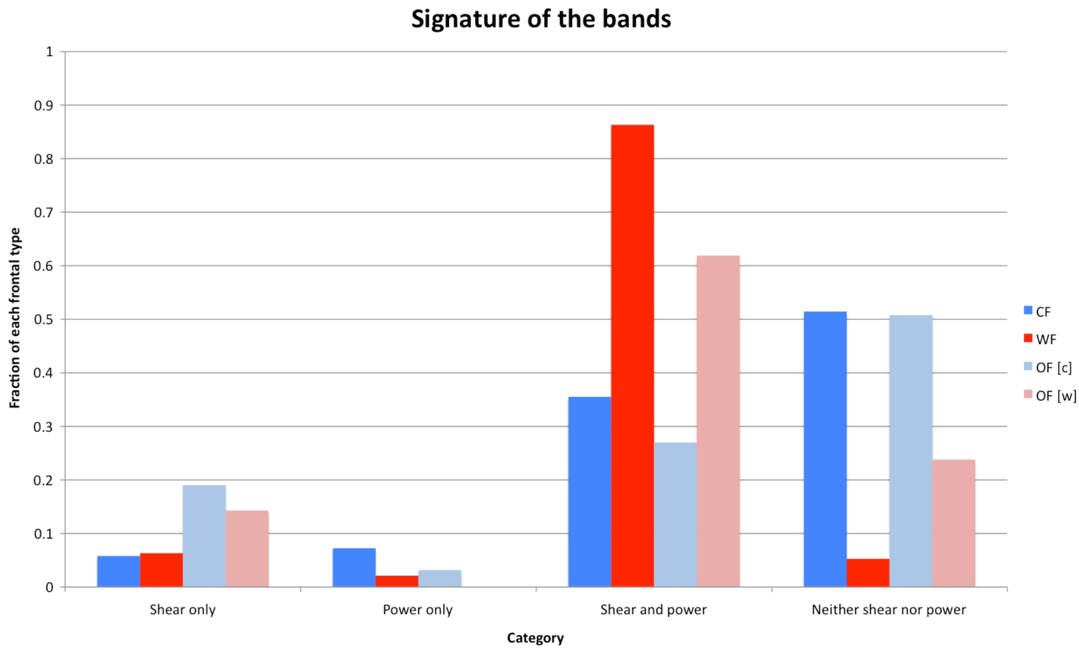

Figure 5. Frontal passages in 2004–2005 classified by the signature of the bands in shear, power, both, or neither and by type of front: cold fronts (CF), warm fronts (WF), cold frontal segment of occluded fronts (OF [c]), and warm frontal segment of occluded fronts (OF [w]). 'Neither shear nor power' is the same as 'no bands' in Figure 4.

zones only above 700 mb. Why cold fronts should lack strong shear signatures is not known at this time.

Multiple bands of clouds and precipitation have been observed in other synoptic environments (Schultz *et al.*, 1997; Schultz and Steenburgh, 1999; Dixon *et al.*, 2000; Novak *et al.*, 2004). Whether these previously published bands are related to the observed bands in this study remains an open question.

6. Conclusion

We have examined the signatures of frontal passages in data collected by an MST wind-profiling radar in the UK. Dates of frontal passages over the radar were determined from DWD surface analyses during 2004–2005. Fronts in the MST radar were identified by maxima in the vertical shear of the horizontal wind vector and the return signal power. The resulting data set consisted of 296 cold, warm, and occluded fronts. Most warm fronts (and warm frontal segments identified from occluded fronts) were associated with multiple bands in shear, power, or both. In contrast, such bands were not present with most cold fronts (and cold frontal segments identified from occluded fronts).

Specifically, the results of this 2-year climatology raise the following questions:

1. What causes the multiple bands observed in shear and power, which are particularly common with warm fronts?
2. What is the reason for the lack of signatures in shear and power associated with cold fronts?

The results of this climatology motivate further work on the structure and evolution of fronts, possibly to be addressed during upcoming field campaigns to collect *in situ* data with research aircraft.

Acknowledgements

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