

ESTIMATING THE WIDTH OF A TYPICAL COLD FRONT

W. P. Roeder (1) and R. L. Gall (2)
Institute of Atmospheric Physics
The University of Arizona, Tucson, AZ 85721

ABSTRACT

Using a thermograph and some simple methods for estimating the velocity of a cold front passing over Tucson, we show that this front had a width of ~ 20 km or less.

1. INTRODUCTION

Recent research has shown that some surface cold fronts have most of their horizontal temperature gradients contained in a zone on the order of 5 km wide (Bond et al., 3) and perhaps as little as on the order of 100 m (Shapiro et al., 4). Carbone (5) has also measured narrow precipitation bands (~ 5 km) associated with cold fronts, which suggest that the fronts themselves may also be very narrow. This has been met with surprise and perhaps doubt by some meteorologists who generally regard the mature frontal zone to be much broader (Cahir et al, 6). In fact, as Shapiro et al. (4) note, the recent work has brought the view of the frontal scale full circle. Early investigators assumed fronts to be nearly discontinuous (Abercromby, 7; Bergeron, 8) with widths on the order of 10 km (Eliassen, 9). However, with the development of synoptic surface and upper air networks (Bjerknes and Palmén, 10) and the decline of continuous recordings, the view of discontinuous fronts yielded to that of wide transitional zones with widths on the order of 100s km. This width is, in part, an artifact of the spacing of the surface observation stations (~ 100 km) Shapiro et al., 4). The recent instrumented tower observations show that at least some fronts are very narrow, returning us to the original view of discontinuous fronts.

Perhaps some of the argument that fronts are generally broad zones is due to work over the past 10–15 years on frontal dynamics. While theoretically some fronts could become discontinuities within a reasonably short period of time (Hoskins and Bretherton, 11), it is usually argued that the horizontal and vertical shears that would develop in the frontal zones prior to that time would be very unstable to small-scale disturbances. These disturbances would oppose further contraction of the frontal zone, and hence very narrow frontal zones are unlikely. Orlanski et al. (12) argue that additional dynamical processes in the front itself, other than this turbulence, may prevent frontal contraction to very small scales.

Shapiro et al. (4) note that the original view of discontinuous fronts originated, in part, from the many thermograph records made over the years as fronts passed over weather stations. Any student of synoptic meteorology is well aware that temperature falls of 10°C or more in a half hour or less during a cold-front passage are not uncommon. In fact, many traces show much of the temperature fall occurs over even shorter periods. Assuming a typical frontal speed of 15 m s^{-1} and that most of the temperature gradient passes the station in 30 min, then the frontal zone defined by the zone containing this temperature gradient is less than 30 km wide. While this is still much larger than indicated by Shapiro et al. (4) and Carbone (5), it is much smaller than is often believed. This estimate is probably an upper estimate on the width of many fronts; often the bulk of the temperature fall occurs in 10 min or less.

In this note, we examine the width of an ordinary cold front that passed over Tucson, Arizona, on 6 February 1986. Since there was nothing extraordinary about this front, one might assume that the results are fairly representative of cold fronts in general.

2. CASE STUDY

We estimated the frontal width using $D = V(\Delta t)$, where D = frontal width, V = velocity of the front, and Δt = time for the total change of temperature from the frontal passage to occur. Fig. 1 shows the temperature change atop the Physics and Atmospheric Sciences (PAS) Building, University of Arizona, in Tucson, to be 5.6°C in 0.68 h. The latter will be used as Δt in all the following estimates of D .

We estimated V by four methods: Tucson transit time, frontal motion on NMC surface analyses, post frontal winds, and cloud motion on GOES imagery. We also tried to estimate V from NWS Radar Summaries, but the front was too ill-defined on these charts.

The Tucson transit time was estimated by comparing the frontal passage times at the PAS Building, Tucson International Airport (TUS) and Davis-Monthan Air Force Base (DMA). Correcting for a two-minute error in time setting on the PAS wind-recorder trace, frontal passage (defined as the onset of the wind-shift, which agrees with the onset of temperature fall for this front, see Fig. 1) at the PAS Building was 07/0032 GMT. From Automated Weather Network observations, frontal passage occurred at 07/0142 GMT and 07/0054 GMT at TUS and DMA, respectively. The PAS Building is $11.4\text{ km} \pm 0.2\text{ km}$ and $9.0\text{ km} \pm 0.2\text{ km}$ distant from TUS and DMA, respectively. Estimating the front's direction of motion from GOES imagery and NMC surface analyses to be from $340^\circ \pm 15^\circ$ and projecting the distance vector between the PAS Building and TUS and DMA onto the velocity vector of the front, we calculated the velocity of the front across Tucson. These data give $V = 2.6\text{ m s}^{-1} \pm 0.7\text{ m s}^{-1}$ and $5.89\text{ m s}^{-1} \pm 1.5\text{ m s}^{-1}$ for TUS and DMA, respectively. The difference between these two estimates can be explained, in part, by the judgment of the meteorologists at each station in defining the time of frontal passage. We averaged these two results to obtain a final estimate of the frontal velocity across Tucson of $4.25\text{ m s}^{-1} \pm 1.6\text{ m s}^{-1}$.

We reanalyzed both the 06/1800 GMT and 07/0000 GMT Surface Analyses to better locate the front. These two charts indi-

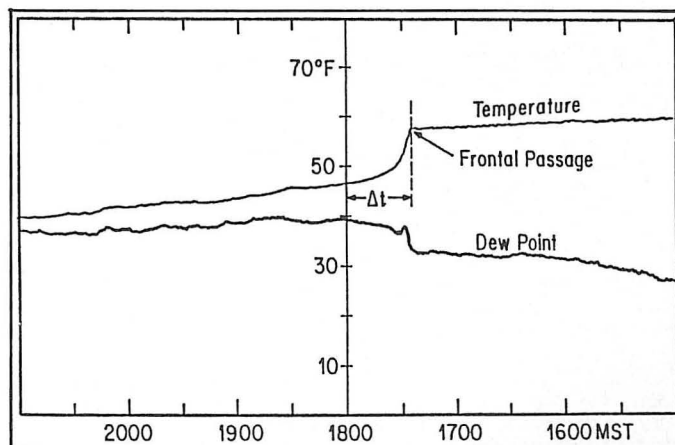


Fig. 1. PAS thermograph trace from 6 February 1986. Δt is the time for the total temperature change due to the frontal passage to occur. FROPA is the time the leading edge of the front reached the PAS Building.

cated a change of position of $450 \text{ km} \pm 140 \text{ km}$ in six hours or $V = 20.8 \text{ m s}^{-1} \pm 6.4 \text{ m s}^{-1}$. Unfortunately, the hourly surface observations between 06/1600 GMT and 07/0001 GMT were not available. These would have allowed a refined estimate of the front's position, but they are not critical to this discussion.

The average wind just after the initial temperature drop began at the PAS Bldg. was $26 \text{ kt} \pm 7 \text{ kt}$ with a maximum gust of 40 kt and from $315^\circ \pm 20^\circ$. If we assume that the front is advected with the component of this velocity perpendicular to the front, then $V = 4.60 \text{ m s}^{-1} \pm 1.26 \text{ m s}^{-1}$. Due to surface friction, this probably represents an upper limit on the velocity of the front.

GOES imagery indicated $V = 11.1 \text{ m s}^{-1} \pm 2.9 \text{ m s}^{-1}$. We computed this estimate by tracking a distinctive cloud feature between 06/1831 GMT and 07/0031 GMT. This cloud feature, which we assumed moved with the front, moved 139 nm in six hours to give the above estimate of V . There is considerable ambiguity in this estimate, since this cloud feature was somewhat diffuse on the GOES picture (Fig. 2), and it is possible that the cloud's position with respect to the surface front changed with time.

From these estimates of the frontal velocity and Δt estimated earlier, we estimate the front's width ($D = V\Delta t$) as follows (in order of what we consider to be decreasing reliability):

Tucson Transit Time:	$D = 10.4 \text{ km} \pm 3.7 \text{ km}$
Post Frontal Winds:	$D = 11.2 \text{ km} \pm 3.1 \text{ km}$
GOES Imagery:	$D = 27.1 \text{ km} \pm 7.0 \text{ km}$
NMC Surface Analyses:	$D = 51.0 \text{ km} \pm 15.6 \text{ km}$

The average of the above is $25.2 \text{ km} \pm 9.8 \text{ km}$.

The wide range in values of D is due, of course, to the wide range of estimates of the front's motion. The methods using the GOES image and the NMC Analyses are detecting the motions on the synoptic scale. Those using the frontal passage over points in Tucson or the post-frontal winds obviously apply to a much smaller scale. As a front moves, its velocity must vary widely according to locale, especially in mountainous regions such as Arizona and, in particular, Tucson, and so consideration must be given to the scale of motion being measured. Since the thermograph measures the width of the front at a point, those methods that measure the motion of the front near that point provide the most reliable estimates of D . Thus, we feel that the calculations using the motion of the front across Tucson most nearly represent the width of the front as it passed across Tucson. Both the Tucson Transit Time and Post Frontal Winds estimates are in good agreement with each other. We consider the Tucson Transit Time the better estimate, since the Post

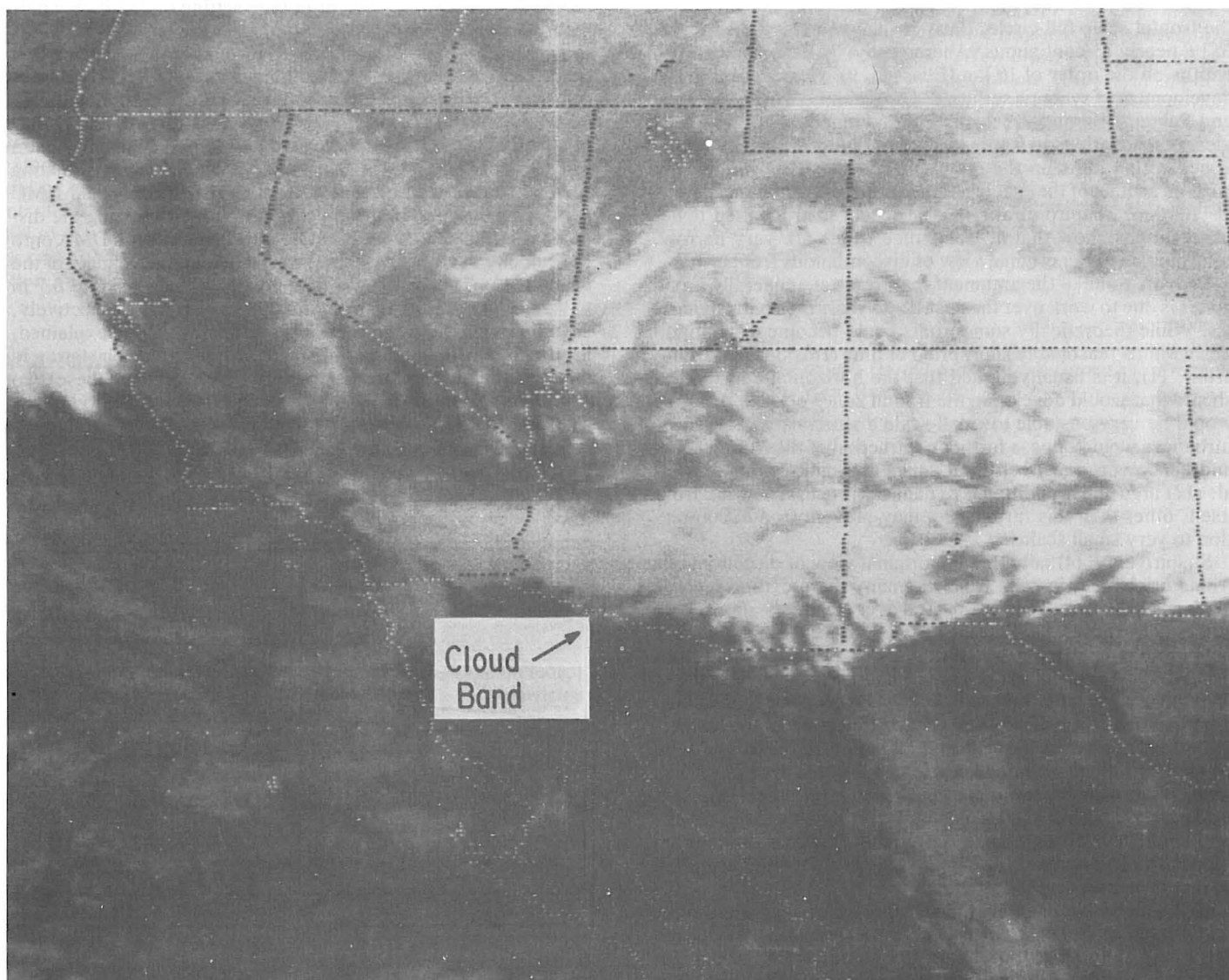


Fig. 2. GOES imagery 0031 GMT 7 February 1986. The arrow marks the long, narrow cloud feature used to track the front.

Frontal Winds estimate requires the important assumption that the front moves with the perpendicular projection of these winds. The estimate from the NMC Surface Analysis is probably our poorest, partly because the front's position is resolved only to the spacing of the reporting stations and partly because locating a weak front in the mountainous terrain of Arizona is difficult. The GOES Imagery estimate is hampered by problems in tracking individual features and, as stated above, by giving an overall estimate of the front's motion through Arizona, which may differ from the front's motion through Tucson. We've included these less reliable estimates as a caveat to others who may try to measure frontal widths and to indicate the magnitude of the error that may be encountered when mixing the scales over which V and Δt are estimated.

In any event, it is reasonable to expect the front's actual velocity to be bracketed by the values estimated here. Due to the vagaries in these estimates, we conclude that D is on the order of 20 km, but perhaps as small as 10 km. This is surprisingly close to the frontal width estimates of 10 km of early investigators (Eliassen, 9).

Our estimate for Δt may be large. Close examination of Fig. 1 shows a very rapid temperature fall, about half of the total temperature drop, during the first 0.16 h of the frontal passage. One could regard this large temperature gradient as representing the frontal zone. The temperature fall within the frontal zone appears to be approximately exponential and given by $T = (T_0 - T_F)e^{-t/\tau} + T_F$, where T_0 and T_F are the pre-frontal and post-frontal temperatures, respectively, t is the time since the leading edge of the front reached the measuring point, and τ defines an e-folding time. We measured the temperature and time at points on our frontal temperature trace to provide five estimates of τ . The average of these gave $\bar{\tau} = 0.28$ h. Using the Tucson Transit Time frontal velocity, our preferred estimate, this e-folding time yields a frontal width of only $4.2 \text{ km} \pm 1.4 \text{ km}$. Note that the response time of the PAS Building aspirated thermister thermometer is 5 s; thus the 0.16 h temperature fall represents many instrument time constants, and so the temperature fall is adequately resolved by this device.

We examined nine additional fronts between November 1985 and February 1986, using the preferred Tucson Transit Time method and our conservative Δt (time for total change of temperature from the frontal passage to occur). The average frontal width from these ten cases is 9.9 km with a standard deviation (σ) for the average of 1.2 km. Using the e-folding time yields: $\bar{D} = 2.9 \text{ km}$ with $\sigma = 0.5 \text{ km}$. The Δt s were all less than one hour. The average Δt was 0.6 h, $\sigma = 0.03 \text{ h}$. The average e-folding time was 0.17 h, $\sigma = 0.03 \text{ h}$.

3. CONCLUSION

It can be shown, using equipment traditionally available in a weather station (thermograph, weather maps, station weather reports, etc.), that fronts certainly can be narrower than the hundreds of kilometers usually taught in synoptic meteorology classes. Fig. 2 shows that the front passing over Tucson on 6 February 1986 was very weak. The temperature drop associated with the front's passage was only 5.6°C (10°F) and only 0.22 in of rain was recorded at the PAS Bldg. Despite its weakness, this front had a width on the order of twenty kilometers or less. We believe that similar calculations on stronger cold fronts, such as are often observed in the Midwest, might show even narrower widths. Resolution of the width in such fronts, however, might be restricted by the response time of typical thermographs.

ACKNOWLEDGEMENTS

We thank Detachment 13, 25th Weather Squadron, for the use of their archived data. Margaret Sanderson Rae edited the final manuscript. This research was supported by National Science Foundation Grant ATM-8407714.

NOTES AND REFERENCES

1. William P. Roeder, a captain in the U.S. Air Force, received his B.S. degrees in Physics, from the University of Pittsburgh, and Meteorology, from the Pennsylvania State University, and his M.S. degree in Atmospheric Sciences from the University of Arizona. He is pursuing his Ph.D. degree in Atmospheric Sciences at the University of Arizona through the Air Force Institute of Technology. His current research is the application of artificial intelligence to weather forecasting.
2. Dr. Robert L. Gall is a professor in the Institute of Atmospheric Physics at the University of Arizona. He received his B.S. degree in Meteorology from the Pennsylvania State University and his M.S. and Ph.D. degrees from the University of Wisconsin. His current research interests concern the internal structure of the Arizona monsoon, gravity wave generation during frontogenesis as well as other aspects of frontogenesis and tornado dynamics.
3. Bond, N.A., and Fleagle, R.G. 1985: Structure of a cold front over the ocean. *Q. J. R. Meteor. Soc.* 111, 739–759.
4. Shapiro, M.A., Hampel, T., Rotzoll, D. and Mosher, F. 1985: The frontal hydraulic head: A micro- γ scale ($\sim 1 \text{ km}$) triggering mechanism for meso-convective weather systems. *Mon. Wea. Rev.* 113, 1166–1183.
5. Carbone, R.E. 1982: A severe frontal rainband. Part I: Stormwide hydrodynamic structure. *J. Atmos. Sci.* 39, 258–279.
6. Cahir, J.J., Carlson, T.N. and Lee, J.D. 1978: A Laboratory Course in Synoptic Meteorology. Pennsylvania State Univ., Dept. of Meteorol., University Park.
7. Abercromby, R. 1887: *Weather*, London Press, London, pp. 178–179.
8. Bergeron, T. 1959: *Methods in scientific weather analysis and forecasting: An outline in the history of ideas and hints at a program*. In: *The Atmosphere and the Sea in Motion*, (ed. B. Bolin). Rockefeller Institute Press, New York, pp. 440–474.
9. Eliassen, A. 1959: *On the formation of fronts in the atmosphere*. In: *The Atmosphere and the Sea in Motion*, (ed. B. Bolin). Rockefeller Institute Press, New York, pp. 277–287.
10. Bjerknes, J., and Palmén, E. 1937: *Investigations of selected European cyclones by means of serial ascents*. *Geofys. Publ.* 12, 1–61.
11. Hoskins, B.J., and Bretherton, F.P. 1972: *Atmospheric frontogenesis models: Mathematical formulations and solutions*. *J. Atmos. Sci.* 29, 11–27.
12. Orlanski, I., Ross, B., Polinsky, L. and Shaginaw, R. 1985: *Recent discoveries in the theory of fronts*. In: *Advances in Geophysics*, Vol. 28B, (ed. S. Manabe). Academic Press, Orlando, FL, pp. 223–252.