THE REPRESENTATION OF FRONTS

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Summary: As the horizontal resolution of NWP models increases validation of mesoscale features of weather systems becomes important. Here we outline the findings from recent mesoscale observations of fronts made in special field programmes. A summary of the mesoscale structures that are now known to exist at fronts is then made. Finally the problems NWP models might have in properly representing these structures will be discussed.

1. INTRODUCTION

Fronts can be amongst the most intense near-discontinuous phenomena in the atmosphere. Data taken from an instrumented tower (Shapiro 1984) and individual barograph and thermograph traces show that frontal transitions can occur over vanishingly small space and time scales. However the majority of fronts do not exhibit such an extreme structure and involve a more gradual transition from one air-mass to another over horizontal distances up to 100 km and over time periods of up to an hour. As NWP models improve in horizontal resolution one can ask whether problems will arise in describing these transitions. It is a common experience in the models that as the horizontal grid-length is reduced the fronts have larger thermal gradients, greater precipitation, larger vorticity etc, and it can be asked whether there is a limit? It is attractive to hope that, for example, in the frontal ascent zone, the finite horizontal resolution of a numerical model will accurately represent the total upward mass flux by increasing the peak vertical velocity in inverse proportion to the horizontal width of the ascent zone.

It is clear that as for other mesoscale systems it is crucial that as much is known about the small-scale structure of fronts as possible to validate NWP models. Over the last decade there have been several field programmes specifically aimed at describing the mesoscale structure of fronts. Here we will summarize the findings from these programmes; notably CYCLES, FRONTS 87, and FRONTS 92. There have also been field projects on mid-latitude cyclones such as GALE, CASP, and ERICA which have been focussed more on the synoptic and larger mesoscale aspects. Brief mention will also be made of a future experiment in the FRONTS series to take place around 1997 led by British and French groups.

As a result of these field programmes research in this field is focussed on various mesoscale features of fronts. In section 3 we will summarize the main areas of active interest and their recent findings. This will include discussion of rainbands and conditional symmetric instability (CSI), the role of cloud microphysics and in particular ice evaporation, along and across front instabilities such as Kelvin-Helmholtz instability, the development of secondary frontal cyclones, line convection and its along-front structure, and the structure of the sloping frontal surface including the low-level jet.

In section 4 the implications for NWP models of these mesoscale features will be explored. Issues such as what determines the intensity and narrowness of a front and how the controlling mechanisms can be described by the models will be raised. There has been recent speculation as to whether CSI should be parameterized in these models or not. An important point is that given the aspect ratio of a frontal surface it is perhaps more relevant to be discussing the impact of improvements in vertical rather than in horizontal resolution. It is likely, given their importance in frontal dynamics, that improvements in cloud microphysical parameterizations will be necessary particularly in the representation of ice physics. Fronts also represent a key area when it comes to the assessment of the need for a non-hydrostatic NWP model. The intensity and small horizontal scale of frontal updraughts near the surface are relevant in that discussion.

In this paper the key areas covered in the oral presentation will be summarized by means of reference to the important published papers in the field. This written paper is in the form of an extended abstract for the talk rather than a comprehensive review paper in itself.

2. RESULTS OF FIELD OBSERVATION PROGRAMMES

The following are recent references giving details of the findings of field observational programmes:

SCILLONIA - warm fronts over eastern Atlantic (Browning et al 1973)
CYCLES - fronts over west coast of USA (Matejka et al 1980)
FRONTS 84 - summer fronts over western France (Lemaitre and Scialom 1992)
FRONTS 87 - cold fronts over eastern Atlantic (Thorpe and Clough 1991)
GALE - genesis of Atlantic lows (Dirks et al 1988, Martin et al 1992)
CASP - Canadian Atlantic storms project (Stewart et al 1990)
ERICA - explosively developing cyclones over western Atlantic (Nieman and Shapiro 1992)
FRONTS 92 - frontal wave cyclones over eastern Atlantic

In these experiments a combination of research aircraft in-situ and dropsonde, enhanced radiosondes, (dual-) Doppler radar, and surface mesoscale network data have been obtained.

3. MESOSCALE STRUCTURES AT FRONTS

3.1 Structure of the sloping frontal surface

The field projects mentioned above have provided a detailed mesoscale view of the structure of the sloping frontal surface. In Thorpe and Clough 1991 the front is resolved from dropsonde data with a spacing of about 30 km over a distance of about 600 km in the cross-front plane. A key parameter is the vertical velocity and unfortunately this can only be inferred indirectly. This remains one of the key variables to be properly quantified in the frontal environment and mesoscale objective analysis is crucial in being able to provide reliable estimates. Direct observation of the vertical velocity using dual-Doppler radar has an accuracy of perhaps 0.5 ms^{-1} which is insufficient to capture the extensive sloping ascent occuring over the majority of the frontal zone.

From the data already obtained it is clear that fronts are, on horizontal scales of 50 km or greater in the across front direction, relatively smooth sloping surfaces. On those scales this means that semi-geostrophic theory can be used to describe frontal dynamics, as discussed by Hoskins 1982, but with the important extension that ascent is predominantly saturated and in a state of near neutrality to CSI, see Thorpe and Emanuel 1985 and Emanuel et al 1987. The latent heating leads to significant anomalies of potential vorticity (PV) in the lower frontal surface. Values of order 1.5 PVU or 5 times the usual value have been observed. From the definition of PV in a predominantly two-dimensional front it can be seen that the absolute vorticity, ζ, is given in terms of the Richardson number, Ri, based on the along-front shear:

$$\zeta/f \sim 1/Ri + PV_f/PV_0$$

where PV_f is the frontal potential vorticity and PV_0 is the typical value of potential vorticity at that level away from the front. For the PV_f just quoted when the vorticity is of order 9 f the Richardson number at the front falls to a quarter; if there is no PV anomaly at the front this critical vorticity is 5 f. These zones are typically of horizontal scale less than or of order about 100 km in the cross-front direction. This can lead to secondary processes such as Kelvin-Helmholtz instability in the along-front direction and secondary frontal cyclones occurring.

Also on horizontal scales of order or less than about 50 km the front can exhibit CSI and convective circulations. The sloping frontal surface is often broken-up into a series of step-features in which the role of cloud microphysical processes, such as those associated with CSI, become important; see Thorpe and Clough 1991.

3.2 Kelvin-Helmholtz instability at fronts

As frontogenesis takes place the vertical shear at the front increases both in the cross and along front directions. This leads to zones of low Richardson number and the possibility of the onset of Kelvin-Helmholtz instability. The figures quoted in section 3.1 show that for such waves in the along-front direction, $Ri < 1/4$ is likely in a front with a vorticity of 9 f if the PV anomaly in the lower frontal zone is of order 1.5 PVU. Recent observations made by Nielsen 1992 and Wakimoto et al 1992 show that fronts can also be subject to such instabilities in the across front directions with horizontal scales of a few kilometres.

3.3 Rainbands and CSI

It is now well known that frontal precipitation is often organised into bands oriented approximately parallel to the fronts; see Matejka et al 1980. The cross-front scale of these bands can be as small as 20 km but might more typically be of order 50 km. An important area of research is concerned with the role of conditional symmetric instability (CSI) in the generation and structure of these bands. Recent references on this topic include: Lemaitre and Scialom 1992, Jones and Thorpe 1992, Thorpe and Rotunno 1989, Knight and Hobbs 1988, Bennetts and Hoskins 1979. An important diagnostic quantity for CSI is the equivalent potential vorticity (PV_e) or alternatively the relative slopes of absolute momentum and equivalent potential temperature surfaces. Universal instability criteria for CSI are if $f\ PV_e < 0$ or $f\ m'\ x' > 0$ where m' is the anomaly in absolute momentum of a parcel lifted along a neutral buoyancy curve over a horizontal distance x' in the cross-front direction with f being the Coriolis parameter. These criteria emphasize the fact that in CSI parcels typically move along shallow sloping paths; the often-used term "slantwise convection" is not appropriate.

3.4 Cloud Microphysics

Most mid-latitude frontal precipitation events involve an important role for ice and snow microphysical processes. The role of the evaporation of snow under the sloping frontal surface has recently been discussed by Clough and Franks 1991. This evaporation can, it is thought, lead to enhanced inflow toward the front; see Thorpe and Clough 1991. It seems that near saturated downdraughts, albeit sloping along the front, are a feature of fronts as well as of cumulonimbus systems.

3.5 Line convection

It has been known for more than a decade that active cold fronts have a narrow intense preciptation band known variously as the narrow cold-frontal rainband or line convection; see Browning 1986 for details. The line is perhaps only 5 km wide and 2 km deep but in this band the vertical velocities are typically 6 ms^{-1} with precipitation rates of between 50 and 100 mm h^{-1}. The line can exhibit variations along the front with line segments of about 20 km in length rotated anticyclonically with respect to the mean frontal orientation being common-place; Parsons and Hobbs 1983 and Hobbs and Persson 1982.

3.6 Frontal cyclones

Frontal zones can also be the location for secondary cyclogenesis much as envisaged by the so-called Norwegian school model of the polar front. A recent field project, FRONTS 92, took place to the west of the UK to make dropsonde observations of such frontal waves during March and April 1992. Three intensive observation periods took place. This will be followed by an international project, FRONTS-NEXT, later this decade on this phenomenon. These waves are decidedly sub-synoptic and, as described in a recent climatological study by Nielsen and Dole 1992, typically two small-scale cyclones are located along a front, separated by about 450 km; cyclones with a radius of 300 km not being uncommon. The prediction of these secondary waves is a significant forecasting problem. Recent theoretical research on frontal waves has been carried out by Schär and Davies 1990, Joly and Thorpe 1990 and 1991, and Thorncroft and Hoskins 1990.

4. PROBLEMS POSED BY FRONTS FOR NWP MODELS

4.1 Intensity of fronts

Can the field projects give any guidance to the question of whether there are limits on frontal ascent velocities? It must be recognized that this is the most difficult question to ask of observations. Current thinking would suggest that on horizontal scales of 50 km or more typical ascent rates are rarely more than 30 cm s^{-1} and vorticity is rarely more than 4 f. But on smaller scales it is clear that these figures can be exceeded substantially. For example in line convection there are reliable estimates of 8 m s^{-1} or more. Frontal PV values are large as quoted in section 3.1 and vorticity can probably be almost as large as one likes. Discussion of the frictional boundary layer effects on frontal structure is given in Cooper et al 1992.

The question of the factors which limit the intensity of fronts is still an open one. It is likely that the various frontal instabilities such as frontal waves, K-H instability, and line convection segments are manifestations of ways in which fronts produce small-scale mixing preventing collapse. However it is believed that in certain circumstances fronts exist in the atmosphere in a collapsed (discontinuous) state. How common this is and whether there is a geographical variation is not known.

4.2 Parameterization of CSI and precipitation forecasts

For current global models it is an important issue as to whether CSI should be parametrized to improve precipitation forecasts. Recent schemes for this have been described by Nordeng 1987, Lindstrom and Nordeng 1992, and Chou and Thorpe 1992. Given that the cross-front scale of rainbands is less than 50 km then it would appear that this process should be accounted for implicitly via a parametrization scheme rather than explicitly where the process will not be properly represented. In Chou and Thorpe 1992 a scheme is devised in the context of the current operational mass flux scheme for convection in the ECMWF global model. The scheme operates as a quasi-horizontal mixing of momentum along equivalent potential temperature surfaces. Such a scheme may also be important in dry zones in the upper troposphere in mid-latitude fronts and, incidentally, in the tropics where f PV < 0 is satisfied. These zones are known to lead to problems in operational models and isentropic momentum mixing will lead to the eradication of those zones of instability.

4.3 Cloud microphysical parameterization

Ultimately a proper representation of fronts will rely on the complexity of the cloud microphysical processes which are included in the operational NWP model. Currently these are crude and there is no doubt that explicit water variables are needed with both liquid and solid phases being represented.

4.4 Vertical resolution

Fronts are essentially horizontal surfaces and the evidence is that the ascent can take place in an extremely thin sheet along the frontal surface. Hence the representation of that ascent depends more on vertical than on horizontal resolution. It is clear that grid-points as close together as 100 m in the vertical are necessary to begin to resolve this sloping ascent. Persson and Warner 1991 show that spurious gravity waves can be produced if insufficient vertical compared to horizontal resolution exists in an explicit simulation of CSI. An optimal combination is if the ratio of the vertical to horizontal grid-lengths is similar to the slope of the front.

Ultimately if the detail of the precipitation in convective elements is to be predicted then a non-hydrostatic model will probably be necessary.

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