The Relationship between Fronts, Frontal Zones and Airstream Boundaries

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DEFINITIONS:
Axes

• **Axis of Dilatation** \((\psi_d)\)

\[
\tan 2\psi = \frac{E_{\text{SH}}}{E_{\text{ST}}}
\]

Orientation where parcel pairs experience the greatest separation rate

• **Axis of Non-Rotation** \((\chi)\)

\[
\sin 2(\psi_d - \chi) = \frac{\zeta}{E}
\]

Orientations where parcel pairs do not experience any rotation about their center
Parameters

• Instantaneous Contraction Rate

\[ c = \frac{E - D}{2} \]

Rate two parcels, oriented along the axis of contraction, come together

• Extrapolated Contraction Rate

\[ \mathcal{C} = \frac{(E^2 - \zeta^2)^{1/2} - D}{2} \]

Rate two parcels, oriented along the axis of non-rotation, come together

• Frontogenesis Function

\[ \mathcal{F} = |\nabla \theta| \frac{E \cos 2\beta - D}{2} \]

The potential temperature gradient multiplied by rate two parcels, oriented across the potential temperature gradient, come together.
Structures

• **Airstream Boundary**
  The boundary between regions of similar spatial history; characterized by high time-averaged contraction rates

• **Frontal Zone**
  The boundary between regions of similar densities; characterized by high gradients of potential temperatures

• **Front**
  The superposition of an airstream boundary upon a frontal zone; characterized by high gradients of potential temperatures and high time-averaged contraction rates
ILLUSTRATIONS:
Uniform Flow

Although $\psi_d$ and $\psi_c$ represent the orientations of maximum growth and decay, respectively, in situations where $\zeta \neq 0$ parcels oriented along these axes will rotate away from those axes toward regions of lower growth and decay rates.

In the flow shown in Figure 1, parcel pairs oriented along the axes of contraction and dilatation remain oriented along those axes. In comparison, in the flow shown in Figure 2, parcel pairs oriented along the axes of contraction and dilatation rotate away from those axes.

The more representative dilatation and contraction rates, then, would be the growth and decay rates along the axes of zero rotation (see axes $\chi_d$ and $\chi_c$ in Figure 2) for it is along those axes that parcel pairs will eventually find themselves (assuming such axes exist).
Idealized Vortex

If $|\zeta| > E$ then there is no axis of non-rotation and the extrapolated contraction rate $C$ is imaginary. Consequently, its square can be used to identify embedded vortices (see red shaded regions in figures to the right). Parcels within these regions remain in the vortex, rotating about one another.

When positive, the square of the extrapolated contraction rate can be used to identify regions where airstream boundaries are being generated (see red isoplethed regions). Parcels in this regions eventually separate (assuming $D = 0$).

The extrapolated contraction rate, $C$, represents the long-term rate at which two parcels on opposite sides of the airstream boundary come together during some time in the past assuming constant flow. Since such long-term contraction rates are related to airstream boundaries, it is suspected that the extrapolated contraction rate is more closely related to the genesis of airstream boundaries than the instantaneous contraction rate.

The extrapolated contraction rate is equivalent to the instantaneous local Lyapunov exponent (and the square root of the efficiency factor) and, as such, provides a link between the theoretical framework of chaotic mixing and the kinematic framework posed by synoptic meteorology.
ERICA IOP-5

When the airstream boundary is oriented parallel to the isotherms, frontogenesis is enhanced. When the airstream boundary is oriented perpendicular to the isotherms, the isotherms are rotated (or kinked). This can be seen in the simulation of the idealized vortex in diffluent flow.

Airstream boundaries can exist separately from frontal zones. In the simulation of ERICA IOP-5, a non-frontal feature (i.e., no significant thermal gradient or frontogenesis) is present east of the IOP-5 feature (which is toward the west in the first frame). This feature maintains its airstream structure until it becomes incorporated into the growing IOP-5 storm.
Figure 1: Four flow fields with zero vorticity. [a] Stretching deformation only. [b] Equal magnitudes of stretching and shear deformation. [c] Same as [a] with convergence. [d] Same as [b] with convergence. Solid green axes show the axes of dilatation (ψ_d) and contraction (ψ_c).
Figure 2: The same four flow fields as in Figure 1 but with some vorticity. Solid blue axes show the axes of zero rotation.
Figure 3: The same four flow fields as in Figure 2 but with $\zeta = E$. 
Figure 4: The same four flow fields as in Figure 2 but with $\zeta > E$. 
Figure 5: Doswell vortex in diffluent flow at 0 h. Isolines of potential temperature (black lines), embedded vortex (red shading of negative $C_{ND}^2$ values), frontogenesis (green lines), extrapolated contraction rates (red lines; positive $C_{ND}^2$ values). Letters A–L represent parcels.
Figure 6: As in Figure 5 but at 12 h.
Figure 7: As in Figure 5 but at 24 h.
Figure 8: ERICA IOP-5 simulation at 8901190600. Precipitation rate (yellow shading), embedded vortices (red shading of negative $C_{\text{ND}}^2$ values), isotherms of potential temperature (black lines), frontogenesis (green lines), extrapolated contraction rates (red lines; positive $C_{\text{ND}}^2$ values).
Figure 9: As in Figure 8 but at 8901190900.
Figure 10: As in Figure 8 but at 8901191200.
Figure 11: As in Figure 8 but at 8901191500.
Figure 12: As in Figure 8 but at 8901191800.
Figure 13: As in Figure 8 but at 8901192100.
Figure 14: As in Figure 8 but at 8901200000.
Figure 15: As in Figure 8 but at 8901200300.
Figure 16: As in Figure 8 but at 8901200600.