6

FRONTS

The topic of MSM Chapter 6 is fronts. We know that fronts are important, based on our experience with daily weather. What physical processes lead to the formation of fronts? How can we conceptualize the processes that produce important sensible weather in the vicinity of fronts? How can we identify frontal structure using observations or numerical model forecast output? The conditions that accompany frontal passages at a given location can vary widely. Sometimes, a front will be accompanied by severe weather and heavy precipitation. Other times, a strong front may bring large changes in temperature or humidity, but may not be accompanied by any precipitation whatsoever. What factors are responsible for these different outcomes?

Our objectives in this chapter are to answer the preceding questions. Learning outcomes include 1) recognition of the key processes of frontogenesis from analyzing standard observations, and also from reviewing the derivation of the frontogenesis equation, 2) the ability to utilize the frontogenesis function in weather analysis and forecasting, and 3) developing an IDV bundle, from scratch, to plot the frontogenesis function for a real-data case.

This chapter includes the following exercises:

6.1. Simplified Frontogenesis Function: Derivation and Interpretation
6.2. A Frontal Case Study
6.3. Plotting the Frontogenesis Function Using IDV

Each exercise in this manual uses these typefaces for clarity:

Normal typeface is used for background information, technical instructions, motivating questions, and learning objectives. **Bold indicates assigned actions and questions that students are expected to respond to in their report.** A `constant width` typeface is used to indicate text that can be found exactly on the IDV software (usually on the `Dashboard` or `Legend` areas).

The word **Optional:** is used to set off suggestions for further explorations.

6.1. Simplified Frontogenesis Function: Derivation and Interpretation

One way to understand fronts and the processes leading to their development is to examine the *time-tendency of the magnitude of the horizontal gradient of potential temperature*, in a coordinate system that *follows the wind* (a total or Lagrangian derivative). This quantity $F = d/dt(|\nabla \theta|)$ is known as the *frontogenesis function*.

Because the midlatitude atmosphere remains close to a state of thermal wind balance, changes in the horizontal temperature gradient are accompanied by changes in the vertical shear of the geostrophic flow. In chapter 2, we saw that ageostrophic circulations must arise in order to maintain this thermal wind balance. The upward branch of these circulations can produce important weather impacts. With some modification (called *semi-geostrophy*) for the sub-synoptic length scales (narrowness) of fronts, the general concepts from quasi-geostrophic theory (the disruption of balance by advection or other processes, necessitating the development of ageostrophic circulations to restore or maintain that balance) can help us to understand frontal weather.

The objectives of this lesson are 1) to derive a simplified version of the frontogenesis equation, 2) to perform a scale analysis to evaluate the relative importance of the terms, and 3) to demonstrate a conceptual understanding of the workings of each term.

Following chapter 6.2 of the MSM text, consider a simplified, rotated coordinate system in which the y' axis is always oriented perpendicular to the front, pointing towards the cold side.

a) Using the definition of the Lagrangian derivative, the chain rule from calculus, and the definition of "F" shown below, **derive the simplified version of the frontogenesis**

equation [Eq. (6.2) in the MSM text]. See section 6.2 of the text for additional information about this equation.

$$\text{“F” is } \equiv \frac{d}{dt}\left(-\frac{\partial\theta}{\partial y'}\right) \qquad \frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x'} + v\frac{\partial}{\partial y'} + \omega\frac{\partial}{\partial p}$$

$$F = \underbrace{\left[\frac{\partial\theta}{\partial x'}\left(\frac{\partial u'}{\partial y'}\right)\right]}_{Term\,A} + \underbrace{\left[\frac{\partial\theta}{\partial y'}\left(\frac{\partial v'}{\partial y'}\right)\right]}_{Term\,B} + \underbrace{\left[\frac{\partial\theta}{\partial p}\left(\frac{\partial\omega}{\partial y'}\right)\right]}_{Term\,C} - \underbrace{\left[\frac{\partial}{\partial y'}\left(\frac{d\theta}{dt}\right)\right]}_{Term\,D} \qquad (6.2)$$

b) Perform a *scale analysis* of the terms in this equation for a given meteorological situation or for typical midlatitude frontal situations. **How do typical values of the basic terms in the vicinity of a front compare to those in general synoptic-scale flows?** Note the different characteristic length scales for spatial derivatives in along- and across-front derivatives.

c) For terms A–D, **draw simple sketches (including isentropes, fronts, and wind barbs) of situations in which that term would be negative (*frontolysis*)**.

d) Recall that the *Rossby number* [$U/(fL)$] is a dimensionless measure of the degree of geostrophy of the flow, formed by taking the ratio of the acceleration term to the Coriolis term in the horizontal momentum equation. Using typical values in the vicinity of a front, **develop appropriate Rossby numbers corresponding to the along-front and across-front force balances. Should we expect the quasigeostrophic (QG) equations, developed in chapter 2, to fully describe the dynamics of frontal systems? Discuss.**

6.2. A Frontal Case Study*

During November 2014, cold Arctic air moved southward into the U.S. lower 48 states from Canada. An intense frontal boundary marked the leading edge of this Arctic air mass. Specific objectives for this exercise are 1) to relate basic meteorological fields to the frontogenesis function and some specific physical processes, 2) to relate frontal circulations to **Q** vectors studies in exercise 2.3 and 2.4, and 3) to develop student ability to utilize the frontogenesis function as a tool in frontal analysis and identification.

* We gratefully acknowledge Mr. Tyler Croan, Metropolitan State University, Denver, Colorado, for useful suggestions for this exercise.

Our data source for this exercise will be the NAM 212 grid, with approximately 40-km grid spacing, sufficient to represent the shorter cross-front length scale.

Open the `LMT_6.2_part1` bundle, showing the NAM model run initialized at 1200 UTC 11 November 2014. Examine the lower-tropospheric synoptic situation at the initial time. The only field initially displayed is sea level pressure (`EMSL NONE`, contoured). Locate the intense Arctic anticyclone centered over Canada, and the relatively weak cyclone centered near the Great Lakes.

a) Sharper curvature in the sea level pressure contours may suggest where the frontal boundaries are likely located in this case. **Sketch where you would expect the cold and warm fronts to be in this example,** based just on the sea level pressure and your knowledge of how fronts tend to align with the pressure field. To do this, open the IDV's `Drawing Control` (click on the pencil icon along the top toolbar in the `Dashboard`). Select the `Draw in Current Time` box so the fronts are only shown on the initial time, and adjust the `Z-position` slider to the top so they will remain visible when other displays are turned on. **Draw your fronts, and save an image displaying your subjective frontal analysis for later reference.**

b) Now, check your estimated frontal positions by plotting the near-surface equivalent potential temperature (with display name `theta-e`). Check the boxes to plot the contour or color shaded displays theta-e field. **Was your initial analysis from a) consistent with the theta-e field, or were adjustments necessary? Discuss.**

c) Next, activate the display of `truewindvectors` in order to consider the action of the 975-hPa wind field on the cold front. Deactivate the SLP contours (`EMSL NONE`) to minimize clutter. **Assess the *shearing* and *confluence* terms of the simplified frontogenesis equation** [terms A and B in Eq. (6.2)]. **For the portion of the cold front extending from Texas to southern Illinois, indicate whether each of these terms is frontolytical, frontogenetical, or weak. Justify your answers.**

d) Like most meteorological software, IDV's "Frontogenesis function" includes only the horizontal advection terms [2D shearing and confluence, terms A and B in Eq. (6.2)]. Examining the wind field and 975-hPa equivalent potential temperature isentropes in the vicinity of both the warm and cold fronts, we can see some places where there is strong implied frontogenesis, and others where it is weaker. **Identify one location where you believe, based on your analysis in c), there would be strong frontogenesis. Then, also along either the warm or cold front, identify a location where you believe the frontogenesis is weak. For each location, explain why you selected it.**

e) Now, activate the `Frontogenesis` contour plan view to check your subjective frontal analysis against the frontogenesis function. Deactivate some of the other quantities in order to reduce clutter. **Is the frontogenesis generally strongest on the warm or towards the cold side of the subjectively analyzed frontal boundaries? Why is this the case?** Hint: Examine terms A and B in the frontogenesis function [Eq. (2) or Eq. (6.2) in MSM] and think about where these quantities are maximized. **Do the locations from d) that you identified as strong and weak frontogenesis match the frontogenesis calculation? Discuss.**

f) Step through the forecast sequence. **How does the frontogenesis field change in the first 24 hours of this forecast sequence, for the period ending 1200 UTC 12 November? Is the frontogenesis stronger or weaker at 1200 UTC 12 November than it was at the initial time (1200 UTC 11 November)? Discuss any changes, and offer an explanation for any significant ones.**

g) Now **open the LMT_6.2_part2 bundle. Alert! Uncheck `Remove all displays and data` in the `Open bundle` dialog** to add these displays to your existing view. This bundle will add **Q** vectors to the display. We saw above that confluent flow near the front produced *positive* values of frontogenesis at this time (confirmed by the contours of `Frontogenesis` at the 975-hPa level). **Do we expect Q vectors to point towards the warm or cold side of the front in these areas? Explain.** (Hint: recall section 6.3 in the MSM text, or exercise 2.3 in this manual). Now, activate the **Q**-vector plot (`qvec`) and zoom in to various locations along the cold and warm fronts to note the correspondence between the frontogenesis function and the orientation of the **Q** vectors (at the 975-hPa level).

   i. **Describe the relative magnitude of the Q vectors relative to the strength of the frontogenesis. Is Q larger where the frontogenesis is stronger?**

   ii. Using your knowledge of what the **Q** vector represents from chapters 6 and 2, **discuss why, conceptually, we might expect the Q-vector magnitude to be related to the strength of the frontogenesis**. Can you see or show why, mathematically?

   iii. **Is the orientation of the Q-vector field consistent with your expectations, based on the arguments presented in section 6.3.1 of the text?**

h) Kinematic treatments of frontogenesis sometimes neglect the effect of the frontal *secondary circulation* on the frontogenesis itself (a *tilting of θ surfaces* that can influence the magnitude of the horizontal temperature gradient, term C on the right side of the frontogenesis equation (6.2) above). In a more dynamically complete view, this frontal secondary circulation works in the opposite sense to the horizontal frontogenesis (terms A and B, the main "forcing" for the front's development). We also know that the **Q**-vector convergence should be consistent with the upward vertical branch of the frontal circulation. **If we were to view a cross section perpendicular to the cold front in this case, would we expect to see a *thermally direct* or *thermally indirect* circulation? Would the vertical component of this circulation, the tilting term, act frontogenetically or frontolytically? Explain.**

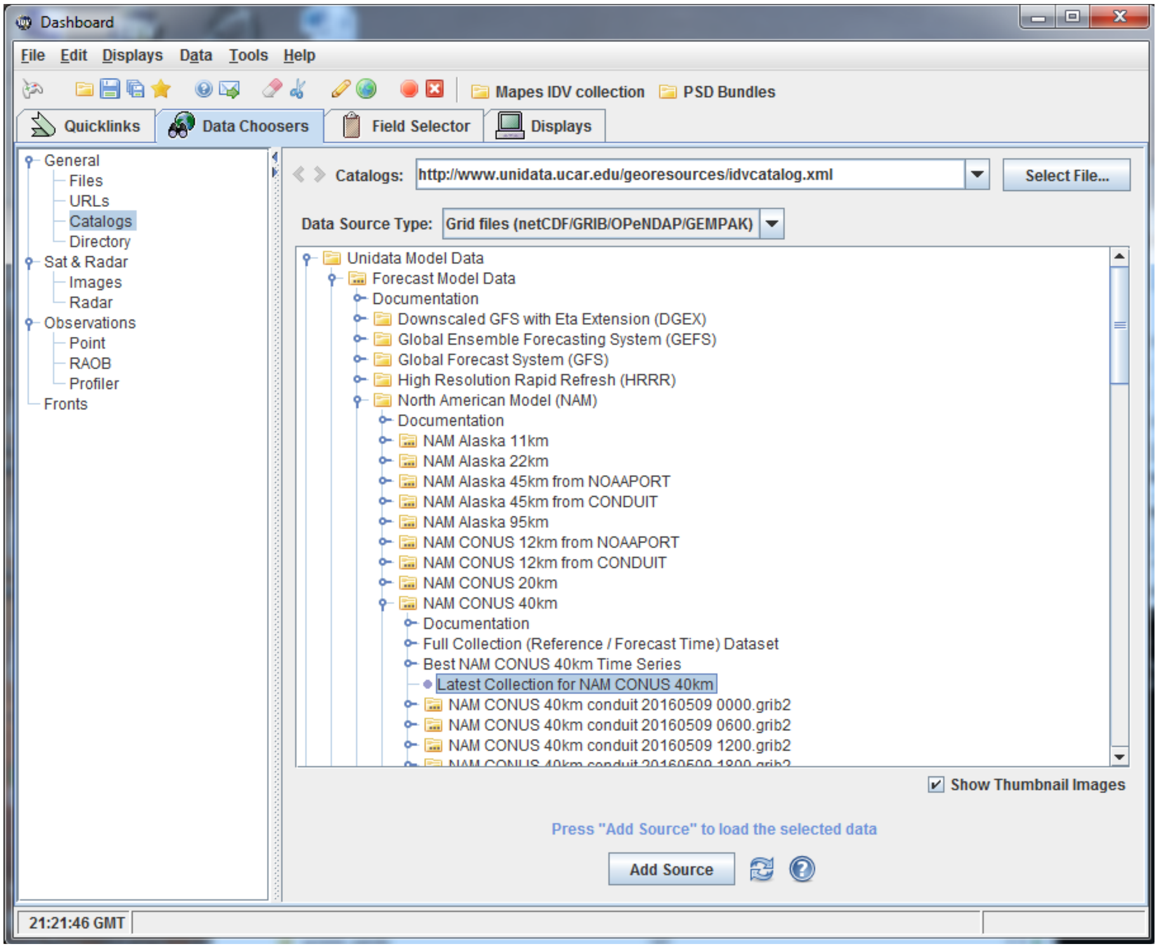
i) Activate the `Vertical Cross Section` displays, and examine vertical motion `OMEG_PRES` in the front-normal cross section. Only negative values (upward motion) are displayed. Deactivate other plotted parameters in order to more clearly display the cross-section variables, and **capture an image. Does the vertical motion in the cross section match your expectations based on QG theory and the previous discussion?** Step through the first several time periods in order to gain a sense of how the frontal circulation evolves over the first 24 h of this NAM model forecast. **Is this frontal circulation deep in vertical extent and likely to produce heavy precipitation, or shallow? How does the depth and strength of the circulation change with time during the first 24 hours of this forecast sequence?**

j) Finally, consider diabatic effects on the thermal gradient, term D in (6.2). Notice that the *total derivative* $d\theta/dt$ is the *diabatic* heating or cooling of air parcels, distinct from all the partial derivatives in (2). **Open the LMT_6.2_part3 bundle, again adding it to your existing displays**. This displays a satellite image valid at 1800 UTC 11 November superimposed on the Rapid Update Cycle (RUC) model analysis valid at that time. Locate the cold front, based on the warm edge of the potential temperature gradient and the 975-hPa height contours. **Is the diabatic term from latent heat release acting frontogenetically or frontolytically in the cold front at this time? Justify your answer. How about in the warm front? Again, discuss and justify your answer.**

6.3. Plotting the Frontogenesis Function Using IDV

The primary objective of this exercise is to illustrate the process of making a frontogenesis display from any gridded data file. A secondary objective is to allow quantitative comparison of IDV-computed frontogenesis values with the scale analysis from section 6.1.

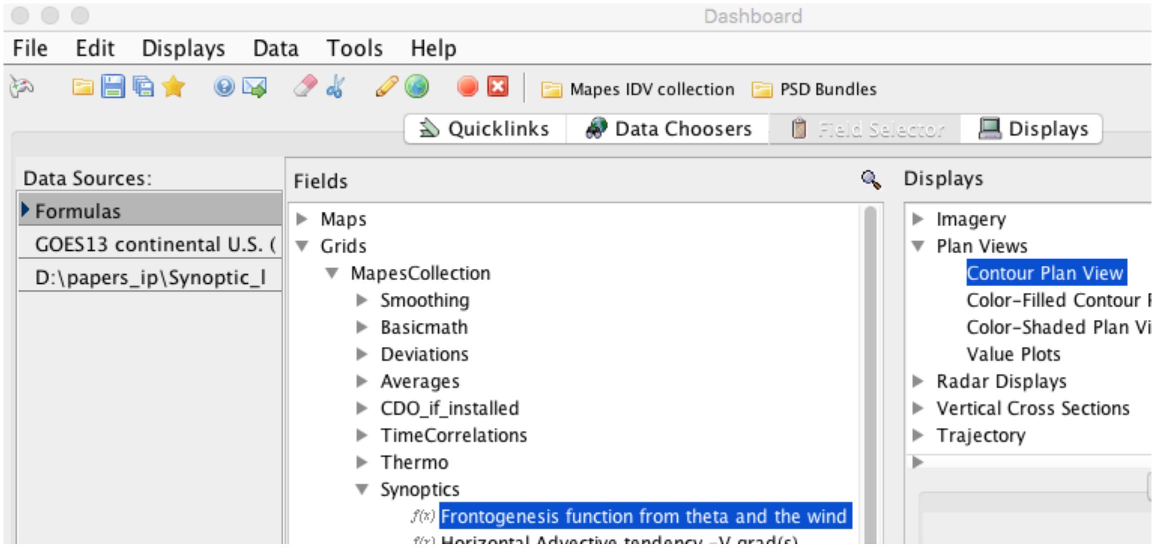
In the IDV `Data Chooser` in the `Dashboard` window, load today's 1200 UTC NAM run, for example, with 80- or 40-km data (this is available in several different catalogs, but the screenshot below illustrates how you might find it in Unidata's IDV Catalog).



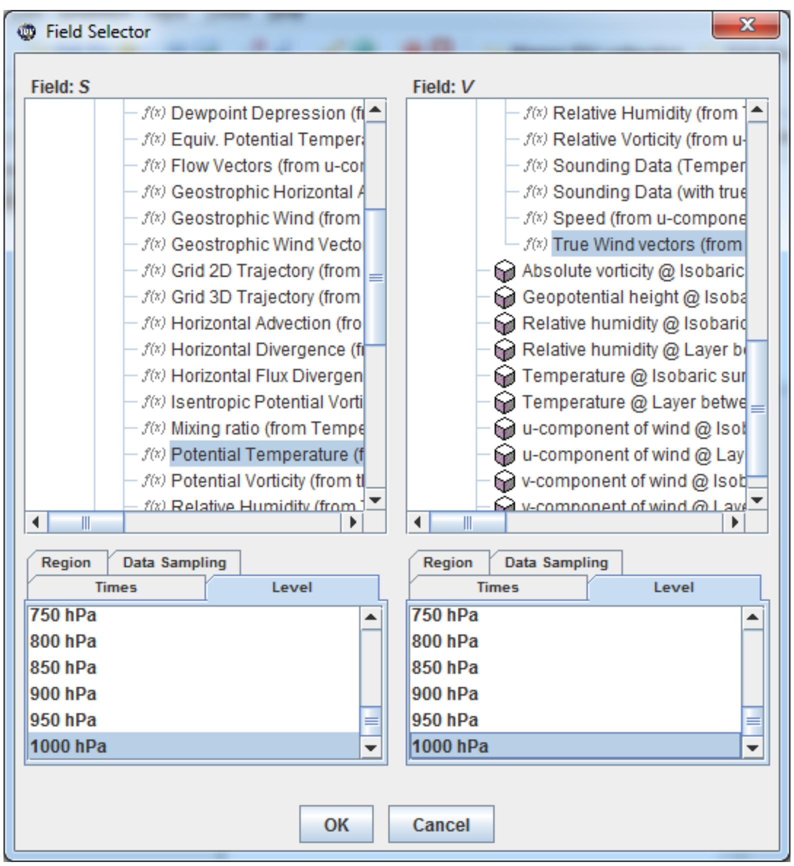
First, **plot the near-surface temperature or potential temperature field as a `Contour Plan View` or a `Color Shaded Plan View`** using elementary operations in the `Field Selector` tab. Based on the result, **identify an area of interest that exhibits strong gradients, which could correspond to a front**.

Next, we will plot the frontogenesis function. Remember, the IDV frontogenesis calculation *only* plots the first two right-hand terms in the frontogenesis equation (6.2) above, confluence and shearing, which are just the horizontal, advective parts. It does not plot the last two: the gradient of diabatic heating/cooling, and tilting of θ surfaces, which would require data on heating rate and vertical velocity.

To contour the frontogenesis function, select the following set of pull-down menus from the `Field Selector` tab in the `Dashboard`:



Once you hit `Create Display`, you will be prompted for the fields that are needed for the computation. For the scalar field (S) select `Derived > Potential Temperature` at some lower tropospheric pressure level. For the vector (V) field select `Derived > True Wind Vectors`, which will be drawn from the corresponding vertical level. You will need to choose these from a `3D grid` data set.



a) **What are the *units* of the frontogenesis function? Does this make intuitive sense?**

b) **Does the order of magnitude of values correspond to your scale analysis from 6.1? Are they in different units? If so, change the units to match.** To do this, click on the frontogenesis function label in the legend and then, under the `Edit` menu, select `Change Display Unit`.

c) **Adjust contour intervals as needed to isolate fronts without too much nonfrontal clutter** (the exact values will be case dependent). **Are there regions that exhibit *frontogenesis* that do not correspond to *traditional fronts*? If so, how can you tell the difference?**

d) **Optional:** Try plotting a 3D isosurface of the `Frontogenesis function` in order to gain a sense of 3D structure. In order to set this up, you will need to use isobaric (3D grids) data. For clarity, consider restricting the range of `Level` for potential temperature and wind (using shift-click on a second value in the `Level` list to select a range), for example 1000 to 800 hPa. What is the three-dimensional structure of the fronts you see? **Do they tend to "lean back" towards the colder air, or are they upright, or do they lean towards warmer air? Why do they seem to have a preferred structural tilt?**

If you are satisfied with the frontogenesis displays you have created, consider saving them as an IDV bundle for future use. To do this, click on `File`, and `Save as...`.
Since you selected the `Latest` file from the `Data Choosers - Catalog`, this bundle will always display the current weather.