Weather Observation and Analysis

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Course Notes

Chapter 13. FRONTS AND FRONTOGENESIS

13.1 Fronts as Temperature Gradients

Fronts were first discovered during World War I, and the name was adopted by analogy to the fronts of battle during the war. Until data from a weather network covering a significant hunk of territory was regularly transmitted and plotted at a central location, it was difficult to recognize the patterns behind the sudden weather changes at different stations.

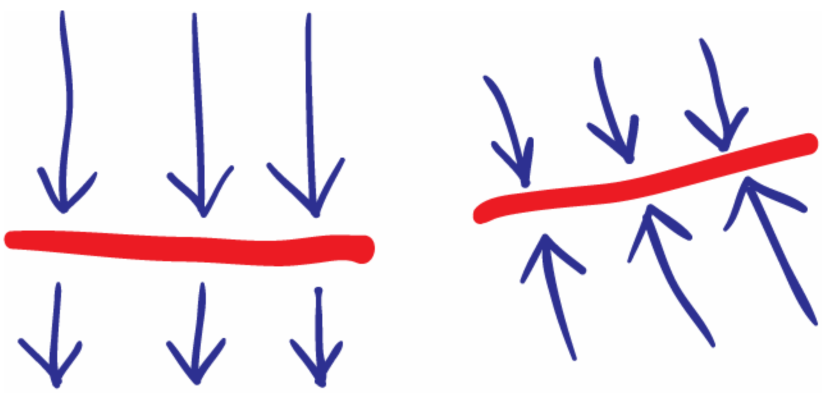
Today, fronts, along with highs and lows, are the most common features of weather maps, and even children are able to recognize the symbols. Nonetheless the working definition of a front remains somewhat elusive, and the decision about where a front lies is a judgment call that experienced weather analysts can disagree about. The basic definition of a front is a narrow, elongated zone with a locally strong temperature gradient. But how narrow is narrow, how elongated is elongated, and how strong is strong?

Some have argued that, because of this ambiguity, we should dispense with the concepts of fronts entirely and simply let the analyses of temperature, wind, pressure, etc. speak for themselves. Such an approach is attractive in its intellectual purity, but in practice, people expect to see fronts, and fronts are intimately related to weather patterns. The non-front folks would argue that the relationship between fronts and weather patterns is anything but simple, and that the mere presence of a frontal symbol without a depiction of the underlying weather elements is likely to be misleading.

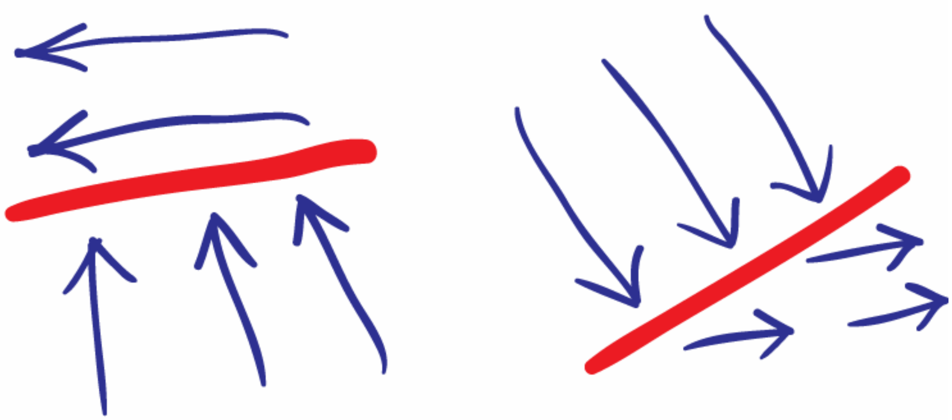
Even the basic definition of a front includes many non-fronts. For example, imagine a coastline separating a warm land surface from a cold ocean. The air above the coastline would meet the criterion of a narrow, elongated zone of locally strong temperature gradient. Yet nobody would consider it to be a true front.

While this argument rages, we will attempt to construct a working definition of fronts that will serve us well enough for the time being. A synoptic-scale front is an air mass boundary that extends up into the troposphere. It includes at least a locally enhanced temperature gradient and a vector wind shift.

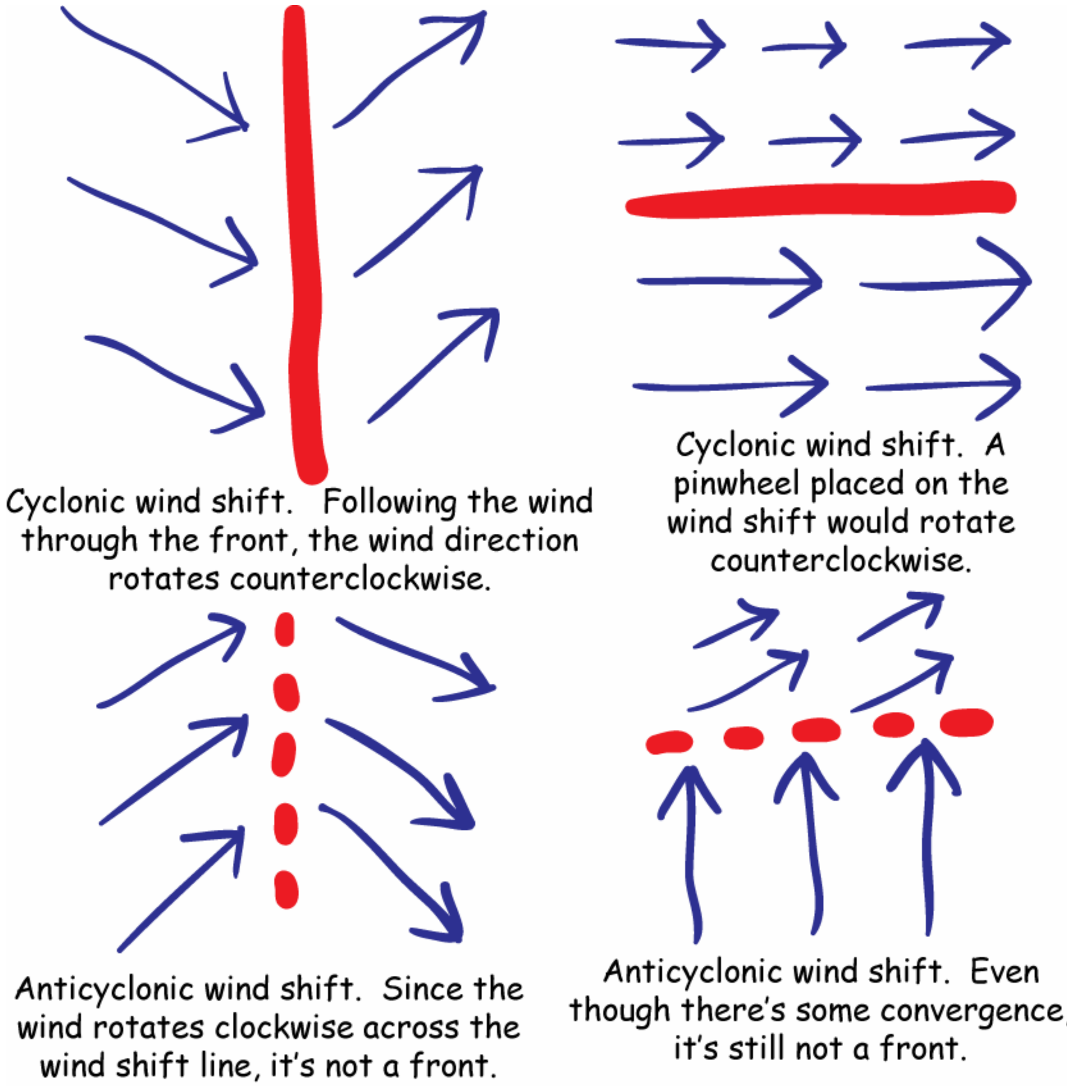
A vector wind shift means that the horizontal wind vectors on one side of the front are different from the horizontal wind vectors on the other side of the front. At ground level, the wind shift is either purely convergent or both convergent and cyclonic. Above ground level, the wind shift is only cyclonic.



Convergent wind shifts. Along the windshift line, there is net flow toward the windshift.



Convergent and cyclonic wind shifts. Not only is there net flow toward the windshift, but the wind direction turns counterclockwise as one follows the wind across the windshift.



Cyclonic wind shift. Following the wind through the front, the wind direction rotates counterclockwise.

Cyclonic wind shift. A pinwheel placed on the wind shift would rotate counterclockwise.

Anticyclonic wind shift. Since the wind rotates clockwise across the wind shift line, it's not a front.

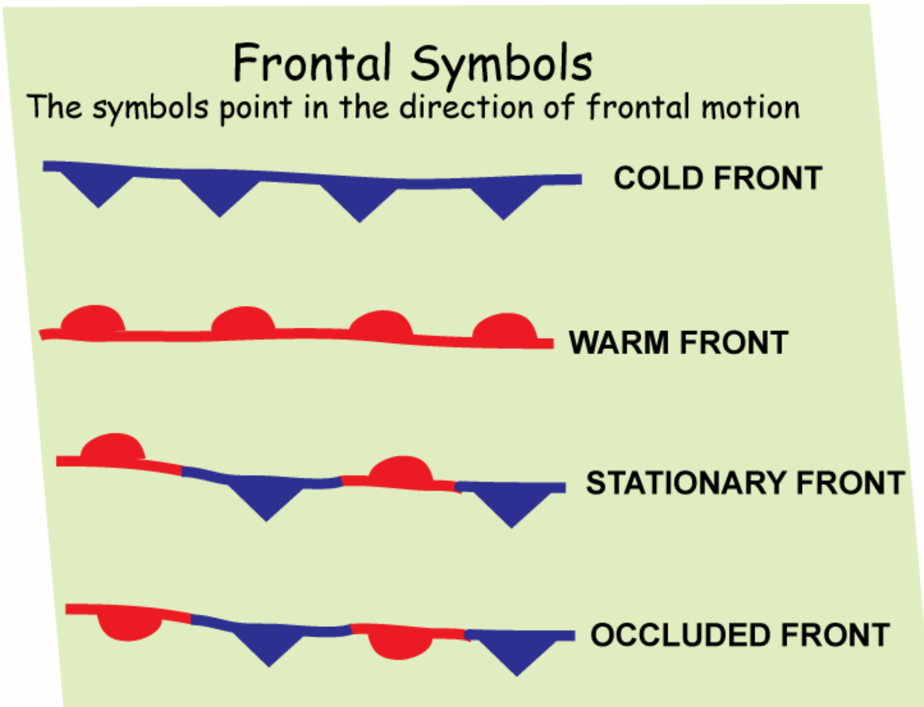
Anticyclonic wind shift. Even though there's some convergence, it's still not a front.

The front must also include a change in pressure gradient consistent with that change in wind. Usually the pressure pattern will take the form of a trough. If there are different air masses on either side of the front, there may also be a dewpoint gradient. The front may also include variations in weather or cloud cover.

The inclusion of "synoptic scale" means the front must be at least several hundred kilometers long. Simple gust fronts, outflow boundaries, and sea breezes are excluded from this category because they are generally too short or too shallow to be considered synoptic-scale fronts. Indeed, there are only five kinds of synoptic-scale fronts: warm fronts, cold fronts, stationary fronts, occluded fronts, and upper-level fronts.

13.2 Surface Fronts

Except for upper-level fronts, all the front types listed in the previous paragraph are surface fronts. They are called surface fronts even though they extend up above the planetary boundary layer, because the strongest wind variations and temperature gradients tend to be at the surface. Surface fronts typically weaken with height, and while it is possible for surface fronts to connect with upper-level fronts and thereby extend through the entire depth of the troposphere, most surface fronts peter out near the 600 mb to 800 mb level.



Surface fronts have specific structural characteristics that are important for understanding the weather associated with them. The following discussion applies specifically to variations of weather elements observed at ground level.

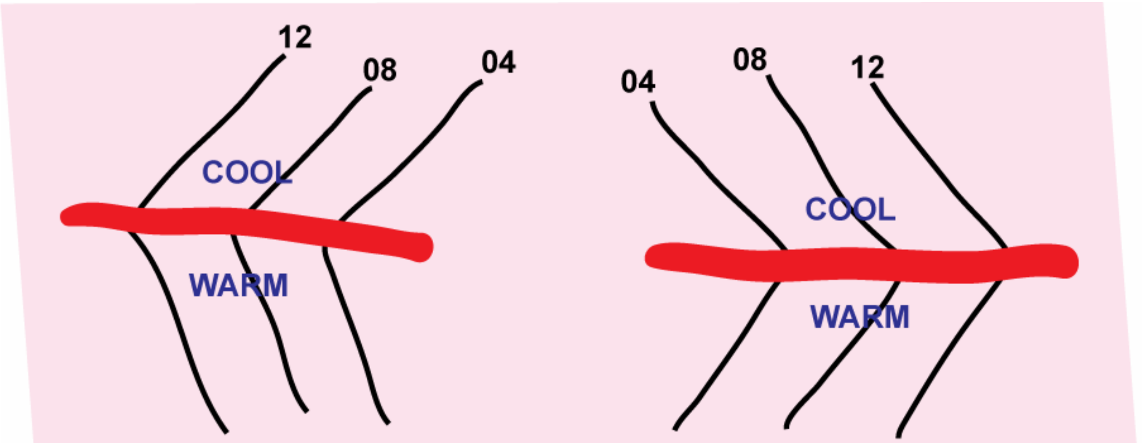
First, the zone of strong temperature gradient is generally much wider than the zone over which the wind shift occurs. In other words, while the temperature gradient zone is rather narrow, the wind shift is very narrow.

Second, the wind shift, which is collocated with (or at worst within a few miles of) the pressure trough, is at the warm edge of the temperature gradient.

Third, if there’s a dewpoint change across the front, the dewpoint change tends to be even more rapid than the temperature change.

Fourth, while there’s often cloudiness and precipitation associated with cold fronts, they can occur on either side of the front, well ahead of the front, or not at all. Warm fronts are a bit better behaved: if there’s to be rain or snow associated with a warm front, it will usually be found ahead of it, on the cold side. The weather associated with stationary fronts and occluded fronts is similar to that associated with warm fronts.

While they tend to have certain distinguishing characteristics, technically the only absolute difference between warm fronts and cold fronts are the nature of the change of temperature as the front passes. Warm fronts bring warmer temperatures, while cold fronts bring colder temperatures. Even in this absolute sense, exceptions can occur if, for example, a cold front passes on a calm night or low clouds are present ahead of a cold front during daytime; both can cause temperatures to temporarily rise when a cold front passes.

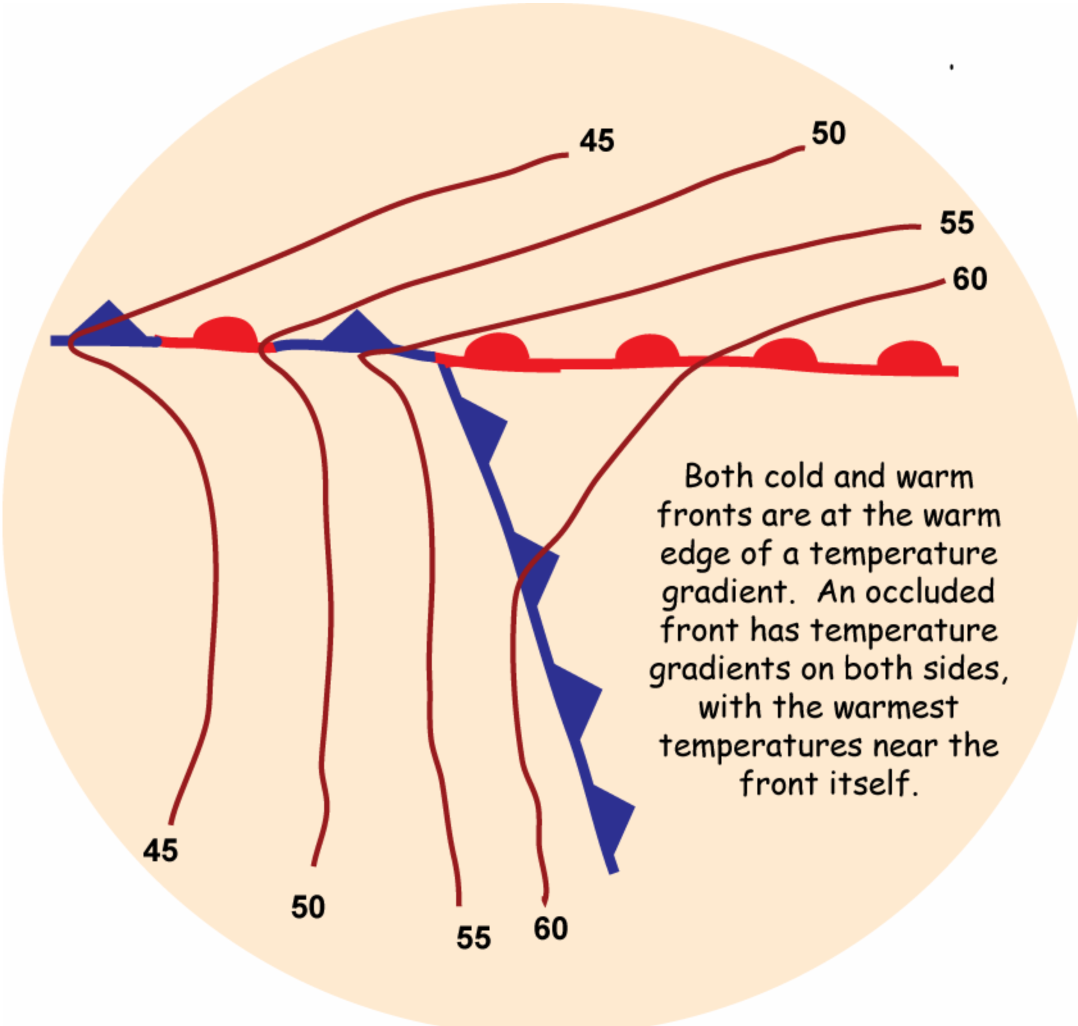


According to the isobars, the geostrophic wind in the figure on the left is blowing from the cool side of the front toward the warm side. Thus, it is a cold front. On the right , the geostrophic wind is blowing from the warm side to the cool side, making it a warm front.

The surface wind and pressure usually tell which way a front is moving: if the average of the winds on both sides of the front would carry the front in a particular direction, that's usually the way the front will move. Using isobars you don't even have to estimate an average: if isobars pass through a front, the direction of the geostrophic wind tells you the direction of frontal motion.

A stationary front is a front that is not moving much. No fronts are perfectly stationary, so how much can a stationary front move and still be stationary? A basic rule of thumb is about five miles per hour, or about two degrees of latitude per day.

At an occluded front, the air ahead of a warm front meets the air behind a cold front. Usually this situation is found near surface low pressure systems, where an occluded front can extend from the vicinity of a low pressure center to an intersection point between the warm and cold fronts. In most cases, the cold front is actually riding up over the top of the warm front, so the occluded front should be drawn as an extension of the warm front. Since both the warm front and cold fronts have temperature gradients, there are two temperature gradients associated with an occluded front: one ahead of the front and one behind. The front itself lies along the axis of warmest temperature and is also marked by a trough and a wind shift.



All warm fronts tilt forward toward the colder air. Cold fronts are not so systematic. While most tilt backward toward the colder air, some tilt forward. Slopes of warm and cold fronts vary widely, even within the same front.

13.3 Upper-Level Fronts and Split Fronts

The final type of synoptic-scale front is the upper-level front. True to its name, upper-level fronts are found in the middle and upper troposphere, but some have been known to extend fairly close to the surface. Unlike surface fronts, which have their wind shift concentrated at the warm edge of the front, upper-level fronts have the wind shift and strong temperature gradient collocated.

Upper-level fronts are most often found in the vicinity of strong jet streams. They are typically oriented nearly parallel to the upper-level winds, and tilt toward the cold air.

That cold litany of facts makes upper-level fronts seem rather boring. A bit more interesting is the fact that all upper-level fronts are really narrow tongues of stratospheric air being dragged down into the troposphere. In a cross section, the high stratification within an upper-level front connects directly with the high stratification within the stratosphere, and aircraft observations have confirmed the presence of stratospheric ozone levels within upper-level fronts.

Upper-level fronts by themselves are not associated with much surface weather, but they are quite significant for aviation forecasting. The zone of an upper-level front often features strong turbulence excited by strong vertical wind shear, so commercial aircraft generally try to avoid them.

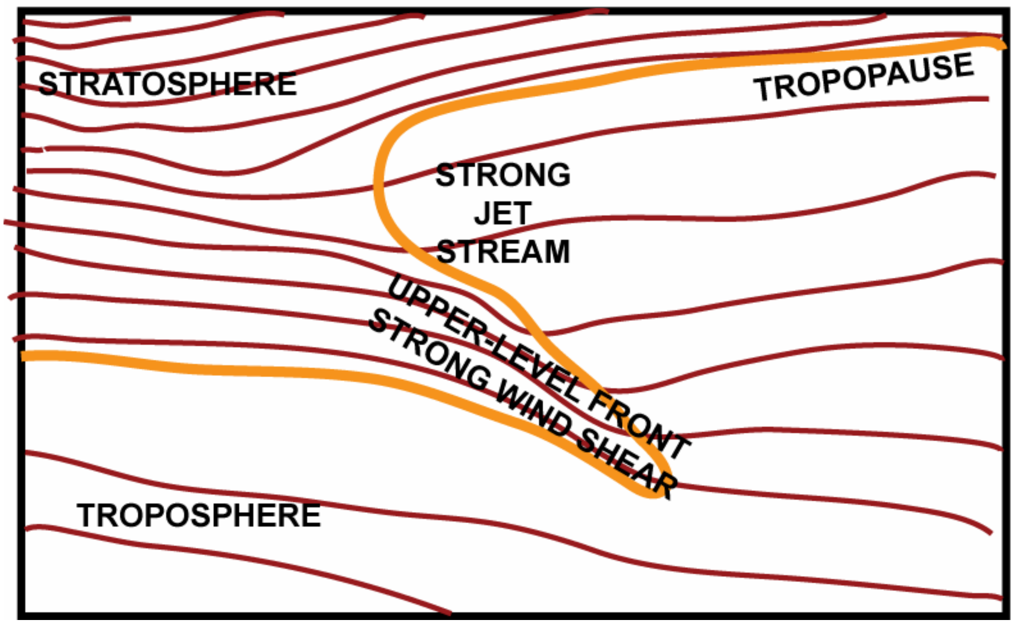
A so-called *split front* is actually two fronts: a surface cold front and an upper-level front that extends ahead of it. The best way to tell if a split front is present is from inspection of both surface and upper-level maps, but if only surface maps are available, the evidence for a split front is a band of moderate precipitation well ahead of the surface cold front, with low clouds and little precipitation associated with the cold front itself. The back edge of the moderate precipitation generally corresponds to the upper-level front. If you are expecting the precipitation to always be along the surface front, a split front can really wreck your forecast.

13.4 Fronts and Wind Shear

According to thermal wind balance, the strong temperature gradients associated with synoptic-scale fronts should be associated with strong vertical wind shear. As with all geostrophic vertical shear, the shear vector (the vector difference between higher-level winds and lower-level winds) should be oriented along the isotherms with warmer temperatures to the right. Since fronts are oriented nearly parallel to isotherms, the vertical wind shear will be almost parallel to the temperature gradient too.

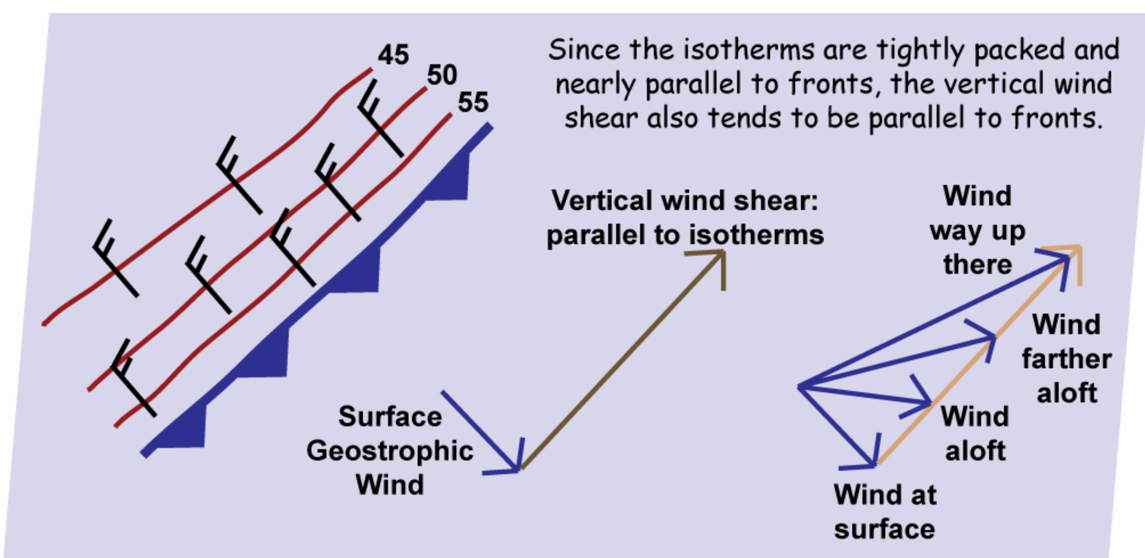
The above statements are consistent with what was earlier noted about upper-level fronts: that they tend to be associated with strong jet streams and be oriented parallel to them. Indeed, upper-level fronts will typically start on the left side of the jet (facing downwind) and slope under the jet, extending out the right side in the middle troposphere. This puts the strongest temperature gradient beneath the jet, where it must be if the wind speeds are to increase rapidly with height up to jet stream level.

In this vertical section, the maroon lines show potential temperature, which increases upward. The upper-level front is simultaneously a tropopause fold, a zone of strong horizongal temperature gradient, and a zone of strong vertical wind shear. A jet stream tends to be located above an upper-level front.



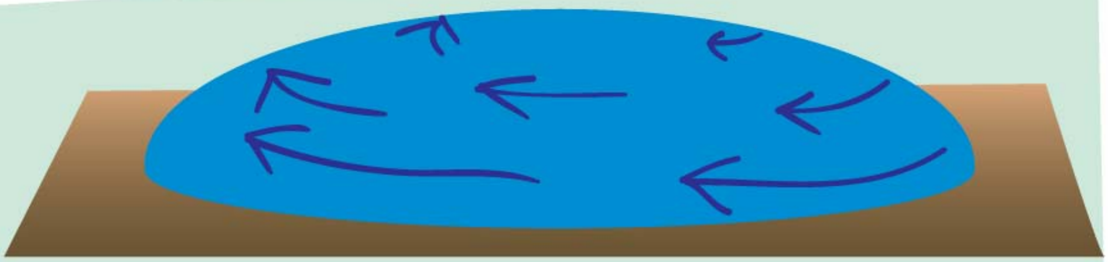
With surface fronts, the shear is not so noticeable, not because it is much weaker but because the temperature gradients and temperature advection seem to attract the most attention.

As an example, consider a cold front oriented northeast-southwest, with the warmer air to the southeast. Suppose the surface winds behind the cold front are blowing from the northwest. Behind the surface frontal position, there must be a strong temperature gradient, so the vertical wind



shear vector must be oriented from southwest to northeast. Add that wind shear to the surface wind and you will get the wind in the low to middle troposphere. In this case, we expect the wind aloft to be out of the west or southwest, depending on the strength of the shear and how high up we choose to go.

It is important to note here that the warm air and cold air can be perfectly “content” to sit side by side with each other. The alarmist statements on various weathercasts about warm and cold air clashing with each other, producing severe weather and tornadoes, is hogwash. Just because you have warm air and cold air next to each other doesn’t mean that the cold air must slide under the warm air and the warm air must be driven up. Sure, the pressure beneath the cold air will be higher than the pressure beneath the warm air, but for synoptic-scale fronts, there’s nothing (except surface friction) to prevent the winds to come into geostrophic balance with the pressure gradient.



A balanced lump of cold air. The wind is represented by the blue arrows. The pressure gradient force is directed outward from the center of the cold blob, but the Coriolis force is directed right of the wind (inward), holding the cold air in place. Note: it only works this way if the blob is big (>100 km). If it’s too small, the cold air will just flow out before the coriolis force has time to induce rotation.

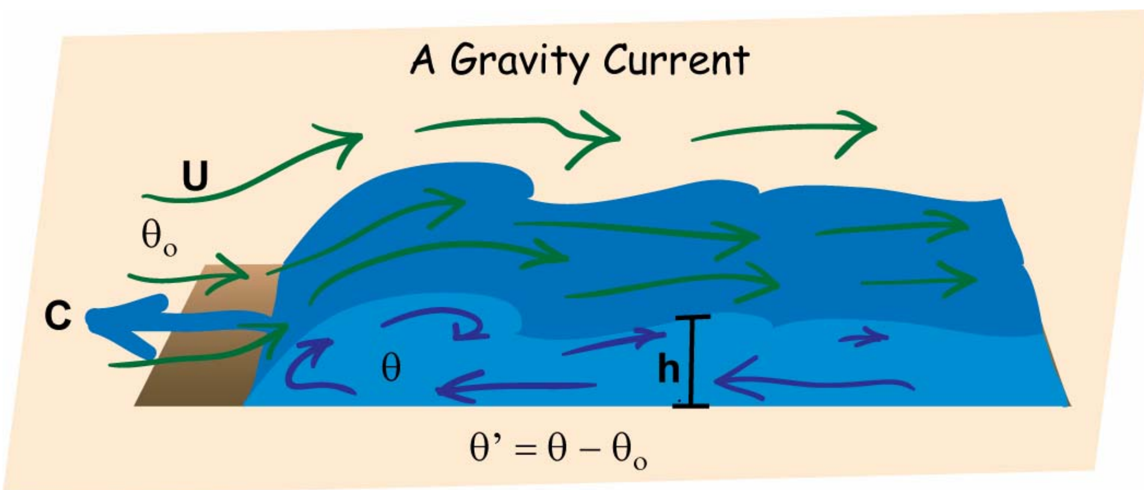
Think about it: you’ve seen geostrophic balance enough times to know that the winds will be blowing parallel to the isobars rather than blowing from high pressure to low pressure. The strong wind shear associated with the frontal zone between warm and cold air masses is also a consequence of geostrophic balance. So while the pressure gradient force might want to cause the cold air to attack the warm air, the Coriolis force is holding the air in place, keeping it moving parallel to the isobars and, aloft, nearly parallel to the front itself. This zen-like state of balance is not nearly as exciting as two air masses clashing, but it is much closer to the truth.

If warm and cold air masses don’t clash, then why are severe weather and tornadoes so often associated with them? Pay attention during the next severe weather outbreak: more than likely, you’ll find that the severe weather is not confined to the fronts but instead occurs in a broad swath within the warm sector. And it is the very shear that keeps the air masses in balance that allows thunderstorms to develop into rotating supercells and occasionally produce tornadoes. The severe weather is not produced by the two air masses clashing, it is produced by the two air masses getting along!

13.5 Gravity Currents

At the surface, with friction, there will be a tendency for the wind to blow partly from high pressure to low pressure. Sometimes this can help cause the leading edge of the front to collapse into a near discontinuity, with several degrees of temperature difference across a kilometer or less. Such sharp discontinuities are often found with smaller fronts as well, such as gust fronts, squall lines, and sea breezes.

Once things get so small and air passes through them so quickly, there's no time for the air to come into geostrophic balance. Instead, a phenomenon called a *gravity current* develops. Gravity currents, also known as density currents, have a sharp leading edge between 100 m and 1500 m deep, sloping back toward the cold air with a slope of about 1:1. Along the interface between the warmer and colder air, instabilities develop because of the strong vertical shear there.



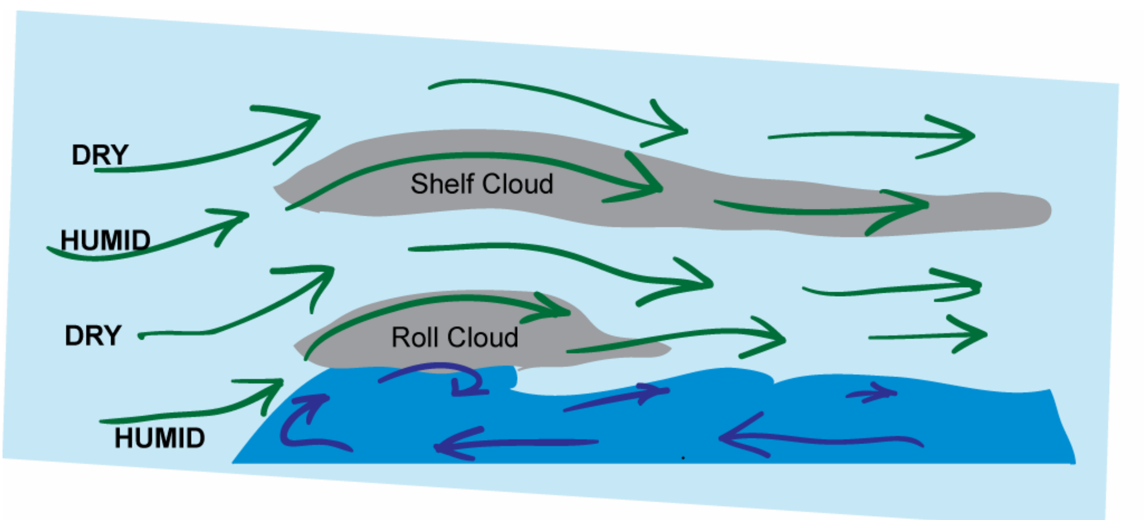
Gravity currents are strange beasts because, quite independent of the sort of dynamical reasoning we have conducted so far, they have a very predictable velocity. The speed C of a gravity current is given by:

$$C \approx U + \sqrt{-g\frac{\theta'}{\theta}h}$$

where *U* is the component in the warm air ahead of the gravity current normal to the gravity current (positive if going away from the gravity current), *h* is the depth of the cold air several miles behind the gravity current, *q* is the potential temperature within the density current, and *q'* is the difference between the potential temperature outside the density current and that within. Plugging in some sample numbers, say a normal wind of zero, a temperature difference of 6 K and a cold air depth of 500 m, the gravity current would be advancing at a speed of about 10 m/s into the warm air.

Notice that in this example, if the warm-air wind had been blowing at 10 m/s toward the cold air, the gravity current would be stationary, with no net velocity. If instead the warm air was blowing away front the gravity current at 10 m/s, the gravity current itself would be trucking along at 20 m/s. In effect, the last term in the gravity current equation gives the speed of the gravity current relative to the warm air.

When the environment of a gravity current is humid, distinctive clouds often form along the gravity current. A *roll cloud* is a cloud that forms due to the upward motion at the head of the gravity current. The cloud can be composed of air from the warm or cold side of the gravity current. When such a cloud appears in a satellite image it is called a *rope cloud*, a term descriptive of how it looks in a satellite image. A *shelf cloud* is a cloud located above the gravity current and represents a layer of humid air aloft that ascends as it passes over the gravity current.



Sometimes a squall line will form along a cold front, and the gravity current speed of the squall line will generally be faster than the speed of the original cold front. As a result, the squall line will propagate out ahead of the original cold front. Since the squall line now marks the leading edge of the strong temperature gradient, the cold front is often drawn coincident with the squall line. But sooner or later, if it doesn't dissipate, the squall line moves so far out ahead of the front that the front and squall line become distinct. It is tricky for a surface analyst to deal with the simultaneous presence of a cold front and squall line.

13.6 Deformation

So far, we've dealt with several important aspects of a vector field, both conceptually and mathematically. Horizontal divergence is the tendency of air parcels to move apart, and is invariably accompanied by some combination of upward and downward motion to replace the air that's moving away. Horizontal convergence is the opposite, and mathematically corresponds to negative divergence. As we'll see in the next chapter, vorticity is the tendency of air parcels to induce spin about a vertical axis on imaginary objects embedded in the air; positive vorticity corresponds to counterclockwise rotation and negative vorticity to clockwise rotation.

The third and last possible property of a horizontal vector wind field is *deformation*. Deformation is the tendency of air parcels to change shape. There's nothing to prevent divergence, vorticity, and deformation to all be present at the same time; pure deformation is when there's deformation but no divergence or vorticity.

The mathematical definition of deformation is rather ugly:

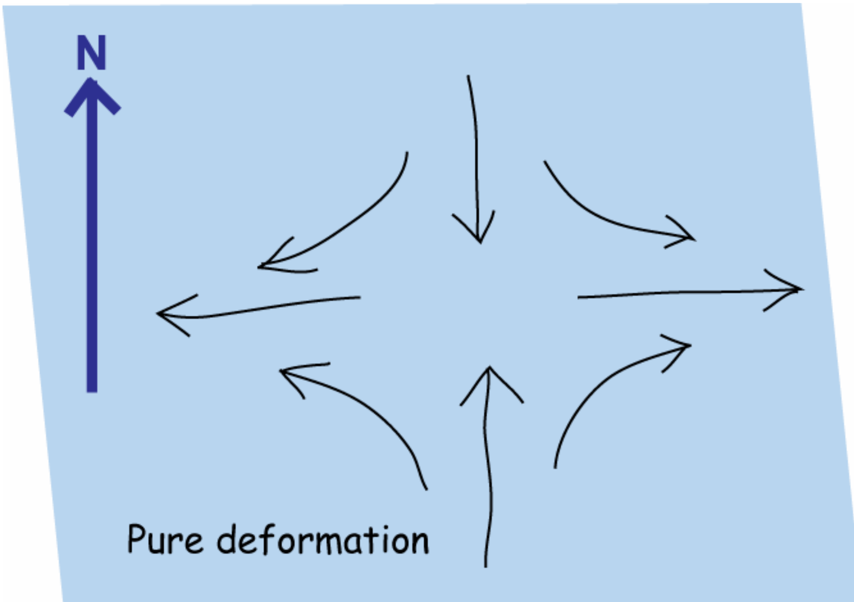
$$D = \sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2}$$

This is not a misprint: the first term in parentheses has a minus sign, so it is not divergence. The second term in parentheses would be vorticity if it did have a minus sign! The similarity of these expressions makes the whole thing a bit of a nightmare for somebody learning the subject.

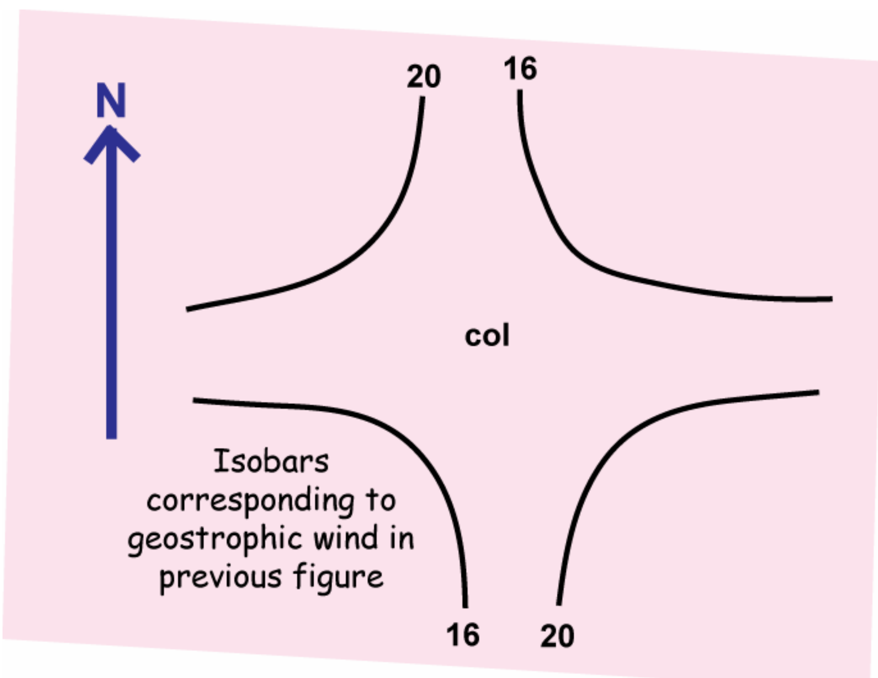
To visualize what pure divergence looks like, let's simplify things and let each quantity in the second term in parentheses equal zero. Not only does that simplify the deformation, but it eliminates any possibility of vorticity. Now, suppose that the rate of increase of u in the x direction is exactly equal to the rate of *decrease* of v in the y direction. This makes the divergence zero as well. Now if we choose (u,v = 0) at the origin, we get a wind field that looks like the diagram on the following page.

Verify for yourself that there is no divergence here by drawing any area and noting that the amount of air going in some sides equals the amount of air going out other sides.

Frequently you will see a wind pattern like this on a weather map. As drawn, assuming geostrophic balance, there would be lower pressure to the southwest and northeast, and higher pressure to the northwest and southeast. At the center, the winds are calm, yet there is neither a high nor

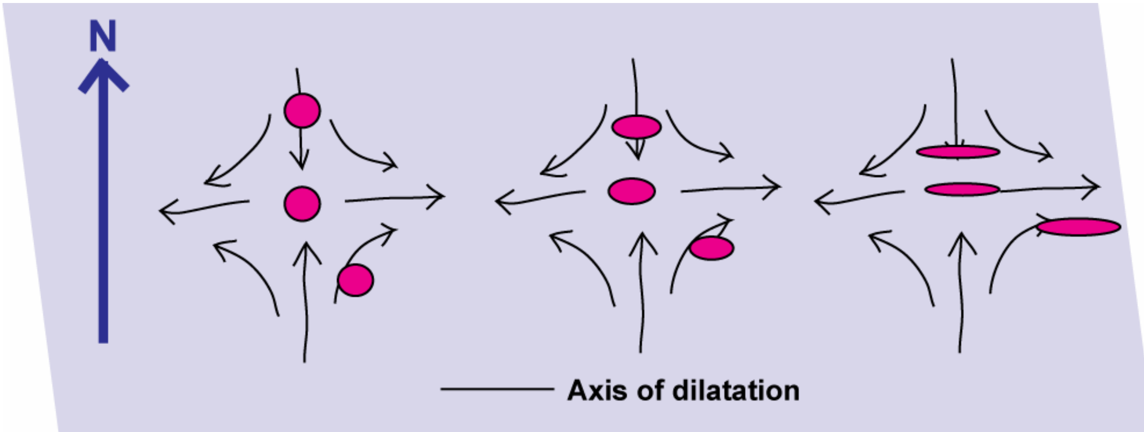


a low there. The name for this feature is a *col* or *saddle point*. The former name refers to a topographic feature, and the latter name refers to the similar appearance of lines of constant height on a saddle,



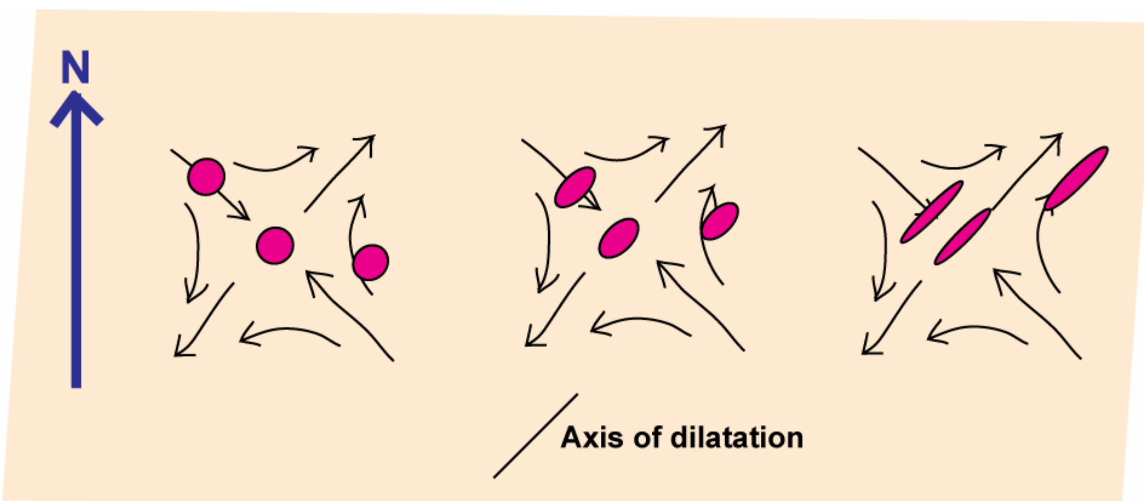
As for deformation, imagine an object placed in the middle of this vector field. The winds will act to stretch the object in the east-west direction and contract the object in the north-south direction. We could say that the object is being deformed, hence the term deformation.

Notice that we need not place the object at the origin for this to happen; deformation is present everywhere. No matter where the object is placed in this vector field, its left and right sides will be moving away from each other and its north and south sides will be moving toward each other.



A useful quantity in connection with deformation is the *axis of dilatation*. This is the axis along which the imaginary object would be stretched (or dilated) most strongly. In the example above, the axis of dilatation is oriented east-west.

Now take the example above and rotate it counterclockwise by 45 degrees. Presumably we have not altered the magnitude of the deformation, since objects would still be stretched or shrunk by the same amount as before. The axis of dilatation will have rotated too, and now would be oriented northeast-southwest.



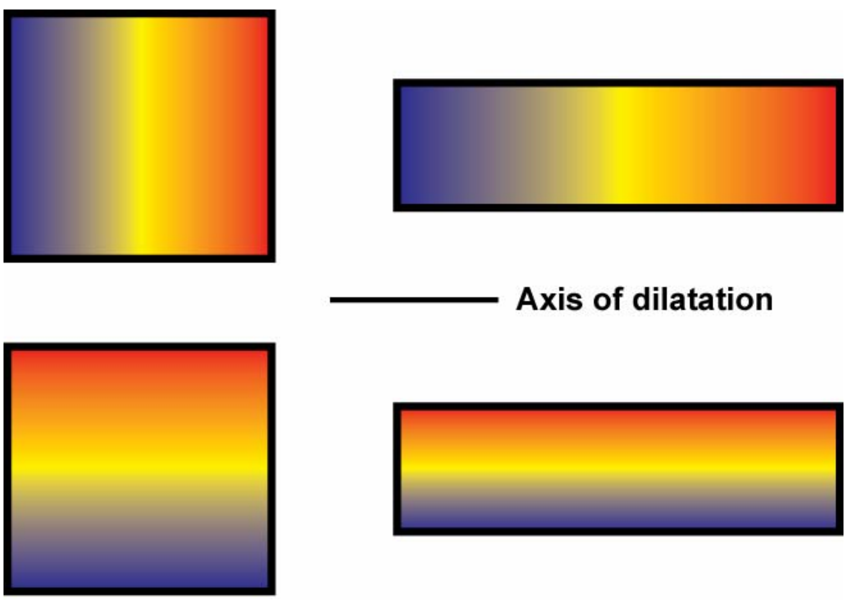
With the rotated wind pattern, consider the mathematical terms in the definition of deformation. After the rotation, each of the derivatives in the first term in parentheses is suddenly zero! (Don't take my word for it, work it out for yourself.) But not to worry, the second term is now nonzero. Since v increases in the positive x direction, the first derivative is positive. Since u increases in the positive y direction, the other derivative is also positive. The lesson here is that there's really nothing special about which of the terms contributes to deformation.

13.7 Deformation and Frontogenesis

Getting back to our previous example, suppose that the object being deformed is an imaginary square. (With deformation, it won't be a square for long!) Suppose further that two opposite sides of the square lie in air with different temperatures. What will happen to the temperature gradient under the action of deformation?

The answer depends on which two sides you pick. If you pick the east and west sides, those sides are becoming farther apart, so the temperature gradient is getting weaker and weaker. If, instead, you pick the north and south sides, those sides are becoming closer together, so the temperature gradient is getting stronger and stronger.

The case of the north and south sides of the square having different temperatures corresponds to isotherms (lines of constant temperature) running east-west, so that temperature changes as you go north or south. In the example deformation flow, the winds are causing the isotherms to become closer and closer together. If instead we had isotherms oriented north-south, the deformation would cause the isotherms to become farther apart.

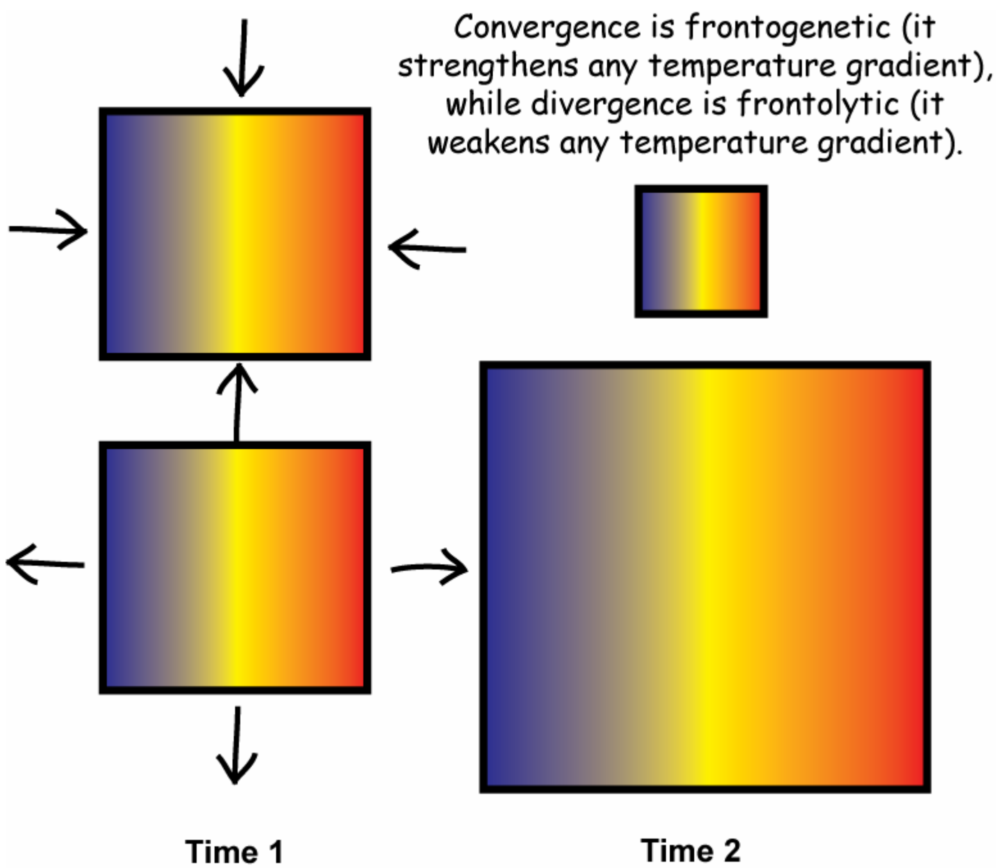


Depending on the orientation of the horizontal temperature gradient and the axis of dilatation, deformation can either weaken or strengthen the gradient.

Whether the isotherms get closer together (and the temperature gradient becomes stronger) or the isotherms get farther apart (and the temperature gradient becomes weaker) depends on the relative orientation of the isotherms and the axis of dilatation. If the two have a similar orientation (in the example case, east-west), deformation will cause the gradient to intensify. In fact, any angle between them less than 45 degrees will lead to intensification. If the angle is larger, all the way up to a maximum of 90 degrees, deformation will lead to a weakening temperature gradient. Right at 45 degrees, deformation will have no effect.

The process by which the temperature gradient intensifies (and, in mathematical terms, the time rate of change of the magnitude of the temperature gradient) is called *frontogenesis*. Frontogenesis is one of the most humorous-sounding words in all of meteorology, just behind "isodrosotherm". The converse process, in which the temperature gradient weakens, is called *frontolysis*.

Deformation is one of the ways frontogenesis can take place, as long as the isotherms are oriented properly relative to the axis of dilatation. Another frontogenetic process is convergence. Both work well, but for large-scale motions the wind is approximately in geostrophic balance and the convergence of the geostrophic wind is almost zero, so big synoptic-scale fronts are almost always produced primarily by deformation.



While it is natural to think of frontogenesis as something that happens to a front, strictly speaking frontogenesis is something that happens to an air parcel that may or may not be embedded within a front. It is actually possible for air to pass through a front, if it experiences frontogenesis on the way in and frontolysis on the way out. This most often happens with upper-level fronts: air comes in one end of the front and goes out the other.

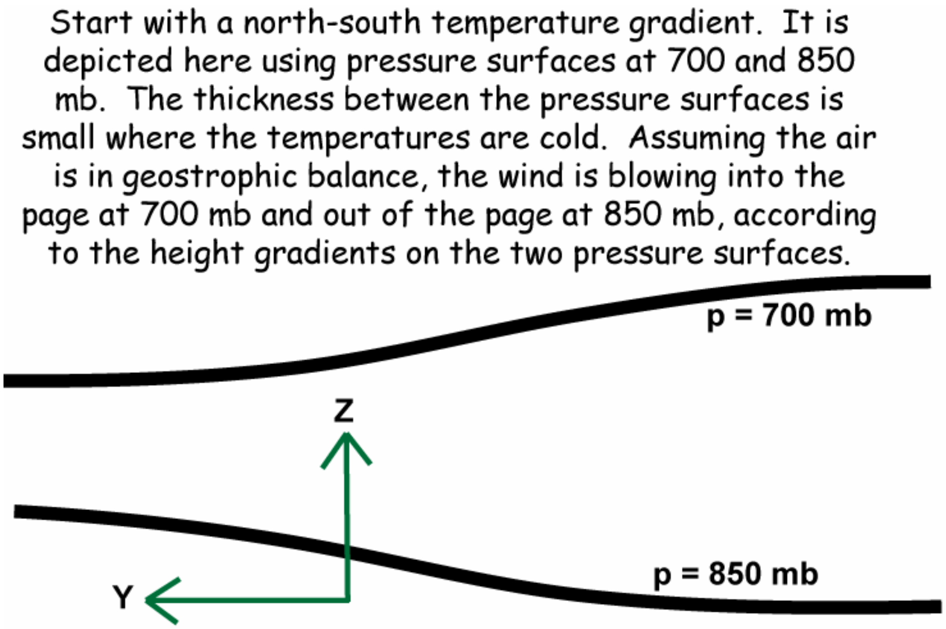
13.8 Frontogenesis and Vertical Motion

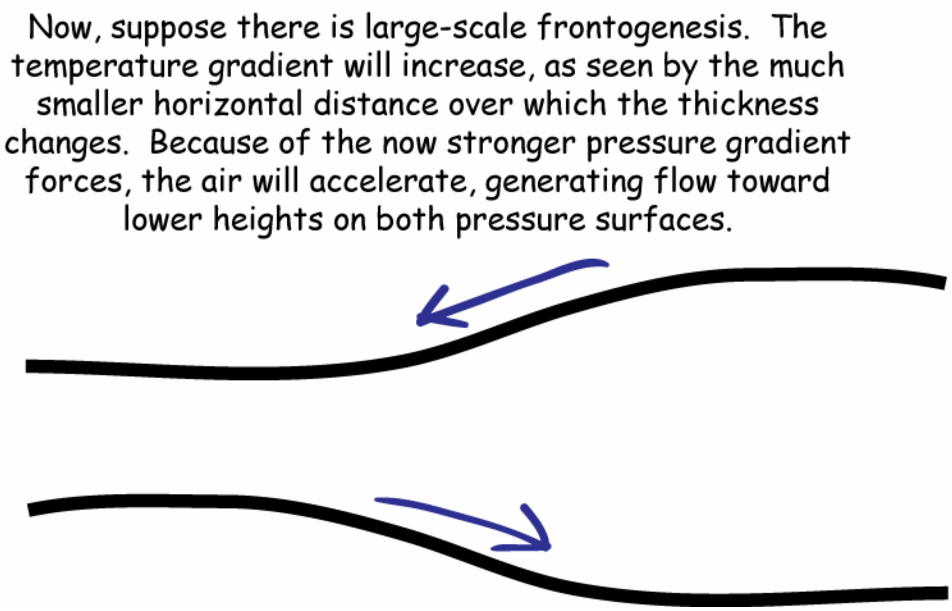
So far we've seen that deformation can happen as a result of large-scale wind patterns and it can produce frontogenesis. Now, at the scale of a synoptic-scale front, the wind will be in thermal wind balance, so if the wind pattern is such as to cause frontogenesis, somehow the vertical shear must be increasing at the same time. For reasons too convoluted to get into here, the same horizontal wind pattern that causes frontogenesis would by itself cause the vertical shear to weaken. So large-scale frontogenesis tries to throw the atmosphere completely out of balance. So what else happens that keeps the atmosphere (nearly) in thermal wind balance?

If the temperature gradient is changing, the pressure gradient must be changing too. In particular, a stronger temperature gradient means a stronger gradient at low levels between high pressure on the cold side and low pressure on the warm side. While the winds may initially have been in geostrophic balance, the stronger low-level pressure gradient will cause an additional acceleration from the cold side toward the warm side at low levels. This, in turn, implies the development of low-level convergence on the warm side and divergence on the cold side. Which itself means upward motion on the warm side and downward motion on the cold side. Mass conservation tells us that aloft there must be divergence on the warm side and convergence on the cold side, so the air would be blowing from warm to cold aloft. We've actually described a complete vertical circulation cell, with low-level air moving from cold toward warm, rising, moving aloft back toward cold, and sinking.

Now stay with me. The horizontal winds just described imply a Coriolis force directed toward the right of the winds. Since the new winds at the surface and aloft are in opposite directions, so too are the associated Coriolis forces. And the acceleration in response to the new Coriolis forces leads to an increase of shear, just the sort of thing we need to keep the atmosphere close to thermal wind balance.

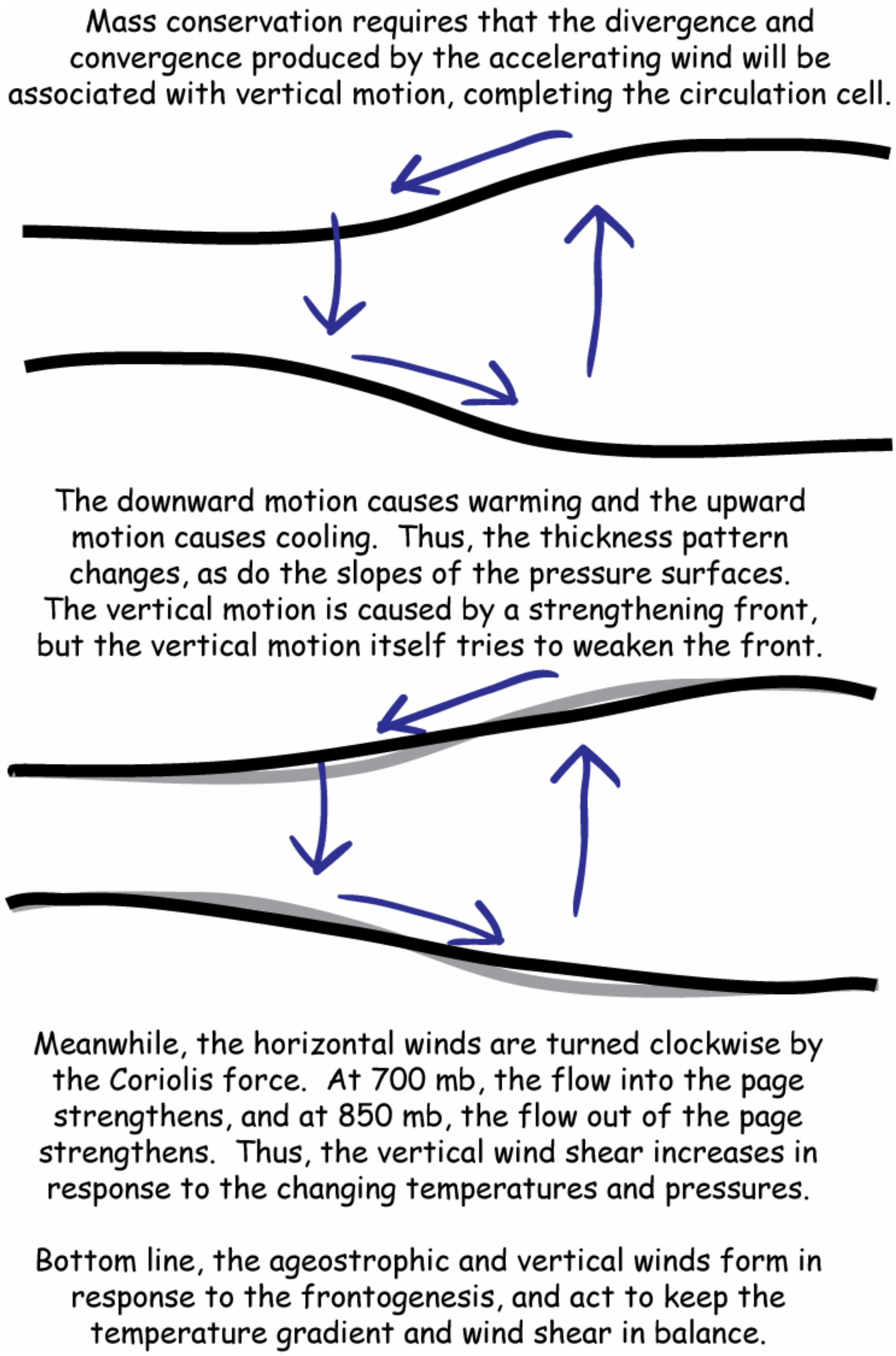
Meanwhile the vertical motions just described involve the air on the warm side of the front rising, so the air over there would be getting cooler. On the cold side, the subsidence leads to warming. On the whole, the temperature gradient would be weakening because of this vertical circulation.



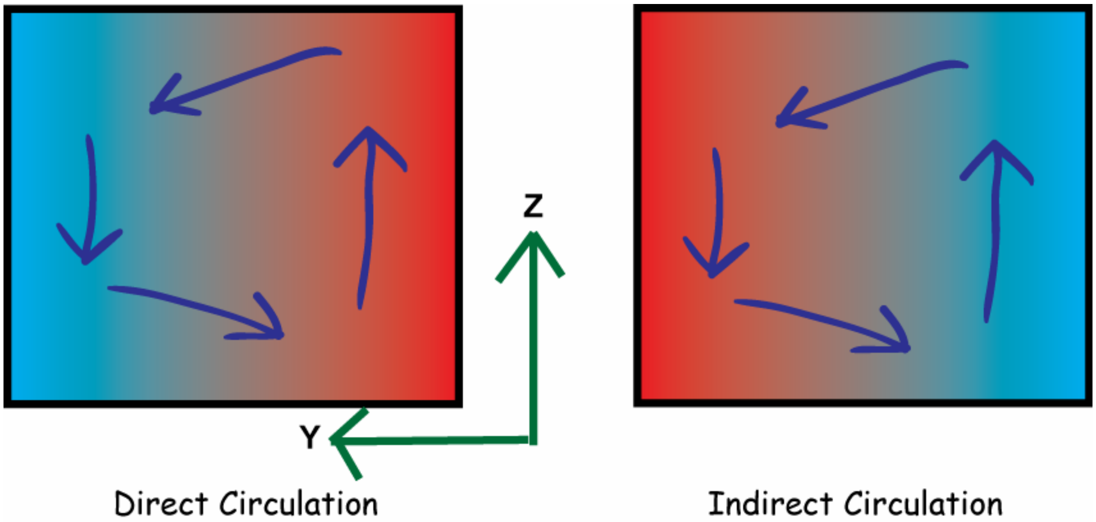


If deformation is causing frontogenesis at a certain rate, one can determine exactly what combination of horizontal accelerations and adiabatic cooling would allow the vertical shear to increase at exactly the same rate as the horizontal temperature gradient. And the mechanism is self-adjusting: too much of this secondary circulation, and the frontogenesis would weaken, the accelerations would weaken, and the secondary circulation would weaken.

This, then, is our first real dynamical example of vertical motion. Frontogenesis is associated with a cause-and-effect chain that leads to upward motion on the warm side of the front and downward motion on the cold side. The term for such a circulation, with the rising air being



warmer than the sinking air, is a *direct circulation*. Conversely, it turns out that frontolysis is associated with upward motion on the cold side and downward motion on the warm side, that being an *indirect circulation*.



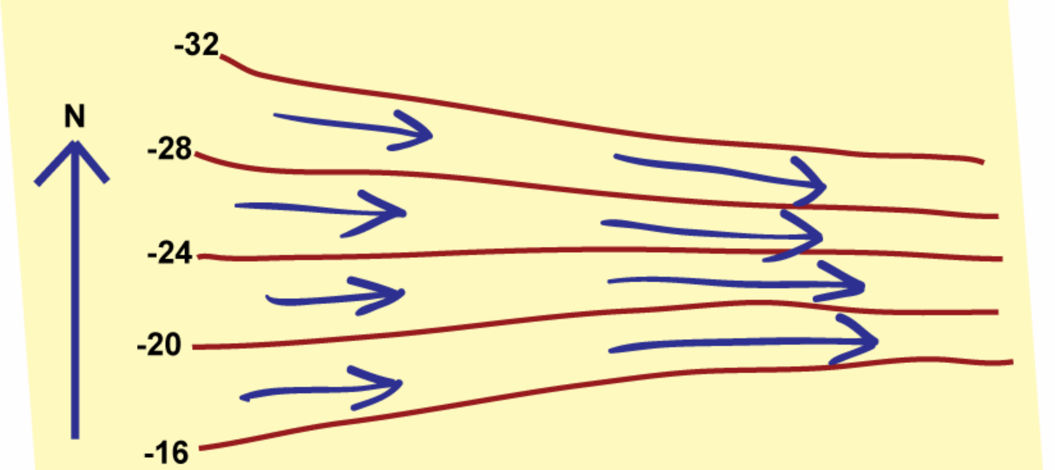
Notice that it is not the mere presence of the front that is causing the upward motion. Instead, it is the tendency of the front to strengthen or weaken that leads to an adjustment process that involves vertical motion.

True, there are other aspects of a front that produce upward motion even if the front is staying constant. One such situation occurs if a gravity current forms on the leading edge of the front. The gravity current will flow toward the warm air, and the warm air will be displaced upward. The other such situation is the convergence that surface friction induces along any trough, including a front. The convergence implies upward motion aloft. But both of these effects are strongest at ground level and would barely be felt at heights of 3 km or more. In contrast, the vertical motion induced by frontogenesis works even for upper-level fronts.

13.9 Fronts and Jet Streaks

Why is a jet streak like a front? Because a jet streak, being an area of very strong winds, will typically have very strong vertical wind shear beneath it, and therefore a very strong horizontal temperature gradient. As air beneath the jet streak flows toward the jet streak, we would expect that, since the height gradient is intensifying, the height contours would be becoming closer together. This confluence would be associated with deformation and therefore (if the isotherms are close to parallel with the wind) frontogenesis.

So as an air parcel begins to move underneath a jet streak, we should expect the same direct vertical circulation as with the earlier frontogenesis example. In particular, there would be upward motion to the right (the warm side) and downward motion to the left (the cold side). Aloft, near the level of strongest winds, there would be a component of motion directed from right to left, across the height contours toward lower heights.



Beneath the entrance region of a jet streak, both the pressure gradient and temperature gradient strengthen downstream. Each air parcel experiences frontogenesis, even though the temperature pattern itself doesn't necessarily change. The vertical circulation associated with frontogenesis results. Thus, there will be upward motion toward the south and downward motion toward the north.

Just arguing on the basis of forces and acceleration, we saw in an earlier chapter that in the entrance region of a jet streak, there must be cross-contour flow toward lower heights on a pressure surface. Here we see that the cross-contour flow is probably the top end of a compete vertical circulation.

Similarly, as air leaves the area below a jet streak, its temperature gradient weakens because of the diffluence. This would mean an indirect circulation, and flow at jet level from low pressure toward high, just as we expect from a simple force argument.

We thus see that a jet streak is a gigantic example of frontogenesis and frontolysis. Just by virtue of the existence of a jet streak and the attempts of air parcels to maintain thermal wind balance, a direct circulation should be present upstream of the jet streak and an indirect circulation downstream. The resulting vertical motion implies that, beneath the jet streak, the warm air to the right (facing downwind) of the entrance region of the jet streak should be rising, as should the cold air to the left of the exit region of the jet streak.

While flow curvature and other effects invariably complicate the picture, the basic description is fine and often applies to severe weather situations in the southern Plains. Forecasters will look for the locations of upper-level jet streaks, and the right entrance region is a favored area for severe weather because of the extra ascent present there.

Questions

1. It’s 9PM at a weather station. The temperature had been rising for several hours, but now finally levels off. The wind, earlier from the east, becomes fairly strong from the south and the low clouds have dissipated. (a) What kind of front just moved through? (b) Sketch a few observations on a weather map to illustrate the spatial distribution of weather associated with this front. Indicate the frontal position with standard symbols.

2. It’s 3AM at a weather station. The temperature had been dropping slowly for several hours, but now suddenly rises as the wind, formerly light from the southwest, strengthens and now blows from the north. The air pressure rises rapidly and the dewpoint drops. A few minutes later, the temperature starts falling again, but faster than before. (a) What kind of front just moved through? (b) Sketch a few observations on a weather map to illustrate the spatial distribution of weather associated with this front. Indicate the frontal position with standard symbols.

3. (a) On a vertical section, sketch the temperature pattern that would be associated with a cold front that tilts toward the cold air. (b) Do the same for a cold front that tilts toward the warm air.

4. What is the horizontal pressure gradient in a col?

5. Sketch a wind field in which the axis of dilation is oriented north-south.

6. Sketch a wind field in which the first term in parentheses in the definition of deformation is zero and the second term in parentheses is negative. Deduce the axis of dilatation.

7. Explain, step by step, what happens with acceleration and vertical motion when the large-scale flow is frontolytical. Use diagrams to illustrate your explanation.

8. Meteorologist A argues that if there’s upward motion on the warm side of the front, there will be adiabatic cooling there and the front will weaken. Meteorologist B argues that if there’s upward motion on the warm side of the front, the front must be strengthening because that’s what causes the upward motion. Can you resolve this conflict?

9. Create a three-dimensional sketch of a jet streak, showing the vertical circulations that are expected to be present at the entrance and exit of the jet streak.