12.307 Weather and Climate Laboratory
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Project 2
Fronts

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Abstract

We inspect fronts crossing the country associated with day-to-day variations in the weather using real-time atmospheric observations. In the laboratory we create fronts by allowing salty (and hence dense) columns of water to collapse under rotation and gravity. We discover that the observed changes in winds and temperature across our laboratory and atmospheric fronts is consistent with Margule's formula (a discrete form of the thermal wind equation) and see that the dynamical balance at work in the atmosphere is the same as in the density fronts created in the rotating tank.

1   Introduction

The air mass over the pole is considerably colder (and dryer) than that over the equator. The most active weather occurs in middle latitudes where the two air masses meet. The transition from cold to warm is not smooth, but is often quite abrupt. There are sharp gradients in temperature and moisture. Much of our day-to-day weather is associated with the evolution of these high gradient - called frontal - regions.

Fig.1 shows an instantaneous map of the temperature at 500 mb over the northern hemisphere. The air to the south is warm, that to the north cold with a pronounced middle latitude temperature gradient - the so called *polar front*. Also shown is a vertical section of the frontal boundary sloping with height and the associated horizontal winds.
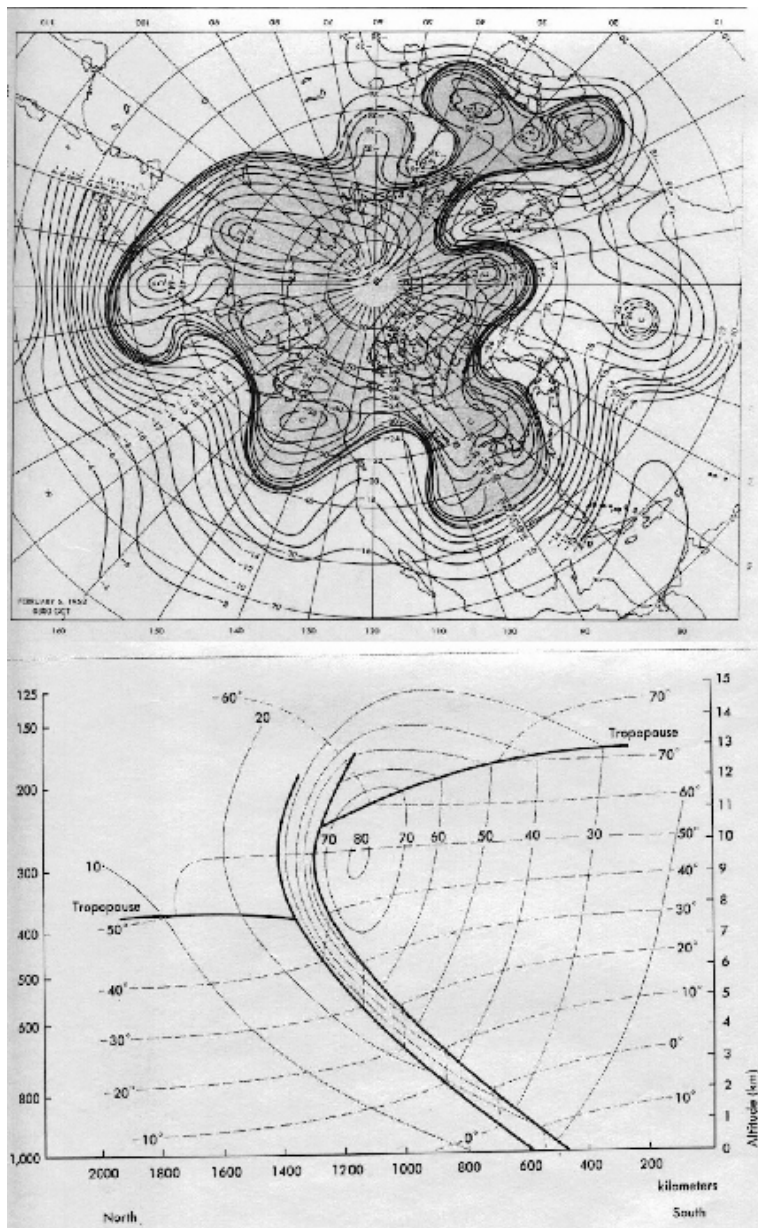
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Figure 1: (top): Northern Hemisphere 500mb temperature in ^0C on Feb 6, 1952. The polar front is marked by the heavy line where the isotherms are close together. The shaded area represents the region of cold polar air. (Bottom): Schematic of a vertical cross section extending north-south through the polar front (heavy lines). Temperature is in ^0C and wind speed in m/s. The thick line is the tropopause, the surface separating the troposphere from the stratosphere. (from E. Palmen and C. W. Newton - Atmospheric Circulation Systems, Academic press, New York, 1969)

Because the density, ρ, of air at a given pressure, p, depends on temperature, T, (remember the ideal gas law: $p = \rho RT$) the front also separates air of different densities. One might wonder why the cold dense air does not slump and flow along the earth's surface, bringing the frontal surface to the horizontal, with light fluid above dense. That, after all, is our common experience - fluid finds its own level.

Here we will investigate why fronts have a pronounced slope and what dynamical balances are associated with them. We will study fronts in a laboratory setting and atmospheric fronts using current weather observations. Fronts also give us a context in which to study 'thermal wind balance', one of the most characteristic and important properties of large-scale circulation in the atmosphere and ocean.

2   Laboratory Experiments

Here we briefly describe one experiment designed to help us think about fronts and the thermal wind equation. More detailed descriptions of how to carry out the experiment can be found in:
http://paoc.mit.edu/labguide/fronts_exp.html.

Notes on relevant theory on thermal wind are attached. They are also available on the 12.307 web.

2.1   Slope of a frontal surface

A vivid illustration of the role that rotation plays in counteracting the action of gravity on sloping density surfaces can be carried out by creating a density front in a rotating fluid in the laboratory, as shown in Fig.2. We place a large tank on our rotating table, fill it with water to a depth of 10 cm or so and place in the center of it a hollow metal cylinder which protrudes slightly above the surface. The table is set in to rapid rotation at a speed of 10 rpm and allowed to settle down for 10 minutes or so. Whilst the table is rotating the water within the cylinder is carefully and slowly displaced by dyed, salty (and hence dense) water delivered from a large syringe. When the hollow cylinder is full of colored saline water, it is rapidly removed (Fig. 3) in a manner which causes the least disturbance possible - practice is necessary!

The initially vertical column of dense salty water slumps under gravity but is 'held up' by rotation forming a cone whose sides have a distinct slope.
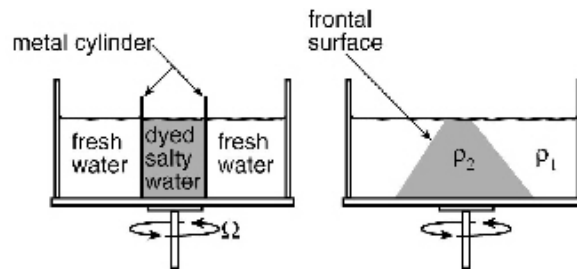
Figure 2: An initially vertical column of dense salty water slumps under gravity but is 'held up' by rotation forming a cone whose sides have a distinct slope.

Figure 3: The cyclinder collapse experiment.

The cone acquires a definite sense of rotation, swirling in the same sense of rotation as the table. We measure typical speeds through the use of paper dots, measure the density of the dyed water and the slope of the side of the cone (the front) and interpret them in terms of the following theory.

The gross features observed in the experiment — the slope of the frontal surface and associated change with height of the horizontal currents — can be rationalized in terms of the following theory.

2.1.1   Theory: slope of a frontal surface following Margules

A simple and instructive model of a front can be constructed following Margules (1906) - see Fig.4 and legend showing a two layer system with light fluid, ρ_1, on top of dense fluid, ρ_2, separated by a discrete interface sloping at angle γ. Since $p = p(x, z)$ and therefore $\delta p = \frac{\partial p}{\partial x}\delta x + \frac{\partial p}{\partial z}\delta z$ for both (ρ_1, p_1) and (ρ_2, p_2) on each side of the interface, and noting that the pressure must be the same at the discontinuity ($\delta p \longrightarrow 0$), then using hydrostatic balance — $\frac{\partial p}{\partial z} + \rho g = 0$ — we see that γ is given by:

$$\tan \gamma = \frac{\frac{\partial p_2}{\partial x} - \frac{\partial p_1}{\partial x}}{g\left(\rho_2 - \rho_1\right)} \tag{1}$$

where ρ_1 is the density of the ambient fluid and ρ_2 is the density within the cone (and $\rho_2 > \rho_1$).

Using the geostrophic approximation to the current —$2\Omega v = \frac{1}{\rho}\frac{\partial p}{\partial x}$ — we arrive at the following form of the thermal wind equation[1]:

$$v_2 - v_1 = \frac{g' \tan \gamma}{f} \tag{2}$$

where $v_{1,2}$ are the component of the current parallel to and on either side of the front, $g' = g\frac{(\rho_2 - \rho_1)}{\rho_2}$ is the 'reduced gravity' and $f = 2\Omega$ is twice the rotation rate of the tank.

We can use Eq.(2) to predict the slope of the sides of the cone observed in the laboratory experiments from the change in density between the cone and the ambient fluid, $\frac{(\rho_2 - \rho_1)}{\rho_2}$, and the measured swirl velocities and density gradients.

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[1]This should be compared to the thermal wind equation for an incompressible fluid is:
$\frac{\partial \mathbf{u}_g}{\partial z} = -\frac{g}{f\rho_o}\widehat{\mathbf{z}} \times \boldsymbol{\nabla}\rho$
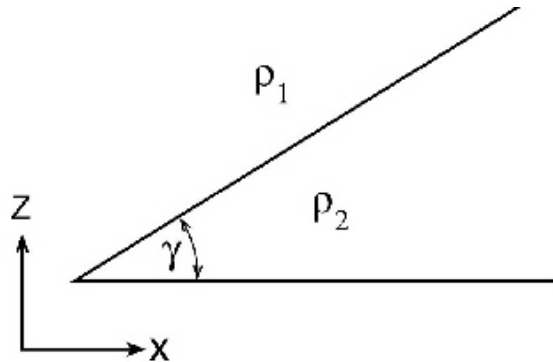See 'Thermal wind notes'.

Figure 4: A simple model of a front following Margules (1906). We imagine a two layer system with light fluid, ρ_1, on top of dense fluid, ρ_2, separated by a sloping, discrete interface. The horizontal axis is x, the vertical axis is z and γ is the angle the interface makes with the horizontal.

3   Atmospheric fronts

As discussed in the Introduction, fronts mark the boundary between different air masses. In this section we will use current atmospheric data to study the structure of observed fronts.

3.1   The polar front

On the global scale the so called "polar front" in middle latitudes marks the boundary between the cold, dry polar air and the warm, moist tropical air- see Fig.1.

Plot the 500mb temperature field using climatological data - for more see http://paoc.mit.edu/labguide/fronts_polar.html.

Identify the region of strong temperature gradient, separating the colder polar air from the warmer tropical air. Choose a location where the polar front is well defined and construct a north-south section of winds and temperature through the front:

(a) Identify the frontal zone between cold and warm air and estimate the frontal slope.

(b) Identify the tropopause and the position of the upper level jet.

(c) Estimate the vertical wind shear. How is vertical wind shear related to the horizontal temperature gradient?

The connection between the wind and the temperature field is summarized in the so called "thermal wind" relationship:

$$\frac{\partial \mathbf{u}_g}{\partial z} = -\frac{R}{fp}\widehat{\mathbf{z}} \times \boldsymbol{\nabla}T \tag{3}$$

For more details see attached notes on Thermal wind.

3.2 Synoptic scale fronts

On a more local scale fronts tends to be found in regions of developing cyclones. The cyclonic circulation around a low pressure centre tends to bring warm moist air northward and cold dry air southward, creating a region of warm air - the *warm sector* - between the *cold* and *warm* fronts, as shown in Fig.5. The accompanying vertical section through the fronts shows that both fronts slope upward with the warmer air rising on top of the colder air giving clouds and precipitation.

In this section we will study the fronts associated with a recent cases of strong cyclone development over the US region.

Fig.6 shows the IR satellite picture and Fig.7 shows the analyzed mean sea level pressure together with the surface obs and the position of the cold and warm fronts on the 12th of February 2009 at 00z, when a strong cold front moved through the Eastern US and it was responsible for an outbreak of severe storms and tornadoes.

3.2.1 The warm front

(a) Plot a section of temperature across the warm front. Identify the frontal zone between cold and warm air and estimate the slope of the frontal surface.

(b) Plot the wind parallel to the warm front. Do you notice any wind shear? How is vertical wind shear related to the horizontal temperature gradient?
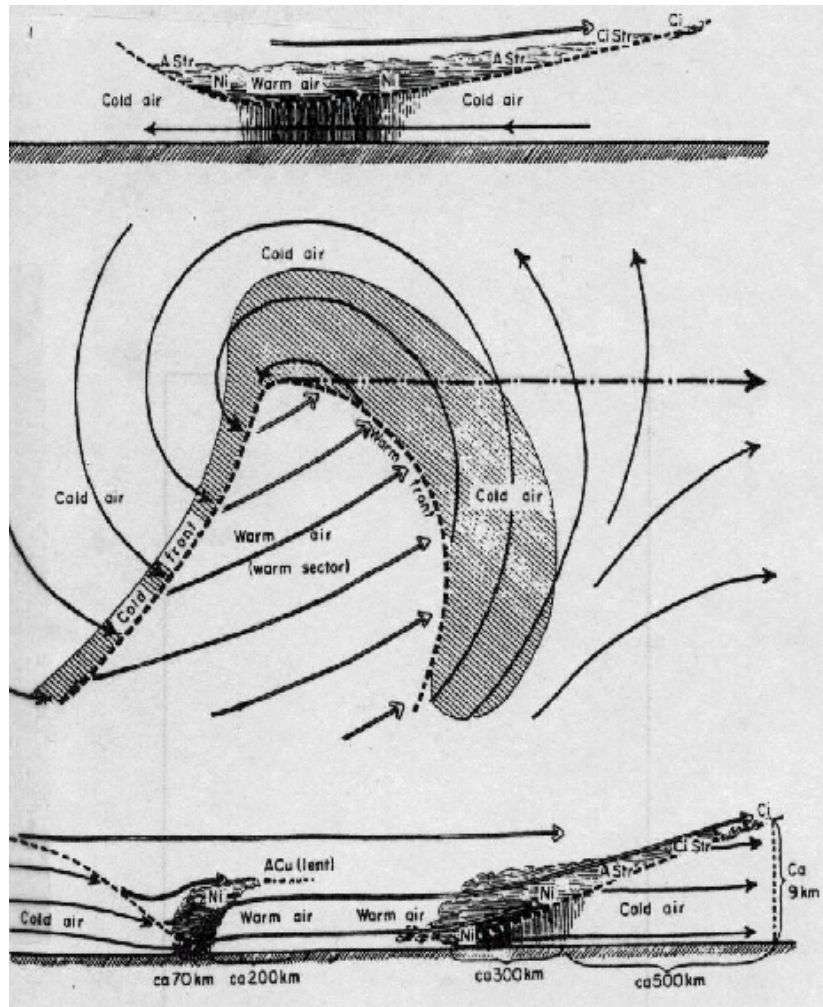
Figure 5: Idealized cyclone, from J. Bjerknes and Solberg (1921). In middle diagram, dash dotted arrow show direction of motion of cyclone; other arrows are streamlines of air flow at the surface. Top and bottom diagrams show clouds system and air motion in vertical sections along direction of cyclone movement north of its center and across the warm sector south of its center.

(c) Use of the Margule's formula Eq.(5) below to estimate the slope of the frontal surface. How does the estimated slope compare to the observed slope?

3.2.2 The cold front

(a) Plot a section of temperature across the cold front. Identify the frontal zone between cold and warm air and estimate the slope of the frontal surface. Compare the slope of the warm front with the slope of the cold front.

(b) Plot the wind parallel to the cold front. Look for regions of strong vertical wind shear. How are they related to the horizontal temperature gradient?

Use of the Margule's formula Eq.(5) below to estimate the slope of the frontal surface. How does the estimated slope compare to the observed slope? For more on synoptic fronts see:
http://paoc.mit.edu/labguide/fronts_synoptic.html.

3.3 Slope of a frontal surface - application of Margules formula

A simple and instructive model of a front can be constructed following the Margules (1906) relation that was used to interpret our cylinder collapse laboratory experiment. Again we suppose that at some height z the density of the air is ρ_2 on one side of the front and then changes discontinuously to ρ_1 on the other [see Fig (4)].

Starting from Eq.(1), show using the ideal gas equation, $p = \rho R T$, that, replacing 2Ω by f,

$$\tan\gamma = \frac{f}{g}\left(\frac{T_1 T_2}{T_1 - T_2}\right)\left(\frac{v_2}{T_2} - \frac{v_1}{T_1}\right) \tag{4}$$

where v is the component of the wind parallel to the front.

We can use (4) to estimate the frontal slope from observations of the changes in temperature and tangent-velocity across the front - for this purpose the following slightly more approximate form can be used, noting that $\frac{T_1}{T_2} \approx 1$:

$$\tan \gamma = \frac{f\left(v_2 - v_1\right)}{g\left(T_1 - T_2\right)/T} \tag{5}$$