

## Quasi-geostrophic approximation, and vertical velocity

GEMPAK has a number of diagnostic functions that we will be exploring today as we continue our examination of the Dec 2012 snowstorm. We will be examining model output from your own WRF model. Today we will use GEMPAK to analyze key processes associated with the open wave stage of the cyclone from the WRF model grids. We will use the \*.nts files that we created last week as examples of upper air maps but will focus on diagnostics of actual processes. In doing so, we will learn about some of the ways that GEMPAK is able to produce detailed maps of processes discussed in lecture that are related to the development of a frontal cyclone. We will also use diagnostic capabilities built into GEMPAK to compute new parameters that will give us insight as to the vertical structure of the cyclone. For this and some later labs, you may want to refer to a gempak document “gempak grid diagnostic functions” available on <http://www.atmos.uwo.edu/~geerts/atsc5160>.

The first task is to log onto bat and then ‘cd’ into the directory you created last week for the model output. You should have soft links to all time periods of interest. Remember that you can find out what grids are in a particular GEMPAK grid file by using the program **gdinfo**. We will again use the program **gdplot2** to create our isobaric maps. As discussed last week, a critical parameter to set in **gdplot2** is GDPFUN. This parameter sets all the variables that you want to contour.

The use your own WRF output in **gdplot2**, you can either use the WRF netcdf (.nc) files directly in NCL (or IDV), or else, you can convert them into GEMPAK (.gem) files. This and future lab exercises are written with specific gempak commands, in particular **gdplot2** and **gdcross2**. The conversion to .gem files also redistributes that data onto constant pressure surfaces. Do not hesitate to use NCL if it can produce output on constant pressure surfaces, and do calculations such as those listed in the pdf “gempak grid diagnostic functions”. Unfortunately, you are on your own in NCL. In 2014 I hope to start using AWIPS-II.

**Skip Part A.** The score (listed above) will be out of 65 points only, rather than 100 points

### Part A: Determining the Rossby number from your own WRF model grid files

To start, we will examine the quasi-geostrophic nature of our developing storm from 12 Z on 19 Dec 2012 to 00 Z on 21 Dec 2012. From the lectures we know that the Rossby number is a good measure of whether the atmosphere can be considered to be in quasi-geostrophic balance. The Rossby number is simply a ratio between the total acceleration to the Coriolis force. Assuming gradient wind conditions this is also a ratio of the ageostrophic wind to the actual wind. The ageostrophic wind, in turn, is simply the vector difference between the actual wind and the geostrophic wind. GEMPAK has many diagnostic capabilities included. To get a glimpse of the sorts of built-in functions, start **gdplot2** and type ‘help gparm’. This will give a long listing of all sorts of parameters and functions. Of interest are some of the vector grids. If you peruse the listing you will find information about standard vector grids:

Standard vector grids are:

WND	Total wind
GEO	Geostrophic wind
AGE	Ageostrophic wind
ISAL	Isallobaric wind
THRM	Thermal wind

The Rossby number is just a ratio of the magnitudes of the ageostrophic wind vector to the actual wind vector. This can be done in GEMPAK by using the ‘mag’ or magnitude function that is under ‘SCALAR OUTPUT GRID’ in your ‘gparm’ listing. ‘mag’ provides the magnitude of any vector. To compute the Rossby number we need to divide

'mag(age)' by 'mag(wnd)'. GEMPAK allows us to do that using the function 'quo' (for quotient) that is one of the basic arithmetic functions in the 'SCALAR OUTPUT GRID' portion of the GPARM listing. We can thus specify

$GDPF = \text{quo}(\text{mag}(\text{sm5v}(\text{age})), \text{mag}(\text{sm5v}(\text{wnd})))$

as a means to compute the Rossby number (sm5v smoothes a vector field). For simplicity, let's assume that a Rossby number of 0.5 is where we might begin to argue that the atmosphere departs significantly from geostrophy.

Note that in regions where  $|\vec{V}| \rightarrow 0$  (no wind), the computation of a Rossby number is meaningless, as  $Ro \rightarrow \infty$ .

Practically, you may want to black out (fill with black) regions with  $|\vec{V}| < 5 \text{ m/s}$ .

Note: gdp2 auto-scales variables, and this is not apparent even if you set the contour or fill interval & range (CINT and FINT). Solution: control the SCALE parameter, e.g. set SCALE=0 (for Rossby number) or SCALE=5 (for vorticity)

## TASKS

### One map (15 points)

A1. Create a map showing contours of the 300-mb height field (60 m increment), the Rossby number (color fill), and the ageostrophic wind AGE (barbs). For this and most future maps, please display a **domain from 22;-120 to 55;-62** (SW to NE corners). I suggest that you examine the 300-mb map at 6 hour intervals from 12 Z on 19 Dec 2012 to 00 Z on 21 Dec 2012. You can view output in xwindows for this part; don't worry about setting parameters that look good as a Postscript file. To help in answering questions below you can keep windows open from a previous time by providing names for your xwindow. For example, setting 'DEVICE = xw | 0030' (for 30 hr forecast, at 18 Z on 20 Dec 2012 although you can name it what you wish) will open a window called '0030'. Each time you create a new contour plot, change the name of the xwindow. You can have several windows open at once so you can compare results quickly. Please create a Postscript file for **12 Z on 20 Dec 2012**. To be clear, label this and all other maps in your homework, e.g. by adding TITLE= 1/-1/^ ~ @ A1: 300 mb height, Rossby # (fill)

### Briefly answer the questions below (5 points each)

- A2. What are the largest values of the Rossby number at 300-mb? Where do they tend to be located in relation with the 300-mb wave pattern? (Ignore the large values in the subtropical ridges, resulting from very small geostrophic wind there.)
- A3. As the 300-mb wave progresses eastward (and the surface cyclone deepens), what changes in the pattern of the Rossby numbers are seen?
- A4. Could you classify the 300-mb trof (trough) associated with the surface cyclone as "quasi-geostrophic"? Explain. (Hint: the QG framework assumes that  $Ro \ll 1$ , at least in the vicinity of the jet stream)
- A5: Discuss the pattern of ageostrophic flow. The theory suggests two components of ageostrophic wind, one *along* to height contours (as in troughs and ridges), and one *across* the height contours (as in a jet streak). Show this ageostrophic flow pattern schematically, by adding some arrows over your map, and the words "jet streak", "subgeostrophic", and/or "supergeostrophic"

## Part B: The non-divergent wind and smoothened potential temperature

Experience shows that derivatives of the field HGHT on constant pressure surfaces show large (absolute) values over the western USA, which has many mountain ranges. The reason for this lies in the linear interpolation from sigma surfaces (which follow the terrain) to pressure surfaces (which do not follow the terrain). The artificial gradients in HGHT (due to vertical interpolation) can be mitigated by significantly increasing the number of sigma levels in your WRF run. Which is why you were recommended to use more vertical levels than the default in WRF.

These artificial gradients are bothersome: recall that the geostrophic vorticity is proportional to the Laplacian of the GP height. Thus fields using geostrophic vorticity, such as the quasigeostrophic fields, will be “contaminated” by small-scale interpolation biases.

To mitigate this challenge, we will use the non-divergent component of the actual wind as a substitute of the geostrophic wind. The reason is that the geostrophic wind, and especially its derivatives such as geostrophic vorticity or the QG forcing terms, are sensitive to geopotential height variations associated with mesoscale gravity waves (usually triggered by the underlying terrain), and thus the gravity waves may dominate the image, rather than the synoptic features.

The non-divergent wind  $V_{nd}$  is available as one of the gempak variables (UND, VND). The potential temperature field can be smoothed using the "gwfs" function (I suggest a weight of 15) and stored as a new variable. To do this, use the gempak command GDDIAG. First, type GDDIAG, then specify your choices

```
GDFILE = $file
GDOUTF = $file
GDATTIM = $date
GLEVEL = 500
GVCORD = pres
GFUNC = gwfs(thta,15)
GRDTYP = s
GRDNAM = thtasm #this stores the smoothed potential temperature
GPACK =
GRDHDR =
```

Run

*After you run you may be prompted to provide a name for variable you are creating. In this case you can just repeat the name you used under the GRDNAM parameter.*

Once these preliminary calculations are completed in GDDIAG, you can use GDPLT2 to plot the non-divergent wind vector ND. In the next Lab assignment, we will calculate and plot more complex fields such as Q-vectors using ND, rather than GEO. For instance, when you specify `GDPFUN = qvec(thtasm, nd)`, it calculates Q-vectors using the new theta field.

## TASKS

### Four maps (10 points)

Show the smoothed theta field at 500mb (red dashed contours) overlaid with the 500mb height (black solid contours) at 00 Z on 20 Dec 2012 (Map B1)

Create three plots of the 500-mb height contours (60-m increment), at 12 Z on 20 Dec 2012, plus, at 500 mb:

- map B2: actual wind barbs, with color fill wind speed (SPED or MAG(WND))
- map B3: geostrophic wind barbs, with color fill wind speed MAG(GEO)
- map B4: non-divergent wind barbs, with color fill wind speed MAG(ND).

Use FINT to control the wind speed fill interval and range, they should be the same for the three maps. Also add a color bar (CLRBAR) for the isotach field. Please add a label, e.g. TITLE= 1/-1/^ ~ @ B1: 500 mb height, wind barbs, wind speed (fill)

**Question B5:** confirm that the cold air pool lags behind the trof at 500 mb at 00 Z on 20 Dec 2012. What does this imply about the vertical structure of this trof (note that I picked 00 Z, an earlier time, before the system occludes).

**Question B6:** Compare the actual, geostrophic, and non-divergent winds. Which one has larger extremes? Which one is most sensitive to local GP height variations?

## Part C: The geostrophic vorticity approximation from the WRF model grid files

One of the key assumptions we have made in deriving the QG equations is that the advective wind can be approximated by the geostrophic wind and that the actual vorticity is about equal to the geostrophic vorticity. From our analysis above, we should feel somewhat confident that the winds are reasonably close to geostrophic. Does this imply that the geostrophic vorticity is a close approximation to the actual vorticity? We will choose the **12 Z on 20 Dec 2012** time to address this question using our WRF model output. Geostrophic vorticity you may remember is related to the Laplacian of the height field and can be expressed as:

$$\zeta_g = \frac{1}{f} \nabla^2 \phi = \frac{g}{f} \nabla^2 Z$$

You will note that the Laplacian of a scalar field can be computed by GEMPAK (again, see ‘help gparm’ and look for ‘LAP(S)’ in the ‘SCALAR OUTPUT GRID’ listing, or in the gempak document “gempak grid diagnostic functions”). The function ‘LAP’ operates on a scalar variable ‘S’. In our case here, the scalar variable is ‘HGT’. GEMPAK is also able to compute the Coriolis parameter and the variable name is ‘CORL’. One way to specify the geostrophic vorticity is to set 0

```
GDPF = mul(quo(lap(hgt),corl),9.81)
```

Here we are using both the ‘quo’ (divides scalar quantities) and ‘mul’ (multiplies scalar quantities) functions to calculate the geostrophic vorticity. At the heart of this operation is the ‘lap(hgt)’ term, which calculates the Laplacian of the height field. Then we need to divide by the Coriolis parameter  $f$  (“corl”), and multiply by  $g$  ( $9.81 \text{ m s}^{-2}$ ). To make sure that you did it right, compare it with

```
GDPF = VOR(GEO)
```

i.e. the vorticity of the geostrophic wind. The parameter of the function ‘VOR’ is a vector  $V$ .

We will compare the geostrophic vorticity to the vorticity of the non-divergent wind,  

```
GDPF = VOR(ND)
```

## TASKS

Three maps (10 points)

Create two plots of the 300-mb height contours (60-m increment, start at 8400 m), at 12 Z on 20 Dec 2012:

- map C1 with actual wind barbs and actual vorticity (VOR(WND))
- map C2 with geostrophic wind barbs and geostrophic vorticity (VOR(GEO)).
- map C3 with non-divergent wind barbs and non-divergent vorticity (VOR(ND)).

Please color fill vorticity, with contours each  $5 \times 10^{-5} \text{ s}^{-1}$ , and with a color key bar below. HINT: use the ‘SCALE’ parameter to specify appropriate scaling factor or power (SCALE=4 or 5). Use the same SCALE for all three winds. Use FINT to control the vorticity fill interval and range, they should be the same for the two maps. Also add a color bar (CLRBAR) for the vorticity field. Please add a label, e.g. TITLE= 1/-1/ $\wedge$  ~ @ C1: 300 mb height, wind vectors, true vort (fill) Save your gplot2 script as an \*.nts file, copy and paste it in your answer document. Use your analysis to answer the following questions:

Answer the questions below (5 points each)

- C4. How do the geostrophic vorticity values compare with non-divergent vorticity values from the WRF model? Explain the differences by comparing values in areas where small wiggles in the height contours appear to be due to gravity waves triggered by the underlying terrain. Hint: there is a mathematical relationship between geostrophic vorticity and wiggles in the height field.

- C5. How do the non-divergent vorticity values compare with actual vorticity values from the WRF model? Explain the differences by comparing the magnitude of the real wind to the geostrophic wind in troughs and ridges.
- C6. On the map B1, show the symbol  $\zeta_{\max}$  at the location of the largest (actual) vorticity values from the WRF model. Show the symbol  $\nabla \zeta_{\max}$  at the location of the largest gradient of vorticity. And show the symbol  $\vec{v} \bullet \nabla \zeta_{\max}$  at the location of the largest values of vorticity advection by the actual wind.
- C7. Look at the surface map you created in Lab 1. With respect to the center of low pressure *at the surface*, where do you find the largest values of 300 mb vorticity and vorticity advection? QG theory expects the 300 mb vorticity advection (increasing with height ...) to be a maximum over the position of the surface low? Is this the case?

## Part D: Examining patterns of vertical velocity from the model grid files

The key variable of interest in the QG system is the vertical velocity. Patterns of precipitation are tied to the vertical motion field. We will examine the spatial distribution of vertical motion in terms of the surface cyclone and upper level wave features for the open wave stage of the cyclone at **12 Z on 20 Dec 2012**. It will be instructive to compare fields of vertical motion with those implied from our idealized cyclone discussed in the lectures. From Part A we know that in most areas the QG approximation can be made, to a first order, for the time selected.

One word of caution: model output does not contain the QG omega vertical motion. The only way to obtain QG omega is by computing the “forcing terms” (related to vorticity & temperature advection), and then do a 2D or (better) a 3D inverse Laplacian operation subject to some boundary conditions. The first step is possible in `gdplot2`. The second is not. Note that an inverse Laplacian operator operation acts as a smoother, because it is a double integral: smaller features are damped more than larger features. The vertical velocity field in the WRF model is obtained *prognostically* (QG omega is a *diagnostic*), it includes vertical advection and of course terrain. You may see fine-scale gravity wave motion, especially in the mountainous western USA, and non-QG circulations along fronts. If you choose to run WRF in a non-hydrostatic mode, then buoyancy can force ascent as well.

Vertical velocity from a mesoscale WRF simulation contains a lot of fine detail. Do not assume that the model is wrong. A highly smoothed WRF vertical velocity field would be a good first-guess surrogate for the QG omega. If you feel the model contains too much fine-scale detail, I suggest that you use the nine-point smoother (‘sm9s’) in this exercise.

For the time listed above, you will construct maps that consist of the 1000-mb height field, the 300-mb height field and vertical velocity at various levels. The idea here is to examine how the vertical velocity field varies with height. You will be creating 4 maps, showing the vertical velocity at 850-, 700-, 500- and 300-mb. To answer questions, start by simply creating maps in the `xwindow` format. To compare multiple maps, again simply change the ‘DEVICE = XW | plotlevel’ where ‘plotlevel’ may refer to the level specified in `GLEVEL` (the level of vertical velocity) or any other name of your liking. Since all maps will show the 1000- and 300-mb heights, you can ‘hard wire’ them in the ‘GDPF’ parameter so that you can simply change ‘GLEVEL’ to reflect the level for vertical velocity. GEMPAK allows us to override the ‘GLEVEL’ command (using the ‘@’ sign) to show variables at a different levels. An example would be:

```
GDPF = hght@300 ! hght@1000 ! sm9s(w)
```

This commands GEMPAK to show the 300-mb height field, 1000-mb height field with vertical velocity at the level specified by ‘GLEVEL’. Consider the use of the ‘sm9s’ command to smoothen the vertical velocity field.

## TASKS

Four maps (10 points)

D1. Hand in a **12 Z 20 Dec 2012** map showing

- the 300-mb heights at 60-m contour intervals (black, thick solid lines, set thickness to 4)
- 1000-mb heights (black, thick dashed lines, 30-m contour intervals, start at 0 m) and
- 300-mb vertical velocity values (solid lines, thickness set to 2, scale of 3 (SCALE=3), CINT=20, with blue contours from -200 to 0 to show sinking motion, and red contours from 20 to 200 to show rising motion).

Next produce identical maps at three levels below:

D2. (500 mb)

D3. (700 mb)

D4. (850 mb)

It is expected that you have the \*.nts files from last week's exercise to help with the GDPF settings for the isobaric maps. Remember to save your command listing as a \*.nts file. We will refer to fields of vertical velocity again next week.

Answer the questions below (5 points each)

Use the 4 maps (at 850-, 700-, 500- and 300- mb) to answer the following questions:

D5. What is the unit of vertical velocity in your WRF output?

D6. At what level do you find the largest values of rising motion? What are the largest values of vertical velocity in units of  $\text{cm s}^{-1}$ ?

D7. Does the region of large-scale ascent ahead of the trof change with height? If so, how so? Is there a westward tilt with height as for the position of trofs (vorticity maxima)?

D8. Physically explain how the updraft patterns are related to the surface cyclone and fronts.