MAE578 Spring 2017 Term Project

Geostrophic and thermal wind balance: Theory and observation

The second half of this course focuses on the dynamics of large-scale flows under the influence of Earth's rotation (Coriolis effect). Analyzing the governing equation of fluid motion in a rotating frame, in Chapter 7 we find that large-scale flows approximately follow the so-called "geostrophic balance" (Eq. 7-3, 7-4, or 7-8 in M&P textbook) that relates velocity to pressure (or height), or the "thermal wind balance" (Eq. 7-18 or 7-24) that relates velocity to temperature. Using these balance relations, one would be able to deduce the velocity field from temperature or pressure/height field, and vice versa. For example, this helps explain why, in the Northern Hemisphere, a low-pressure center in a weather map is associated with a "cyclonic vortex" with a counterclockwise flow pattern. Given the importance of these balance relations, the purpose of this project is to analyze observational data to determine how accurately these relations hold for the real atmosphere.

In the final report, we expect quantification of the error incurred by geostrophic and thermal wind approximation as a function of latitude (tropics vs. mid- and high latitudes) and height (near surface vs. middle/upper troposphere).

In *p*-coordinate, the thermal wind relation can be expressed as (Eq. 7-24)

$$\frac{\partial \boldsymbol{V}}{\partial \ln(p)} \approx -\frac{R}{f} \boldsymbol{k} \times \nabla T \quad .$$

For our purpose, the relation can be recast as

$$\frac{\partial \boldsymbol{V}}{\partial \ln(p)} = -\frac{R}{f} \boldsymbol{k} \times \nabla T + Residue \quad .$$

The goal of this project is to quantify the residue, for instance in terms of the percentage of either of the two major terms in the balance relation. The same analysis should also be done for geostrophic approximation.

The "observational data" that are needed for the calculation will come from one of the "reanalysis" data sets. Those data sets typically have a global coverage and at least 6-hourly temporal resolution. (The raw meteorological observations are spatially and temporally inhomogeneous. They have been interpolated and quality-checked in the process of constructing the reanalysis data sets.) For most of our purposes, an analysis of the monthly mean data (readily available from a public online data archive, see below) is useful enough. Optionally, the dependence of the residue on the time scale of atmospheric motion can be quantified using daily data. The reanalysis data is archived in pressure coordinate. Although one could convert the data back to z-coordinate, for our purpose this is not necessary. If p-coordinate is used to check geostrophic approximation, the balance will be between horizontal velocity and *height gradient* instead of pressure gradient.

The expected length of report is 15-20 pages, including figures and references. In addition to showing the figures from the main calculations, please describe the methodology and precise formulas that are used for the calculations. (For example, in the thermal wind relation, how do you calculate the horizontal temperature gradient and vertical wind shear and compare them at the same location?) To ensure reproducibility, the main results should be accompanied by a description of the specific data used in the calculations. For example, if a figure is produced by analyzing the NCEP Reanalysis monthly-mean temperature data at the 500 mb level from January 2005, please describe such details. A discussion (~ 2-3 pages expected) on how and why the residue varies with latitude, height, and geographical location (e.g., over sea vs. land) is also essential.

The relevant data are archived at several public (free access) websites. We recommend the web portal of NOAA Earth Systems Research Lad/Physical Science Division: www.esrl.noaa.gov. The website is very user-friendly. It is equipped with online tools that allow users to assemble their own data for a specific field averaged over a specific time period. The data are archived in pressure coordinate. An interactive tool at the NOAA website can be used to directly make contour plots from the data archived at that website. Nevertheless, for more complicated calculations (e.g., evaluation of horizontal temperature gradient) one needs to first select and download the data, then write codes to further analyze the data. The reanalysis data are archived in netCDF format. Matlab already has built-in functions for reading and processing files of that format. A short tutorial on exploring the NOAA data website will be given in class. A note on using Matlab to process netCDF data will be provided separately.

To date, many "reanalysis" data sets have been produced by different weather centers around the world. If the online interactive tools as recommended above are used, the composite data would come from the "NCEP Reanalysis I". It is, in fact, the "oldest" reanalysis data set but is sufficient for our purpose. The background of the data set can be found in this paper:

Kalnay, E., et al., 1996: The NCEP/NCAR reanalysis project, *Bulletin of the American Meteorological Society*, **77**, 437-470

More general information about reanalysis can be found at this website: http://reanalyses.org/