MAE578, Spring 2015 Term Project Option 1 Released March 24, 2015

Geostrophic and thermal wind balance: Theory and observation

Background

The second half of our course has focused on the dynamics of large-scale fluid 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 connects velocity to pressure (or height), or the "thermal wind balance" (Eq. 7-18 or 7-24) that connects 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 instance, using the geostrophic approximation, one can use the pressure or height field in a "weather map" to visualize the anticipated flow pattern (i.e., velocity field). 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.

(A) Geostrophic and thermal wind balance

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

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

For our purpose, we can re-cast the relation as

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

Your goal is to quantify how big the *Error* is, for instance in terms of the percentage of either of the two major terms in the balance relation. Please also do the same for the geostrophic approximation.

For the "observational data" you may use the NCEP or ECMWF (ERA) "reanalysis". They have a global coverage and a 6-hourly temporal resolution. (The raw meteorological observations are spatially and temporally inhomogeneous. They have been interpolated and quality-checked in the construction of the reanalysis data sets.) The monthly mean data (readily available from the online data archive, see below) are useful enough for most of our purposes, although an analysis of the daily data will be needed in order to explore the dependence of the *Error* on the time scale of atmospheric motion. Beware that the reanalysis data is archived in pressure coordinate. All relevant formulas have to be written in pressure coordinate before they are used for the calculations. (Alternatively, you can use the formulas in z-coordinate but transform all of the observational data to z-coordinate.)

In the final report, please *quantify* the error incurred by the geostrophic and thermal wind approximation as a function of latitude (tropics vs. mid- and high latitudes), height (near surface vs. upper troposphere), and the spatial and temporal scales of atmospheric motion. The methodology and the formulas used for the calculations should also be described. Computer codes should be provided in the report. It is recommended that the codes be collected in an Appendix. Please be specific about how the calculations are done. In addition to the numerical calculations, it is essential that you discuss why the errors vary with latitude, height, and spatial/temporal scales.

(B) Structure of wind in the planetary boundary layer

The accuracy of geostrophic balance generally deteriorates towards the surface due to the influence of friction. As discussed in class, this will modify the two-way geostrophic balance (between pressure gradient and Coriolis force) into a three-way balance of pressure gradient, Coriolis, and frictional force. As a consequence, near the surface the velocity vectors are no longer parallel to pressure contours. The *planetary boundary layer* (PBL, or Ekman layer) within which friction significantly modifies geostrophic relation is typically about 1 km thick in midlatitude.

Your task is to use the reanalysis data to examine to what extent the theoretical prediction of the structure of velocity within the PBL is true. Using the lowest few levels of the data (e.g., 1000, 925 and 850 hPa if the surface is near sea level), please *quantify* how the horizontal velocity vectors turn with height. The analysis should be done for selected velocity fields (i) in the vicinity of a high pressure center, and (ii) in the vicinity of a low pressure center. The results should be discussed in the context of the aforementioned three-way balance. An additional analysis should be done to examine the contrasting structure of velocity in the PBL in the Northern vs. Southern Hemisphere. (Note that the Coriolis parameter has opposite signs in the two hemispheres.) Lastly, an additional analysis should also be performed to examine the difference in the wind profile in PBL for locations over the ocean vs. over land. (Note that friction is generally lower over the ocean.)

References and further technical detail:

Some background for the reanalysis data can be found in

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

Uppala et al., 2005: The ERA-40 re-analysis, *Quarterly Journal of the Royal Meteorological Society*, **131**, 2961-3012

The relevant data are archived at several websites with public access. For example:

www.esrl.noaa.gov/psd (NOAA Earth Systems Research Lab, Physical Science Division)
- Data Access & Plotting
- Reanalysis Datasets
- Climate Research Data
- Interactive Plotting & Analysis

This website is very user-friendly. It allows users to assemble their own composite of a specific field for a given time period and/or for selected vertical (pressure) levels. The data are archived in pressure coordinate. One can choose to make a plot or download the data. Another useful website is

iridl.ldeo.columbia.edu (IRI/LDEO Climaet Data Library, Columbia University).

This is the web site used by the authors of our textbook to produce the figures for the observed climate. It is less user-friendly but has more tools for performing basic mathematical operations on the data.

Important: The archives of the reanalysis data are usually in netCDF or plain text format. When processing the observational data, you might encounter various technical problems such as those related to data format and the input/out interface for Matlab. *Please start as early as possible and talk to instructor for technical assistance if needed.* A detailed guide of using Matlab to read netCDF data will be provided.

General instruction for the final report

The final report for this project should include the quantitative calculations with their outcome presented in figures and tables. The methodology and the formulas used for the calculations should also be described. Computer codes should also be included in the report.

The suggested length of the term paper is 15 pages, single space, excluding figures, tables, references, and list of computer codes (which can be collected in an appendix). The total length (including all elements) is expected to not exceed 30 pages. This is however not a strict requirement. A shorter or longer paper is acceptable as long as it is of good quality.

All figures must be professionally made (e.g., by Matlab). Hand-drawn figures are not acceptable except for simple schematic diagrams for illustrating a concept. No electronic submission is accepted. Instructor will collect hard copy of the final reports at a designated time, to be announced later. Late submission will not be accepted.