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WHY DO QG DIAGNOSTICS AND NMC MODELS OFTEN DIFFER?

Recently there has been considerable interest in use of quasi-geostrophic (QG) diagnostics to evaluate dynamic forcing for vertical motion. The UA program written by Mike Foster (Southern Region) has been widely distributed and makes it possible to evaluate Q-vectors, divergence of Q-vectors, the Laplacian of the thermal advection, advection of vorticity by the thermal wind, among others. These are all aimed at evaluation of dynamic forcing within the constraints of QG theory. These applications of QG theory offer a considerable improvement over the frequently used approximations such as 500 mb PVA and the overlay of thickness on sea-level pressure charts. However, the numerical models yield solutions of the Primitive Equations (PE), and hence contain processes that go considerably beyond QG theory. Between QG and PE are the semi-geostrophic equations (SG). This Technical Attachment will briefly discuss the differences between QG, SG, and PE approaches, and what this might mean to a forecaster attempting to interpret the NMC models. An appendix offers a mathematical representation of these three approaches.

The momentum equation can be thought of as describing how the wind changes due to advection and due to the local rate of change from other processes. One of the big differences between QG, SG, and PE is how the wind is defined. Consider the total wind as being the sum of the geostrophic and ageostrophic winds. In QG, the wind is simply the geostrophic wind. This is the wind that results when the pressure gradient force and the Coriolis effects are in balance, e.g., the wind is exactly parallel to the height contours. All the vertical motion within QG theory is due to the wind continually readjusting in order to remain in geostrophic balance. The readjustment takes place through the ageostrophic wind. However, the QG momentum equation describes only the advection of momentum by the geostrophic wind and the local rate of change of the geostrophic wind. There is no advection of anything by the ageostrophic wind in a QG system, and no rate of change of the ageostrophic wind is included either. The result is that it is not possible to generate fronts in a realistic time frame in a QG system. Nor is it possible to completely account for large departures from geostrophic balance such as those that might occur near a strong, but small jet maximum.

In a semi-geostrophic system, advection by the ageostrophic wind is included. This is the missing ingredient necessary to produce fronts in a realistic amount of time. The reason for this is because temperature advection (both horizontal and vertical) by the ageostrophic wind is critical in frontogenesis. This makes sense given that frontal regions are often highly ageostrophic. Thus, within the SG framework, fronts and attendant vertical motions are included. The SG momentum equation still lacks description of the local rate of change of the ageostrophic wind, and advection of ageostrophic momentum. No operational models use the SG system, but it is used extensively within the research community and is frequently cited within journal articles.

The primitive equations use the total wind. Advections by both the geostrophic and ageostrophic wind are included, as are the local rate of change of both the geostrophic and ageostrophic winds. Thus, the PE system includes quite a bit that QG does not. This is why the NMC models are capable of showing vertical motion along frontal zones and near jet maxima that show up only poorly or not at all using 500 mb PVA, or even more sophisticated QG estimations such as divergence of Q-vectors. There are also other factors within the NMC models that can produce vertical motion such as convective parameterizations or orographic forcing based on the model's grasp of the earth's terrain. Many diabatic processes are parameterized in the NMC models. Diabatic processes are not included in QG diagnostics, but on the other hand parameterizations of these processes are a potential source of error in the models, e.g., latent heat release can sometimes lead to convective blowup in the model.

To summarize the differences between QG, SG, and PE systems:

QG:
- only advections by geostrophic wind
- only local rate of change of geostrophic wind
- missing all advections by ageostrophic wind
- missing local rate of change of ageostrophic wind
- cannot realistically represent fronts

SG:
- advections by both geostrophic and ageostrophic wind
- missing local rate of change of ageostrophic wind
- missing advection of ageostrophic momentum
- can realistically generate and maintain fronts

PE:
- everything included

What does all this mean to a forecaster trying to understand and use NMC model output? As far as vertical motion is concerned, it should not be a surprise that upward vertical motion (UVV) may be forecast along frontal zones that are not necessarily lined up with areas of 500 mb PVA or even divergence of Q-vectors. Likewise, there may be areas of UVV associated with jet maxima that are difficult to explain in terms of QG diagnostics. And of course, the NMC models will produce vertical motions due to orographic lift and convective processes (although not necessarily correctly). Since the only vertical motion progs received in the field are at 700 mb, this limited view of the model vertical velocity may still not shed much light on what the model is doing. At times, the best indication of vertical motion can be found in the relative humidity fields. The RH will increase in areas of UVV by whatever forcing and at levels other than 700 mb, and vice versa. So, if the RH is going up and there doesn't appear to be any QG forcing involved, the model may still be quite correct.

In the last few years, some research (Barnes, 1986; Antolik and Doswell, 1989) has suggested that a forecaster may be able to critique the quality of model output by comparing it with forcing indicated by the simpler QG diagnostics. These results point out that when model forcing and QG forcing are significantly different, the model often (not always) verifies poorly. This may be due to the aforementioned diabatic processes which are parameterized in the models. The impact of diabatic processes would be especially notable in precipitation, particularly in summertime convection or near fronts.

Acknowledgment

The author would like to credit the explanation of the differences between QG, SG, and PE to Dr. Howard Bluestein of the University of Oklahoma. Dr. Bluestein has two dynamic/synoptic meteorology text books currently in publication that explain these concepts in detail. These books will be available next fall and winter.

References

Antolik, M. S., and C. A. Doswell III, 1989: On the contribution to model-forecast vertical motion from quasi-geostrophic processes. Proceedings of 12th conference of analysis and forecasting, AMS, Monterey, California, 312-318.

Barnes, S. L., 1986: The limited-area-fine-mesh model and quasi-geostrophic theory: A disturbing case study. *Wea. and Forecasting*, 1, 86-96.

APPENDIX

Primitive equation

$$\frac{d\mathbf{U}}{dt} = \frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} =$$

where $\frac{\partial}{\partial t}$ = local rate of change, and $\mathbf{U} \cdot \nabla \mathbf{U}$ = advection by total wind

Quasi-geostrophic

$$\frac{\partial \mathbf{V}_g}{\partial t} + \mathbf{V}_g \cdot \nabla \mathbf{V}_g =$$

where $\mathbf{V}_g$ = geostrophic wind

Semi-geostrophic

$$\frac{\partial \mathbf{V}_g}{\partial t} + \mathbf{V}_g \cdot \nabla \mathbf{V}_g + \mathbf{V}_a \cdot \nabla \mathbf{V}_g =$$

where $\mathbf{V}_a$ = ageostrophic wind