J3.5 EDUCATIONAL MISMATCHES BETWEEN TRADITIONAL DYNAMIC METEOROLOGY LESSONS AND APPLIED FORECASTER TRAINING WITH HIGH-RESOLUTION GRIDDED DIAGNOSTICS

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1. Introduction

Meteorology students are traditionally taught that the Rossby number scales as 0.1 for mid-latitude, synoptic scale motions and that the ageostrophic wind, similarly, is small compared to the geostrophic wind. The development of quasi-geostrophic (QG) theory follows, which provides a convenient framework for diagnosing vertical motions. QG theory also indicates that divergence of the ageostrophic wind induces a transverse secondary circulation at straight jetstreak entrance and exit regions that serves to restore geostrophic balance while playing an important role in frontogenesis. In practice, the ascending branch of these transverse circulations is cited frequently as one ingredient of developing severe convective weather.

Dunn (1991) reviewed how training based on traditional synoptic-scale dynamics has influenced operational forecasting methods, including the choice of pre-prepared diagnostic charts. Just prior to the installation of the AWIPS at National Weather Service (NWS) offices during the early 1990's, Dunn (1991) argued that effective use of gridded diagnostics would positively transform the forecast process. Indeed, as desktop workstations and real-time access to gridded data became readily available to forecasters and educators, Dunn's vision was realized. Meteorology students and practitioners now supplement their theoretical training by viewing QG diagnostics using interactive graphical software. Selected early examples of the movement towards using gridded diagnostics include those presented by Sechrist and Whittaker (1979), Doswell (1987), Schwartz et al. (1987), and Barnes and Coleman (1993).

As operational forecast models continue to develop with increasing resolution and more complex dynamical processes, they include ever more processes that are not included within the relatively simplistic QG framework. Consequently, QG diagnostics computed for real-time gridded model data appear unorganized as patterns become overwhelmed by fine-scale waves associated with mesoscale processes. Barnes et al. (1996) first documented these noisy patterns and explored filtering methods to help improve the relevance of the QG diagnostics. Examples are shown here in section 3.

The fact that high-resolution gridded data produces noisy QG diagnostics is neither surprising (due to the use of higher-order derivatives and the limiting assumptions of the theory itself), nor is it a new discovery. However, the problem is worth reviewing from the perspective of undergraduate meteorology students who are familiar with high-resolution weather maps, but who are gaining their first formal exposure to QG theory. During my experiences teaching undergraduate dynamic meteorology, I found that students often could not produce an explanation for why the QG diagnostics from gridded data appeared so complicated. Some would spend time attempting to "fix" what they interpreted as a graphic plotting error, but most simply gave up in frustration. One explanation for the student's inability to comprehend the noisy diagnostics is that they don't yet grasp the importance of model resolution and the complexity with which dynamical processes are represented. However, it is more likely that students rightly expect the QG diagnostic fields to appear smooth and symmetric since the classic "textbook" interpretation of QG theory is based on a single sinusoidal wave pattern (e.g. Holton 2004). Furthermore, while the mathematical interpretation builds upon familiar, highly simplified conceptual models taught in introductory courses, the high-resolution QG diagnostics present students with an unfamiliar new reality.

The goal of this work is to develop best-practice recommendations for guiding students from traditional QG theory to operational forecasting involving high-resolution gridded diagnostics. First, the current relevance of QG theory in forecast practice is established. Specifically, an updated an-

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swer is needed for the oft-asked question,"Why do we need to know this [QG theory]"? Second, samples of QG diagnostics are developed for models at increasing spatial resolution to exemplify what students might encounter in computer-based laboratory investigations. Finally, a Rossby number probability distribution is obtained from the North-American Regional Reanlysis (NARR) to provide a quantitative description of the difference between the characteristic scales at which QG theory is developed and those which are more truly representative of operational datasets. When combined, it is expected that students shall develop a more complete understanding of the extent to which QG theory may be applied in practice.

2. QG Theory in Operations

Before engaging the question of how best to teach QG theory, it is worth considering its current relevance in operational forecasting. Although it is relatively simple to argue that QG theory is essential for an undergraduate meteorology degree, it is more challenging to convince unexperienced students who are not necessarily seeking graduate degrees. One approach is to review the consistency with which QG-related terms appear in National Weather Service (NWS) Area Forecast Discussions (AFDs).

It is known that NWS AFDs often provide a summary of a forecaster's technical thoughts associated with the current forecast. However, the level of detail presented in the AFDs varies considerably, ranging from simple product updates to lengthy scientific discussions. Such variations are expected given continually evolving forecast complexity and differences in forecaster experience, education, and forecast office standards of practice. Nonetheless, QG-related keywords do appear regularly in the AFDs and are used here as proxy evidence that NWS forecasters seek to apply dynamic meteorology concepts in practice.

NWS AFDs were collected for the period 24 September 2005 through 29 May 2007[1]. A script was written to search the AFDs for the first occurrence of a variety of QG-related keywords, remove duplications (updates), and partition keyword counts by station and season.

Results of the AFD keyword search for the abbreviation"QG" are shown in Figure 1. Other keywords reveal a qualitatively similar pattern,

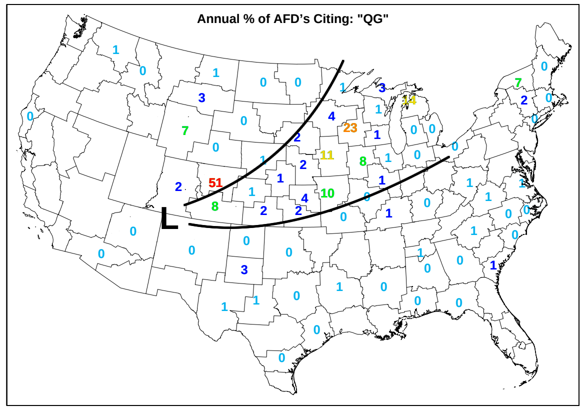

Figure 1: Percentage of National Weather Service Area Forecast Discussions (AFDs) citing the abbreviation QG between 24 September 2005 and 29 May 2007. Percentages are rounded to the nearest whole number. County warning areas remain blank for stations where the "QG" keyword did not appear in any AFDs.

but appear less frequently, especially when seasonally partitioned. A notable exception to this pattern is that the keywords "ASCENT", "JET STREAK", and "RIGHT ENTRANCE" appear with some regularity over the southeastern and eastern U.S. (not shown).

The NWS offices that most commonly cites the term "QG"' (Fig. 1) appear to lie generally along the track of Colorado Cyclones that initiate in the lee of the Colorado Rocky Mountains and progress through their life cycle before dissipating near the Great Lakes (as annotated schematically on Fig. 1). One could argue that forecasters in this region favor the use of QG diagnostics because the extratropical cyclone life cycle is fully represented. In contrast, synoptic-scale systems tend to dissipate while moving ashore along the west coast, while those developing over the Gulf of Mexico or along the U.S. east coast quickly move beyond the zones represented by NWS AFDs. The use of QG diagnostics for jet-stream dynamics during the spring severe season may also contribute to the more frequent use of QG keywords by NWS forecasters in the central region.

Figure 2 shows monthly changes in the frequency with which several different QG-related keywords appear in all NWS AFDs. Keywords Ascent and Jet Streak are cited most frequently. All terms are used less frequently during summer

[1]AFD files were obtained from an archive maintained by David Knight at the State University of New York at Albany

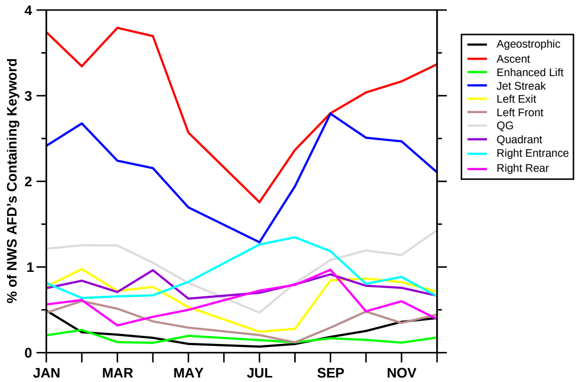

Figure 2: Monthly changes in the percentage of all NWS AFDs citing the indicated QG-related keywords between 24 September 2005 and 29 May 2007.

except for increased use of keywords Right Entrance and Right Rear. The minimal use of the term Ageostrophic is noteworthy, as discussed later.

The overall frequency with which the terms occur in AFDs is small, but the patterns shown in Figs. 1 and 2 do indicate qualitatively that dynamical concepts are used regularly in forecasting. Indeed, it is likely that QG-related concepts are used while preparing forecasts much more than is indicated (recorded) through the AFD format. Thus, although the use of high-resolution gridded data is now ubiquitous in operational forecasting, it remains important to prepare student forecasters with a thorough background in QG theory and its applications. The new challenge is to ensure that forecasters understand the limitations of QG diagnostics with regard to high-resolution analyses and model output.

3. Gridded Diagnostic Examples

Conventional plots of geostrophic absolute vorticity advection $[\mathbf{V}_g \cdot \nabla(\zeta_g + f)]$ are shown here to demonstrate how a simple QG-related diagnostic field becomes impossibly confusing when generated from grids having increasing spatial resolution. The vorticity advection field is shown here because of its contribution to conceptual models of height tendency and vertical motions. Other important diagnostics such as thickness advection or $\mathbf{Q}$-divergence are not shown in this shortened article.

Figure 3 shows that a conventional plot of absolute vorticity advection appears quite reasonable using spectral model data from the NCEP GFS that has been truncated to a 2.5 degree lat./lon. grid. Specifically, anticyclonic (cyclonic) vorticity advection is broadly aligned with areas of rising (falling) geopotential height. When viewing the same field generated from NGM model data on its 80 km grid (Fig. 4), the vorticity advection field becomes much more complicated. The result is similar when viewing vorticity advection from GFS and NAM model output delivered on the 80 km AWIPS 212 grid (not shown). Another example (Fig. 5) shows output from the 12-km NAM after it is interpolated onto the 40-km AWIPS 211 grid. Collectively, figures 3, 4, and 5 show that useful interpretation of the absolute vorticity advection field becomes progressively more difficult to use for simple QG diagnostic applications as data resolution increases.

It is possible to apply a carefully crafted low-pass filter to help isolate the synoptic scale QG diagnostics expected from theory (Barnes et al. 1996). This may have some benefit for students working in computer-based synoptic meteorology laboratory, especially if filtered data were prepared in advance for a specific case-study. However, the availability of high-resolution height tendency and vertical motion fields generated by non-hydrostatic models makes it possible to provide much more physically realistic evaluations of vertical motion. While conceptual models are useful to help characterize changes in the large-scale environment, current model technology helps resolve details in the sub-synoptic scale processes.

At longer lead times, details associated with sub-synoptic scale features become unpredictable. Hence, the ensemble mean is often used for general long-term guidance. Since the ensemble mean is not dynamically balanced, it makes sense to apply QG diagnostics in a predictive capacity. An example of absolute vorticity advection is shown in figure 6 for the 168-hr (7-day) ensemble mean forecast. The geopotential height field is quite smooth and most shorter wavelengths have been removed by averaging. A rather broad gaussian filter was then applied to smooth remaining disturbances in the mean height field before calculating the vorticity advection. These disturbances likely result from aliasing effects in grid interpolation or phase locking shortwave features to the terrain. The result after filtering is a broad, smooth diagnostic field that appears consistent with the height tendency. This field could be overlaid with the differential thick-

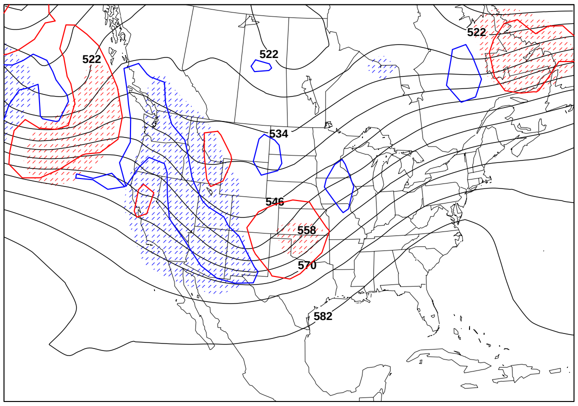

Figure 3: 12-hr forecast of 500 hPa geopotential height (black contours, dm), height tendency shaded in excess of ± 4 gpm/hr, and geostrophic absolute vorticity advection contoured in excess of $\pm 1 \times 10^{-9}$ sec^{-1}. Data from the NCEP GSF model initiated 1200 UTC 7 January 2008 is truncated to a 2.5 degree thinned grid.

ness field to complete the QG-diagnostic evaluation and make general statements about the possibility for hazardous weather.

4. Rossby Number Distribution

Students are traditionally taught that the Rossby number scales as 0.1 for synoptic scale motions. Subsequently, this result is used to infer the presence of an ageostrophic secondary circulation that is consistent with the maintenance of geostrophic and hydrostatic balance. The secondary circulation has been identified in observations and is applied often (perhaps too often) in forecasts of severe convection and intense extratropical cyclones.

Spatial plots of the Rossby number at a given instant in time reveals that it often exceeds unity, and locally may exceed 10! To explore the link between increasing grid resolution and theory, Rossby number calculations were made the North-American Regional Reanalysis in the vicinity of mid-latitude jet streaks (Fig. 7). Results compiled into a probability distribution of Rossby Numbers peaks around 0.3 (Fig. 8). This result suggests that forecasters must apply advanced dynamical concepts involving both synoptic-scale and mesoscale processes to adequately describe evolving forecast scenarios.

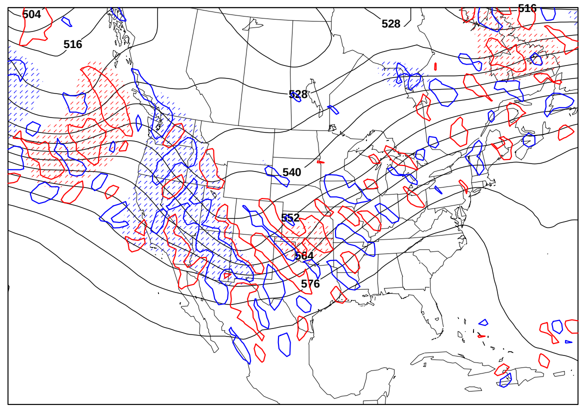

Figure 4: As in Fig. 3, but for output from the 80-km NGM model (AWIPS grid 211). Vorticity advection contoured for values in excess of $\pm 5 \times 10^{-9}$ sec^{-1}.

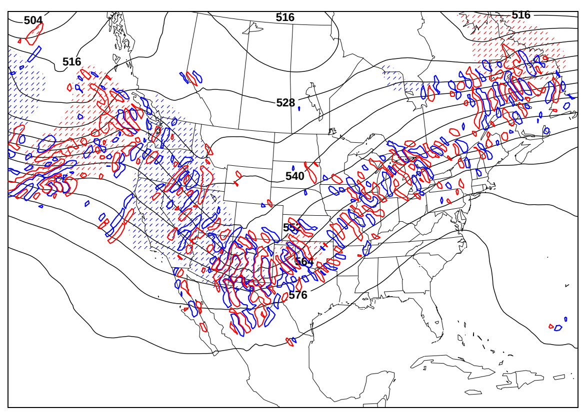

Figure 5: As in Fig. 3, but for output from the 12-km NAM model, distributed on the 40-km AWIPS 211 grid. Vorticity advection contoured for values in excess of $\pm 3 \times 10^{-8}$ sec^{-1}

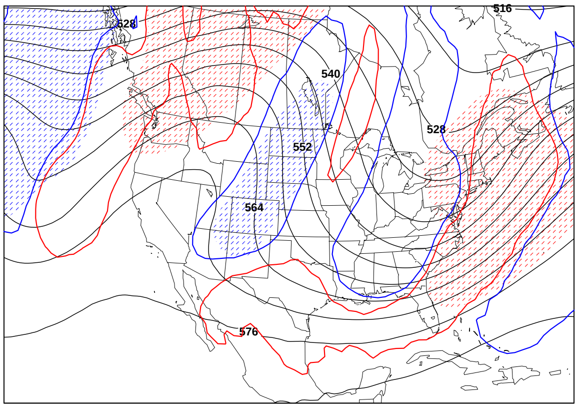

Figure 6: As in Fig. 3, but for the 168-hour GFS ensemble mean forecast, valid 00 UTC 15 January 2008, output on a 1x1 degree grid. Vorticity advection contoured for values in excess of $\pm 1 \times 10^{-10}$ sec^{-1}

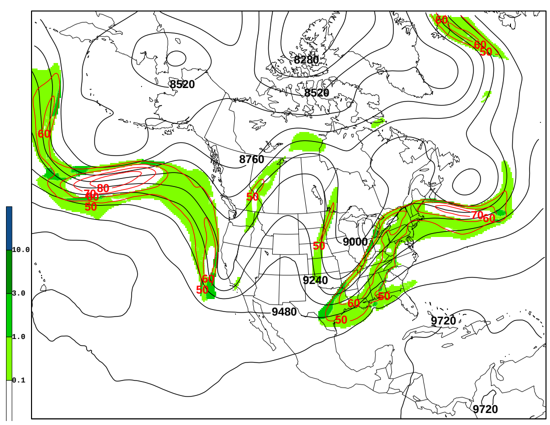

Figure 7: NARR valid 00 UTC 15 April 2007, showing 300 hPa geopotential height, isotachs (above 50 kts), and Rossby number (ratio of the intertial-advective wind to the coriolis acceleration) shaded for regions where the wind speed is between one-half and three-quarters of the domain maximum speed.

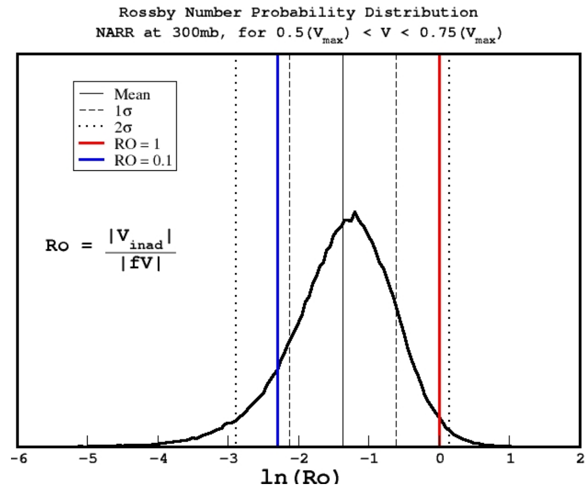

Figure 8: Probability distribution for the natural log of the Rossby Number [$\ln(Ro)$] in the vicinity of 300 mb jet streaks.

5. Recommendations and Future Work

Although QG theory is a useful way to understand dynamical characteristics of typical (i.e., composite) mid-latitude weather systems, it is an over simplification when applied in practice to individual cases, especially when forecasting impact weather at a specific point. Therefore, educators must adapt to the availability of high-resolution datasets by presenting case studies earlier, and more often throughout the student's curriculum, which are designed to highlight both strengths and weaknesses of theories in synoptic-scale dynamic meteorology.

Training should emphasize care in using broad terms of "enhance lift", QG dynamics, etc. The ageostrophic secondary circulation yields strong diagnostics when propoerly and completely analyzed. Examples are coupled jet entrance / exit regions and selected severe weather outbreaks. However, for the severe weather outbreaks, the secondary circulation is too-often cited. Rather than saying "synoptic support", it may be more accurate to say that convective instability is not suppressed by the synoptic environment.

This paper reports on a work in progress. Continued work will involve consultation with forecasters at the NWS and the Unidata COMET program. In general, the work to date has documented the use of QG conceptual models, and the challenges associated with moving students from a theoretical framework towards practical knowledge. A continuing review of scores of published papers reveals numerous opportunities to help students understand more completely how QG-related diagnostics have advanced our understanding of atmospheric processes, but also ways in which the conceptual models can be abused. The availability of high resolution gridded data is, therefore, both a benefit and a hindrance to forecaster training.

6. References

Barnes, S. L., and B. R. Coleman, 1993: Quasi-geostrophic diagnosis of cyclogenesis associated with a cutoof extratropical cyclone The Christmas 1987 storm. Mon. Wea. Rev., 121, 1613-1634.

Doswell, C. A. III, 1987: The distinction between large-scale and mesoscale contribution to severe convection: A case study example. Wea. Forecasting, 2, 3-16.

Dunn, L. B.,1991: Evaluation of vertical motion: Past, present, and future. Wea. Forecasting, 6, 65-75.

Schwartz, B. E., D. M. Rodgers, and J. T. Hawes, 1987: The use and interpretation of numerical weather prediction model output in identifying synoptic-scale environments associated with devlopment of mesoscale convective systems. Wea. Forecasting, 2, 50-69.

Sechrist, F. S., and T. M. Whittaker, 1979: Evidence of jet streak vertical circulations. Mon. Wea. Rev., 107, 1014-1021.