2.1 THE PV BIBLE: APPLICATIONS IN ATMOSPHERIC DYNAMICS

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1. INTRODUCTION

The concept of potential vorticity (PV) has been around in various forms for over sixty years (Rossby 1940; Ertel 1942; Charney and Stern 1962). However, it was not until the remarkable paper by Hoskins, McIntyre, and Robertson (HMR; 1985) that potential vorticity began to be applied to a full range of atmospheric problems, both observational and theoretical, involving balanced flow dynamics.

In certain circles, HMR is known as the "PV Bible": by analogy to the Good Book itself, HMR encapsulates a tremendous amount of received wisdom and guidance. Also by analogy, it is remarkably long compared to most other papers, and it has gained a following almost unmatched in atmospheric sciences.

HMR presented few new results. Neither is HMR a review paper, strictly speaking. It is more precisely a "synthesis paper", bringing together a set of concepts, both well-understood and novel, that collectively present a fundamental view of the balanced dynamics of the atmosphere. The paper is nominally about IPV maps, but its most important contribution lies in the insights presented on Rossby waves, vortices, and barotropic/baroclinic instability.

A citation count of HMR reveals that, as of March 2001, it has been referenced in over 800 scientific articles. The rate of citation is increasing, with 75 citations in the past year alone. The lead authors of these citing papers are predominantly European, reflecting the greater popularity of "PV thinking" on the other side of the Atlantic.

This paper uses HMR as a point of departure to examine the range of current applications of potential vorticity concepts in the atmospheric sciences. We select eleven articles published since Jan. 1, 2000 which reference HMR, and consider how PV concepts are presently being employed to understand atmospheric dynamics.

2. PASSING PV REFERENCES

Many papers refer to HMR because it is perceived as the most complete, concise, or widely known summation of the basics of certain aspects of balanced flow dynamics. These papers illustrate the broad application of PV concepts to research areas considered only tangentially by HMR, if at all. Since HMR is not fundamental to the subject of these papers, they typically reference HMR in passing.

An example of how distantly concepts of Rossby wave dynamics may be applied is Li et al. (2000). This paper, an expansion of Lovelace et al. (1999), discusses accretion disks, flat disks of gas which are trapped by the gravitational pull of massive stars or black holes. A fundamental issue regarding accretion disks is the mechanism by which angular momentum is transported outward, allowing gases to collapse inward toward the center. Lovelace et al. (2000) and Li et al. (1999) show that an instability analogous to barotropic instability arises for realistic parameter ranges, and hypothesize that the subsequent breaking of Rossby waves would lead to the generation of long-lived vortices, which would migrate away from the seat of the instability while transporting angular momentum. HMR is used as the standard reference for Rossby wave dynamics in the Earth's atmosphere.

Closer to home is the paper by Chang (2000), which examines Rossby wave packets in the Southern Hemisphere. Chang's work in this and other papers shows that medium-scale (wavenumber 4-8) midlatitude ridges and troughs typically form Rossby wave packets. Growth of upper-level waves occurs at the downstream end of the wave packet due to horizontal Rossby wave energy propagation. Chang shows that by the time baroclinic energy conversion is the dominant mode of intensification for an individual trough, the trough has already reached maximum intensity and is losing energy downstream. Thus, while baroclinic development is the primary source of energy for the wave packet as a whole, it is not the primary source of energy for a typical cyclogenesis event within that wave packet. HMR is referenced as providing a clear description of the dynamics of nonmodal growth.

Juckes (2000) relies on HMR for providing a clear description of the process of nonlinear growth and stabilization of cyclones. The subject of Juckes' paper is the process governing mean midlatitude static stability, and HMR is used to argue that a uniform PV gradient (which was hypothesized by Held 1982) is not the normal outcome of saturation of cyclogenesis. Instead, Juckes proposes that the static destabilization associated with cyclogenesis leads to moist convection, which places a lower bound on midlatitude stratification. From this, Juckes hypothesizes that the mean stratification can be estimated from the lower bound (moist-neutral) plus half the variance.

Ford et al. (2000) employs a more fundamental concept from HMR: the concepts of balanced flow, potential vorticity inversion, and the idea that the large-scale evolution of the atmosphere can be known, perhaps precisely, through balanced dynamics. Ford et al. ultimately conclude that this idea is false, that a true slow manifold does not exist. They analyze the shallow water equations and expand the equation set assuming small Froude number. Ultimately, at fourth order in Froude number, the flow field is found to depend not simply on the instantaneous potential vorticity field, but on the history of the potential vorticity field for all time. Since this complication does not arise at lower orders, Ford et al. coin the term "slow quasi-manifold" to describe an idea that, while not precisely accurate, remains conceptually very useful.

3. USING PV TO UNDERSTAND RESULTS

A second set of papers uses HMR in a more fundamental manner, applying the techniques and concepts of HMR directly to discern the meaning of particular results or ideas.

One such paper is Scaife and James (2000), which is concerned with the stratospheric response to tropospheric planetary waves. Scaife and James use a primitive equation model of the stratosphere, forced by an idealized lower boundary representing the troposphere. In remarkable agreement with the highly-simplified modeling results of Holton and Mass (1976), they find three stratospheric circulation regimes: a steady regime for weak forcing, an unsteady regime for moderate forcing, and a major warming regime for strong forcing. To understand the unsteady regime, they rely on IPV maps, which shows that tongues of low-PV air are repeatedly advected eastward and poleward, forming isolated eddies which ultimately dissipate. A fundamental description of this process depends on the use of PV concepts as found in HMR, although it should be noted that HMR did not originate these ideas.

Clough et al. (2000), relies on the PV thinking of HMR rather than the IPV map paradigm itself. Clough et al. is concerned with the effect of ice sublimation processes on cyclone structure and evolution. Using HMR's PV thinking, Clough et al. argue that the flat dipole of PV generated by sublimation should have a predominantly local response and not affect the overall cyclone. This prediction is verified by their primitive equation modeling results.

Chaigne and Arbogast (2000) use neither PV thinking nor PV maps. Yet, their paper relies fundamentally on HMR because it utilizes PV inversion to understand cyclone development. PV inversion dates back to Kleinschmidt, and HMR only quoted a result from Thorpe (1986), but HMR effectively started the widespread use of PV inversion as a diagnostic tool that was later employed by Davis and Emanuel (1991) and others. Here, Chaigne and Arbogast extract individual PV anomalies, either neutralizing or negating them, and reinitialize numerical forecast models through PV inversion. The resulting model runs are used to understand the role of the PV anomalies in cyclogenesis.

4. PV IS FUNDAMENTAL

The final set of papers relies on potential vorticity and HMR in fundamental ways, such that it is doubtful the insights and techniques would be possible otherwise.

The first such paper is Badger and Hoskins (2001). The problem addressed by Badger and Hoskins is whether PV thinking can be used to understand the nature and growth of optimal finite-time growth structures. Indeed it can: Badger and Hoskins show clearly how rapid, non-modal growth is fundamentally related to complex vertical PV structures, such that structures without any initial vertical tilt can be acted on by shear to develop an upshear tilt and concomitant rapid growth. The process involves the initial existence and subsequent displacement of "shielding" PV anomalies above and/or below the primary anomaly. The role of a background PV gradient in altering the most effective height of the initial perturbation is also demonstrated. This particular paper has wide implications. For example, the results suggest that Clough et al.'s (2000) inference that sublimation is dynamically insignificant may apply only instantaneously, and that shear acting on the sublimation-generated PV structures would be capable of causing rapid growth .

Wandishin et al. (2000) also rely on both PV thinking and PV inversion, in this case to take a different look at the problem of upper-level frontogenesis. Wandishin et al. argue that the process is better understood in the context of tropopause folding, and they use PV inversion to demonstrate how the quasi-horizontal (isentropic) advection of PV into tropopause folds is a fundamental consequence of cyclogenesis. The winds associated with the low-level cyclone act on the sloping tropopause to steepen it upstream of the cyclone itself, and this steepening enhances the differential advection. The result is an upper-level front and tropopause fold, understood without explicit reference to vertical motion or its diagnosis using the Sawyer-Eliassen equation or the omega equation.

The final paper we consider here, by Wu and Wang (2000), may prove to be very useful. It is also far afield from any topic dealt with directly by HMR. The idea of Wu and Wang is that tropical cyclone motion can be understood through analysis of the wavenumber 1 potential vorticity tendency of the hurricane vortex at low and mid levels. The technique outlined by Wu and Wang permits attribution of tropical cyclone motion to specific dynamical processes, such as beta drift, a tilted upper-level anticyclone, and diabatic heating. The resulting description of tropical cyclone motion is both complete and dynamically meaningful. The technique was only applied to an idealized model by Wu and Wang; its usefulness for studying observed cyclones is yet to be determined. And as can be seen by the broad range of papers in just the last year that rely on HMR, the ultimate usefulness of the PV Bible is still to be determined as well.

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