14A.3 POTENTIAL VORTICITY AS A TOOL FOR ASSESSING DYNAMICAL IMPACTS OF LATENT HEAT RELEASE IN MODEL FORECASTS

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1. INTRODUCTION

Although the utility of potential vorticity (PV) first became apparent in the 1930's, it was not until the landmark paper of Hoskins et al. (1985) that PV principals became widely applied in atmospheric research. During the re-emergence of PV in the years following the Hoskins et al. publication, questions regarding the utility of "PV thinking" in an operational forecasting setting naturally arose. For example, plots of potential temperature on the dynamic tropopause (typically defined as a PV surface of value between 1 and 2 PVU[1]) can be extremely useful because PV surfaces intersect the core of all major jet streams, even those centered at differing altitudes (Morgan and Neilsen-Gammon 1998).

Despite these advantages, it is our sense that PV has yet to gain widespread acceptance by the operational forecasting community in the U.S. There are several possible reasons for this, including (i) a lack of emphasis on PV concepts in undergraduate university curricula, (ii) a lack of training of operational forecasters in PV methodology, (iii) the time-consuming and technically challenging task of PV inversion, and (iv) the failure to convincingly demonstrate that the use of PV can provide information not obtainable via more traditional means. It is this last reason that we wish to address here.

Rather than emphasizing upper-tropospheric representation of phenomena such as tropopause folding and stratospheric PV extrusions, we will here advocate a somewhat different utilization of PV concepts, with *emphasis on PV as a means for identifying the dynamical feedbacks associated with latent heat release* and the accompanying PV ***non-conservation***. The goal of this study is to provide examples of situations where the application of PV tools can provide insight above and beyond that obtainable using traditional forecast methods.

There is no question that numerical weather prediction (NWP) has become entrenched as the most important forecasting tool for today's operational weather forecaster. Despite verifiable improvements in forecast accuracy that have accompanied the remarkable advance of NWP, several previous studies (e.g., Doswell 2004; Mass, 2003; Bosart 2003) have noted that there is also a cost in terms of the time available for forecasters to diagnose the meteorological situation as they sift through an ever-increasing volume of NWP output. In order to best assess the quality of available model guidance, forecasters need to recognize the differences in the guidance provided by various NWP models and understand *why* these differences exist. This ability is hindered by the fact that it is difficult for operational forecasters to stay abreast of changes made to the models run at the National Centers for Environmental Prediction (NCEP). Therefore, it is a challenge for forecasters to be aware of details of the representation of critical physical processes in NWP models that may profoundly influence the model solution. Forecasters must also have the ability to use observations and high-frequency model analyses to evaluate short-term model forecasts if they are to have the confidence necessary to make significant adjustments to model guidance in the midst of a potentially high-impact event, which is a non-trivial task.

Latent heat release (LHR) is a critical physical process, and its associated dynamical feedbacks can have a large impact on a wide range of meteorological phenomena. It is widely recognized that quantitative precipitation forecasting (QPF) is the least accurate parameter in NWP forecasts (e.g., Fritsch and Carbone 2004), and inaccurate QPF can result in the misrepresentation or overprediction of LHR, which can introduce significant errors into the synoptic-scale forecast. This is particularly true for convection, and model representation or parameterization of organized convection (e.g., Wang and Seaman 1997).

Here, we advocate examination of lower-tropospheric PV in conjunction with several other model output parameters that will serve to (i) alert forecasters to which synoptic or mesoscale features in the model output are strongly influenced by LHR, (ii) provide forecasters with a means of assessing the uncertainty in a particular feature in model output, (iii) allow forecasters the opportunity to determine the sign of model biases for specific features, and (iv) provide a conceptual and dynamical model with which forecasters can understand the physical or model processes responsible for a given feature. Most importantly, through the use of PV diagnostics, forecasters can have an improved recognition of those situations in which they are most able to add value to a model forecast. Case study examples will

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[1] 1 Potential Vorticity Unit (PVU) = 1.0 x 10^{-6} m^2 s^{-1} K kg^{-1}

be presented that demonstrate the utility of PV concepts in the operational forecast setting.

2. BACKGROUND

Potential vorticity is the product of the absolute vorticity and the static stability, and is defined after Rossby (1940) and Ertel (1942) as:

$$PV = -g(\zeta_\theta + f)\left(\frac{\partial \theta}{\partial p}\right) \qquad (1)$$

where $\vec{\eta}$ is the absolute vorticity vector, ρ is the density, and θ is the potential temperature. In the Northern Hemisphere high- (low-) PV air is associated with cyclonic (anticyclonic) absolute vorticity and/or high (low) values of static stability (Hoskins et al. 1985). In other words, PV maxima (minima) are associated with upper troughs (ridges), low (high) geopotential heights and cyclonic (anti-cyclonic) flow. In addition, Bretherton (1966) showed that anomalies of *θ* at the surface can be considered surrogate PV features, with warm (cold) areas of *θ* analogous to PV maxima (minima).

Of the two components of "PV thinking" outlined by Hoskins et al. (1985), the concept of PV conservation offers utility in operational interpretation of NWP output by allowing unambiguous identification of nonconservative processes. Since PV is conserved in an isentropic framework in the absence of diabatic processes and friction; it is *not conserved* in the presence of diabatic processes, making it an ideal indicator of the impact of latent heating in the atmosphere. The feedback on atmospheric dynamics from latent heating can impact cyclone evolution, low-level jets, moisture transport, and QPF, all of which can be important in forecasting sensible weather in potentially high-impact events.

Latent heating due to precipitation processes impacts the PV distribution by altering the two components of PV, the absolute vorticity and the static stability. The effects of LHR below the level of maximum heating are to increase the static stability and hydrostatically lower the heights, thus increasing the absolute vorticity as the flow converges into the area of lowered heights. The increase of both the static stability and absolute vorticity necessitates an increase in the PV below the level of maximum heating. The opposite occurs above the level of maximum heating, resulting in a decrease in PV. Therefore, LHR associated with precipitation processes generally leads to an increase (decrease) of PV below (above) the level of maximum heating. In the presence of vertical wind shear, this diabatic PV re-distribution is offset from vertical and occurs along the absolute vorticity vector, as discussed by Raymond (1992). The rate of PV generation or destruction is determined by the magnitude and gradient of the latent heating and the magnitude of the absolute vorticity (Stoelinga 1996).

A second principal of PV methodology, invertibility, allows one to quantify the impact of any piece of PV on the remainder of the atmosphere by numerically solving a boundary value problem assuming an independent balance relationship between the wind and temperature fields (Davis and Emanuel 1991). The output of the inversion includes the balanced wind and geopotential height fields associated with the portion of the PV field inverted. It is important to note that balance conditions beyond geostrophy can be employed to recover a substantial portion of the ageostrophic flow (Davis et al. 1996).

Previous case studies have shown that diabatic PV maxima in the lower troposphere can impact the evolution of extratropical cyclones (e.g., Davis and Emanuel 1991; Davis 1992; Stoelinga 1996; Plant et al. 2003). In many case the diabatic PV maximum enhances the coupling and mutual interaction between the upper-tropospheric PV maximum and the surface *θ* maximum, leading to a stronger feedback process and a more intense cyclone (e.g., Davis et al. 1993; Stoelinga 1996). However, in other cases the diabatic PV maximum can hinder the interaction of the tropopause and surface waves (Davis et al. 1992).

Diabatically-generated lower-tropospheric PV maxima can significantly impact the wind field in this layer of the atmosphere where moisture values are generally large. This can significantly modify moisture transport and ultimately precipitation distribution by enhancement of the low-level jet (e.g., Whitaker et al. 1988; Lackmann and Gyakum 1999; Lackmann 2002; Brennan and Lackmann 2005). Additionally, enhanced low-level jets can result in the transport of high-momentum air to the surface, resulting in damaging wind gusts in convective or non-convective situations.

Since most of today's operational NWP models continue to be run at a grid-spacing insufficient to resolve cumulus convection, the use of cumulus parameterization (CP) schemes continues in most operational NWP models. The variability in CP scheme design includes how they activate or "trigger", the manner in which thermodynamic adjustments are applied, and the degree of interaction with other model physics schemes (e.g., Kuo et al. 1996; Baldwin et al. 2002; Mahoney and Lackmann 2005). Accordingly, there can be significant variability in if, when, and where different schemes activate and how they re-distribute heat and moisture. Therefore, the LHR from different CP schemes can significantly impact the evolution of the PV distribution in an NWP model.

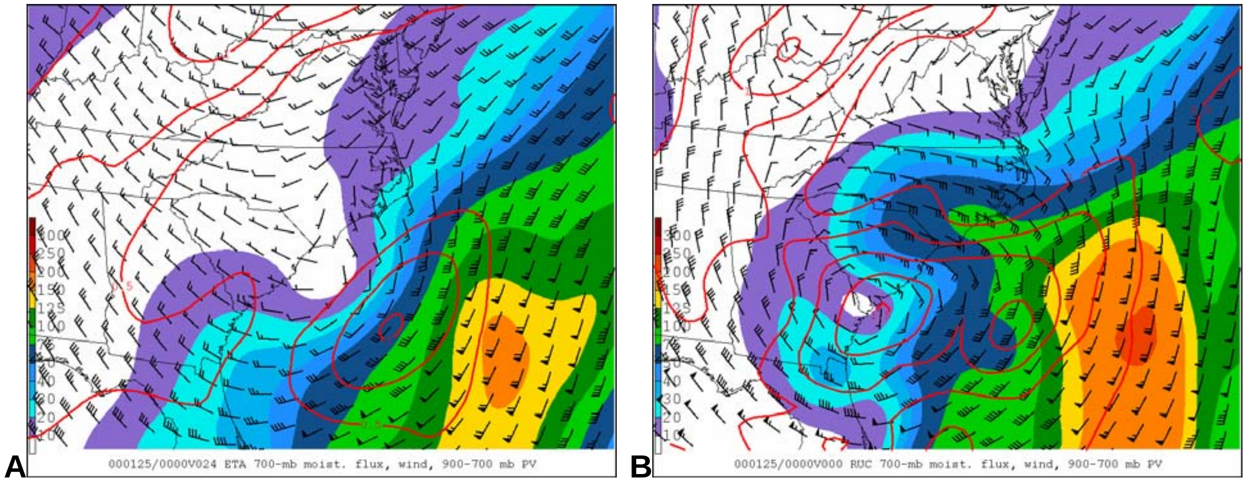

Figure 1. 700-hPa kinematic moisture flux (color shaded, g kg^{-1} m s^{-1}), 700-hPa winds (barbs, kt), and 900–700-hPa PV (red contours every 0.25 PVU above 0.5 PVU) from (a) 24-h Eta model forecast and (b) RUC model analysis valid at 00 UTC 25 January 2000.

3. CASE STUDIES

a.) Moisture transport in extratropical cyclones

The East Coast cyclone of 24–25 January 2000 was a major forecast failure, as operational NWP models failed to produce heavy precipitation in a region that received heavy snowfall from the Carolinas northward into the Washington D.C. area. Brennan and Lackmann (2005) used piecewise Ertel's PV inversion to show that a lower-tropospheric PV maximum initially generated by latent heating associated with incipient precipitation (IP) over Alabama and Georgia early on 24 January was critical to the moisture transport into the region of heavy precipitation in the Carolinas and Virginia. The IP was unforecasted by the operational NCEP models initialized only 6–12 hours prior to its formation, and the absence of this area of substantial latent heating meant that these model forecasts were unable to generate the critical PV maximum, and ultimately failed to capture the moisture transport into the Carolinas and Virginia later in the event.

A comparison of the 24-h forecast of 900–700-hPa layer PV from the 00 UTC 24 January 2000 Eta model run (Fig. 1a) to the analysis from the RUC model at that time (00 UTC 25 January 2000, Fig. 1b) clearly shows that the Eta model did not forecast the large PV maximum centered along the coast of Georgia and South Carolina analyzed by the Rapid Update Cycle (RUC) model at this time. The cyclonic circulation associated with this PV maximum enhanced the onshore flow at the 700-hPa level over the eastern Carolinas, where 30–35 kt of easterly flow generates moisture flux values of 50–100 g kg^{-1} m s^{-1} in this region (Fig. 1b). In contrast, the Eta forecast without the PV maximum along the coast shows only 5 kt or less of wind in this region with a variable direction and moisture flux of 10 g kg^{-1} m s^{-1} or less (Fig. 1a). Results from the PV inversion in Brennan and Lackmann (2005) showed that the lower-tropospheric PV maximum was responsible for 20–25 kt of this onshore flow over the eastern Carolinas, significantly enhancing the moisture flux into the region of heavy precipitation.

In a future case such as this where a large area of LHR was unforecasted by the operational models, forecasters could utilize PV methodology to recognize how an area of unforecasted latent heating could impact the lower-tropospheric PV distribution. This could be confirmed by examining high-frequency model analyses of the PV distribution (i.e. RUC analyses) and lower-tropospheric wind field. Using PV thinking, forecasters could anticipate the impact that lower-tropospheric PV maxima might have on the moisture transport and cyclone evolution and use this knowledge to adjust model guidance accordingly.

b.) Coastal cyclogenesis

Previous studies have documented the influence that convective latent heat release can have during the cyclogenesis process (e.g., Kuo et al. 1996). It is also widely recognized that the prediction of convective precipitation remains problematic in operational NWP models, and that parameterized convection in particular can contribute to the challenge (e.g. Wang and Seaman 1997; Davis et al. 2003). To demonstrate how PV concepts can be used by forecasters to help them recognize features in model forecasts that are tied to the parameterization of convection in models, we present model forecasts and PV diagnostics from the coastal cyclone event of 17 February 2004 (see Mahoney and Lackmann 2005 for additional details).

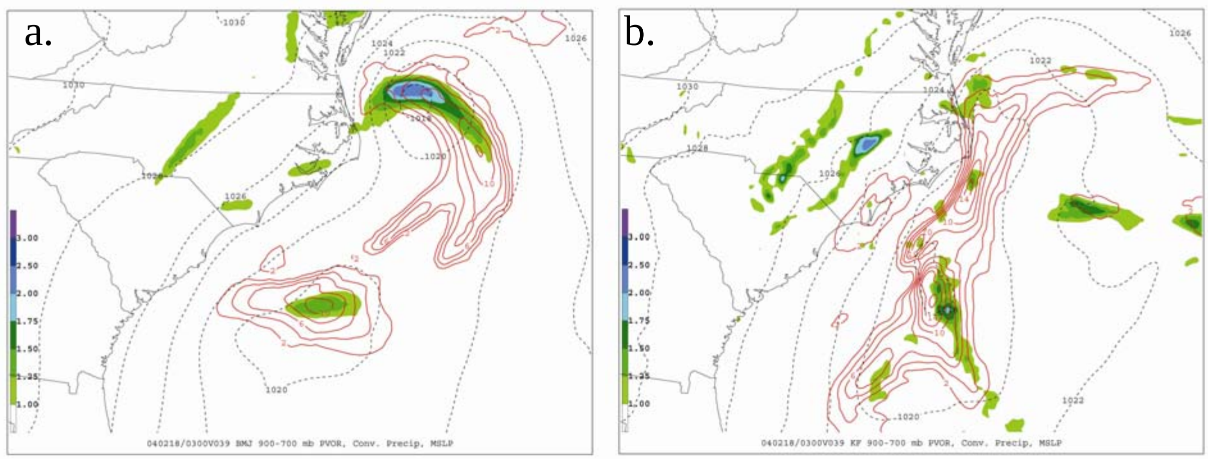

Figure 2. (a) Workstation Eta forecast of 900–700 hPa potential vorticity (PVU (1 PVU = 10-6 m^3 s^{-1} K kg^{-1}), shaded as in legend at left of panel), SLP (hPa, dashed contours), and 3-h convective precipitation forecast (mm, red solid contours) valid 21 UTC 17 Feb. using (a) BMJ CP scheme and (b) KF CP scheme.

During the 17 February 2004 event, a strong upper-level trough moved eastward across the southeastern US, while at the same time an Appalachian cold-air damming (CAD) event was underway (not shown). As the upper trough approached a coastal front that was located to the east of the CAD event, cyclogenesis ensued, both in model forecasts and in the real atmosphere. Operational forecasters, as well as the authors, recognized that local maxima of convective precipitation were collocated with the formative surface cyclone centers (Fig. 2a). Given the inherent uncertainty of parameterized convection, these features were viewed with somewhat less confidence than other features of the model forecast.

In order to examine the sensitivity of the cyclogenesis to the choice of CP scheme, Mahoney and Lackmann (2005) re-ran the Workstation Eta model forecast with all conditions identical except for use of the Kain-Fritsch (KF) CP scheme in place of the Betts-Miller-Janjic (BMJ) scheme. The resulting forecast (Fig. 2b) confirms that the character of the coastal cyclone in this case was extremely sensitivity to convective parameterization.

By plotting the lower-tropospheric PV along with the convective precipitation forecast and sea level pressure, one can easily identify features that are tied to CP scheme activity. While the purpose is not to demonstrate the superiority of one CP scheme over another, it is clear that by the use of PV diagnostics to identify lower-tropospheric diabatic PV maxima that are generated by the parameterized convective activity, one can more easily assess the forecast confidence in these features.

c.) Low-level jet

Low-level jets can be important to moisture transport and the transport of high-momentum air to the surface, which can result in wind damage at the surface in both convective and non-convective events. To demonstrate how forecasters can recognize the enhancement of a low-level jet by latent heat release through PV concepts, we present an event from 1 December 2004 that resulted in widespread wind damage in 15 states from the mid-Atlantic into New England, resulting in more than $1.5 million of property damage, two fatalities, and five injuries (NCDC 2005).

At 12 UTC 1 December 2004, a surface cyclone was located in western New York State with a surface warm front extending eastward to northern New England and a surface cold front extending south into the central Carolinas (not shown). A prominent band of precipitation was seen in radar imagery along and ahead of the cold front over the Mid-Atlantic states at 09 UTC (Fig. 3). Through the period from 09–12 UTC a 900–700-hPa PV maximum formed in the wake of this precipitation ahead of the advancing cold front, reaching a magnitude of 1.25 PVU by 12 UTC in the RUC analysis (Fig. 4).

A low-level jet was seen at the 850-hPa level east of the PV maximum where wind speeds increase to more than 70 kt from central Virginia to eastern Pennsylvania (Fig 4b). By 15 UTC the low-level jet continued to intensify to the east of the PV maximum reaching into New York and southern New England (not shown).

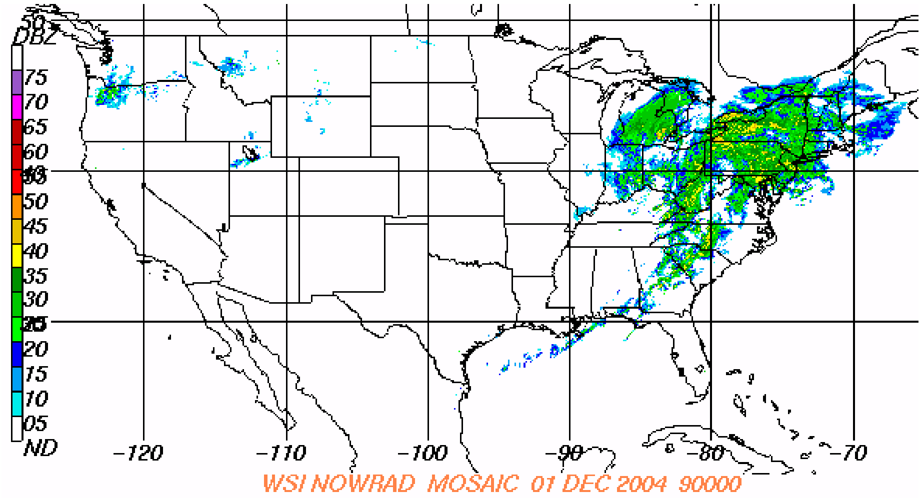

Figure 3. Radar mosaic imagery valid at 09 UTC 1 December 2004.

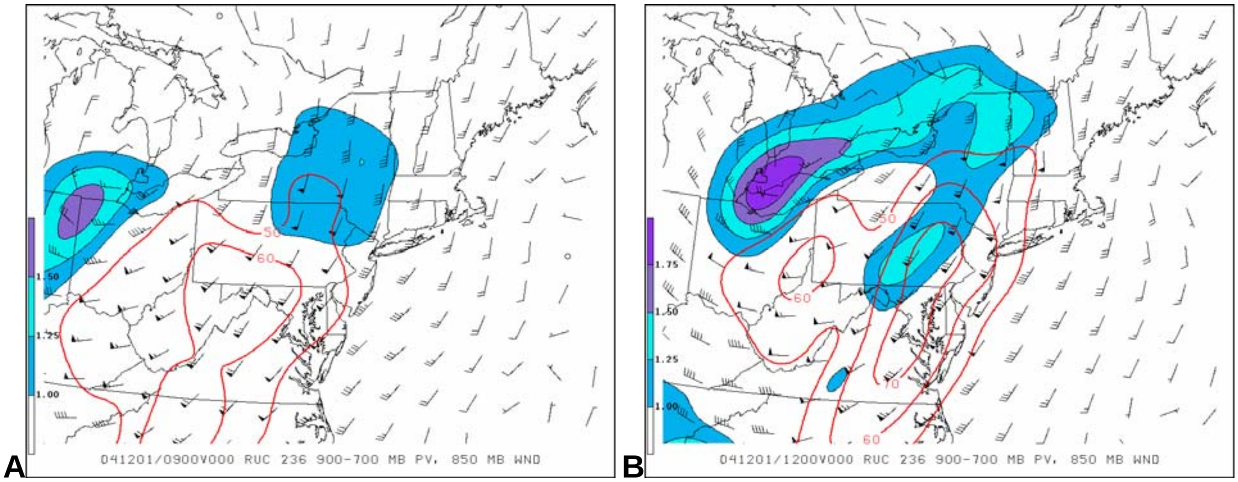

Figure 4. RUC analysis of 900–700-hPa PV (color shaded every 0.25 PVU starting at 1.00 PVU), 850-hPa wind (barbs, kt), and 850-hPa isotachs (red contours every 10 kt starting at 50 kt) valid at (a) 09 UTC and (b) 12 UTC 1 December 2004.

By overlaying model analyses of lower-tropospheric PV, winds, and radar imagery, forecasters can identify situations when a lower-tropospheric PV maximum associated with latent heating is enhancing the intensity of a low-level jet. By comparing model forecasts of precipitation, the PV distribution and wind speed to analyses, forecasters may be able to recognize situations when the model forecast of the jet may be degraded due to misrepresenting or underforecasting LHR.

4. DISCUSSION

Although there are documented advantages to using tropopause maps and plots of isentropic PV as a means of diagnosing upper-tropospheric dynamics, it can be argued that alternate techniques can provide forecasters with much of the same information. However, here we argue that the use of PV as a means to identify and diagnose diabatically produced lower-tropospheric PV maxima represents a more compelling motive for operational forecasters to embrace PV concepts, as fewer alternatives exist that allow forecasters to assess the dynamical impact of often highly uncertain diabatic processes in a model forecast.

The conservation property of PV allows a generally reliable method for (i) identifying those lower-tropospheric features that are driven strongly by model latent heat release, and (ii) obtaining a ready estimation of the dynamical impact that these features may have on the forecast evolution. Bearing in mind the uncertainty inherent in model QPF, particularly that due to parameterized precipitation, the use of PV in this manner provides forecasters with a tool that can be used in conjunction with ensemble forecasts to yield a sense of forecast confidence in given features of a model forecast.

We advocate plotting of lower-tropospheric (e.g., 900–700 hPa) PV and winds, with convective and/or total precipitation superimposed in order to provide a generally reliable indicator of those PV features associated with model-generated latent heat release. Additional research, fine-tuning of graphical displays, and training modules could serve to help this forecasting tool gain a deserved acceptance in the operational forecasting community in general.

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