On the Importance of the Precipitation Mass Sink in Tropical Cyclones and Other Heavily Precipitating Systems

Gary M. Lackmann[+]
North Carolina State University, Raleigh, North Carolina

Richard M. Yablonsky
North Carolina State University, Raleigh, North Carolina

1. INTRODUCTION

When water vapor is converted to cloud and precipitation and subsequently removed to the surface via precipitation, there is a corresponding hydrostatic pressure decrease due to the reduction of mass in the overlying column. Pressure changes resulting from the addition or removal of water vapor are currently neglected in most applications. However in heavily precipitating systems such as tropical cyclones, this neglect is questionable. The purpose of this research is to quantify the precipitation mass sink mechanism in a tropical cyclone using a mass budget, a potential vorticity budget, and numerical sensitivity experiments. A brief case study of Hurricane Lili (2002) will be presented.

Our working hypothesis is that changes in the pressure field due to the precipitation mass sink mechanism are not negligible for tropical cyclones and perhaps are not negligible for other heavily precipitating systems. Three tests of this hypothesis are presented here or summarized, including (i) a mass budget, (ii) a potential vorticity (PV) budget, and (iii) numerical sensitivity experiments. Here we will focus primarily on two sets of numerical experiments, one using an idealized axisymmetric hurricane model (Rotunno and Emanuel 1987) and the other utilizing the workstation version of the National Centers for Environmental Prediction (NCEP) Eta model (Mesinger et al. 1988).

2. BACKGROUND

The isobaric mass continuity equation is usually written without source and sinks terms:

$$\nabla \cdot \vec{v} + \frac{\partial \omega}{\partial p} = 0, \qquad (1)$$

where $\vec{v}$ is the horizontal velocity vector and ∇ is the horizontal gradient operator. However, as noted by Trenberth (1991), a more accurate form of (1) is

$$\nabla \cdot \vec{v} + \frac{\partial \omega}{\partial p} = E - P, \qquad (2)$$

where E and P represent evaporation and precipitation source and sink terms, respectively. Trenberth (1991) notes that at a given atmospheric level, the right side of (2) is negligible. However, Trenberth also notes that when (2) is integrated vertically, the relative importance of the right side increases owing to strong cancellation in the left-hand terms, with no such cancellation in E – P.

Assuming a hydrostatic atmosphere, the pressure at a given height is approximately proportional to the total mass of the overlying air. Therefore, water mass removal via downward precipitation flux will lower the pressure at a given altitude. Similarly, evaporation from the surface adds mass and thereby increases the pressure, but evaporation tends to occur at a slower pace over a broader area relative to convective precipitation.

Many current numerical weather prediction models account for water mass conservation in a separate water-substance continuity equation. However, the corresponding alteration in the model pressure-tendency equation is usually neglected. One of the goals of this study is to determine whether this is justifiable. This neglect of moisture sources and sinks in NWP models has been questioned by Trenberth (1991), Gu and Qian (1991), Qiu et al. (1991), Qiu et al. (1993), Van den Dool and Saha (1993), Savijärvi (1995),

[+] *Corresponding author address:* Dr. Gary M. Lackmann, North Carolina State University, Department of Marine, Earth and Atmospheric Sciences, Raleigh, NC 27695-8208. E-mail: gary@ncsu.edu

and more recently by Davies et al. (2002) and Lackmann and Yablonsky (2004).

3. MASS AND PV BUDGET SUMMARY

The initial test of the hypothesis presented above involved simply computing the mass of precipitation reaching the surface within a 100-km radius of Hurricane Lili during the deepening phase of that storm, and comparing this to the mass loss needed to explain the area-averaged pressure decrease over the corresponding time interval. If the rainwater mass was much less than that needed to produce the pressure decrease, then the hypothesis could be rejected. However, as presented in Lackmann and Yablonsky (2004), the results demonstrated that the rainwater mass actually exceeded the mass loss needed to explain the observed pressure decrease by nearly a factor of 3, meaning that the hypothesis could not be rejected *a priori*.

This is not to say that all of the pressure decrease was due to precipitation mass loss; on the contrary, we recognize that net divergence in the air column owing to other mechanisms was predominantly responsible for the pressure decrease. However, because the precipitation mass loss was comparable in magnitude, this effect plays a potentially significant role in the hurricane mass budget.

Within isentropic layers that are characterized by net vapor removal through condensation or other processes, PV substance (a.k.a. isentropic absolute vorticity) will be concentrated, and the corresponding PV will increase in the layer. As demonstrated by Schubert et al. (2001), the PV tendency equation thus has a term corresponding to the precipitation mass flux divergence. Computation of the mass-sink contribution to the PV budget for Hurricane Lili reveals a consistently positive contribution, with differences maximized at and beneath the melting level. See Lackmann and Yablonsky (2004) for details. The latent heating term was much larger than the mass sink term, but strong cancellation was observed in the former.

Both the mass and PV budgets suggest that the mass sink effect may be important, but these results did not allow a *quantitative* measure of this contribution. Thus we turn to numerical sensitivity experiments in order to better study this process, including nonlinear feedback effects.

4. MODEL SENSITIVITY EXPERIMENTS

Dr. Kerry Emanuel has generously provided us with the use of the idealized nonhydrostatic axisymmetric numerical model of Rotunno and Emanuel (1987), which we have since modified to include the precipitation mass sink terms. Also, Dr. Fedor Mesinger has made available to us code modifications needed to incorporate the mass source/sink terms into the workstation version of the NCEP Eta model (e.g. Mesinger et al. 1988).

4.1 *Nonhydrostatic Axisymmetric Model*

The nonhydrostatic axisymmetric numerical model of Rotunno and Emanuel (1987) is based upon the original model developed by Klemp and Wilhelmson (1978) and modified by Willoughby et al. (1984). In its present form, the model uses the governing equations for compressible, axisymmetric flow on an f-plane in cylindrical coordinates. The conservation of mass equation, which in essence is a nondimensionalized pressure tendency equation, is as follows:

$$\frac{\partial \pi}{\partial t} + \frac{\bar{c}^2}{c_p \bar{\rho}\bar{\theta}_v^2}\left\{\frac{1}{r}\frac{\partial\left(ru\bar{\rho}\bar{\theta}_v\right)}{\partial r} + \frac{\partial\left(w\bar{\rho}\bar{\theta}_v\right)}{\partial z}\right\} = 0. \qquad (3)$$

Eq. (3) can be modified to include the precipitation mass sink effect as follows (neglecting evaporational effects):

$$\frac{\partial \pi}{\partial t} + \frac{\bar{c}^2}{c_p \bar{\rho}\bar{\theta}_v^2}\left\{\frac{1}{r}\frac{\partial\left(ru\bar{\rho}\bar{\theta}_v\right)}{\partial r} + \frac{\partial\left(w\bar{\rho}\bar{\theta}_v\right)}{\partial z}\right\} = \left.\frac{\partial \pi}{\partial t}\right|_{\text{msnk}}, \qquad (4)$$

where

$$\left.\frac{\partial \pi}{\partial t}\right|_{\text{msnk}} \approx \frac{R}{c_p P_0^{R/c_p}} P^{R/c_p - 1} \left.\frac{\partial p}{\partial t}\right|_{\text{msnk}} \qquad (5)$$

and

$$\left.\frac{\partial p}{\partial t}\right|_{msnk} \approx -g\int_z^{z_T} \bar{\rho} u \frac{\partial q_l}{\partial r}\, dz + g\bar{\rho}_z \left(w - V_T\right)_z q_{lz}. \qquad (6)$$

In this way, the pressure is now modified at each model level to account for both the vertically integrated lateral advection of hydrometeors in the overlying column and the hydrometeor flux

through the bottom (i.e. the current model level) of the column.

Sensitivity experiments were performed using the default input parameters by running the model without code modifications (CTRL) and with code modifications to account for the precipitation mass sink in the model pressure tendency equation (MSNK). The MSNK simulation begins to deepen earlier than CTRL (not shown), but during the most rapid intensification period, neither MSNK nor CTRL is systematically deeper than the other. Between 168 and 216 hours, the central pressures in both runs oscillate between relatively higher and lower values, but after 216 h, MSNK remains deeper than CTRL. Also, MSNK continues to oscillate at the end of the model run, suggesting possible future deepening, whereas CTRL approaches a steady state. Note that at times, the difference in central pressure between the two runs is ~15 hPa (not shown). The difference in maximum tangential wind speed between the runs is ~10 m s^{-1}.

The differences for the CTRL and MSNK runs of the axisymmetric model are relatively small, but nevertheless they are not negligible. Other aspects of the storm structure and evolution are also different, including the radius of maximum wind (not shown).

4.2 *Workstation Version of the NCEP Eta Model: Hurricane Lili (2002) Simulations*

The workstation version of the NCEP Eta model is hydrostatic, which simplifies the inclusion of the precipitation mass sink effect. The modifications to the Eta model, provided by Dr. Fedor Mesinger of NCEP, are similar in form to those for the axisymmetric model presented above. Lackmann and Yablonsky (2004) present additional details on these model modifications, which couple water loading effects to the mass source/sink effect.

Sensitivity experiments were performed with (MSNK) and without (CTRL) the precipitation mass sink modifications for several simulations of Hurricane Lili (2002) and Hurricane Isabel (2003). Here, we will present results from Hurricane Lili, which affected the Gulf of Mexico and the Gulf Coast of the U.S. during early October, 2002.

The model simulation presented here was run with 15-km grid spacing without nesting, 60 vertical levels, and using the Kain-Fritsch cumulus parameterization scheme option. The run was initialized from the Global Forecast System (GFS) 95-km analysis from 00 UTC 1 October and used GFS lateral boundary conditions updated every 6 hours.

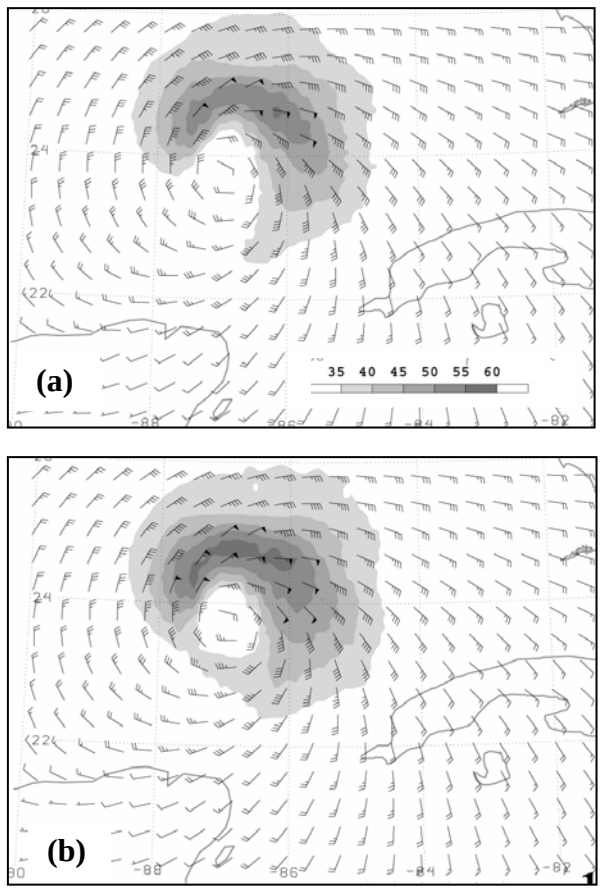

Fig. 1. CTRL (a) and MSNK (b) simulations of Hurricane Lili for 30-hour simulation from Eta model, valid 06 UTC 2 Oct., including 10-m winds (standard convention) and isotachs (shaded as in legend in panel (a).

Comparison of Figs. 1a and 1b indicates that the 20-m winds in the vicinity of Lili were stronger in the MSNK run. This difference is more easily visualized and quantified in Fig. 2, which shows a difference field of 10-m wind speed between the two runs. At this time, wind-speed differences were between 6 and 12 kt, but cross

sections indicate that wind speed differences were greater than 15 kts at slightly higher altitudes (Fig. 3). A stronger cyclonic circulation exists throughout the depth of the troposphere in the MSNK simulation.

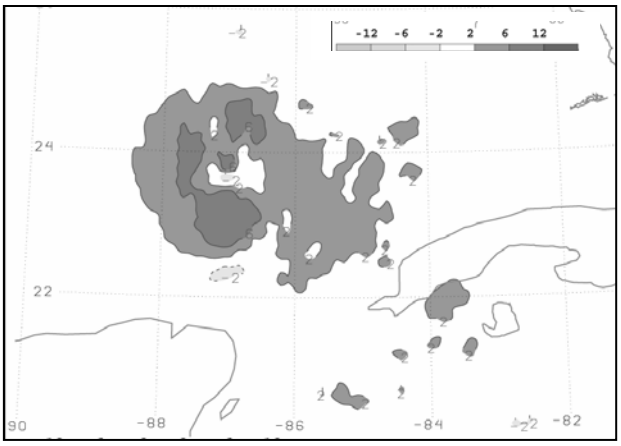

Fig. 2. Difference field (MSNK – CTRL) for 10-m wind speed (kt) at 30 h, shaded as in legend at top of panel.

The corresponding difference field of geopotential height is shown in Fig. 4. Consistent with hydrostatic arguments, the differences are largest near the surface and below the freezing level.

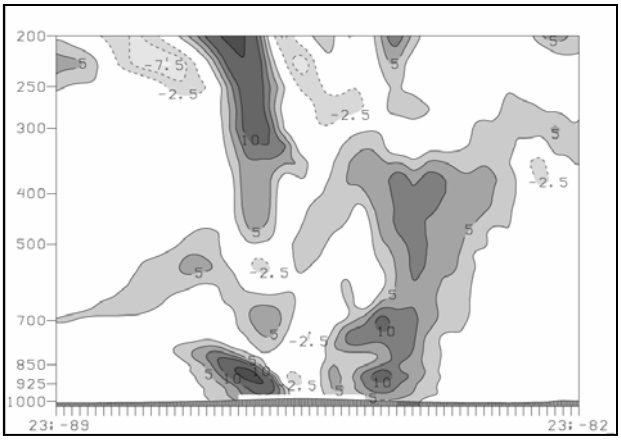

Fig. 3. East-west cross-sectional difference field of wind speed (MSNK – CTRL), for 24 h simulation valid at 00 UTC 2 Oct.

The sea-level pressure and precipitation fields for the 30-h simulation are depicted in Fig. 5, along with the difference field in sea level pressure in Fig. 6. Differences exceed 4 hPa by this time, consistent with the stronger wind speeds. Given that the Eta model CTRL run did not deepen the storm very strongly, this additional 4 hPa of deepening represents an increase of approximately 30% over the control run.

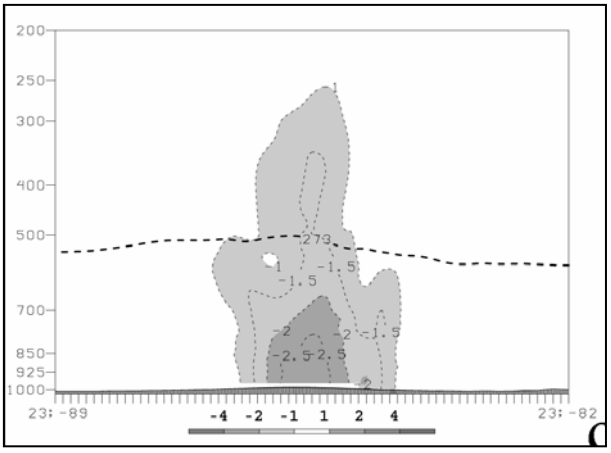

Fig. 4. As in Fig. 3, except cross section of geopotential height difference (shaded and light dashed lines, dam) and CTRL freezing level (bold dashed line).

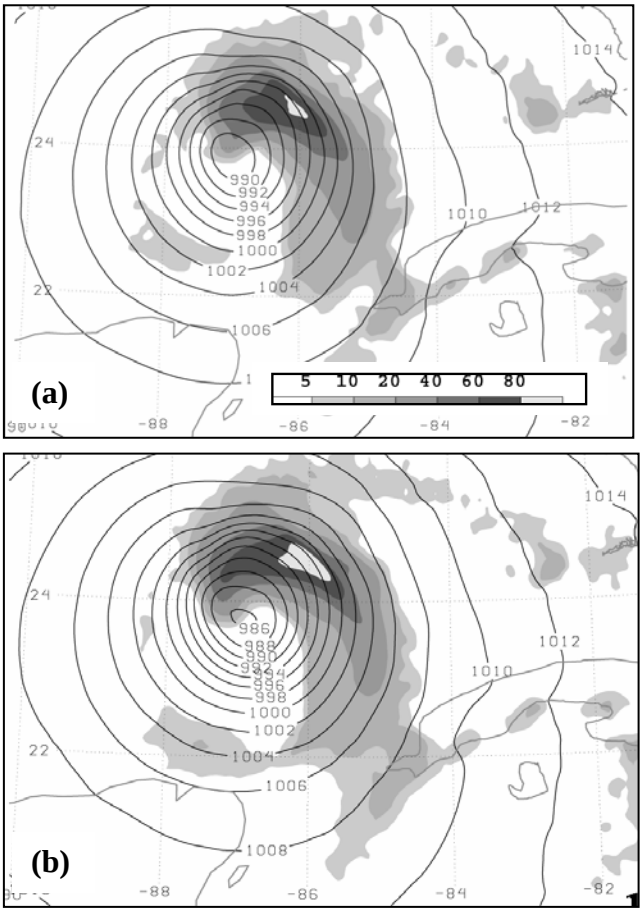

Fig. 5. Eta model sea-level pressure (hPa) and 3-hourly precipitation (shaded as in the color bar) at 30 h for (a) CTRL, and (b) MSNK. Rainfall in mm and shaded as in legend in (a).

Rainfall rates in the two model runs at forecast hour 30 are shown in Fig. 5. Precipitation rates were generally larger in the MSNK run, and the central pressure was consistently lower in the vicinity of Lili throughout the simulations. Figure 6 reveals that the greatest difference in sea-level pressure between the runs (>4 hPa lower in MSNK than CTRL) is near the center of the model hurricane, which is consistent with most of the other hours near the end of the model forecast cycle (not shown). Also, asymmetries in the model pressure field difference tend to coincide with the regions of greatest model QPF disparity between the runs, suggesting the varying degree of interaction between rain rate and pressure tendency in MSNK and CTRL.

5. CONCLUSIONS AND FUTURE WORK

Additional background, and details concerning the mass and PV budget results can be found in Lackmann and Yablonsky (2004). The results of all of the hypothesis tests indicate that although the precipitation mass sink is not a dominant effect, it is not negligible. Additional experiments with Hurricane Isabel (not shown) demonstrate larger differences than for Lili, a storm in which the Eta model did not deepen significantly. The precipitation amounts from Eta model simulations of Lili are considerably smaller than satellite-derived rainfall estimates, suggesting that model simulations that more accurately represented the rainfall would exhibit considerably larger differences Ongoing research includes study of midlatitude convective flooding events, heavily precipitating extratropical storms, and other tropical cyclones.

6. ACKNOWLEDGEMENTS

This research was funded by NSF grants ATM-0079425 and ATM-0334427, awarded to North Carolina State University, and an American Meteorological Society Graduate Fellowship, awarded to Richard M. Yablonsky. Special thanks to Drs. Kerry Emanuel and Fedor Mesinger, and to Mr. Matthew Pyle at NCEP, for the means to pursue model sensitivity experiments. The PSU/NCAR MM5 model was made available through NCAR, sponsored by the NSF.

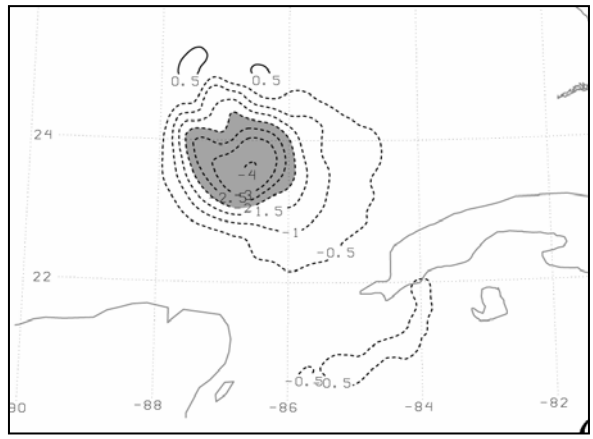

Fig. 6. Sea-level pressure difference field, MSNK – CTRL, for 30-h Eta simulation.

7. REFERENCES

Davies, T., M. Diamantakis, and A. J. Malcom, 2002: Moist NWP equations and missing terms. Preprints, *15th Conf. on Numerical Weather Prediction*, San Antonio, TX, Amer. Meteor. Soc., 41–42.

Emanuel, K. E., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43,** 585–604.

Gu, H., and Z. Qian, 1991: A discussion about the role of water vapor source/sink term in continuity equation of numerical models. *Chin. Sci. Bull.*, **36,** 16–21.

Klemp, J. B., and R. B. Wilhelmson, 1978: The simulation of three-dimensional convective storm dynamics. *J. Atmos. Sci.*, **35,** 1070–1096.

Lackmann, G. M., and R. M. Yablonsky, 2004: The importance of the precipitation mass sink in tropical cyclones and other heavily precipitating systems. *J. Atmos. Sci.*, **61,** in press.

Mesinger, F., Z. I. Janjic, S. Nickovic, D. Gavrilov, and D. G. Deaven, 1988: The step-mountain coordinate: Model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment. *Mon. Wea. Rev.*, **116,** 1493–1518.

Qiu, C.-J., J.-W. Bao, and Q. Xu, 1991: The significance of mass sink due to precipitation. *Proc. 9th Conf. on Mesoscale Processes, Amer. Meteor. Soc.*

Qiu, C.-J., J.-W. Bao, and Q. Xu, 1993: Is the mass sink due to precipitation negligible? *Mon. Wea. Rev.,* **121,** 853–857.

Rotunno, R., and K. A. Emanuel, 1987: An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a nonhydrostatic axisymmetric numerical model. *J. Atmos. Sci.,* **44,** 542–561.

Savijärvi, H., 1995: Water mass forcing. *Contr. Atmos. Phys.,* **68,** 75–84.

Schubert, W. H., S. A. Hausman, M. Garcia, K. V. Ooyama, and H.-C. Kuo, 2001: Potential vorticity in a moist atmosphere. *J. Atmos. Sci.,* **58,** 3148–3157.

Trenberth, K. E., 1991: Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses. *J. Climate,* **4,** 707–722.

Van den Dool, H. M., and S. Saha, 1993: Seasonal redistribution and conservation of atmospheric mass in a general circulation model. *J. Climate,* **6,** 22–30.

Willoughby, H. E., H.-L. Jin, S. J. Lord, and J. M. Piotrowicz, 1984: Hurricane structure and evolution as simulated by an axisymmetric, nonhydrostatic numerical model. *J. Atmos. Sci.,* **41,** 1169–1186.