P1M.11 THE PRECIPITATION MASS SINK IN TROPICAL CYCLONES

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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 water vapor sources and sinks are often neglected meteorological applications. This neglect warrants scrutiny, however, in heavily precipitating systems such as tropical cyclones. The purpose of this research is to quantify the precipitation mass sink mechanism in a tropical cyclone using numerical model experiments for the case of Hurricane Lili (2002).

The hypothesis to be tested here is that changes in the pressure field due to the precipitation mass sink mechanism are not negligible for tropical cyclones and perhaps for other heavy precipitation systems. Three tests of this hypothesis were undertaken by Lackmann and Yablonsky (2004), including (i) a mass budget, (ii) a potential vorticity (PV) budget, and (iii) sensitivity experiments with numerical models. 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, as is done to obtain a pressure-tendency equation, the relative importance of the right side increases owing to strong cancellation for the left-hand terms, with little such cancellation in E – P.

To the extent that hydrostatic balance holds, the pressure at a given height is approximately proportional to the total mass of the overlying air column. Therefore, condensation and subsequent 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 broader areas 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), and more recently by Davies et al. (2002) and Lackmann and Yablonsky (2004).

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3. MASS 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 on this basis.

This is not to say that all of the observed 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 to that corresponding to the observed pressure decrease, we must investigate whether this effect plays a significant role in the hurricane mass budget.

4. MODEL SENSITIVITY EXPERIMENTS

Dr. K. Emanuel of MIT 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 is essentially a nondimensionalized pressure tendency equation, is given by:

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

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

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

where

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

and

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

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, as evident from (6).

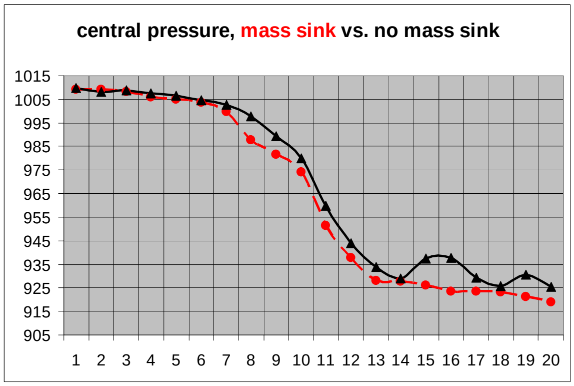

Fig. 1. Central pressure as a function of time in the axisymmetric model for the CTRL (black line) and MSNK (red line) simulations. The abscissa begins at forecast hour 72 and runs through hour 208.

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 (Fig. 1), and remains stronger than the CTRL run for most of the integration thereafter. Also, MSNK continues to oscillate at the end of the model run, suggesting possible future deepening, whereas CTRL approaches a steady state (not shown). Note that at times, the difference in central pressure between the two runs is ~15 hPa (Fig. 1). The difference in maximum tangential wind speed between the runs is ~10 m s^{-1} (not shown). Other aspects of the storm structure and evolution are also different, including the radius of maximum wind (not shown).

4.2 *Workstation Eta Simulations: Lili (2002)*

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. The continuity equation, as represented in the original Eta model (Mesinger et al. 1988) in eta coordinates is

$$\frac{\partial}{\partial\eta}\left(\frac{\partial p}{\partial t}\right)+\nabla\cdot\left(\vec{v}\frac{\partial p}{\partial\eta}\right)+\frac{\partial}{\partial\eta}\left(\dot{\eta}\frac{\partial p}{\partial\eta}\right)=0, \qquad (7)$$

where $\eta \equiv \frac{p-p_T}{p_S-p_T}\eta_S$ and $\eta_S = \frac{p_{ref}(z_S)-p_T}{p_{ref}(0)-p_T}$.

When this equation is modified to account for vapor sources and sinks, an additional term appears:

$$\frac{\partial}{\partial\eta}\left(\frac{\partial p}{\partial t}\right)+\nabla\cdot\left(\vec{v}\frac{\partial p}{\partial\eta}\right)+\frac{\partial}{\partial\eta}\left(\dot{\eta}\frac{\partial p}{\partial\eta}\right)-\frac{dq}{dt}\frac{\partial p}{\partial\eta}=0 \cdot \qquad (8)$$

A modified form of the surface-pressure tendency equation [obtained from integration of (8)] is included in the modified form of the Eta model.

Sensitivity experiments were performed with and without the 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.

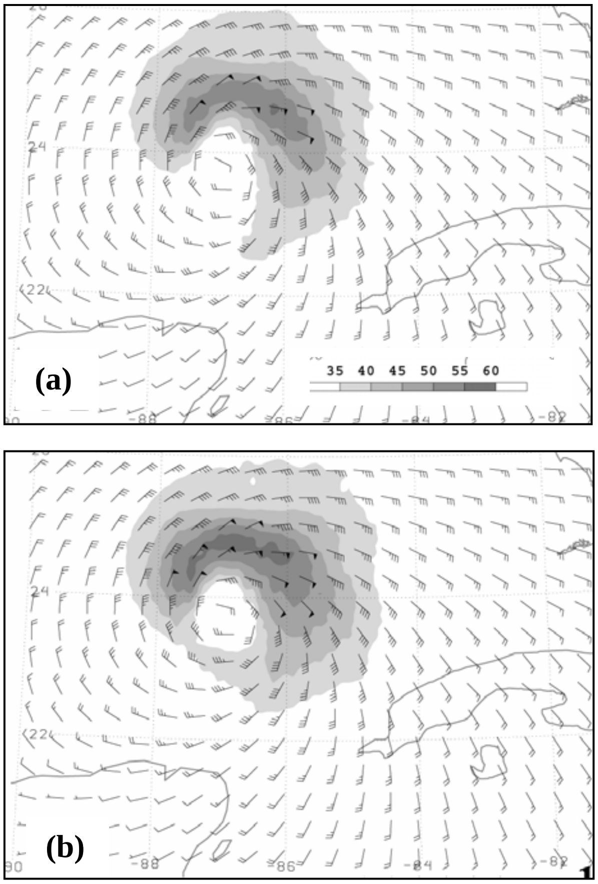

Fig. 2. CTRL (a) and MSNK (b) simulations of Hurricane Lili for 30-hour simulation from Eta model, valid 06 UTC 2 Oct., including 10-m winds (standard convention) and isotachs (shaded as in legend in panel (a).

Comparison of Figs. 2a and 2b indicates that the 10-m winds in the vicinity of Lili were stronger in the MSNK run. This difference is more easily visualized and quantified in Fig. 3, 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. 4). A stronger cyclonic circulation exists throughout much of the depth of the troposphere in the MSNK simulation.

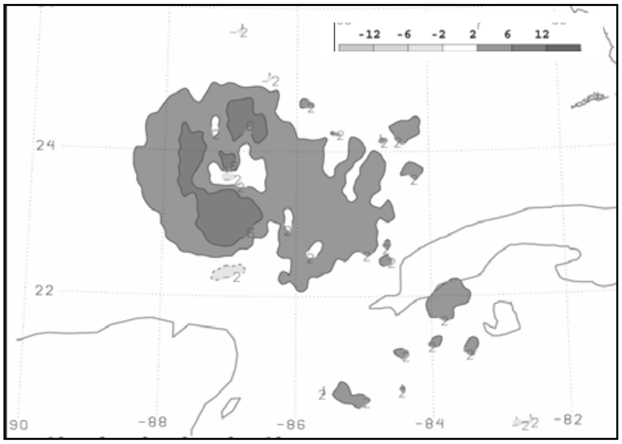

Fig. 3. Difference field (MSNK – CTRL) for 10-m wind speed (kt) at 30 h, shaded as in legend at top of panel.

The corresponding difference field of geopotential height is shown in Fig. 5. Consistent with hydrostatic arguments, the differences are largest near the surface and below the freezing level.

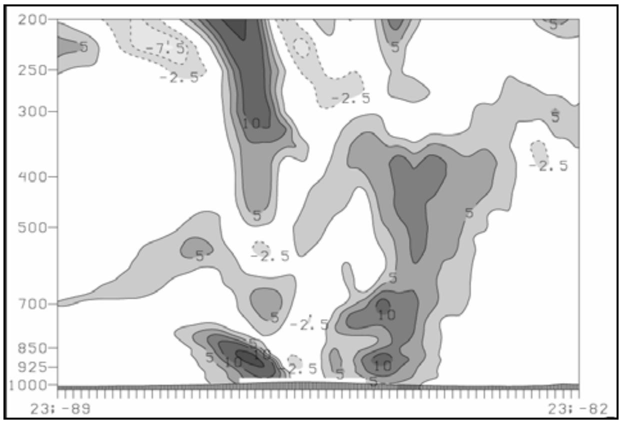

Fig. 4. East-west cross-sectional difference field of wind speed (kt, MSNK – CTRL), for 24 h simulation valid at 00 UTC 2 Oct.

The sea-level pressure and precipitation fields for the 30-h simulation are depicted in Fig. 6, along with the difference field in sea level pressure in Fig. 7. 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.

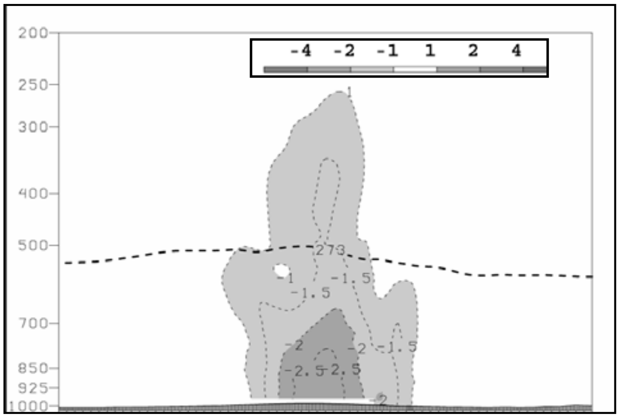

Fig. 5. As in Fig. 4, except cross section of geopotential height difference (shaded and light dashed lines, dam) and CTRL freezing level (bold dashed line).

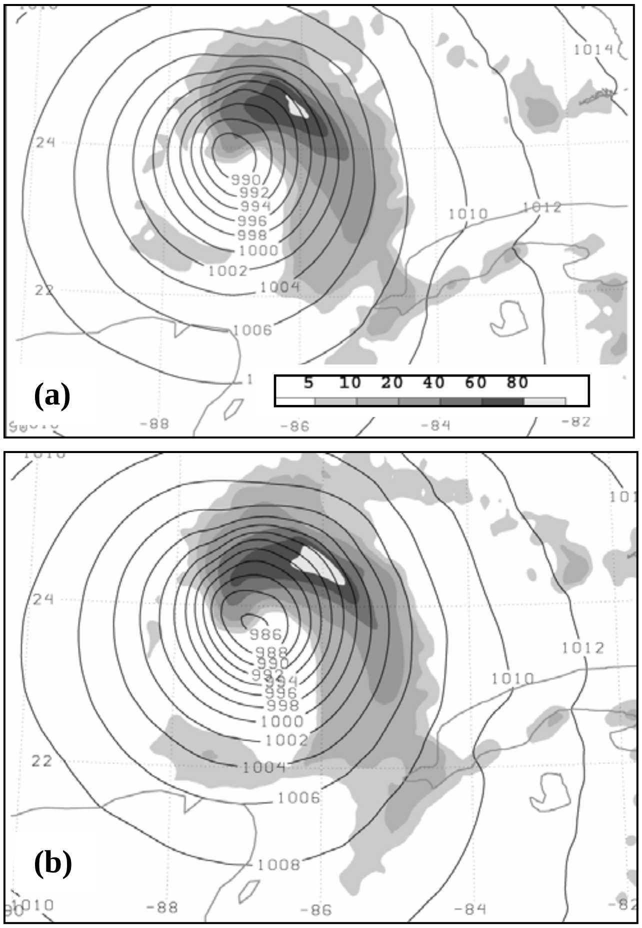

Fig. 6. Eta model sea-level pressure (hPa) and 3-hourly precipitation (shaded as in the color bar) at 30 h for (a) CTRL, and (b) MSNK. Rainfall in mm and shaded as in legend in (a).

Rainfall rates in the two model runs at forecast hour 30 are shown in Fig. 6. 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 7 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.

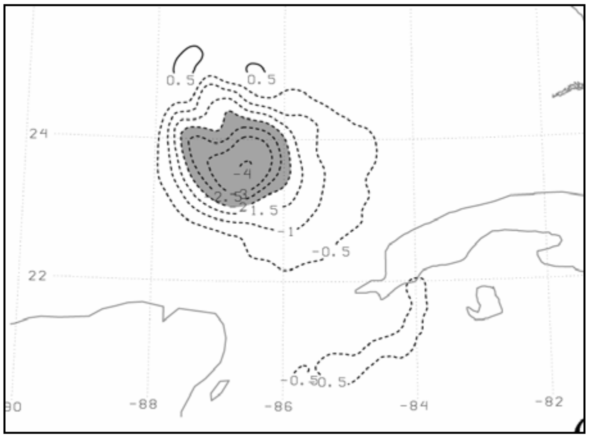

Fig. 7. Sea-level pressure difference field, MSNK – CTRL, for 30-h Eta simulation.

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 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.

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