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The Hurricane Intensity Issue

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Abstract

The intensity issue of hurricanes is addressed in this paper using the angular momentum budget of a hurricane in storm-relative cylindrical coordinates and a scale-interaction approach. In the angular momentum budget in storm-relative coordinates, a large outer angular momentum of the hurricane is depleted continually along inflowing trajectories. This depletion occurs via surface and planetary boundary layer friction, model diffusion, and "cloud torques"; the latter is a principal contributor to the diminution of outer angular momentum. The eventual angular momentum of the parcel near the storm center determines the storm's final intensity. The scale-interaction approach is the familiar energetics in the wavenumber domain where the eddy and zonal kinetic energy on the hurricane scale offer some insights on its intensity. Here, however, these are cast in storm-centered local cylindrical coordinates as a point of reference. The wavenumbers include azimuthally averaged wavenumber 0, principal hurricane-scale asymmetries (wavenumbers 1 and 2, determined from datasets) and other scales. The main questions asked here relate to the role of the individual cloud scales in supplying energy to the scales of the hurricane, thus contributing to its intensity. A principal finding is that cloud scales carry most of their variance, via organized convection, directly on the scales of the hurricane. The generation of available potential energy and the transformation of eddy kinetic energy from the cloud scale are in fact directly passed on to the hurricane scale by the vertical overturning processes on the hurricane scale. Less of the kinetic energy is generated on the scales of individual clouds that are of the order of a few kilometers. The other major components of the energetics are the kinetic-to-kinetic energy exchange and available potential-to-available potential energy exchange among different scales. These occur via triad interaction and were noted to be essentially downscale transfer, that is, a cascading process. It is the balance among these processes that seems to dictate the final intensity. [PUBLICATION ABSTRACT]

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ABSTRACT

The intensity issue of hurricanes is addressed in this paper using the angular momentum budget of a hurricane in storm-relative cylindrical coordinates and a scale-interaction approach. In the angular momentum budget in storm-relative coordinates, a large outer angular momentum of the hurricane is depleted continually along inflowing trajectories. This depletion occurs via surface and planetary boundary layer friction, model diffusion, and "cloud torques"; the latter is a principal contributor to the diminution of outer angular momentum. The eventual angular momentum of the parcel near the storm center determines the storm's final intensity. The scale-interaction approach is the familiar energetics in the wavenumber domain where the eddy and zonal kinetic energy on the hurricane scale offer some insights on its intensity. Here, however, these are cast in storm-centered local cylindrical coordinates as a point of reference. The wavenumbers include azimuthally averaged wavenumber 0, principal hurricane-scale asymmetries (wavenumbers 1 and 2, determined from datasets) and other scales. The main questions asked here relate to the role of the individual cloud scales in supplying energy to the scales of the hurricane, thus contributing to its intensity. A principal finding is that cloud scales carry most of their variance, via organized convection, directly on the scales of the hurricane. The generation of available potential energy and the transformation of eddy kinetic energy from the cloud scale are in fact directly passed on to the hurricane scale by the vertical overturning processes on the hurricane scale. Less of the kinetic energy is generated on the scales of individual clouds that are of the order of a few kilometers. The other major components of the energetics are the kinetic-to-kinetic energy exchange and available potential-to-available potential energy exchange among different scales. These occur via triad interaction and were noted to be essentially downscale transfer, that is, a cascading process. It is the balance among these processes that seems to dictate the final intensity.

1. Introduction

In this paper we explore two avenues for the hurricane intensity issue. Both of these are diagnostic approaches and are applied here to the datasets derived from a very high resolution forecast model. A somewhat reasonable hurricane intensity forecast from a high-resolution model was necessary in order to portray the workings of the proposed diagnostic frameworks. The two approaches described here can be labeled the angular-momentum-based diagnosis of hurricane intensity and a scale-interaction-based diagnosis of the storm's energetics. In the former approach, a reservoir of high-angular-momentum air from the outer reaches of the hurricane has a large control on its intensity. That outer angular momentum is affected by the torques the parcels experience as they move toward the highintensity region. The latter approach asks about implications of the cloud scales on the eventual energy (which indirectly relates to the intensity) of a hurricane.

The initial datasets for this study came from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis plus dropwindsonde datasets from research aircraft and satellite data. A list of acronyms appears in Table 1. Furthermore, this study is based on a somewhat realistic simulation of a hurricane (Hurricane Bonnie of 1998) that was generated using a nonhydrostatic microphysical mesoscale model [the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MMS)]. The model output datasets were used here to carry out the diagnostic enquiries.

This study became possible because of two recent advancements in data and modeling. The third and fourth Convection and Moisture Experiments (CAMEX-3 and -4, respectively) are recent field experiments in which joint data initiatives of the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and the U.S. Air Force provided an extensive coverage of observations. These agencies deployed as many as six research/operational aircraft for the surveillance of hurricanes on a daily basis. These research aircraft deployed as many as a total of 100 dropsondes per day providing profiles of winds, temperature, humidity, and pressure. In addition to these, a NASA aircraft provided specialized moisture profiles from the Lidar Atmospheric Sensing Experiment (LASE). Another major dataset was composed of 1/2° latitude × 1/2° longitude operational analysis data from the ECMWF. Using these datasets, we performed variational data assimilation (Rizvi et al. 2002; Kamineni et al. 2003, 2005) to analyze the CAMEX storms of the years 1998 and 2001. This mix of datasets provides a unique coverage of observations for hurricane modeling.

In the modeling area, it is now possible to carry out high-resolution simulation with mesoscale nonhydrostatic microphysical models. Numerous recent applications with the MM5 have shown the possibility for such simulation. Braun (2002) analyzed the storm structure and eyewall buoyancy of Hurricane Bob using a multiply nested MM5 with moving nest capability and demonstrated reasonable distributions of vertical motion in the eyewall. Similar studies were carried out by different research groups to resolve the cloud-scale features of hurricanes using MM5, for example, Bao et al. (2000), Braun and Tao (2000), Chen and Yau (2001), Davis and Bosart (2001), Davis and Trier (2002), Zhang and Wang (2003), and Liu et al. (1999). A multiply nested model with an inner resolution of 1 km provides the possibility for asking questions on the role of the model's deep convection on the intensity changes of hurricanes.

In his seminal papers on atmospheric energetics in the wavenumber domain, Saltzman (1957, 1970) laid the foundations for studies of scale interactions. Exploring the energy exchange between waves and waves, and between waves and zonal flows, he portrayed the mechanism for the driving of the middle-latitude zonal flows (i.e., the zonally averaged jets) in the atmosphere. That framework was in spherical coordinates. For studies of a hurricane, it is relatively straightforward to cast this system onto a cylindrical coordinate system, the details of which are provided in the appendix. This transformation provides information on the kinetic and available potential energy exchange among the azimuthally averaged flows and other azimuthal waves. The cloud (convection) scale being much smaller than that of the hurricane, the mode of communication of information from the cloud scale to the hurricane scale was not clearly apparent. The scale of convection (updrafts and adjacent downdrafts) is of the order of a few kilometers, whereas the scale of the hurricane is of the order of several hundreds of kilometers. Clearly the issue of scale interaction needs exploring in this context. A budget of kinetic energy for the scales of the hurricane can be revealing about its intensity.

The angular momentum perspective starts with a large reservoir of high angular momentum air at large radii. That air is generally brought into the storm's interior along inflow channels of the lower troposphere. That large angular momentum (following parcel motion) is depleted by the surface and internal friction torques (cloud torques) and by the pressure torques. The parcel arrives at inner radii where the storm intensity (the maximum sustained near-surface wind of the hurricane) is explicitly determined from the value of the angular momentum the parcel arrives with. This paper attempts to provide some insight on these two different approaches for the understanding of hurricane intensity.

2. Observational aspects

Hurricane Bonnie developed from a vigorous tropical wave that spawned a tropical depression to the east of the Lesser Antilles, near 15°N, 48°W, around 1200 UTC 19 August 1998. After moving west-northwestward for several days, the tropical cyclone turned toward the northwest and north-northwest, as shown in Fig. 1. Bonnie became a tropical storm at about 1200 UTC 20 August, and the system strengthened into a hurricane by 0000 UTC 22 August. This hurricane made a recurvalure and landfall along the coast of North Carolina. It weakened to a tropical storm around 1800 UTC 27 August, but rcintensified into a hurricane when it moved back over the Atlantic. Bonnie then moved on a generally northeastward-to-eastward track and lost its tropical characteristics on 30 August. The hurricane was rather intensively monitored by hurricane reconnaissance and surveillance aircraft. Our study covers a 72-h period between 22 and 25 August 1998. During this period, Bonnie's maximum winds varied from 33.5 to about 51.5 m s^sup -1^. A visible satellite image [Geostationary Operational Environmental Satellite (GOES)] during this period (Fig. 2) at 1615 UTC 23 August 1998 showed a well-defined storm with active banding to its south. However after Bonnie recurved and interacted with a frontal system, the cloud cover became elongated northeastward. The satellite imagery of the storm during our study period is similar to that seen in many category 3 hurricanes of the Atlantic basin having winds close to 100 kt (51.5 m s^sup -1^). We shall not describe the detailed structure of Hurricane Bonnie here since this is a well-studied storm and is described in some detail by Pasch et al. (2001) in their seasonal summary and by our laboratory (Rizvi et al. 2002).

a. Data and method of analysis

The dalasets for this study came from diverse sources: ECMWF, CAMEX-3, and satellite datasets. The procedure of generating the analysis includes the following steps: 1) The initial state and boundary conditions for this modeling study were prepared using operational real-time ECMWF analyzed data files (provided at 0.5° latitude × 0.5° longitude grid and 28 vertical levels. 2) Six research aircraft provided dropsonde and special moisture-profiling datasets (the LASE instrument). There was midtropospheric surveillance from two NOAA WP3 aircraft, a NOAA G-IV near the tropopause level, a NASA P3 aircraft, a NASA DC-8 (flying near the 250-hPa level), and a NASA ER-2 flying near 60 000 ft in the lower stratosphere. These datasets were analyzed using our Florida State University (FSU) three-dimensional variational data assimilation (3DVAR) following Rizvi et al. (2002) and Kamineni et al. (2003, 2004, manuscript submitted to J. Atmos. Sci.) where the hurricane forecast impacts from these additional observations of the CAMEX field campaign were addressed. This analysis was carried out on a spectral resolution of T170 (transform grid spacing approximately 70 km). 3) These datasets were next subjected to physical initialization (i.e., rain-rate initialization) following Krishnamurti et al. (1991, 2001). Here rain-rate estimates were derived from the microwave instruments on board the Tropical Rainfall Measuring Mission (TRMM) [the TRMM Microwave Imager (TMI)] and three Defense Meteorological Satellite Program (DMSP) satellites [(Special Sensor Microwave Imager (SSM/I)]. These analyzed datasets were simply interpolated using bicubic splines onto a variable grid resolution of the MM5 used in this study.

b. The PSU-NCAR Mesoscale Model

The numerical simulation of Hurricane Bonnie of 1998 was carried out using the nonhydrostatic PSUNCAR Mesoscale Model (version 3.6) (Dudhia 1993). A 72-h simulation of Hurricane Bonnie (0000 UTC 22 August 1998-0000 UTC 25 August 1998) was made using a variable-resolution nested configuration. Here we used four domains (Fig. 1) with a horizontal grid spacing of 27, 9, 3, and 1 km and having domain size of 98 × 94, 186 × 222, 369 × 444, and 501 × 501 grid points, respectively. These grid meshes included 23 vertical half-sigma (σ) levels. The 27- and 9-km domains were one-way nested whereas the 3- and 1-km nests were two-way nested. The physics options used for the coarser grids at 27 and 9 km included the Betts-Miller cumulus parameterization (Betts and Miller 1986, 1993), a simple ice explicit scale cloud microphysics scheme (Dudhia 1989), the Medium-Range Forecast (MRF) planetary boundary scheme (Hong and Pan 1996), and a cloud radiative scheme of Dudhia (1989). The physics options for the 3- and 1-km grids were similar to the coarse grid simulations except that no cumulus parameterization scheme was used, and convection was explicitly handled.

The combined six-aircraft CAMEX flights for the surveillance of an entire storm were only conducted on a few successive days. Thus it was not possible to validate in detail the performance of the MM5 using these field campaign observations. However, the simulated details, at the high resolution, were sufficiently realistic in terms of structure, motion, and intensity to carry out the main objectives of this study, which are the angular momentum and the scale-interaction perspectives. The observed maximum reported winds from the National Hurricane Center for days 1, 2, and 3 of this study were 46, 51, and 51 m s^sup -1^ and the corresponding model-predicted maximum winds at the 850-hPa level were around 27, 35, and 45 m s^sup -1^, respectively. The central pressure comparisons were observed estimates 962, 954, and 963 hPa, and the model-predicted values were 1002, 996, and 984 hPa. It is to be noted here that there is a clear lack of ability of MM5 in simulating the storm efficiently. The model wind speeds and pressure do not capture the actual intensity and that may have some impact on the results presented in this paper. The observed and predicted tracks of Hurricane Bonnie were illustrated in Fig. 1. There are clearly some track errors but that was not a primary issue here. It is our experience that ensemble averaging of tracks from multimodels appears to generally do better than single models (Krishnamurti et al. 2000; Williford et al. 2003).

Some of the initial state fields of this study are illustrated in Figs. 3a and 3b. The sea level pressure on 22 August at 0000 UTC, shown in Fig. 3a, depicts a low pressure system to the southeast of the outer model domain. The MMS's initial central pressure at this time was approximately 1006 hPa and the maximum winds were 24 m s^sup -1^ (the best-track values were 991 hPa and 32 m s^sup -1^). Strong pressure gradient to the north was indicative of the strong trades. The scale of this closed low pressure field extended from 71° to 65°W. The tangential wind maxima (Fig. 3b) at the initial time were around 24 m s^sup -1^ to the north of the storm and were of the order of 13 m s^sup -1^ to the south of the storm. The weakest winds are located over the storm center. Figures 4a-c show the streamlines at the 850-hPa level from the forecasts of the mesoscale model at the end of days 1, 2, and 3. The northwestward motion of the storm is reasonably captured by the forecast. An interesting and prominent feature is the evolution of an asymptote of convergence to the south (by day 3 of forecast; Fig. 4c). This feature, in storm-relative coordinates, was an important inflow channel for Hurricane Bonnie.

3. The angular momentum approach on the interpretation of hurricane intensity

The angular momentum perspective starts with a large reservoir of high angular momentum air at the large radii. That air is generally being brought into the storm's interior mainly along inflow channels of the lower troposphere. That large angular momentum (following parcel motions) is depleted by the surface and internal frictional torques, by pressure torques, and by cloud torques. The parcel arrives at the inner radii where the storm intensity (the maximum surface wind of the hurricane) is determined by the value of the angular momentum with which the parcel arrives at that location. This could be called an "outer thrust" that seemingly determines the hurricane's intensity. The weakness of this argument is that the inflow channel is assumed to be a prescribed entity here. One can ask, how did that come about? An "inner thrust," a second perspective, calls for a detailed knowledge of the structure of the convective storm clouds. Knowing better microphysics, we can perhaps model these clouds more accurately and precisely, and these clouds may carve out the inflow channels in the first place. The angular momentum story could well be a consequence of a systematic and organized cloud growth.

One well-known pressure asymmetry in hurricanes arises from the so-called beta gyres (Chan and Williams 1987, 1994). If the symmetric part of the pressure field of a hurricane is removed from its total pressure field, then one can visualize these beta gyre structures. The structure generally contains higher pressures to the right of the storm's center and lower pressure to its left. Figure 6 illustrates this structure for Hurricane Bonnie (1998) for the sea level pressure from day 3 of the forecast. The beta gyre represents one of the most prominent pressure asymmetries of a hurricane. The presence of a beta gyre implies the presence of pressure torques. This is usually on rather larger scales, that is, azimuthal wavenumbers 1 and 2, and the amplitude of this torque is rather small. Another contributor to pressure torque comes from the deep convective elements (simulated by the high-resolution model) that carry pressure perturbations vertically. With vertical motions of the order of 1 to 10 m s^{-1}, small-scale pressure perturbations, on the order of a few hectopascals on the scale of these deep convective elements, abound in the predicted pressure fields. Because of the smaller hori/ontal scales of these convective elements, these perturbations can convey robust local pressure torques. However, on either side of these pressure perturbations, opposite signs of the azimuthal pressure gradients are found; thus, the increase and decrease of angular momentum essentially cancel along segments of inflowing trajectories from these pressure perturbations. The effect of frictional and cloud torques is described in the following subsections.

b. Frictional torques

In the version of the MM5 that is used in our study, the surface fluxes of momentum are defined via a bulk aerodynamic formula (Deardorff 1972; Grell et al. 1995). Here the constant flux layer is 86 m deep. The disposition of surface fluxes above the constant flux layer within a PBL follows the MRF PBL scheme that was based on the work of Hong and Pan (1996). This is a nonlocal scheme that permits countergradient fluxes of moisture by large-scale eddies. The eddy diffusivity coefficient for momentum is a function of the friction velocity u^* and the PBL height is a function of a critical bulk Richardson number. The vertical disposition of these subgrid-scale surface momentum fluxes is carried out using the K theory. The profiles of implied subgrid eddy momentum fluxes determine the vertical distribution of surface fluxes. The frictional torques, $-F_{\theta}r$, thus have vertical distributions. They largely mimic the surface torques through several vertical levels.

The outputs of the vertical fluxes of momentum between the surface level and the top of the PBL were stored for each hour of the forecast. In addition to these, the MM5 includes parameterization for the subgrid-scale vertical diffusion of momentum that was also retrieved and stored. The resolved vertical fluxes of momentum by shallow and deep convection were explicitly calculated from the fields of u, v, and w. These were also stored at intervals of 1 h. These provided a complete inventory of the momentum fluxes at the surface, in the PBL, and in the rest of the model column. The large outer angular momentum of inflowing air is constantly eroded by the frictional torques. This field varies from hurricane to hurricane largely due to different distribution of wind speeds, storm size, and from the dependence of the diffusive exchange coefficients as a function of height and the Richardson number.

In this study, we divide the frictional toques $-F_{\theta}r$ into several parts, those arising from surface friction, those arising from planetary boundary layer friction, and the explicit cloud layer friction determined from the torque of the vertical eddy flux convergence of momentum. In addition to these there are also torques arising from model diffusion. All these torques, except the cloud torque, are added together in the term, $-F_{\theta}r$, whereas the cloud torque is separately considered. This is done deliberately to focus on the impact of cloud torques on the angular momentum budget and intensity changes in a hurricane environment.

4. The scale-interaction perspective

The hurricane's scale can be described by a few azimuthal wavenumbers (e.g., wavenumbers 0, 1, 2), which was noted in our analysis of the rainwater mixing ratio (Krishnamurti and Jian 1985a,b). The field of rainwater mixing ratio in these high-resolution forecasts carries the signature of individual deep convective cloud elements. Figures 7a and 7b illustrate the predicted rainwater mixing ratio at the 850-hPa level for days 2 and 3 of the forecast. An azimuthal spectral analysis of these fields shows that a sizeable portion of the variance of the rainwater mixing ratio is accounted for by the first few harmonics in the innermost region. In Figs. 8a and 8b we show the power spectra of the rainwater mixing ratio for the initial time (shown as t = 1) and at hour 24 (shown as t = 2). The results for radii 0-40, 40-200, and 200-380 km are presented here. At radii less than 200 km, a considerable amount of the power resides in these low wavenumbers. At the outer radii (200-380 km) the distribution shifts to smaller scales. The same result emerges when we examine the azimuthal spectra of the tangential velocity. The larger scales of the rainwater mixing ratio spectra are a clear reflection of the organization of convection. It thus appeared reasonable to designate wavenumbers 0, 1, and 2 as the hurricane scales. On the other hand, the scales of the individual deep convective clouds appear to reside around the azimuthal wavenumbers 20 to 30. Following Saltzman (1957, 1970), it is of interest here to explore the interactions between the hurricane and the cloud scales. These interactions can be broadly described by (a) available potential to eddy kinetic; (b) eddy kinetic to eddy kinetic; and (c) available potential to available potential. In somewhat further detail, the following are 12 salient and grouped energy exchange components that comprise the total system. (The appendix includes the mathematical details.)

(i) $\langle APE_o K_o \rangle$ is the conversion of azimuthally averaged (subscript o) available potential energy (APE) to the azimuthally averaged kinetic energy (K). This is a mechanism for the maintenance of hurricane intensity. This is akin to warm air rising and relatively colder air sinking from the Hadley-type vertical overturning. In our hurricane domain, which encloses the entire troposphere below 100 hPa and the entire atmosphere within $r \le 500$ km, the rising of warmer air occurs near the eyewall clouds and the rainbands. The sinking of relatively cooler air occurs outside of the rainband and inside of the eyewall.

(ii) $\langle APE_l K_l \rangle$ denotes long-wave (subscript l) vertical overturnings on the salient asymmetric scale of the hurricane such as azimuthal wavenumbers 1 and 2. Since this overturning arises from a quadratic nonlinearity among vertical velocity and temperature on the individual long-wave scales, this can only contribute to an in-scale energy exchange; that is, available potential energy of wavenumber 1 can only generate eddy kinetic energy for wavenumber 1, with the same being true for wavenumber 2. These overturnings generate eddy kinetic energy, thus contributing to an asymmetric velocity maximum. These waves generally exhibit phase locking, thus normally adding up to a single velocity maximum describing the principal hurricane asymmetry. It is relevant to make a note on the eyewall convection here. There has been much discussion on eyewall convection and its possible impact on hurricane intensity (Braun 2002). Along a circular eyewall, if several tall cumulonimbus clouds are located along its circular geometry, then the possibility clearly exists for the clouds to directly impact wavenumber 0. The azimuthally averaged heating along the eyewall would generate azimuthally averaged available potential energy. That can be directly converted to azimuthally averaged kinetic energy (on the scale of wavenumber 0) from the vertical overturnings (ascend along the eye-wall and descend inside and outside of the eye-wall). Here we can see a direct role of organized clouds amplifying the hurricane intensity. Furthermore, local variations of deep convection along the eyewall can also produce local asymmetry in vertical circulations, local generation of available potential energy, and local conversion to eddy kinetic energy for higher wavenumbers such as 1, 2, and 3. Thus, local enhancement of intensity can also arise from the presence of organized local manifestation of the cloud-scale vertical overturnings (akin to local Hadley-type overturning).

(iii) $\langle APE_s K_s \rangle$ is the contribution from the smaller-scale (subscript s) overturning. This can only produce eddy kinetic energy on the same scales because of the previously stated quadratic nonlinearity $-\sum_i (\omega_{ci} T_{ci}/p)$, where ω is the vertical velocity and T is the temperature at those scales.

(iv) $\langle H_o APE_o \rangle$ is the generation of available potential energy from heating (H), also arising from a quadratic nonlinearity (i.e., the product of heating and temperature) and as such can only generate potential energy on the scale of that heating. The azimuthally averaged (wavenumber 0) heating generates available potential energy only on this scale.

(v) $\langle H_l APE_l \rangle$ is an in-scale generation of available potential energy from the long-wave scales of heating.

(vi) $\langle H_s APE_s \rangle$ is the smaller-scale heating and can only generate available potential energy on the same (smaller) scales.

(vii) $\langle APE_s APE_l \rangle$ is the nonlinear exchange of available potential energy from waves to waves. The available potential to available potential is a triad interaction among waves that satisfy certain trigonometric selection rules. Here, the possibility exists for smaller cloud scale (a pair of waves) to transfer available potential energy to another azimuthal wave or vice versa. Once such a transfer occurs, the "in-scale vertical overturning" can in principle transfer the available potential energy of azimuthal waves to the kinetic energy of that scale. This in turn can, in principle, indirectly contribute to the intensity of the hurricane. In these triple product nonlinearities, energy exchanges are dictated by selection rules. If three scales m, n, and p interact, then p has to be equal to m + n, m - n, or n - m in order for a nonvanishing exchange to occur. This is the basis for triad interactions (Krishnamurti et al. 2003). This calls for two scales interacting with a third scale resulting in the growth or decay of the potential energy of a scale. This invokes sensible heat transfers from (or to) the other two scales or vice versa. The available potential energy generated by heating on cloud scales could perhaps be transferred up the scale to the available potential energy of the larger scales. That available potential energy of the larger scales can get converted to kinetic energy of the larger azimuthal scales by in-scale vertical overturning. The alternate possibility is that an organization of convection along the azimuthal coordinate can directly contribute to the growth of azimuthally averaged kinetic energy from the azimuthally averaged available potential energy of the hurricane, and these upscale nonlinear transfers may not prove to be important for the driving of the hurricane scale. A purpose of this paper is to formally compute these interactions among the cloud scales and the hurricane scales toward addressing the hurricane intensity issue from such possibilities (see section 5).

(viii) [left angle bracket]K^sub s^K^sub l^[right angle bracket] is the nonlinear exchange of kinetic energy among different scales. This is another possible exchange of energy among waves. The equation for the kinetic energy exchange among different waves is nonlinear, and also invokes triple products. Thus, two waves from among the long waves can in principle interact with smaller cloud scales to provide nonlinear energy exchanges. These are exchanges among various waves in the azimuthal direction. Here the same trigonometric selection rules apply for these energy exchanges. For the hurricane intensity problem, we might be interested in the growth of kinetic energy of a low wavenumber such as 1 or 2 at the expense of other pairs of azimuthal waves. Triads such as 1, 7, and 8; 1, 8, and 9; 2, 15, and 13; and 2, 12, and 10 are possible examples that satisfy the selection rules. Thus a pair of scales within the dimensions of clouds can in principle transfer energy to the lower wavenumbers that describe a hurricane. This is a direct way by which a cloud scale can drive a hurricane scale. The possibility exists for such energy exchanges to go up- or downscale. A formal computation, presented in section 5, clarifies these issues in the context of the model output.

(ix) [left angle bracket]K^sub o^K^sub l^[right angle bracket] is an exchange of kinetic energy between the azimuthally averaged flows and the long azimuthal wavenumbers. This is akin to the familiar barotropic energy exchange. It invokes the covariance among the azimuthally averaged tangential motion and the eddy convergence of flux of momentum. This can go either way depending on the stabilizing or the destabilizing nature of the shear flows within the hurricane.

(x) [left angle bracket]K^sub o^K^sub l^[right angle bracket] is the same kind of energy as described in (ix) above except that shorter scales replace the azimuthal long waves. The mathematical formulation is the same as for (ix) above.

(xi) [left angle bracket]APE^sub o^APE^sub l^[right angle bracket] is the available potential energy exchange among azimuthally average flows and azimuthal long waves. This is analogous to a wave zonal exchange of available potential energy. The direction of this exchange depends on the radial temperature gradients for wavenumber 0 and the radial transport and convergence of flux of heat (C^sub p^T) by the long waves. The signs of computations dictate whether this heat transfer is up or down the thermal gradient.

(xii) [left angle bracket]APE^sub o^APE^sub s^[right angle bracket] is the available potential energy exchange among azimuthally averaged flows and shorter waves. The mathematical treatment of this exchange is presented in the appendix, and the explanation is the same as (xi) above except that long waves are to be replaced by shorter waves.

All these components of energetics presented in this paper were formulated using quasi-static primitive equations (see the appendix for mathematical details of the formulation).

5. Results of computations

a. Angular momentum budget following inflowing trajectories in the storm-relative frame of reference

In Fig. 9, we illustrate a trajectory of an air parcel constructed using the motion field (u, v, w in storm-relative coordinates, following the method described in Krishnamurti and Bounoua (1995). Also shown are the 850-hPa horizontal wind isopleths for a final map time of 0000 UTC 25 August. This trajectory terminates in the vicinity of the velocity maxima of the hurricane at the 850-hPa level. Based on our forecasts, this parcel originates on 22 August at 0000 UTC from the 336-hPa level. A 3-day motion of the parcel is illustrated here. This parcel generally descends from the upper troposphere to the 850-hPa level.

We next illustrate in Table 2 the angular momentum budget following a parcel's history. This table shows the parcel's positions (as a function of time), the parcel's pressure, the angular momentum (M) of the parcel, the change in angular momentum (ΔM) across 12-hourly parcel motion segments, the contribution from pressure torque experienced over 12-hourly parcel motion segments, the contribution by net frictional torque (excluding cloud torque) experienced by the parcel along these segments, and finally the effects of cloud torque in its contribution (computed as a residual) to the changes of angular momentum of the parcel. The angular momentum change due to the pressure torque was of the order of 10^sup 6^ m^sup 2^ s^sup -1^. The negative values can be related to a beta-gyre-type asymmetry that the parcel encountered to the right of the storm motion where it moved toward higher pressure, ∂z/∂θ > 0. The net change in angular momentum for the inflowing parcel was negative throughout, since the parcel was moving closer to r = 0 for most of the time. The angular momentum change due to frictional torque (excluding the cloud torques) above the 850-hPa surface arises from horizontal and vertical subgrid-scale diffusion in the free atmosphere, while above the 850-hPa level these effects were small. The angular momentum change due to cloud torque was another manifestation of explicit frictional torque resolved by the model (see Fig. 11 for an example of such computation). The values along the trajectory, over all 12-hourly segments, were negative, implying that cloud torque contributed to a net divergence of eddy flux of momentum of the parcel. This acts to reduce the angular momentum for the inflowing parcel. It is also clear from the table that the largest change of the angular momentum (in storm-relative coordinates) arises from the parcel encountering such cloud turbulence.

Explicit friction is that part of the model friction that comes from the parameterization of the surface layer and the planetary boundary layer physics. Furthermore, the model's vertical diffusion of momentum is also included in the computations. These were all explicitly coded within the MM5's formulation. We contrast the resolved cloud friction and cloud frictional torque with the "cloud torque." The frictional torque (-Fθr) was calculated at each level and interpolated onto the space-time segments along the trajectories. The frictional torque largely reflects its contribution to loss of outer angular momentum by the surface friction and its vertical disposition. This is larger as we approach the storm's center where the surface winds were stronger.

The pressure torque in a nonhydrostatic model generally reflects the presence of clouds in the model. The pressure of liquid water (overload) and vertical acceleration contribute to vertical acceleration of the order of 10^sup -4^ to 10^sup -5^ m s^sup -2^ over such regions. Pressure perturbations of the order of 1 hPa were found in the model output over such regions. The pressure field was not entirely radially symmetric but had shown some interesting departures, as can be seen in Fig. 10 where the 3-day forecast of sea level pressure distribution for Hurricane Bonnie from the model run is illustrated. Parcels passing through such regions encounter large pressure torque. Over the entrance and exit regions of such deep convcctive elements the pressure torques tend to be opposite in sign, thus canceling out any net significant contribution. The explicit cloud torque turned out to be a major contributor to the diminution of the outer angular momentum of inflowing parcels. The essential angular momentum of the air at the destination point (at hour 72) was largely influenced by the cloud torque. A net divergence of flux of momentum by the clouds contributed to the negative values of (ΔM^sub CT^) and a net diminution of angular momentum along the segments as noted in the trajectory (Table 2). These explicitly resolved clouds by the mesoscale model reduce the outer angular momentum considerably (by as much as 40%), thus ending up providing an intensity of 45 m s^sup -1^ for the storm's maximum sustained surface winds. These backward trajectories were deliberately constructed from the regions of the strong winds to the storm exterior. We are only showing the history of one parcel here; several such trajectories were in fact constructed that essentially confirmed these same results.

Figures 11a-e illustrate computations relevant to the cloud torque. Here results between hours 48 to 49 of a forecast trajectory are considered. This segment of the 1-h trajectory contains roughly 301 subintervals over which relevant model output data were illustrated. In Fig. 11a we present the vertical velocity along this cloud element. The vertical velocity reached almost 10 m s^sup -1^ near subinterval 100. This is one of the inner deep convective cloud elements of the hurricane. The corresponding values of W'V'^sub θ^ at two vertical levels (500 and 600 hPa) for this cloud segment are shown in Figs. 11b and 11c, respectively. Strong positive values of the vertical eddy flux of momentum were of the order of 30 m^sup 2^ s^sup -1^ with an increase of the eddy flux at the upper level by roughly three units within the cloud. This led to a net divergence of flux of momentum and a measurable cloud torque (negative value) in Fig. 11d. This contributed to a sizeable reduction of the absolute angular momentum along the inflowing trajectory from the cloud-scale turbulence. The largest negative value within the cloud was of the order of -90 m^sup 2^ s^sup -2^. Cloud turbulence also contributed to a smaller net increase, 50 m^sup 2^ s^sup -2^, downstream from the region of maximum ascent. This is just one example of the so-called cloud torque for a single cloud element. The many simulated deep convective cloud elements collectively play an important role in determining the inner angular momentum and thus on the storm's intensity. Figure 11e shows a longer trace along a 3-h trajectory (between hours 48 and 51) of W'V'θ that illustrates the nature of the cloud turbulence in a hurricane model. The mean value of W'V'θ during these 3 h was around +7 m^sup 2^ s^sup -1^, which shows that clouds at this level (600 hPa) contributed to a net upward flux of momentum.

b. Scale interactions

We have formulated the energetics for a quasi-steady system. Since the storm wa s over the ocean, the use of a pressure coordinate was felt quite suitable. The quasistatic components of the datasets were easily derived from the model's earth-following sigma to the pressure coordinate system. We first present the results for these processes that invoke quadratic in-scale energy conversions. All of the results presented here are in storm-centered cylindrical coordinates and are mass integrals between radii r^sub 1^ and r^sub 2^, around the azimuthal coordinate, and between 100 hPa and the earth's surface.

3) ENERGY EXCHANGES DUE TO NONLINEAR TRIAD INTERACTIONS

In Figs. 14a and 14b we show the gain or loss of energy for wavenumbers 1 and 2 for the eddy kinetic energy (Fig. 14a) and eddy available potential energy (Fig. 14b), which arise from interactions of these scales with all other permitted scales. Along the abscissa we show the forecast hours. The results shown here are vertically integrated values through the troposphere over the three different regions, that is, inner, middle, and outer radii bound. The obvious result is a net loss of energy at all radii lor the hurricane scale (wavenumbers 1 and 2) from these scale interactions. The largest losses occurred at hour 72 when the storm had the strongest intensity. The cascade was strongest for wavenumber 1 when it interacts with other permitted scales.

4) SUMMARY OF OVERALL ENERGY EXCHANGES IN THE AZIMUTHAL WAVENUMBER DOMAIN

The overall results of the energy exchanges are summarized in Fig. 15. These are 72-h averages during this entire time Bonnie had hurricane wind strength. These energy exchanges are mass averaged based on the equations given in the appendix. The vertical integrals cover the atmosphere between the ocean surface and the 100-hPa level. Three colors distinguish the results over different radial belts. (All units of energy exchange are normalized to m^sup 2^ s^sup -3^). Three categories of energy exchange are grouped here: (a) azimuthally averaged wavenumber 0, (b) azimuthal long waves, wavenumbers 1 and 2, and (c) azimuthal short waves, wavenumbers 3 to 180. The first two categories are designated as the hurricane scales, and the third one is arbitrarily labeled as the cloud scales (subscript s), although this naming is not entirely correct. This energy diagram is not a complete energy cycle. We have not discussed the dissipation of energy terms here; only the transformation of energy terms is presented in this diagram.

For all of these scales, the generation of available potential energy from heating and the conversion of available potential energy to eddy kinetic energy are described by the in-scale processes. These are interestingly the largest in the inner 40-km radii for wavenumber 0. That reflects the hurricane-scale organization of heating and of the covariances of heating and temperature, and vertical velocity and temperature. This arises from the organization of clouds along azimuthal wavenumber 0. The next in magnitude is contribution for the long waves, where again clearly there is a contribution from the organization of clouds on the azimuthal wavenumbers 1 and 2. The combined contribution for wavenumbers 3 to 180 is less than 10% of those for wavenumber 0. The largest values of the generation of APE and its conversion to EKE occur at the inner radii $0 < r < 40$ km. This is the region of the heaviest rains in the MMS's simulation of Hurricane Bonnie. The values fall off rapidly as we proceed to the outer radial belts.

The barotropic energy exchange comprises kinetic energy exchange from wavenumber 0 to the other waves. The long waves as well as the cloud scales essentially extract energy from the azimuthally averaged wavenumber 0. Among these, some of the largest barotropic energy exchanges are from the wavenumber 0 to the long waves. At the different radial belts these values range from 78.6 to 58.4 to 30.75 m^sup 2^ s^sup -3^ (× 10^sup -6^). This shows that the hurricane scale (azimuthally averaged wavenumber O) is barotropically unstable to the long-wave scales (wavenumbers 1 and 2). Thus we can infer that the large-scale asymmetries in the hurricane's intense winds can arise from barotropic dynamics-that is in addition to the possible translation asymmetry, which arises from the motion of a symmetric vortex in a uniform steering flow. This kinetic energy exchange from the wavenumber O to the long wave is largest in the inner radial belt from O to 40 km where the maxima of the cyclonic vorticity of the hurricane reside.

The other areas of energy exchange are the kinetic to kinetic and available potential-to-available potential. These are the nonlinear three-component exchanges among different scales. The arrows connecting K^sub t^ to K^sub s^ and APE^sub l^ to APE^sub s^ show the collective exchanges from the long- to the short-wave scales summarized here. This is essentially a cascading process where energy is conveyed from the larger to the smaller scales. The kinetic energy exchange K^sub l^ to K^sub s^ is much larger in magnitude compared to those of P^sub l^ to P^sub s^. The inner radial belt $0 < r < 40$ km carries the largest nonlinear energy transfers. There are also available potential energy exchanges between the azimuthally averaged wavenumber 0 and the waves. Those exchanges are all directed from waves to the wavenumber 0. The largest such exchanges are at the inner radii $0 \le r \le 40$ km. The magnitude of the energy transferred by the long waves are larger compared to that from the short waves to the zonal. These exchanges are related to the radial transfer of heat (up the gradient) toward wavenumber 0. The longer waves seem more efficient in reinforcing the warm core of the hurricane in this sense. This is the overall energy exchange scenario from the very high resolution simulation of Hurricane Bonnie of 1998.

6. Concluding remarks and future work

The hurricane intensity issue is among the major unsolved scientific problems presently. This paper presents two possible frameworks-scale interactions among clouds and hurricane and an angular momentum perspective for this problem. The deep convective elements within a hurricane have dimension of the order of a few kilometers each. The role of cloud-scale heating, generation of available potential energy, and its transformation to eddy kinetic energy can only be an in-scale (i.e., individual cloud scale) process since these processes involve quadratic nonlinearities. The quadratic nonlinearities are the covariances among heating and temperature, and vertical velocity and temperature. Hence, the only avenue for that energy to drive the hurricane would be through nonlinear triad interactions between kinetic and kinetic energy, and available potential to available potential energy among cloud scales and the hurricane scale. That naïve picture is not what is borne out by the computations based on datasets derived from mesoscale nonhydrostatic microphysical models. The key finding is the organization of convection on the azimuthally averaged wavenumber 0 and the large-scale asymmetric scales of the hurricane; that is, wavcnumbcrs 1 and 2 precede all that. Those scales are inferred from the decomposition of the liquid water mixing ratio fields that carry clearly the deep convective cloud signatures. The generation of available potential energy and its transformation to kinetic energy thus takes place directly on the larger scales of the hurricane. This is brought about by the organization of convection-a topic that is not addressed in this paper. The other major component in the framework of scale interactions is the energy exchanges among scales via triad interactions. These are the exchanges from kinetic to kinetic and available potential to available potential energies. Those results among a triplet of waves (hurricane scales and other scales) show largely a cascade of energy; that is, hurricane scales lose energy when they interact with other scales. The issue of organization of convection can be addressed by starting from an unorganized prehurricane state and by a continual monitoring of the spectral form of the liquid water mixing ratio and its interactions with the rest of the dynamics, physics, and microphysics. Such a study can provide insights on the scale interactions that lead to an organization of convection. This study required a highresolution (up to 1 km) multiple-nested regional mesoscale model that resolves clouds explicitly. A recent version of the PSU-NCAR Mesoscale Model (nonhydrostatic with microphysics) was used in this study.

A second aspect of this study was on the angular momentum perspective, on the torques that diminish the angular momentum along inflowing trajectories of air parcels. They reveal that "cloud torques" play a major role in this diminution of outer angular momentum and in the eventual intensity of the hurricane that it attains. The important role of cloud torques along segments of the entire trajectory of a parcel with maximum storm wind suggests that improved microphysical parameterizations may have an important role on the final intensity of a predicted storm. Since all of these findings are based on model output datasets, future studies on model sensitivity are needed on areas that impact the intensity the most. These are the vertical overturnings by organized convection and the cloud torques. This suggests that even details of microphysical parameterizations within clouds might require careful testing within these explicitly cloud resolving mesoscale models. Clearly, carefully designed numerical experiments are needed to sort out these outer and inner thrust issues in their correct perspectives for addressing the sensitivity of hurricane intensity to various parameters. Most likely, these issues are intercoupled. Field experiments that carry out detailed measurements of microphysical parameters that affect the life cycle of clouds may also provide insights for model sensitivity studies. Understanding of hurricane intensity may require a rather large series of model sensitivity studies on resolution (horizontal and vertical), data coverage, data assimilation, nonconvective rain (definition of threshold relative humidity), PBL physics, radiative transfer and clouds, and parameterizations within the equations of water vapor, cloud water, rainwater, cloud ice, snow, graupel, and number concentrations of cloud ice.

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