Interaction Of Hurricane And Cloud Scales: Contribution To Hurricane Intensity

L. Stefanova, T.N. Krishnamurti, and S. Pattnaik,
Dept. of Meteorology, Florida State University

Abstract

The kinetic energy budget of hurricanes' asymmetry is calculated using scale interaction approach. MM5 simulations of hurricanes Charley of 2004 and Katrina of 2005 are used to diagnose the kinetic energy interactions involving azimuthal wave numbers one and two, which represent the dominant asymmetries. We find that the wave-mean kinetic energy interactions and the potential to kinetic energy conversions are the dominant processes affecting the kinetic energy at wave numbers one and two. In an area-averaged sense the wave-mean interactions prevail. The wave-wave interactions are found to be large only in localized regions but their area-averaged contribution is found to be small. There appears to be a relationship between the kinetic energy tendency of wave numbers one and two and the hurricanes' intensification, particularly in the case of Katrina, which was a significantly stronger and larger storm with a much better defined asymmetric component.

1. Introduction

The overwhelming amount of kinetic energy of tropical cyclones is contained within the azimuthal mean, followed by the kinetic energy of the asymmetric flow components largely contained at azimuthal wave numbers one and two. The energetics of the asymmetric flow is relevant to the hurricane intensity issue. In an intense hurricane the superposition of azimuthal wave numbers one and two and the mean flow can define the strongest winds in a hurricane. The present study concerns the changes of kinetic energy of the asymmetric part of the circulation in rapidly intensifying hurricanes on the example of hurricanes Charley of 2004 and Katrina of 2005. We have used the Pennsylvania State University (PSU)-National Center Atmospheric Research (NCAR) fifth generation state of the art mesoscale model MM5 (Dudhia 1993; Grell et al. 1995) to produce somewhat reasonable short-term forecast at high resolution during the rapid intensification phase of each storm. The MM5 is a non-hydrostatic, fully non-linear, terrain following sigma coordinate mesoscale model which has well demonstrated its ability to simulate hurricane at cloud resolving scale by several researchers (Liu et al 1997, 1999). For the present study we have integrated the model within a triply nested (27km, 9km and 3km for the simulation of Charley, and 18km, 6km and 2km for the simulation of Katrina) grid and in a two way interactive manner .The finest model grid domain is designed with an intention to better resolve the inner core of the hurricane. All required fields are cast into storm-centered cylindrical coordinates. The scale interaction approach, pioneered by Saltzman (1957), is used to diagnose the wave-wave and wave-mean interactions within the storms' interior. Calculations are performed only at those times during which the simulated storm is entirely within the finest nested grid. We had previously examined the salient energy transformations of a mature hurricane (Krishnamurti et al, 2005) using the scale interaction approach. In that study we found that the generation of available potential energy from the covariance of heating and temperature was principally contributed at the low wave numbers (i.e., zero, one and two). At these same scales, vertical overturning contributed to a generation of kinetic energy, explaining the storm's intensity. The smaller azimuthal scales contributed to a cascade of kinetic energy away from the hurricane scales. A motivation for the present study was to ask whether that picture was in any way altered when we examine intense hurricanes during their phase of rapid intensification.

The totality of scale interactions carries exchanges between heat sources and sinks, the available potential energy, and the kinetic energy for all spatial scales. The problem involves quadratic non-linearities representing in-scale processes, such as the generation of available potential energy from the heating and conversion of potential to kinetic energy, as well as triple product non-linearities representing wave-wave interactions for both the potential and the kinetic energy among different scales.

In this study the focus is on the kinetic energy at wave numbers one and two, representing the asymmetric component of the flow within a hurricane. The kinetic energy of the asymmetries can change due to a) interactions with the azimuthal mean flow; b) conversions between the potential energy of the asymmetric flow and the kinetic energy of the asymmetric flow; c) wave-wave interactions involving both components of the asymmetry (i.e. wave numbers one and two), d) wave-wave interactions involving energy transfers between the asymmetries and smaller scales, and e) dissipation of kinetic energy due to friction. The spatial scale of the symmetric and asymmetric components of a hurricane's circulation is on the order of several hundreds of kilometers. In contrast, the individual cloud scales are on the order of a few kilometers. The clouds however are organized on the scale of the hurricane, i.e., at azimuthal wave numbers zero, one and two. This is evidenced by an azimuthal spectral analysis of fields such as the model rainwater mixing ratio.

2. Results: Charley

In spectral space, the forecast-derived kinetic energy of Charley is primarily contained at azimuthal wave numbers zero, one and two. The area of maximum winds is between approximately 20 and 60 km away from the storm center. The maximal kinetic energy is found between 06 and 09 Z on 13 August. The principal asymmetries of Charley are relatively weak and not confined to the inner radii. The kinetic energy of wave numbers one and two is generally largest below 500 mb and is strongest outwards of the 20 km radius. At higher wave numbers attributable to cloud-scale motion there is an area of cloud-scale kinetic energy maximum in the eye wall – at about 20 km radius away from the storm center and some additional broadly distributed maxima towards the outer radii. Of course, the kinetic energy contained in the cloud scales at all times is significantly smaller than that contained at wave numbers one and two, which in turn is smaller than that contained at wave number zero. In terms of vertical velocity, wave numbers zero, one and two show activity generally between the 20 and 60 km radii, while the cloud scales show strong vertical velocities at all radii, and with larger magnitudes. The distribution of temperatures at azimuthal wave numbers one and two shows strong amplitudes near the eye wall, particularly between 700 and 400 mb.

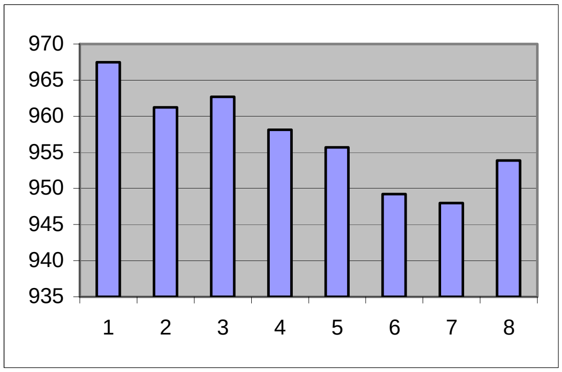
The energy exchanges affecting the kinetic energy of the storm asymmetry are the main focus of this study. Following the non-linear energy exchange framework, the kinetic energy at a given wave number can be changed due to: quadratic kinetic energy interactions with the azimuthal mean; wave-wave interactions involving just the asymmetries themselves; wave-wave interactions between the asymmetries and the cloud scales; in-scale potential to kinetic energy conversions; in-scale frictional dissipation. The latter term is not calculated in this study.

We find that at the scale of the asymmetric motion the dominant term in the kinetic energy tendency is the wave-mean interaction. This exchange is dominated by the barotropic terms. The wave-mean interactions are most intense in the area of maximum winds, which is roughly between 20 and 60 km away from the storm center. The region in which the most active interactions occur tilts outward with height. The kinetic energy wave-mean interactions are predominantly positive valued, indicating gain of kinetic energy at the scale of the principal asymmetries.

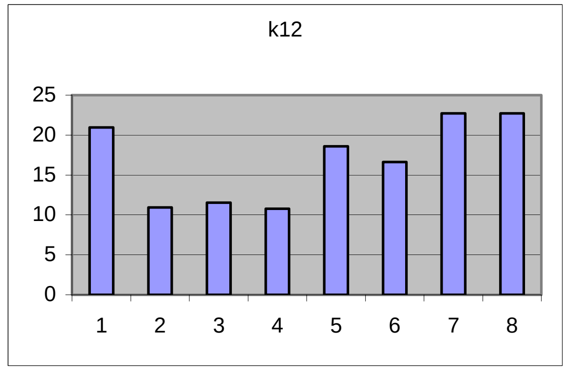
The second most important term is the in-scale potential to kinetic energy conversion. It manifests as areas of both positive and negative contributions. There is generally a dipole structure near the eye wall, with the inner part carrying a negative sign, and the outer part carrying a positive sign. The area of positive contribution to the kinetic energy is generally strongest before the storm's maximum intensification. The next by order of importance term in the kinetic energy budget is the wave-wave kinetic energy interaction. It has to be pointed out that this term only vanishes when integrated over a closed domain but is not zero locally. Most vigorous interactions are found in the same area, 20-60km radii. The kinetic energy interaction of the asymmetries the with cloud scales is smaller than the preceding terms by an order of magnitude. The sign of these interactions is mostly negative, indicating loss of energy to the cloud scales, and the exchanges are smaller than the rest by an order of magnitude.

The forecast central pressure for Charley is shown in Fig 1a. The horizontal axis indicates the forecast time in three hourly intervals starting at 21Z on 12 August 2004 until 15Z on 13 August 2004. Fig. 1b shows the 20-60 km radii (strongest winds region) volume-averaged kinetic energy contained at wave numbers one and two as a function of forecast time. The kinetic energy of the principal asymmetries tends to be inversely related to the central pressure, i.e., the asymmetries are strongest when the storm is most intense. The contribution of the calculated energy exchanges to the tendency of the asymmetries' kinetic energy, also volume-averaged between 20 and 60 km radii, is shown in Fig. 1c. The contribution of the interactions with the mean to the kinetic energy of azimuthal wave numbers one and two (labeled as k0k12) is the leading term, followed by the contribution from potential to kinetic energy conversions (labeled as p12k12). It has to be pointed out that the contribution of the potential to kinetic energy conversions can, locally, be as large or larger than the wave-mean kinetic energy interaction, but because of its dipole structure its volume-averaged contribution is smaller. The net wave number one and two kinetic energy tendency seems to correlate well with the overall intensity of the storm.

a)



b)



c)

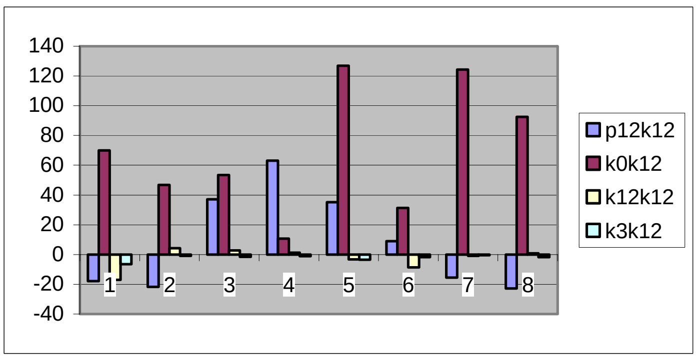


Fig. 1: Time series of the forecast a) central pressure (mb), b) vertically and radially (20-60km) averaged kinetic energy contained in the asymmetry (m^2s^{-2}) and c) vertically and radially (20-60km) averaged contributions to the kinetic energy tendency of the asymmetry ($10^4m^2s^{-3}$) for the eight forecast times, at three hour intervals.

3. Results: Katrina

Katrina was a significantly stronger and larger-sized storm compared to Charley, with a much lower central pressure and stronger winds at all forecast times. Compared to the simulation of Charley, the simulation of Katrina has a much more pronounced asymmetric component, mainly concentrated in the region of the eye wall. The kinetic energy contained in the cloud scales is also larger than that in Charley and is more broadly spread out. In terms of vertical velocities, as expected, the cloud scales account for the majority of variance.

As with Charley, the dominant term in the kinetic energy tendency comes from the interaction with the azimuthal mean. Not surprisingly, the magnitude of the interactions is significantly stronger for Katrina. The interactions with the mean are strongest between about 20 and 80 kilometers away from the center. Their sign is predominantly positive, indicating a gain of kinetic energy at the scale of the asymmetries. The second leading term in the kinetic energy tendency is again the in-scale potential to kinetic energy conversion. It again has a dipole structure, with a negative sign (indicating loss of kinetic energy) inwards of about 40 km radius, and a positive sign (indicating kinetic energy gain) from 40 km outward. Third in importance is the wave-wave interaction term involving only the asymmetries. This term tends to have a positive contribution inwards of 20 km, a negative contribution between about 20 and 30km, and a positive contribution between 20 and 40 km.

Compared to Charley, the interaction of the asymmetries with the cloud scales is stronger for Katrina, but it is still the smallest term in the kinetic energy budget of wave numbers one and two. The interactions are mainly in the 20-60 km band, and have a predominantly negative sign, indicating loss of energy to the cloud scales. Time series of the forecast central pressure, the magnitude of the kinetic energy of wave numbers one and two, and the different components of the kinetic energy budget of wave numbers one and two are shown in Figure 1a,b,c for the forecast of Katrina, in three hourly intervals starting at 12Z on 28 August 2005 until 21Z on 29 August 2005. Here again it is seen that the amplitude of the asymmetries is related to the storm intensity, and that the tendency of the asymmetries' kinetic energy is related to the storm intensification. The magnitudes of both the kinetic energy and the kinetic energy exchanges for the asymmetries are substantially larger in the forecast of Katrina compared to the forecast of Charley. The dominant term in the exchanges is still the wave-mean kinetic energy interaction. Its amplitude tends to be well correlated to the intensification of the storm. Due to the strong dipole structure of the term, area averaging squashes the contribution of the potential-to-kinetic energy exchange. The area averaged contribution of wave-wave interaction of wave numbers one and two, while smaller in magnitude, does display a positive contribution to the net tendency of the kinetic energy.

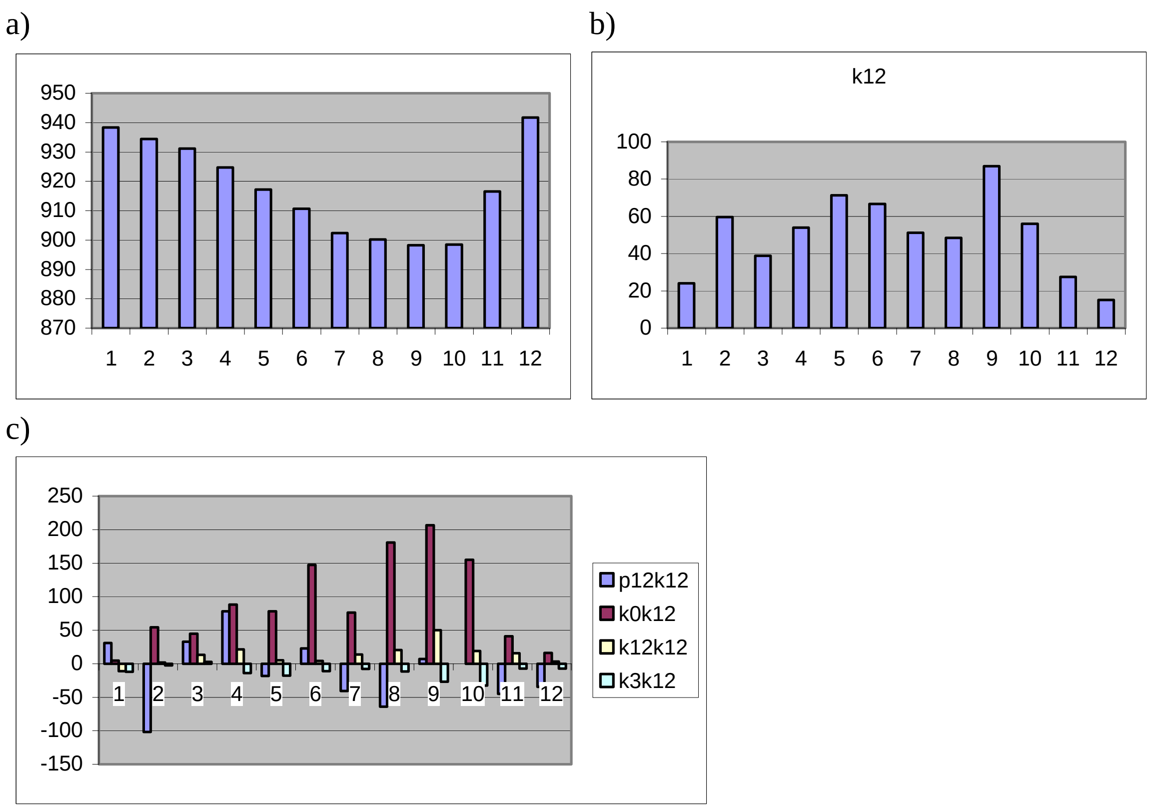


Fig. 2: As in Fig. 1, except for the twelve forecast times for Katrina

4. Summary and Conclusions

The largest contribution to the growth of kinetic energy at the scale of azimuthal wave numbers one and two appears in the wave-mean interaction via barotropic instability of the azimuthally averaged hurricane flow. This raises the question of where does the azimuthally averaged hurricane itself derive its kinetic energy. The answer to this would most likely be related to the Hadley-type vertical overturning resulting in the conversion of potential to kinetic energy at wave number zero. That in turn requires the generation of potential energy at the scale of wave number zero, which would have to come from the azimuthally averaged heating and its correlation with the thermal field. The second largest contribution to the kinetic energy at wave numbers one and two comes from in-scale potential to kinetic energy conversions. This contribution is generally negative in the innermost radii of the storm, and positive further out. The wave-wave interaction between wave numbers one and two can be relatively strong in narrow regions in the area of the eye wall but the area-averaged effect of the wave-wave interaction term is relatively small. Interaction with cloud scales generally leads to loss of kinetic energy for the scale of wave numbers one and two.

The majority of the hurricane scale interactions appear to be happening on the larger azimuthal scales. Disorganized clouds do not seem to play a major role for the hurricane scale motions. This suggests that data sets describing the larger scales may be adequate for studying the mechanisms of intensity change. It appears that the starting point for these scale interactions is the organized clouds on the large scales. That most likely occurs through initial dynamical processes during the storm genesis. Thereafter the mutual interactions among the azimuthal wave numbers zero, one and two seem to be the major components of the kinetic energy budget. This is fortunate because some of the essence of these findings can perhaps be highlighted from a selected single level reconnaissance flight data set. It should be possible to examine these major components of scale interactions from a large sample of gridded flight level data sets. Such an enquiry may provide some short-range outlooks for possible storm intensification or weakening.

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