

Tropical Cyclone Structure And Intensity Change

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LONG-TERM GOALS

The long-term goals of our research are to understand the interactions between tropical cyclones and their surroundings, and how such interactions influence tropical cyclone structure and intensity.

OBJECTIVES

The primary objective of this proposal was to understand the interactions of upper tropospheric potential vorticity centers and tropical cyclones, and to develop a "path to operations" that will allow prediction of tropical cyclone intensity change during such interactions. This objective is an extension of our previous ONR-funded work.

The second objective was to understand the mechanisms behind the clustering of tropical cyclone occurrence in time, with the ultimate goal of predicting the presence of multiple tropical cyclones in advance. This represents a new initiative. Early studies have been for the eastern Pacific Ocean, but are now being extended to the western Pacific.

APPROACH

The first objective has been approached by observational studies using gridded analyses from the European Centre for Medium Range Weather Forecasting, and by numerical simulations of the tropical cyclone outflow layer during trough interactions. Individual case studies have been successful in the past. We are now carrying out broader studies of multiple storms in the Atlantic Basin over a 12-year period in order to define the range of behaviors of tropical cyclones during trough interactions, and to develop methods for intensity prediction during such episodes.

The second objective has made use of gridded analyses from ECMWF and gridded analyses of outgoing longwave radiation (OLR). Both have been low-pass and band-pass filtered where appropriate.

Graduate students Anantha Aiyyer, Deborah Hanley, and Michael Dickinson and research associates David Vollaro and Steven Skubis have worked on various aspects of the problem. Anantha shared the

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prize for best student paper at the 22nd Conference on Hurricanes and Tropical Meteorology sponsored by the American Meteorological Society.

WORK COMPLETED

The first five pieces of work discussed below relate to studies of tropical cyclone-trough interactions. M.S. student Anantha Aiyyer has just completed his thesis (Aiyyer, 1998) on the outflow layer modelling. The model has been applied to several idealized cases of tropical cyclones interacting with upper potential vorticity anomalies, as well as two real-data cases.

A study of Hurricane Danny of 1985, which intensified during a trough interaction just before landfall, was completed and published in the *Journal of the Atmospheric Sciences*. A study of the potential vorticity interpretation of the interaction of Hurricane Elena (1985) with a midlatitude mobile trough was published in *Journal of the Atmospheric Sciences*.

PhD student Debbie Hanley has constructed a number of tropical cyclone-centered composites of various fields (Hanley, 1999) during trough interactions and in the absence of trough interactions (for comparison): (i) favorable (meaning the tropical cyclone intensifies during interaction) superposition cases; (ii) favorable "distant interaction" (i.e., non-superposition) cases, where the upper trough did not approach to within 500 km of the tropical cyclone, (iii) favorable extratropical transition; (iv) favorable no trough (intensification when no upper PV anomaly was present); (v) unfavorable no trough; and (vi) unfavorable with trough.

A paper entitled "Environmental influences on the rapid intensification of Hurricane Opal (1995) over the Gulf of Mexico" was submitted to *Monthly Weather Review*. This work describes the influences of a trough interaction, a warm eddy in the ocean, and internal dynamics during the intensification and weakening of Hurricane Opal.

The remaining pieces of work relate to the clustering of tropical cyclones and related large scale influences. PhD student Michael Dickinson has enlarged our Caribbean PV gradient sign reversal studies to include a 10-year climatology of the entire globe combined with a 10-year climatology of outgoing longwave radiation (OLR). This will be presented at the next Conference on Hurricanes and Tropical Meteorology (Dickinson, 1999). Mike has also completed a study of the life cycle of the meridional gradient of potential vorticity in the western Pacific during the TOGA/COARE experiment.

The paper "Potential vorticity, easterly waves, and eastern Pacific tropical cyclogenesis", by Molinari, Knight, Dickinson, Vollaro, and Skubis, appeared in the *Monthly Weather Review*.

A paper entitled "Origins and mechanisms of eastern Pacific tropical cyclogenesis: A case study" has been completed and submitted to *Monthly Weather Review*. This work describes the large-scale influences on the genesis of Hurricane Hernan (1996) in the eastern Pacific.

RESULTS

The tropical cyclone outflow layer simulations showed that a critical factor during tropical cyclone-trough interactions is the intensity of convection in the underlying storm. The tropical cyclone was represented in the model by mass and momentum sources. When the source terms were included, the upper potential vorticity (hereafter PV) anomaly did not cross the center, and the potential vorticity

gradient between the tropical cyclone and the PV anomaly was much larger. The result was a much stronger forcing of radial-vertical circulations. Physically, this result occurs both because convection behaves like a source of low PV and because the divergent flow with the convection advects this low PV outward. The combined effect is to prolong and intensify the interaction. We conclude that when a tropical cyclone moves over cold water, so that the convection no longer reaches the outflow layer, trough interactions are much more likely to weaken the tropical cyclone. This is indeed observed.

The Hurricane Danny (1985) case showed that the PV superposition principle described earlier (Molinari et al., 1995) also held for a weak tropical storm encountering a localized upper trough, much like a "TUTT" cell. As in our earlier Hurricane Elena case (Molinari et al, 1995) and our tropical cyclone outflow layer simulations described above, the upper positive potential vorticity anomaly never crossed the tropical cyclone center and reversed the deepening process. In both cases, the upper potential vorticity anomaly that reached the tropical cyclone core was comparable in scale to the tropical cyclone. We believe this scale matching is a critical aspect of favorable interactions. We concluded that the superposition process and the related variation of diabatic heating represented a useful conceptual foundation for understanding the intensification of tropical cyclones during trough interactions.

The composites during trough interactions have shown that relatively small scale, shallow upper PV anomalies are much more likely to produce tropical cyclone intensification than large, deep anomalies. This result is consistent with PV inversion reasoning and with our previous case studies. The "distant interaction" cases show the tropical cyclone embedded in the entrance region of an upper jet streak. Intensification appears to occur as a result of the superposition of upward motion associated with the jet over the storm.

The Hurricane Opal paper results provided support for our previous theories, and extended them to include the influence of sea surface temperature variations and inner core response to the upper tropospheric trough. Opal was found to have deepened rapidly as the upper tropospheric divergence field associated with the trough approached the incipient tropical cyclone core. The "warm eddy" in the waters of the Gulf of Mexico contributed, but only after the favorable trough interaction had begun. When the trough axis itself approached the core of Hurricane Opal, the tropical cyclone weakened. This represented an unfavorable trough interaction brought about because the scale of the trough was much larger than that of the tropical cyclone, and thus contained very large vertical wind shear.

The global climatology shows that meridional PV gradient sign reversals are amazingly common in the tropics. Some are geographically fixed by land and ocean, while others (in the Pacific, for instance) occur with the intra-seasonal oscillation, and thus have a broad rather than localized favored region. Surprisingly, the oceanic ITCZ is not in general a favored region for such sign reversals. We are now comparing the results to a global climatology of easterly wave and tropical cyclone frequency.

During the TOGA/COARE period, Mike Dickinson found a life cycle in the meridional PV gradient sign reversal as the Madden-Julian Oscillation went through its life cycle. Over a three-week period, low-pass filtered PV first increased northward monotonically, then developed a kink and eventually a sign reversal at the latitude of strongest meridional gradient of OLR. Then the OLR gradient weakened as the heating weakened and spread poleward, and the sign reversal vanished. We speculate (still unproven) that lateral PV mixing by eddies played a major role in this cycle. Mike will be examining the band-passed power in the higher-frequency modes to see whether waves were generated preferentially during the period of sign reversal, and whether tropical cyclone frequency was also

related to previous PV gradient sign reversals. We are optimistic that this work will shed some light on the possible relationship between PV gradient sign reversals, easterly waves, and the clustering of tropical cyclones in time.

The paper "Potential vorticity, easterly waves, and eastern Pacific tropical cyclogenesis" gave a specific application of the above study. It showed a remarkable correlation between the strength of the negative potential vorticity gradient in the Caribbean and subsequent occurrence of tropical cyclones in the eastern Pacific. The meridional PV gradient, convective heating measured by outgoing longwave radiation data, and eastern Pacific cyclone occurrence all varied on the time scale of the Madden-Julian oscillation. It was hypothesized that upstream wave growth in the dynamically unstable region provided the connection between the MJO (or any other convective forcing) and the associated enhanced downstream tropical cyclone frequency. We are extending these results to other basins.

The paper "Origins and mechanisms of eastern Pacific tropical cyclogenesis: A case study" found that Hurricane Hernan (1996) developed in association with a wave in the easterlies that could be tracked back to Africa. It was found that a dynamically unstable background state accompanied the development of Hernan. Intriguingly, a westerly surge in the wind field preceded the development of Hernan. This surge appeared to be similar in time and space scales to those described in the western Pacific. The surge was associated with a northward shift in the monsoon trough. The results of this paper should have application in the western Pacific, where cyclogenesis also occurs in the presence of a monsoon trough.

IMPACT/APPLICATIONS

The tropical cyclone-trough interaction studies have great potential for development of operational criteria for prediction of tropical cyclone intensity during such interactions. This remains one of the major goals of our studies. We believe the single most important variable in whether a trough interaction will produce deepening of a tropical cyclone is the horizontal scale of the trough: a large trough contains too much vertical shear and is unfavorable; a small-scale trough (300-400 km in diameter) allows a favorable superposition between the two positive potential vorticity anomalies (trough and tropical cyclone).

The studies of clustering of tropical cyclones could turn out to be useful for longer-range prediction of tropical cyclone occurrence. The eastern Pacific studies should have application to other basins, particularly the western Pacific and Australia, that have monsoon troughs.

TRANSITIONS

The studies on trough interactions have implications for the operational prediction of tropical cyclone intensity, which remains in its infancy. The software that has been developed as part of this effort on tropical cyclone-trough interactions has been sent on request to two other groups of researchers to aid in their studies of tropical cyclone intensity change.

RELATED RPROJECTS

We are conducting a study under NSF support of easterly wave dynamics in the Atlantic. In concert with Professor Bosart of my department, I am working on hurricane-trough interactions and

precipitation after landfall as part of the US Weather Research Project. Lance Bosart, Peter Black of NOAA/HRD, Chris Velden of the University of Wisconsin, PhD student Edward Bracken of SUNYA, and I collaborated on a study of the unexpected intensification and later weakening of Hurricane Opal as it approached the Gulf coast.

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IN-HOUSE/OUT-OF-HOUSE RATIOS

All of the work is done at the University at Albany, State University of New York.