Tropical Cyclone Structure And Intensity Change

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LONG-TERM GOALS

The long-term goals of our research are to understand the nature of the interactions between tropical cyclones and their surroundings, and the impact of these interactions on tropical cyclone intensity.

OBJECTIVES

The primary objectives are: (i) To evaluate tropical cyclone intensity change during interactions with upper tropospheric troughs, and to develop some rules to govern prediction of such intensity change; and (ii) To study the outbreaks of multiple tropical cyclones in the Western Pacific Ocean to understand what large-scale characteristics are associated with these outbreaks. The first of these is an extension of previous work under ONR support, while the second represents our first concentration on Western Pacific tropical cyclones.

APPROACH

The first objective has been approached by two types of observational studies using gridded analyses from the European Centre for Medium Range Weather Forecasting (ECMWF): individual case studies and composite studies. The second objective has made use of time filtering of both ECMWF gridded analyses and outgoing longwave radiation (OLR) data.

Graduate students Anantha Aiyyer, Deborah Hanley, and Michael Dickinson and research associate David Vollaro have worked on various aspects of the project.

WORK COMPLETED

The first two pieces of work discussed below relate to studies of tropical cyclone-trough interactions. Debbie Hanley completed her PhD entitled "The Effect of Trough Interactions on Tropical Cyclone Intensity Change". This was presented in last year's report and will not be discussed here.

A paper was submitted titled "A composite study of the interactions between tropical cyclones and upper-tropospheric troughs", by former PhD student Debbie Hanley, Molinari, and Daniel Keyser. It is currently under review.

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A paper entitled "Environmental Influences on the Rapid Intensification of Hurricane Opal (1995) over the Gulf of Mexico" appeared in the February 2000 *Monthly Weather Review*.

The remaining pieces of work relate to the generation of tropical cyclones and related large scale influences. A paper by PhD student Michael Dickinson and Molinari was accepted *by Monthly Weather Review*, entitled "Climatology of Sign Reversals of the Meridional Potential Vorticity Gradient over Africa and Australia". Dickinson also completed a study of sequential development of three Western Pacific tropical cyclones that will be submitted for publication in Fall 2000.

A paper entitled "Origins and Mechanisms of Eastern Pacific Tropical Cyclogenesis: A Case Study" appeared in the January 2000 *Monthly Weather Review*. A paper "Planetary and Synoptic Scale Influences on Eastern Pacific Tropical Cyclogenesis" was accepted by *Monthly Weather Review* and will appear in the September 2000 issue.

RESULTS

In the paper "The Effect of Trough Interactions on Tropical Cyclone Intensity Change", several insights were gained into tropical cyclone-trough interactions by studying a large number of storms that occurred over a 12-year period. More than two thirds of tropical cyclones over warm water were found to intensify during trough interactions. We consider this an important finding, because forecasts often reflect a likelihood of weakening under such circumstances. It was found that a threshold value of vertical wind shear (beyond which deepening would not occur) was approximately 12 ms^{-1} when a trough was approaching a tropical cyclone, but only 7 ms^{-1} when no trough was present. The approach of an upper tropospheric trough creates a positive influence, favorable in-up-out circulation organized by potential vorticity dynamics, and a negative influence, increased vertical wind shear. The former allows tropical cyclones to better resist the latter during trough interactions. We believe the major factor in whether or not a tropical cyclone will intensify during a trough interaction relates to the scale of the trough: large and/or deep troughs produce strong upper tropospheric winds, and thus vertical wind shear, far out ahead of the trough. As a result, tropical cyclones experience vertical wind shear for a longer period, and are much more likely to weaken before favorable potential vorticity interactions can occur. Conversely, small, shallow troughs are most favorable. One complication arises in the application of these concepts to storms in real time: a large-scale trough can fracture, with only a shallow, weak potential vorticity anomaly actually interacting with the storm. This trough fracturing resembles the "equatorward wave breaking" of Thorncroft et al. (1993).

The Hurricane Opal paper extended the study of trough interactions to include the influence of sea surface temperature variations and inner core response to the upper tropospheric trough. Opal deepened more rapidly than any previous Atlantic basin storm, then filled equally rapidly; neither was well forecast. We found that deepening followed the approach of the upper tropospheric divergence field associated with the trough to the center of the storm. The "warm eddy" in the waters of the Gulf of Mexico contributed to deepening, 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 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. A dynamically unstable background state accompanied the growth of the wave, which crossed central America at levels just above the mountain tops. A tropical depression formed underneath the wave just west of the Gulf of Tehuantepec. The results provide strong support in this case study for an African origin to eastern Pacific disturbances; development in the eastern Pacific clearly occurred in association with this wave from upstream.

The paper "Planetary and Synoptic Scale Influences on Eastern Pacific Tropical Cyclogenesis" addressed the role of the Madden-Julian Oscillation (MJO) on eastern Pacific tropical cyclone frequency during the 1991 season. It was shown that 12 of 13 tropical cyclones formed during the active MJO. During each active MJO period, storms tended to form first to the east and south, then progressively further westward and northward with time. The results showed that cyclogenesis occurred when easterly waves from upstream passed through the convectively active phase of the MJO. Waves were present in equal numbers, but did not develop, during the inactive MJO phase. The ITCZ shifted northward during the active MJO, and every eastern Pacific storm developed on the ITCZ. The results thus presented a unified picture of the MJO, the ITCZ, and the upstream easterly waves in producing the observed tropical cyclone distribution in the eastern Pacific.

The paper "Climatology of Sign Reversals of the Meridional Potential Vorticity Gradient over Africa and Australia" examined waves in the easterlies that are tropical cyclone pre-cursors, and the creation of sign reversals of the meridional potential vorticity gradient associated with the generation of such waves. Sign reversals were present in Australia for the same reason as in Africa: the existence of desert poleward of warm equatorial ocean. The combination created potential vorticity sources and sinks that produced the unstable basic state associated with the sign reversal. Surprisingly, evidence for easterly waves was lacking in the Australian region. It was suggested that the 3000 km length of the unstable region in Australia (vs. more than 5000 km in Africa) was insufficient to allow time for easterly wave generation. It appears that the strength of the sign reversal in Australia will not have application to predicting outbreaks of multiple tropical cyclones.

The major effort in this and upcoming years will relate to the work PhD student Michael Dickinson has begun on tropical cyclones in the Western Pacific. The major findings of this work thus far are (i) Mixed Rossby gravity waves from the central Pacific are often pre-cursors to multiple storms in the Western Pacific; (ii) Such events occur almost exclusively during the active period of the MJO; and (iii) Such events occur where Rossby-gravity waves meet the eastern end of the monsoon trough, where multiple formations are known to occur. The significance of this work is that it identifies what we believe is a major formation mechanism in the Western Pacific, and it integrates several phenomena: MJO, monsoon trough, equatorial waves, and the genesis of tropical cyclones.

Figures 1 and 2 next page show two synoptic maps from the three-week period of this study. The wind vectors represent the mixed Rossby-gravity wave packet, which shows as a train of clockwise and counterclockwise vortices. These plots are generated using a 6-10 day bandpass filter of the wind field. The shading in Figures 1-2 represents the *lowpass*-filtered OLR (varying on scales greater than 20 days) associated with the MJO. The individual highs and lows clearly follow the MJO envelope, and a sequence of three tropical cyclones forms (including one in each figure below) over a three-week period. Other calculations and figures (not shown) indicate that a mixed Rossby-gravity wave packet moves slowly eastward as the disturbances within it move westward; tropical cyclones form about once every eight days, as each cyclonic eddy within the packet reaches its maximum intensity. The sequence keeps occurring until the background MJO moves away to the east.

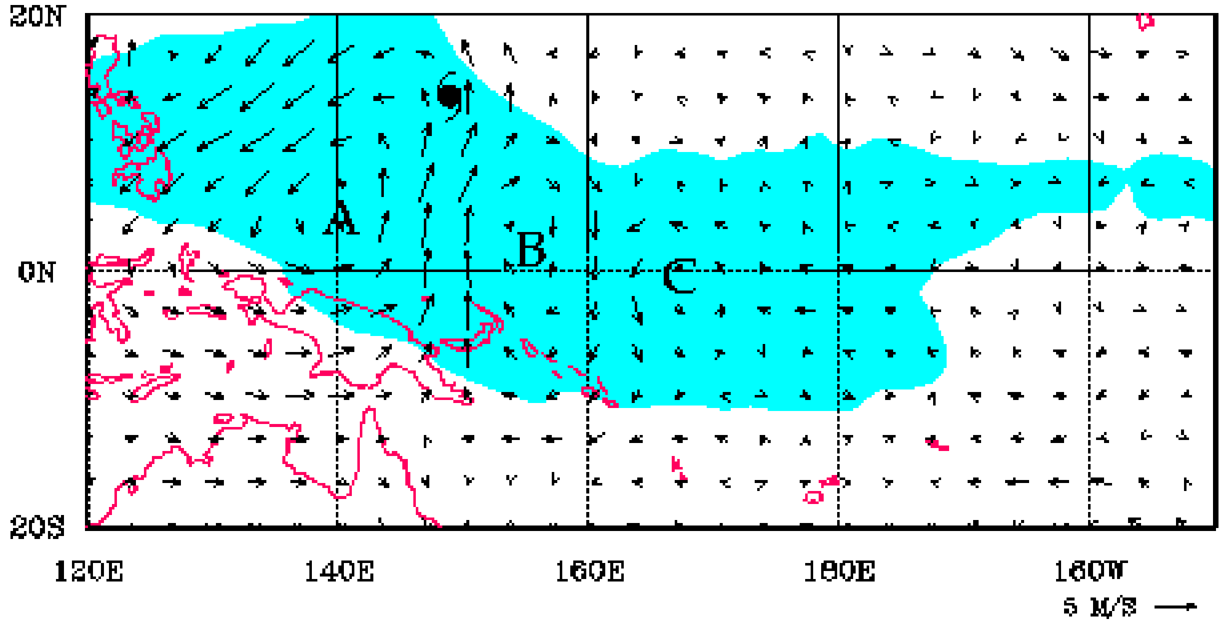

FIGURE 1

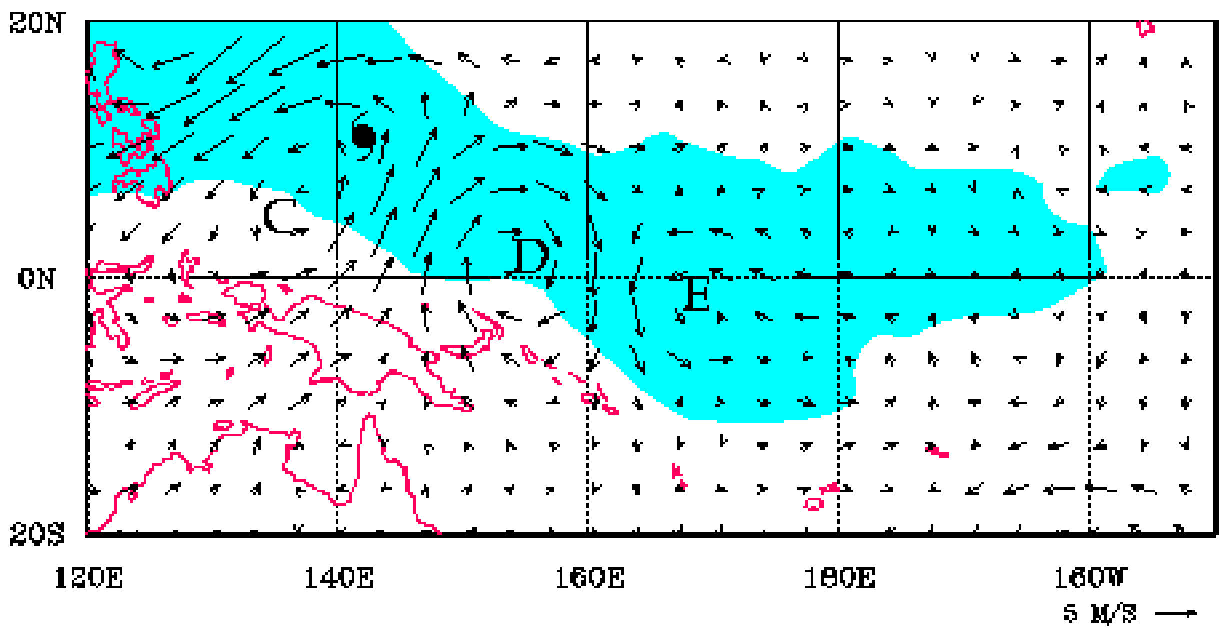

FIGURE 2

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 kind of interaction is one of the most common, and least well forecast, of any that occur. Based on potential vorticity principles and the observational study noted earlier, 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, as described above.

The Pacific studies of cyclogenesis provide some evidence concerning why clusters of tropical cyclones tend to form in time, followed by quiet periods. The relationship of the MJO and cyclogenesis was described earlier (Liebmann and Hendon, 1994). Our work adds to this the role of meridional PV gradient sign reversals, and the growth of waves from upstream in the active MJO region, in repeated cyclogenesis. We view the case study of the origin of some western Pacific disturbances from Rossby-gravity waves as a significant finding. To our knowledge, it is the first synoptic case study of an equatorial wave (rather than a traditional easterly wave) that leads to subsequent tropical cyclogenesis.

There is currently a fair amount of controversy over the role of easterly waves in tropical cyclogenesis in the western Pacific. It is notable that Rossby-gravity waves do not have a typical easterly wave signature, but rather an equatorial wave signature in convection. They may thus not be easily trackable in satellite pictures by traditional methods, and this may contribute to what we believe is the incorrect opinion of many scientists that waves in the easterlies are unimportant in the Western Pacific.

TRANSITIONS

Because five-day forecasts of tropical cyclone positions are needed for optimum fleet positioning by the Navy, such forecasts must take into account the fact that a storm could rapidly develop from a pre-existing disturbance during the five-day period. The studies on Western Pacific multiple tropical cyclone outbreaks raise the possibility of identifying active periods of tropical cyclone formation several days in advance. Our major efforts during the next year will involve determining how frequently the Rossby gravity wave/MJO precursor acts in the West Pacific.

RELATED PROJECTS

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 precipitation in tropical cyclones 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 the study of the unexpected intensification and later weakening of Hurricane Opal as it approached the Gulf coast.

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