

Liam Cavanaugh

Superstorm '93 and Related Articles

This list provides a bibliography and summarization of articles about Superstorm '93 and directly related to the storm, forecasts of the storm, and the storm's formation and intensification.

(1) Overview of the 12-14 March 1993 Superstorm

(Kocin, Shumacher, Morales, Uccellini)

Bulletin of the American Meteorological Society; Vol 76; 02/95; pp. 165-182

The paper gives background and some detailed information on Superstorm '93, and provides a basic understanding of the meteorological events of the storm. The paper goes through three different looks at the storm, including effects and impacts, a synoptic overview of the surface and upper level atmospheric conditions for each day, and a mesoscale discussion of the formation of the cyclone over the Gulf of Mexico.

Effects and Impacts: pp. 165

- about 100 directly related deaths (media reports to 270)
- \$2 billion in damage (1.6 in Florida)
- Record low sea level pressures
- Widespread snowfall, 90 million people with 1 in. + of snow
- Record low temperatures across much of southern U.S. (2 degrees F Birmingham)
- Most extensive distribution of heavy snow across the eastern U.S. in modern times.

Synoptic Overview: pp. 167-176

- **12 March:** Thunderstorm development Texas/Mexico border
- Surface low pressure over northern Mexico
- Developing 850 mb circulation at 1200 UTC
- 30 m/s increase of upper level jet streak downstream (Ohio Valley)
- **13 March:** Coastal flooding in Florida, Squall line moving through
- 971 mb pressure by 1200 UTC – 29 mb drop in 24 hours – not unheard of
- Massive circulation around cyclone (1/4 of U.S)
- Heavy snows up to Pennsylvania/New Jersey
- Circulation center moving northward into NC/DE
- **14 March:** Lowest pressure at 0000 UTC (960 mb)
- Storm track west of urban corridor, less snow in biggest cities, some rain
- Blizzard condition west of low pressure center (New York State)
- Exits U.S. by 1800 UTC

Mesoscale Discussion: pp. 176-181

- Two cold fronts, leading front small temp. gradient, trailing front brought coldest air
- Squall line developed along two troughs in Gulf, moved over Florida then out to sea, 11 tornadoes, 47 deaths.

- 1.5 mb/h deepening – much faster than expected by models (due to latent heating/convection?)

(2) Performance of the NMC Global Medium-Range Model (Caplan)

Bulletin of the American Meteorological Society; Vol 76; 02/95; pp. 201-212

The second part of the papers from NMC gives an analysis of the model accuracy for the storm. The paper goes into detail about the accuracy of the forecast 4-5 days ahead of the development, and critiques what the MRF model did well and did not do well. The paper explains that the forecasts along and to the north of the storm track were excellent in terms of strength and position of the system, while the forecasts over the Gulf of Mexico were consistently too weak. An outline of the good and bad parts of the models:

Forecast of Mean Sea-Level Pressure

- MRF consistently underestimated the rate of deepening from 0000 to 1200 UTC 13 March (storm over Gulf of Mexico)
- Later deepening was anticipated well and even overestimated for the period of 1200 UTC 13 March to 0000 UTC 14 March
- Storm position and intensity at 0000 UTC 14 March well predicted from 9 March runs on. See maps pp. 202-203
- The European Centre for Medium Range Weather Forecasts (ECMWF) model and UK Meteorological Office (UKMO) models (UKMET) were compared to the MRF, ECMWF model showed lower central pressure starting in initial 8 March runs for 1200 UTC 14 March timeframe, while MRF and UKMET were not as low.
- At 4 & 3 days out, ECMWF predicted 20 mb lower central pressure. **WHY?**
- **POOR INITIAL CONDITIONS** over the Gulf of Mexico were used in MRF and UKMET models, and ECMWF tends to overintensify large cyclones.
- **Poor initial cond: Also see pp. 201**
- Ensemble prediction on 0000 UTC 10 March shows models in agreement for major East Coast storm.

Middle Troposphere Forecast

- Rapid change in global jet stream pattern was predicted by mean sea level pressure (MSLP), with a major low latitude trough over southeastern U.S. (500 mb)
- Change in circulation pattern was well predicted, but the speed of the trough and the rate of intensification were underestimated, and the **Interaction of two short wave troughs was not resolved.**
- The trough troughs were shows as a double low pressure center in the forecasts.
- There was high skill involved with the forecast (highest in 8 years) possibly due to magnitude of anomaly.
- 72, 60, and 48 h forecasts produced center too weak and frontal trough too slow.

- No forecast of the 35-40 m/s winds that hit Florida.
- Models showed the 540 dam line well from southern Apps into Virginia, with good rain/snow line, but may have greatly underestimated precipitation amounts from Apps to the east.

**(3) Forecasting of the 12-14 March 1993 Superstorm
(Uccellini, Kocin, Schneider, Stokols, Dorr)**

Bulletin of the American Meteorological Society; Vol 76; 02/95; pp. 183-199

The third paper, this article refers in depth to the success and failure of the forecasts for Superstorm '93. The paper goes through the various time frames, and the accuracy of the forecasts generated by the Meteorological Operations division of the NWS. The lack of accurate forecast of the deepening of the central low pressure over the Gulf of Mexico is examined, and the increasing accuracy as the development neared is noted. The article then goes into the details of how the MOD forecasters were in contact with local NWS offices, and how these offices issued statement/watches/warnings to the public. The details of the manual forecasts based on the model guidance is critiqued throughout the paper, although the authors are quicker to blame the models for forecasting problems than the forecasters, possibly due to biases as forecasters themselves. The words success and shortcomings are used, but not failure to represent the way the forecasts are examined.

MOD Forecasts

- Early skepticism of major cyclogenesis due to cyclones earlier in season being weaker than forecast by models, skepticism faded as MRF showed consistency in forecasts over multiple runs.
- COMMENT: Forecasts by humans often depend on how well recent forecasts are, i.e. forecasters are weary of predicting "big one".
- 3 days before event, model differences were significant. The UKMET and ECMWF showed the low pressure center further north at development than MRF.
- UKMET and ECMWF alternated between far inland (Lake Ontario) and off the coast for low pressure center for later track, which concerned forecasters because these models had correctly had cyclones west of Appalachians earlier in the year.
- MOD followed the MRF because it was consistent and also showed the system being associated with increasing jet streaks over Ohio Valley and amplification of upper-level trough/ridge pattern, both of which are precursors for major East Coast Storms. (see pp. 188)
- MOD confidence in the track/intensity of the storm was assisted by an ensemble forecast on 10 March of 14 MRF forecasts, and by a new MRF-based statistical package that had the conditional probability of snow (CPOS).
- CPOS was high: 50% for cities N and E of Washington DC and 85% for West Virginia.
- The failure of the forecasts from MOD was that they did not see the rapid deepening in the Gulf of Mexico coming from early models.

- First short range models involving the system were initialized 1200 UTC 11 March. (LFM, NGM, ETA, AVN) Showed intense cyclone over East Coast, Heavy Snow.
- MOD issued storm summary statements about the storm every 6 hours, predicting well that powerful storm would hit East Coast. Used words “unusually severe” and “perhaps record breaking”. Issued first at 2200 UTC 11 March.
- The MOD and local forecasters used the “hurricane hotline” to communicate and attempt to improve forecasts and keep in agreement: Concerns in snowfall amounts and rain/snow line continued even as storm developed.
- Forecasters faced most difficulties with initial formation over the Gulf of Mexico.
- **Valid 0000 UTC 13 March:**
- 48-24 hrs out, forecast had low pressure at 1006 mb over Florida Panhandle (this would be several hundred km NE and 22 mb too high of actual)
- Pressure (intensity) forecasts were closer as 0000 UTC 13 March approached, but 12 hr forecast had 993 mb, still 9 mb too high.
- Forecasters disregarded LFM model showing much deeper cyclone moving out of the Gulf of Mexico, citing the tendency of the model to overdeepen cyclones due to “convective feedback”. The feedback of latent heat release on the cyclogenesis was significant in this case. (How would this be predicted?)
- **Valid 1200 UTC 13 March:**
- At 36 hrs, 996 mb was predicted (by human forecasts), and the forecast pressure reduced with every 12 hr period, down 20 mb to 976 by the time the 12 hr forecast came out, still 5 mb higher than the recorded pressure of 971 mb.
- **Valid 0000 UTC 14 March:**
- The MOD 48 hr forecast, after noticing that the models continued to underdevelop and underdeepen the system, was released with a forecast central pressure of 963 mb. This forecast was 3 mb below lowest model, a good correction by MOD forecasters, the actual pressure was 960 mb.

- When the cyclone began to develop on 12 March, rain/snow line was predicted just west of urban corridor.
- The models changed significantly in the next 24 hrs, but forecasters decided that they did not think that deepening would occur as models suggested over Virginia.
- Snowfall of 20+ inches in Kentucky and Ohio was much more than forecast.
- See pp. 193 for MOD snow forecasts.

Local Forecasts

- Very long Watch and Warning lead times, see chart pp. 194
- Winter Storm warning lead times up to 43 hours, with Blizzard Warnings 10-24 hours before snow started falling anywhere.
- State of Emergency in many states, all highways closed in Penn, national guard activated for entire storm.
- Short term forecasts and WSR-88D radar details, see pp 196-197

Overall, somewhat biased article towards the forecasters, but makes clear that that forecasts were very good in general, and even the specific short term forecasts were good. The watch/warning lead times were unprecedented.

**(4) A Snowfall Impact Scale Derived from Northeast Storm Snowfall Distributions
(Kocin, Uccellini)
Bulletin of the American Meteorological Society; Vol ?; 02/04; pp. 177-194**

The article presents a new scale for classifying winter snowstorms affecting the Northeast U.S. Kocin and Uccellini have tried to create a scale that measures snowstorms based on a mathematical formula taking into account amounts of snow over size of areas, and amounts of snow over size of populations, and categorizing them. The scale takes into account the formula, and then ranks storms from 1 to 5, with 5 being the most severe.

- In a scale created by Hart and Grumm, taking into account the normalized departure from climatological means, the March 1993 superstorm ranked 3rd among storms in the 53 yr time period studied.
- Kocin and Uccellini feel that storms should be characterized by their unique, extensive distribution of snowfall in the NE urban corridor, because that is where the greatest impact is.
- Have created the Northeast Snowfall Impact Scale (NESIS) to rate snowstorm impacts.
- The NESIS calculation is given on pp. 179-181
- March 1993 superstorm has the highest NESIS rating of 12.52, which gives it one of only 2 storms with a category 5 ranking. The other is 6-8 Jan 1996. 70 storms were studied in this, the 70 that Kocin and Uccellini feel were most significant in last 100 yrs.
- NESIS values of 10+ are given a category 5 rating.

This paper by Kocin and Uccellini offers a new perspective possibly on how to categorize a “superstorm.” Because the two are “winter weather experts,” can the scale they create be used to classify a superstorm? Is a category 5 snowstorm now a superstorm because they say it is? Does the algorithm being used take enough into account to be considered an accurate ranking system? For example, 2 inches of ice on the roadways of the NE population centers would not even show up on this scale as an extreme storm, even if a great amount of snow fell over not as populated areas slightly inland. Something to think about...

**(5) Natural Disaster Survey Report: Superstorm of March 1993
U.S. Department of Commerce; National Oceanic and Atmospheric
Administration; National Weather Service, Silver Spring, MD.**

For the summary of useful information in the Natural Disaster Survey Report, refer to Appendix A.

(6) The Blizzard of 12-15 March 1993 in the USA and Canada

(R. Brugge)

**“Weather” pub. by the Royal Meteorological Society;
March 1994 Vol. 49 No. 3; pp. 81-89**

This article is a summary written in a journal of the Royal Meteorological Society. The article recaps the major events and impacts of the storm, but does not go into any extensive details. An overview of the accurate forecasts of the storm is given, but no new information is given beyond that of sources 1,2, and 3.

- Some information is given about the public statements that were made to the public by the NWS, and pp82-84 have a few of the winter weather statements.
- The synoptic development is given briefly day by day, followed by snowfall totals and other impacts.
- No other new news is given, making this article relatively useless to us.

(7) A Classification Scheme for Winter Storms in the Eastern and Central United States with Emphasis on Nor'easters

(Zielinski)

Bulletin of the American Meteorological Society; January 2002. pp. 37-51

This article is a classification system developed before that of source 4, by Kocin and Uccellini. The goal of the classification system is to summarize the potential impact of future winter storms for given categories of Intensity and Duration, particularly as related to snowfall amounts. The article discusses in length several storms, including some mention of the March 1993 Superstorm, which ranks as a high category 4 storm.

- The first category used to evaluate storms is the Storm Intensity. The intensity takes into effect three things: Central Low Pressure Difference, Rate of Deepening of Central Low Pressure, and Maximum Pressure Gradient between central low pressure and central high pressure of adjacent anticyclone.
- Storm intensity weights all of these relatively equally, and has a scale to divide intensity into categories of 1-5, with 5 being the most intense.
- The second factor taken into account by system to determine impacts is the Duration Factor. DF also ranges from 1-5, with 5 being slowest moving.
- Both factors taken into account when determining impacts, but Storm Intensity used more than duration. Pp 48-49 give chart of many impacts (precip, winds, coastal) based on intensities of storms.
- Superstorm 93 Reached only a high category 4 storm under this system, but stayed at that status for more than 24 hours.

- SS93 was a relatively fast mover, only category 2 duration factor.
- The combination of filling and fast movement reduced snowfall amounts over New England to lower than was expected given the history of the storm. The storm dropped to a category 3 over this northern area.

This classification system creates a much different and more inclusive system than the one offered by Kocin and Uccellini. The scale takes into account the intensity of the storm at any moment on its path, making the scale useful in expected impacts, rather than simply looking back on what has happened and rating it.

(8) *RM to read**

The March 1993 Superstorm Cyclogenesis: Incipient Phase Synoptic- and Convective-Scale Flow Interaction and Model Performance.

(Dickinson, Bosart, Bracken, Hakim, Schultz, Bedrick, Tyle)

AMS; Monthly Weather Review; 1997 Vol. 125 pp. 3041-3072

This article focuses on the intense strengthening of Superstorm 93 over the Gulf Of Mexico. Beginning with the fact that the 975 mb central low pressure while still over the Gulf of Mexico was the deepest cool season storm to affect the Gulf of Mexico in the 1957-present period studied, the article goes on to look at the reasons why the low strengthened so quickly (see figures 1 a,b pp. 3042). The paper is very technical in the examination of the Potential Vorticity (PV) phenomena that came together over the Gulf of Mexico with this storm. The model performance and representation of the initial cyclogenesis is examined, with a look at the effects of latent heating and convection on the rapid deepening of the storm.

- Unusual early intensification was not well forecast by the Regional Analysis and Forecast System (RAFS) or the MRF.
- Large forecast underestimates of the central low pressure (Figure 1b) occurred during a period of widespread convection near the storm's center - pp. 3042
- Hypothesis of paper: Model's inability to simulate properly the bulk effects of cumulus convection contributed significantly to the poor forecasts.
- Coupling Potential (CP) examined with several PV anomalies moving across the U.S. towards the Gulf of Mexico. CP is the difference between THETA-T and THETA-E. Negative values indicate the atmosphere is susceptible to deep convection given a suitable lifting mechanism and adequate moisture.
- The growth of low level PV occurs beneath decreasing Pt (and associated ridging on the DT) consistent with the expected development of an area of anticyclonic circulation above a region of extensive latent heat release.
- Failure to simulate properly cold surges east of the Rockies is a common systematic failure of the NCEP operational models. Pp 3053
- Pp 3054: Results suggest that the MRF model adequately captured the mass and winds fields associated with the precyclogenetic phase of SS93, but is inadequate

at later times as cyclogenesis proceeds in the presence of deep convection. **This suggests that inadequate parameterized model physics may contribute to the poor forecasts of the incipient SS93 cyclogenesis.**

- More model failures: Unforecast nonconservation of THETA-T prevents the MRF model from capturing the significant advection at lower levels of THETA-T over the rapidly intensifying storm. Unable to capture favorable cyclogenesis pattern.
- MRF also continues to fail to capture rapidly strengthening southwesterly jet ahead of PV anomaly from Arkansas to Ohio. (**JET STREAKS?**)
- Diabatic heating effects associated with convection over northwestern Gulf of Mexico was better forecast in the ECMWF model during development phase of SS93. This and Influences of Convection explained of pp 3058-3060
- The heat flux (latent heat) discrepancy between the observations and model forecasts over the Gulf of Mexico are attributed to 1) both weaker wind speed and low-level thermal gradient forecasts in the models (**especially in MRF**) 2) in the **underestimate of the SST over the Gulf of Mexico in the models, especially the MRF**. See pp. 3060-3063
- Strong SST gradient from the Mississippi Delta out into the Gulf of Mexico, and the gradient and baroclinic zone discussed pp. 3062-3063.
- For summary of why such deep cyclogenesis occurred, including the lateral and vertical interaction of long-lived PV anomalies, exceptionally unstable airmass over Gulf of Mexico, and Amplifying Trough/Ridge pattern, see summary a. pp 3063-3064
- **MODEL ERROR SUMMARY:** “The MRF failure to simulate properly the incipient SS93 cyclogenesis over the Gulf of Mexico can be linked to the inability of the model to replicate the observed widespread convective outbreak in the storm environment triggered by the approach of PV anomaly “C” see pp 3064-3065.
- This was shown to not have been based on initial conditions OF THE PV ANOMALY because the anomaly was represented well the day before.
- The ECMWF had a much better forecast of the cyclogenesis over the Gulf of Mexico based on several factors discussed on pp 3065. (Did forecasters have access to the ECMWF model?)
- Author comment: A closer look is needed at how the MRF and ECMWF parameterize convection.
- Medium Range: The article says that the ability of the models to forecast the east coast storm four days in advance without correctly predicting the deepening in the Gulf of Mexico suggests that the PV anomaly “A” (on the northern branch of the jet) would have been enough to cause a major North American cyclone due to the natural baroclinic zone from the Gulf Coast to the Atlantic Coast in winter.
- Pp.3070: Results: “*Our results suggest that the exceptional intensity of the incipient SS93 cyclogenesis over the Gulf of Mexico can be associated with 1) an evolving large-scale flow pattern that favored the establishment of the positive phase of the PNA pattern over North America with a deepening trough downstream of the Rockies; 2) the presence of a strong PV anomaly in the STJ that triggered the onset of widespread convection over Southeastern Texas and offshore as it moved eastward across Mexico; 3) a positive feedback between*

ascent, low-level convergence, cyclonic vorticity production, deep convection and the advection of lower values of THETA-T and higher values of Pt in the presence of a stronger than forecast baroclinic zone and a stronger than analyzed SST gradient; and 4) an increase in THETA-T and associated decrease in Pt, both attributable to latent heat release downshear of the developing cyclone, that facilitated self-development through enhanced downshear ridging and the development of a strong outflow aloft.”

(9) *RM to read**

A Diagnostic Analysis of the Superstorm of March 1993

(Huo, Zhang, Gyakum, Staniforth)

AMS; Monthly Weather Review; 1995, Vol. 123; pp. 1740-1761

This article is a discussion about a different type of model that the team used to attempt to better predict the rapid deepening SS93 over the Gulf of Mexico. This article first goes through the atmospheric conditions at the time of the development, and the sources of those atmospheric conditions. A very good synoptic overview is presented regarding reason why the system strengthened so rapidly over the Gulf of Mexico. The paper then goes into the details of the runs of the Canadian Regional Finite-Element (RFE) model, and how that model predicts the deepening over the Gulf of Mexico.

Introduction pp. 1740-1741

- Necessary ingredients for explosive cyclogenesis are strong baroclinicity, short-wave troughs, stratospheric extrusions, upper-level jet streaks and lower-level jets, symmetric instability and weak static stability, latent heat release, and surface sensible and latent heat fluxes
- Upper-level and low-level elements are often dynamically coupled through vertical and ageostrophic circulations that are aided by upright or slantwise convection.
- Inconsistencies in models are due to imperfect initial conditions, poor grid resolution, or improper model physics representations.

Synoptic Overview pp. 1741-1745

- **1200 UTC 12 March**
- SST was more than 3 degrees Celsius above the monthly normal (Gilhousen 1994)
- 850 mb: Weak warm advection ahead of the low, with a very cold air mass and strong temperature gradients advected southward east of the Rockies. This led to a rapid increase in baroclinicity along southern seaboard.
- Presence of strong southern flow is an indicator of ample moisture being transported into baroclinic zone for subsequent latent heat release.
- Two short wave troughs in middle troposphere were associated with amplifying vorticity centers.

- Upper troposphere had a “double jet” structure one ahead and one behind upper level trough. This structure is known to have some part in the effect of tropopause depression on extratropical cyclogenesis.
- Westerly jet intensified rapidly in response to enhanced baroclinicity: The presence of such strong jet streaks is an indication of strong baroclinicity which would determine the subsequent explosive deepening of the storm.
- **0000 UTC 13 March**
- Warm front moving north near east coast, while there is a squall line over central Gulf of Mexico.
- High cloud tops at center of storm: 28000-34000 feet.
- Short-wave troughs intensifying and vorticity maxima increasing. The eastern trough near the low pressure center caused positive vorticity advection toward the low, which appears to have played an important part in the initial development of the cyclone.
- Low level jet formed ahead of the cold front, providing warm moist air to the system.
- The westerly jet had intensified rapidly, and the northwesterly jet had intensified some, with the low pressure system beneath the right entrance of the jet streak (see pp 1743) which is a position favorable for surface cyclogenesis (Uccellini and Johnson 1979)
- **1200 UTC 13 March**
- Warm front parallel to east coast had strengthened
- Low-level jet had increased in strength, significant moisture transport from tropical ocean to warm sector of the cyclone.
- 500 mb: Two short-wave troughs merge and produce negative tilt. Vorticity centers strengthen and merge.
- Surface cyclone situated at right entrance of northern jet streak, and left exit of southern jet streak, which is a more favorable position for cyclogenesis (Uccellini and Kocin 1987)
- **0000 UTC 14 March**
- Storm entered occlusion stage, began filling slowly
- Mid and upper-level disturbances reach maximum intensity
- Two jet streaks intensify further
- Figures of 850 hPa, 500 hPa, 250 hPa, and surface maps are available in this section.

Numerical Prediction System and Model Predictability pp. 1745-1751

- The details of the RFE model runs are presented in this section, making some note of the importance of adding the latent heat release to the models. Without including convection in the models, the vorticity of the system is grossly underestimated.

Possible Deepening Mechanisms pp. 1751-1759

- Latent heat release: pp 1751-1753 describe the model run on the system with and without the effect of latent heat release included. It is found in this paper that without latent heat release, the path of the storm stays very similar to that with latent heat release, but the storm is weaker in intensity and slower in

- displacement. **This is particularly significant in the first 12-hr integration, in which the latent heat release accounts for the explosive deepening of the storm.** This coincides with the rapid development of the prefrontal squall line and precipitation along the warm front.
- After the first twelve hours, the runs begin to agree on the deepening of the storm, suggesting a reduced impact of latent heat release after the initial 12-hr period.
 - **LATENT HEAT ACCOUNTS FOR 40% OF THE DEEPENING BY THE END OF THE 36-hr INTEGRATION**
 - Jet Streaks: The importance of the jet streak is that the transverse circulations appear to play a role in the transport of moist, unstable air in the warm sector to the warm-frontal zone, and then release the moist symmetric instability.

(10) An Application of Potential Vorticity Inversion to Improving the Numerical Prediction of the March 1993 Superstorm.

(Huo, Zhang, Gyakum)

AMS; Monthly Weather Review; February 1998; Vol. 126; pp.424-436

This article recognizes the fact that poor initial conditions over the Gulf of Mexico were a major problem in the model's lack of a good forecast of the initial cyclogenesis of SS93. The article gives some of the failures of the models, such as lower than actual surface temperatures and displacement of the low pressure center from its actual location. The paper then goes on to describe a possibility for creating initial condition over the Gulf of Mexico to fill the void in the model's initial conditions.

- Underestimating the low-level (surface) temperatures would slow the initial spinup of the storm.
- Error in the location of the system low pressure may lead to errors in predicting the storm's movement. The southwestward displacement that the models had from the actual location put the storm in a less favorable position to interact with the PV anomalies moving across the region.
- The underestimation of the low-level temperature over the Gulf of Mexico will reduce both the potential moisture content and the baroclinicity between the Gulf of Mexico and the southern plain.
- To try and fix these "errors" in the model based the lack of available initial conditions, the idea is to use surface observations and a potential vorticity inversion to create conditions of the upper atmosphere for the model to use in the runs.
- In doing this, the scientists used the RFE model with the new initial conditions created by potential vorticity inversion. The model performed much better in these runs using SS93 than the model outputs without the new initial conditions. (For an explanation of the potential vorticity inversion see pp. 425-430) The model had the storm intensifying more over the Gulf of Mexico, had the squall

line forming and moving over Florida, and had the broad band of precipitation near the warm front. The idea seemed to be a success in this case.

Although the model worked better in this case with the created initial conditions, the authors have noted that it was only tested for this case, and more work should be done to see if it was a one time deal. They also note that it may only work for storms on the East Coast. Still, the fact that initial conditions (an obvious problem with the forecast of SS93 over the Gulf of Mexico) were created in a way that the forecast was improved is a good step towards improving future forecasts.

(11) Large-Scale Antecedent Conditions Associated with the 12-14 March 1993 Cyclone (“Superstorm ‘93”) over Eastern North America

(Bosart, Hakim, Tyle, Bedrick, Bracken, Dickinson, Shultz)

AMS; Monthly Weather Review; September 1996; Vol. 124; pp. 1865-1891

This paper outlines the development of SS93 based on the global-scale set up and interaction of potential vorticity anomalies in the Gulf of Mexico and East Coast of the United States. The article uses Dynamical Tropopause Analysis to track the PV anomalies for nearly a month, culminating with the formation of SS93. This is a continuation of previous articles that have stated that these same PV anomalies, and their merger, were the cause of such an intense extratropical cyclone. The paper also talks about why SS93 was such a unique storm, and what may have caused the uniqueness.

- There were at least three PV anomalies in the eastern U.S. when the formation of the Superstorm took place over the Gulf of Mexico. Two anomalies came onshore from the Pacific Ocean and tracked with the subtropical jet stream across Northern Mexico and Texas.
- PV anomaly “D” was the cause for some convection in Mexico, but appears not to have been the cause of the major cyclogenesis.
- PV Anomaly “C” came across Northern Mexico and out over the waters of the Gulf of Mexico, aiding in the initial cyclogenesis and rapid deepening of the Superstorm.
- The third anomaly (“A”) was located in the Polar Jet, and dropped in towards the eastern U.S. out of Alaska and Canada. “A” approached the east coast on 13 March.
- “A” and “C” merged over the Chesapeake Bay at the time of the storm’s reaching maximum intensity.
- PV anomalies are often associated with pockets of low THETA-T and high Pt (low potential temperatures and high pressure values)
- The uniqueness of the superstorm is attributed by the authors to four “multiscale” processes: 1) The observed amplification of the planetary scale flow during 8-14 March 1993. 2) Air mass warming, moistening, and destabilization in association with dissipating PV anomaly “D”. 3) The merger of PV anomalies “A” and “C” associated with arctic and tropical air, within a larger scale confluent background flow. 4) The delayed arrival of “A” behind “C” allowed MSLP to remain

relatively low and allowed the channel of cold air to surge southward east of the Rockies. This eliminated the high THETA-E over the Gulf of Mexico, and allowed the baroclinic zone to remain in place. This zone was the focal point for the initial cyclogenesis of SS93.

(12) The Value of NDBC Observations during March 1993's "Storm of the Century"

(Gilhousen)

Weather and Forecasting: Notes and Correspondence Vol 9; June 1994

Pp. 255-264

This article outlines the importance of the National Data Buoy Center (NDBC) in the forecasting of cyclogenesis over the Gulf of Mexico. The paper explains several indications that the buoys gave forecasters of a rapidly deepening cyclone over the northwest Gulf of Mexico on 12 March. The author then points out several forecast areas that could have improved had the forecasters taken a closer look at the surface observations from the buoys.

- Pressure measurements at two buoys off the Texas coast were 4-6 hPa lower than forecast.
- Ocean Wave Observations: Some of the steepest waves NDBC has ever measured.
- Warm eddy "Eddy Vasquez" caused SST's to be several degrees warmer than normal under the track of the storm, causing a strong SST gradient due to cooler coastal shelf waters. This resulted in higher baroclinicity and more energy for the storm.
- The eddy was larger and warmer than indicated in the National Hurricane Center (NHC) analysis, but the buoys showed this warming in the SST observations.
- The 17 hPa fall in pressure in 18 hours (at 28 degrees latitude) classifies the storm as a "bomb", as Sanders and Gyakum (1980) classify a bomb as a low with CLP fall of at least 13 hPa in 24 hours at that latitude.
- First "bomb" in Gulf of Mexico since 1983.
- Initial placement of low by forecasters put it at least 70 miles Southeast of actual position. Pp 257
- The extreme wave steepness showed an early warning sign of a rapidly deepening storm.
- Infrared SST chart pp. 261
- SST gradients and departures from mean pp. 262
- Given the NDBC evidence "an astute forecaster could have forecast a much deeper storm than anticipated for the Eastern Gulf" pp 263.

(13) The 13 March 1993 Severe Squall Line over Western Cuba

(Alfonso, Naranjo)

AMS: Weather and Forecasting; March 1996; Vol. 11; pp. 89-102

This paper examines the squall line that was formed over the Gulf of Mexico and moved across Florida and Cuba on March 13, 1993. The authors examine how and why the squall line formed, and then go into the effects that the line had on Cuba. The squall line was the largest in area to ever be recorded over Cuba. Although there was some advanced notice of the approaching squall line, the damage was still extreme.

- There was a 300 hPa jet streak interacting with a low level jet over the Eastern Gulf of Mexico where the squall line formed.
- The squall line was associated with a strong, well-defined cold front.
- It was the most damaging squall line ever recorded in Cuba
- Line produced damage up to F2 on the Fujita scale.
- Cuba recorded 10 casualties and over \$1 billion in economic losses.
- There were three elements present that are necessary for the occurrence of deep convection: 1) Presence of deep, moist layer in lowest levels 2) Sufficiently deep lapse rate above moist layer, and 3) Lifting Mechanism (this was provided by strong southern short-wave trough)
- The squall line was formed by the back building process: For more information on this development process refer to Bluestein and Jain (1985)

(14) The Mesoscale Evolution of the Early Cyclogenesis of the March 1993 Storm of the Century

**(Pfeiffer, Kaplan, Lin, Riordan, Lackmann, Waight, Ensley)
Conference proceedings, unknown, #13.9**

The authors of this article give a new look at another possible source of ignition for the rapid convection and cyclogenesis of SS93 over the Gulf of Mexico. The paper looks at a cold pool that originated over the upper Rio Grande Valley on March 11, and expanded and migrated toward the Texas Gulf Coast by the next day. This mid-level cold pool provided instability in the atmosphere in the region of cyclogenesis.

- Failure of operational forecasts may have been due to inadequate simulation of the organized convection or poor initialization of the SST field along the Gulf Coast
- Mid-level cold pool along the Texas Gulf Coast may have been a source of the convective available potential energy (CAPE)
- Cold pool was evident in the 0000 UTC 12 March ECMWF analysis as a 700 hPa cold trough just north of Brownsville.
- The cold pool initiated at about 0600 UTC 11 March just west of Del Rio, Texas.
- Pool expanded as low-level warming triggered shallow convection, which produced evaporatively cooled air at the mid-levels.
- Results show that the cold pool is produced in response to frontogenetic circulations confined to the western Gulf Coast, possibly enhanced by SST gradients along the coast.

(15) The 12-14 March 1993 Superstorm: Synoptic and Mesoscale Overview and Operational Forecast Performance
(Kocin, Uccellini, Schumacher, Morales, Schneider)
Conference Proceedings? Unknown Origin Pp. 302-309

This article is a quick summary and overview of the development and forecasts of SS93. The paper does not provide much more than the information in sources 1-3, and is primarily an overview of those three papers. Interesting notes and other sources to look at are noted below.

- The deepening of the storm (29 mb in 24 hours) was equivalent to 52 mb in 24 hours at 60 degrees latitude.
- Winds in the upper-level jet streak over the NE United States increased over 30 m/s in 12 hours.
- Intensification of the downstream jet streak is documented for other cases of rapid cyclogenesis: Chang 1982, Keyser/Johnson 1984, Uccellini 1991
- Interactions of upper and lower level Isentropic Potential Vorticity (IPV) Maxima have been noted for other rapidly developing cyclones, and this is known to be a diagnostic marker for the interactive processes associated with upper-level jet streaks and latent heat release during the rapid development phase of the cyclone: Gyakum 1983, Whitaker 1988, Davis and Emanuel 1991.
- "The storm developed as the result of an interaction between an upper-level shortwave trough and associated jet streak moving east toward the Gulf of Mexico and a second shortwave trough and polar jet that amplified as it propagated southeastward from the Rocky Mountain states to the Gulf Coast."

(16) The Effects of Assimilating Rain Rates Derived from Satellites and Lightning on Forecasts of the 1993 Superstorm
(Alexander, Weinman, Karyampudi, Olson, Lee)
AMS; Monthly Weather Review; July 1999, Vol 127; Pp. 1433-1457

This article describes one way that the numerical prediction of Superstorm '93 (as a case study) and other cyclone intensification can be improved. The suggestion is that by assimilating time series rain rates in the storm that the convection of the storm is better simulated. The article also suggests that a better simulation of the convection would produce better forecasts of the deepening of the storm over the Gulf of Mexico, and a better forecast of the squall line.

- Inadequate specification of the divergence and moisture in the initial conditions in numerical models can result in "spinup" problems

- Latent heat release can be a key ingredient in the intensification of extratropical cyclones
- Improved assimilation of rain rates in early stages of numerical simulation results in improved forecasts of the intensity and precipitation associated with extratropical cyclones
- It is difficult to obtain good estimates of rain rates over data sparse regions (e.g. Gulf of Mexico)
- In this study, passive microwave sensors, infrared sensors, and lightning flash information (as well as digital image morphing) can be combined to create a continuous time series of rain rates, which can be assimilated into numerical prediction models and results in improved forecasts.
- PSU-NCAR MM5 model used in the study
- The combined use of the three ways to produce rain rates resulted in a less than 2 mb error in the final 12 hours of the simulation, and a close proximity of the low pressure center to the observed low pressure center, while the other models runs with less rain rate data, as well as the control (the runs from 1993) have a displacement of hundreds of kilometers behind the storm.
- Forecasts of geopotential height (500 mb) and MSLP are much improved, as are the forecast precipitation fields.
- The use of rain rate assimilation allowed the models to produce the squall line, but the more information added (microwave, then infrared, then lightning) the better the forecast of the squall line became.
- The models using only microwave and infrared DID NOT replicate the rapid deepening or the squall line over the Gulf. The lightning had to be added to see these.
- “We have tried to show how utilizing a unique source of data (lightning) was the key to improving forecasts of an exceptional case of cyclogenesis” pp 1455
- May be due to the fact that lightning is a better proxy of the convective rate rather than total rate (stratiform precip)

(17) Evaluation of the Contemporary Ocean Wave Models in Rare Extreme Events: The “Halloween Storm” of October 1991 and the “Storm of the Century” of March 1993

(Cardone, Jensen, Resio, Swail, Cox)

AMS; Journal of Atmospheric and Oceanic Technology; February 1996; Vol 13; pp. 198-230

This article is a critique/evaluation of the models that are used over the Atlantic Ocean to measure wave heights. During both of these storms, buoys recorded wave heights near Nova Scotia over 15 meters. The authors use the data from these storms to attempt to validate the ocean wave models based on these two extreme events. To determine if these models are correct, the wind fields over the Atlantic Ocean are first derived from observational data, using ship and buoy observations, and then the fields are used to create wave “hindcasts.”

- Wind speeds must be adjusted (due to 20 meter anemometer height) to create the wind fields and evaluate the wave models.
- All four models used created excellent wave conditions (in hindcast) for waves up to 12 meters.
- The four show “considerably greater skill” than the real time wave analyses in the same models operating at the U.S., Canadian, and European centers.
- Although the wave models predicted the sea state up to 12 meter height, they tended to underpredict extreme sea states. This maybe due to uncertainties in the wind fields or to biases in the wave models at high sea states.
- Although the models did disagree in the time series hindcasts, they all tended to disagree similarly, with average agreement over time histories, which may show errors in the wave models physics.
- A similarity between the extremely high waves in these two storms appears to be the wave generation along a dynamic fetch associated with surface wind maxima or jet streaks.
- With the models underestimating the waves consistently in high seas, there is a need for more study on correcting wind field errors to correct wave models. This may not be possible without the addition of more buoys to create better initial conditions. Pp 229
- The study suggests that extreme sea states may be much more common than earlier thought off the East Coast of North America, and extreme wave climatology needs to be updated, and possibly reevaluated.

(18) The 1993 Superstorm Cold Surge: Frontal Structure, Gap Flow, and Tropical Impact

(Schultz, Bracken, Bosart, Hakim, Bedrick, Dickinson, Tyle)

AMS; Monthly Weather Review; January 1997; Vol. 125; pp. 5 - 39

This article discusses the cold surge that affected Mexico and Central America during and immediately following the Superstorm of March 1993 (SS93). The paper discusses what it classifies as a cold surge tied for the second most intense in the time period studied (1980-1993) based on the latitude that the cold air was advected to, and the 24 hour temperature decreases. Although the article does not directly relate to SS93, it does show one effect that a storm of that magnitude can have.

- Surges of cold air from the United States into Mexico/Central America are associated with anticyclones that often occur in the wake of cyclogenesis east of the Rocky or Sierra Madre Mountains.
- These surges can bring Northerly winds up to 30 m/s, air temperature decreases of 15 degrees C in 24 hours, low clouds and heavy precipitation on East and Northeast facing slopes in Mexico and Central America.

- A Central American Cold Surge (CACS) is the leading edge of an anticyclone that originates poleward of Mexico and penetrates to a least 20 degrees N. This leading edge is identified by the onset of strong North winds at the surface
- Although the cold air stays along the Eastern sides of the mountains, there are “leaks” through several gaps in the mountains with winds reported as high as 60 m/s in these regions.
- The SS93 CACS: The southernmost extent was 7 degrees N. There was a 15 degree Celsius temperature decrease in 48 hours at Merida, Mexico.
- The cold surge was very deep, extending up to 700 hPa.
- Pp. 13-20 go through the initiation, maturation, decay, and details of the cold surge as related to the SS93.
- Pp. 20-33 provide an extensive report on the mesoscale aspects of the cold surge, including charts and figures of the fronts/winds/temperatures over North and Central America. Also included are the data from several cities in the U.S., Mexico, and Central America.
- The surge was extraordinary due to topographic channeling and due to the dynamics of a low-latitude short-wave trough and confluent jet entrance region associated with the subtropical jet favoring the deep penetration of the surge into the tropics.

(19) Anticyclonic Rings in the Gulf of Mexico

(Elliott)

AMS; Journal of Physical Oceanography; November 1982; Vol. 12;pp.1292-1309

The paper describes a little studied (at this time especially) phenomenon in the Gulf of Mexico where rings (or eddies) break off from the Loop Current that is over the Eastern Gulf and move westward. These pockets of warmer and more saline water are found to be a regular occurrence and are essential to the dynamics of the Western Gulf. The rings are tracked, and the size, speed, and impact of these rings are examined in detail.

- There are two dominant (semi-permanent) features of circulation in the Gulf of Mexico: the intense Loop Current system to the east and an anticyclonic cell of circulation along the western boundary.
- Cochrane (1972) concluded that a necessary condition for ring formation was a “Yucatan meander” that joins with the semi-permanent “Florida meander” to create a cold, low salinity ridge through the Loop Current, thus separating a ring.
- The Loop Current can enter the Gulf in fall or spring, with subsequent eddy separation in winter or summer.
- Rings are identified by higher temperatures and salinity of more than 36.6‰ (where the average in the Gulf of Mexico is 34.4‰).
- Rings that separate from the main current can translate into the western Gulf, and can retain their identity to the Western Boundary.
- The mesoscale circulation of the Gulf changes rapidly with time (3 rings in 8 months studied)

- The overall mean vector velocity of the rings is 2.1 km/day at a direction of 279 degrees to North (Just north of west)
- The mean radius for the rings is 183 km.
- Rings survive about one year on average (in this study)
- Rings create a flushing of the waters in the Gulf of Mexico: 1 ring is about 7% of the total volume of the Gulf.
- Rings are also an important part of the Gulf's heat and salt budget.
- 0.74 rings per year are needed to balance the salt in the western Gulf with the fresh water input.

(20) Separation of Warm-Core Rings in the Gulf of Mexico

(Sturges, Evans, Welsh, Holland)

AMS; Journal of Physical Oceanography; February 1993; Vol 23; pp 250-268

This paper describes in more detail the way in which the warm rings separate from the Loop Current in the Gulf of Mexico. After providing information about these rings, and the observations of how they do indeed separate, the paper describes a model created to try to predict the separation of the rings. The model is described as doing a good job in showing rings separations, with relatively small errors. The paper provides a good starting point for the modeling of the warm-core rings.

- The process of loop (ring) separation is not clear or sudden: the ring drifts away from the Loop Current.
- The paper provides excellent charts of the separation and location of the rings throughout, going through a complete cycle of a rings from formation to formation of the next ring. Charts showing current fields are showing in detailed week to week analysis of the model runs.
- There is detailed information on separation of rings in papers by Lewis and Kirwan.
- The shortcomings of the model are the errors in the transport: the ring is too small and the velocities are too low.
- The deep, vortex-like patterns in the deepest levels of the ring propagate to the west at greater speeds than the surface levels of the ring. This is consistent with observations made by Hamilton (1990)

(21) The Frequency of Ring Separations from the Loop Current

(Sturges)

AMS; Notes and Correspondence; July 1994; Vol.24; pp. 1647-1651

This article is an expansion on the Sturges' look into the separating rings from the Loop Current in the eastern Gulf of Mexico. Instead of describing the phenomenon in this

article, however, the author looks at the timing between separations of the rings to determine any pattern-like characteristics.

- The rings do not always separate at the same time of the year, but the timing between them does not appear to be random.
- By looking at historical data of separation times as given by Vukovich (1988), there appear to be concentrations (peaks) in the distribution of time between separations.
- The method used to determine these separations was the data taken from infrared satellite imagery over the Gulf of Mexico. There is a problem with this imagery in that it cannot be taken in the summer months due to uniformly warm SST's, which causes a gap in the data and a possible source of errors in this study
- The separations appear to be on a bimodal type of system, as there are two peaks, one at an 8-9 month interval and the other at a 13-14 month interval
- Interestingly, another study done by Vukovich found a single peak at 11-12 months, which is the average of the two, but when broken down by Sturges, the 11-12 month area is a minimum for separations.

(22) The Frequency of Ring Separations from the Loop Current

A Revised Estimate

(Sturges)

AMS; Notes and Correspondence; July 2000; Vol. 30; Pp. 1814-1819

As a revision to the first estimate of the frequency of separation from the Loop Current, this article uses another 8 years of data, and data found in a different manner, to recalculate the time between ring separations. Instead of using satellite infrared imagery to determine when rings separate, satellite ocean altimetry is used, because that method is more precise, without gaps in the summer.

- Table of all suspected separations is given on pp. 1817.
- A new estimate of the time between separations is given, that is not close at all to the first estimate. There are now peaks at 6 months and 11 months, with a secondary peak at 9 months. If a smoothing program is run on the distribution, the single peak appears at about 12 months, which is described by the author to be an inaccuracy due to the smoothing.
- The satellite altimetry is much more precise than the infrared, and a sample chart of a separated ring is given, clearly showing sea surface heights.
- MY NOTE: The two storms that I have found which have rapidly deepened over the western Gulf of Mexico (Feb 1983, Mar 1993) were both almost exactly 9 months after a ring separation. This *could* indicate that the position of the warm ring over the western Gulf (an possibly right up against the Texas coast) is a major factor in why these storms deepened so rapidly. However, there have not been enough of these storms to offer any conclusive evidence. A look at the satellite imagery from the ERS-1, ERS-2, and Poseidon satellites may show that

the rings were in the area of cyclonic strengthening, but that will take a further look (and possibly more similar storms).

(23) Synoptic-Dynamic Climatology of the “Bomb”

(Sanders, Gyakum)

AMS; Monthly Weather Review; October 1980; Vol. 108; Pp. 1589-1606

The paper from 1980 is an original look into the idea of a meteorological “bomb” that was defined before, and studied more thoroughly by the two authors. The paper looks at a three year period 1977-1979, and all of the “bombs” in that period in the Northern Hemisphere. A Meteorological “bomb” is defined by a 24 mb drop in central low pressure in 24 hours. After normalizing based on latitude, there were 257 “bombs” in the study period.

- A bomb is classified by a 24 mb CLP drop in 24 hours, which is equivalent (due to the change in latitude) to 28 mb at the pole and 12 mb in 24 hours at 25 degrees N.
- The bomb is primarily a maritime event with most land occurrences over the Eastern U.S. Bombs are most frequent in the westernmost Atlantic and Pacific oceans, 5-10 degrees poleward of the zone of maximum winter initial cyclogenesis frequency. They are most common within or just north of the warm waters of the Gulf Stream/Kuroshio.
- The highest frequency of bombs is in January, but they tend to occur in the months from September to March.
- Bombs tend to form when a 500 mb trough is located near the center of the storm. The trough is most commonly south and west of the system center.
- The mean location for the trough is 400 miles WSW of the surface center.
- The article looks at SST's to see if there is a connection between warm water and rapid deepening, as is the case with tropical cyclones: This is not the case for extratropical cyclones. Instead, there appears to be a relationship between explosive deepening and a strong SST gradient.
- A detailed study and quasi-geostrophic analysis of the 1978-79 bomb season are given.
- There are significant underestimates of explosive deepening of cyclones by the NMC “PE” model of the time.
- Suggestion by authors is that the bulk effect of cumulus convection is a necessary physical ingredient, missing in the NMC models.

(24) Using Normalized Climatological Anomalies to Rank Synoptic-Scale Events Objectively

(Hart, Grumm)

AMS; Monthly Weather Review; September 2001; Vol. 129; Pp. 2426-2442

This article is another approach to create a scale for synoptic-scale events, much as Kocin and Uccellini have tried to do in 2004 for snowstorms. The approach considers all storms, not just snowstorms, and ranks them based on their departures from climatological averages. This “objective” approach considers averages for regions and time of year to rank storms, without taking into effect social concerns such as population density.

- The standard deviation of each climatological event is based on the departure of four factors from normal, and then adding their standard deviations. This creates a total standard deviation (M-total) that ranks each storm.
- The four factors contributing to M-total are height, temperature, and wind (from 1000 mb to 200 mb) and specific humidity (from 1000 mb to 300 mb)
- The most extreme events are those with the largest departures from climatological normal extending the full depth of the troposphere.
- The climatological normals are created by looking at the 53 year period from 1948-2000, and taking averages for each day, months, and season, as well as decade.
- M-total is calculated for the eastern U.S. for every 12-hr period from 1948-2000
- SS93 ranks third on the list with an M-total of 4.577. The highest ranking storm has an M-total of 4.95
- The paper provides a look at the top 20 largest anomalies, and then the top 10 largest in each variable.
- There is a month by month look at the largest anomalies, and their averages, as well as a decade by decade look at the largest anomalies.
- Pp. 2437-2439 gives a comparison of large anomalies to ENSO and other ocean events: The results of these comparisons are that a strong ENSO event increases the activity over the domain (M-total) by about 5%.
- The modulation due to ENSO on daily extreme weather is minimal when compared to natural atmospheric variability on the synoptic scale.
- A M-total of 4 occurs about every 4-5 years, whereas one of 4.5 occurs about every 15 years.
- “There do not appear to be any long term trends in the frequency of extreme events.”

NOTE: It appears that this scale does indeed develop a more meteorological ranking system for extreme synoptic events by discounting social impacts. The scale is based solely on the entire troposphere’s departure from normal.

(25) Planetary- and Synoptic-Scale Characteristics of Explosive Wintertime Cyclogenesis over the Western Atlantic Ocean

(Lackmann, Bosart, Keyser)

AMS; Monthly Weather Review; December 1996; Vol. 124; Pp. 2672-2702

This paper outlines the characteristics of the atmosphere that are necessary for explosive cyclogenesis. The study is done by creating composites of the atmospheric conditions 72 hours before to 72 hours after the rapid deepening of the systems. 42 storms are used to create the atmospheric composites that the results are based up, and a control of 25 non-explosive storms' composites is also created to show what features are lacking in the non-explosive cases.

- The series of 6-day composites is based on 42 storms that exhibited explosive cyclogenesis over 12 seasons.
- The composite is looked at for anomalies in the atmosphere that would cause the rapid intensifications to occur. The authors came up with 5 notable features of an explosive cyclone composite
- 1) A negative 500 mb geopotential height anomaly over the North Pacific, indicative of strengthening and southward shifting of the Pacific jet stream.
- 2) A quasi-stationary troposphere deep ridge over western North America
- 3) Two predecessor troughs that cross the east coast of North America approximately 72 and 36 hours before the onset of surface strengthening.
- 4) A cyclogenetic mobile upper trough that becomes organized in a northwesterly flow approximately 24-36 hours before the onset of surface deepening, and cross the East Coast at the onset of surface deepening.
- 5) A middle and upper-tropospheric trough ridge that develops east of the surface cyclogenesis region 24-48 hours after the onset of surface deepening.
- There is also a 250 mb level jet streak located immediately upstream of the cyclogenetic upper trough 24 hours prior to coastal crossing.
- The control storms lacked the features of the Pacific trough, western ridge, and predecessor troughs.
- Finally, the findings conclude that when there is a case of multiple explosive cyclogenesis events in succession, that the planetary-scale features of the atmosphere play a more important role than when there is one occurrence of cyclogenesis individually (this can occur based on synoptic-scale conditions).
- This study was done only for storms which began deepening in the western North Atlantic in a 10 degree by 10 degree region around 38 degrees N and 70 degrees W.

(26) Medium-Range Prediction of An Extratropical Cyclone: Impact of Initial State

(Zou, Kuo, Low-Nam)

AMS; Monthly Weather Review; November 1998; Vol. 126; Pp. 2737-2763

The article is a discussion of the impact of initial state in predicting cyclogenesis up to 5 days in advance. The storm that was used for this study was a storm that formed over the

Western Atlantic off of the East Coast of the United States during the ERICA experiment. The storm was the ERICA IOP-4 which occurred January 4-5 1989. The purpose of the project was to determine what could be done to improve the medium range forecasts of cyclogenesis by looking at numerically improved initial conditions.

- Short-range prediction of East Coast cyclogenesis has improved significantly over the last decade due to better model resolution, physical parameterization, and good analysis of upstream conditions. Medium-range prediction has not improved as much due to difficulty of predicting longer-range upstream conditions.
- The authors use the PSU/NCAR MM5 model with varying initial conditions to examine the effects on forecasts from 36 hrs to 120 hrs.
- The forecast skill improved as the lead time was shortened, and the MM5 could only predict the cyclogenesis 4.5 days in advance, as the 5 day forecast did not have the formation of a cyclone.
- Better initial conditions were formed by taking later observations, and minimizing errors in earlier initial conditions. The better initial conditions improved the 5-day forecasts to the point where the forecasts with new initial conditions were better than the forecasts 12 hrs later.
- The main uncertainties in the initial conditions, and possible ways to improve forecasts, were the tropospheric temperature analysis over the Rock Mountains and Mexico, as well as a systematic model bias of a PV anomaly over the Gulf of Mexico (at least partially due to the data sparse region of the Northern Pacific) pp.2751
- Modification of the PV anomaly's initial conditions did not have as much of an effect on improving the model forecast of cyclogenesis as improvements in the tropospheric temperature analysis did, because the temperature analysis was the indicator of how strong the baroclinic zone would be over the Atlantic.
- There are numerous charts throughout the paper showing forecasts and model runs, especially in the section from pp. 2744-2754.

(27) Interaction of Potential Vorticity Anomalies in Extratropical Cyclogenesis. Part I: Static Piecewise Inversion

(Huo, Zhang, Gyakum)

AMS; Monthly Weather Review; November 1999; Volume 127; pp. 2546-2561

This paper is a technique that the authors use to create a better understanding of the interactions of the PV anomalies associated with SS93. The technique used is called PV piecewise inversion that was designed by Davis and Emanuel (1991) to create wind and temperature fields around a PV anomaly by using the PV distribution and boundary potential. By creating these fields, the vertical and lateral interactions of the PV

anomalies is studied, and the effect that the PV anomalies had on the deepening of the Superstorm is examined.

- The contributions of all PV anomalies to the surface development increase with the more time that passes during the SS93 development.
- The two upper-level dry PV anomalies contribute the most to the rapid deepening of the storm, followed by the lower-level thermal anomaly, and then by latent heat release.
- In SS93, there was a favorable phase tilt between the upper and lower level anomalies that allowed mutual interactions where the anomalies enhanced each others circulations.
- The background flow advections effects dominate the effects of either vortex-background interaction or vortex-vortex interaction during the rapid deepening of the storm.
- The vortex-vortex interactions of the upper-level PV anomalies cause the negative tilt of the upper-level trough during the rapid deepening.
- The upper level dry PV anomaly contributes the most to the surface cyclone depth (53%)
- The surface thermal anomaly (thermal advection) contributes 28% to the cyclogenesis, while the low to mid-level moist PV anomaly contributes only about 19%.
- There are extensive details of the contributions of every type of interaction to the whole storm in sections 4-6 of this article.

(28) Interaction of Potential Vorticity Anomalies in Extratropical Cyclogenesis. Part II: Sensitivity to Initial Perturbations

(Huo, Zhang, Gyakum)

AMS; Monthly Weather Review; November 1999; Volume 127; Pp. 2563-2575

This study is the second part of evaluating the effects of the Potential Vorticity (PV) anomalies on the rapid deepening of SS93. This part of the sequence studies the difference that varying initial conditions plays in the strength of the cyclone. The first part of the article uses the static piecewise inversion of the PV anomalies to separate them individually. The anomalies are then either strengthened or taken out of the initial conditions, and the effect on the cyclogenesis is noted. The northern and southern upper-level troughs associated with these PV anomalies are found to have dramatically different effects on the rapid deepening.

- The advections of the northern and southern troughs toward the cyclone are important to the surface cyclogenesis.

- Without the northern trough, the advection of the southern trough toward the surface center decreases, and the surface development is greatly impeded.
- When the northern trough's strength is doubled, however, the advectations of both troughs increases, the southern by the northern PV anomaly, and the northern by background flow. This causes the development to be dramatically enhanced.
- In contrast, if the southern trough is doubled in strength, the progression of the northern trough slows, and the surface development is decreased. A stronger cyclone develops in the absence of the southern trough.
- **“Despite pronounced model sensitivity to the intensity of the superstorm, the large changes in perturbations do not change the track of the storm, indicating the importance of background flow in determining the storm’s track.”**
- In this case, the northern trough is most important in the rapid development of SS93, because it is stronger and better coupled with the surface disturbance than the southern trough. The southern trough only plays an important role in the initial organization of the cyclone.
- The authors note that while the conclusions cannot be generalized yet for other storms, it appears that in some short-wave-trough mergers, the vortex-vortex interactions do not necessarily lead to a stronger cyclone.

(29) A Characteristic Life Cycle of Upper-Tropospheric Cyclogenetic Precursors during the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA)

(Lackmann, Keyser, Bosart)

AMS; Monthly Weather Review; November 1997; Volume 125; Pp. 2729-2758

This article is an earlier paper by the same authors as #25, and provides insight not as much into the events that cause rapid cyclogenesis, but focuses directly on how one of these events, an upper-level precursor disturbance, originates and evolves leading up to cyclogenesis. The paper looks at the life cycle of these disturbances, the mechanisms that allow them to evolve, the effect of low frequency flow on the life cycle of the disturbances, and aspects of the life cycle that are especially conducive to rapid surface cyclogenesis. Although good information is given about one storm during the ERICA experiment, only some sparse general cyclogenesis information is given, and none on Gulf of Mexico storms or SS93.

- In the 18 ERICA storms, there was a characteristic life cycle of the upper tropospheric disturbances that included: The formation of an initially elongated region of locally high tropospheric pressure in association with a mid-tropospheric front, followed by the compaction of this disturbance into a more circular configuration, and rapid cyclogenesis as the disturbance passes offshore into the Western Atlantic Ocean.

- Tilting was found to be a critical vortex-generation and frontogenesis mechanism immediately after coastal crossing.
- The role of the background flow is to facilitate the development of the upper precursor by providing a conducive environment for mid-tropospheric cyclogenesis.
- Surface cyclogenesis is favored by the low frequency flow **which may steer the precursor over the warm Gulf Stream waters.**
- There is a good figure on pp. 2755 which summarizes the characteristic precursor life cycle.

(30) The Use of Digital Warping of Microwave Integrated Water Vapor Imagery to Improve Forecasts of Extratropical Cyclones (Alexander, Weinman, Schols)
AMS; Monthly Weather Review; June 1998; Volume 126; Pp. 1469-1496

This article provides a technique that the authors are attempting to apply to the PSU/NCAR MM5 model that has been used in earlier papers, and use a warping technique to improve forecasts with that model. Several storms are used, including the ERICA IOP-4 storm, as well as SS93. The article seems to be a precursor to #16, in which the satellite and lightning data are used to create a better forecast. In this paper, only the satellite data are used, and then “tied down” using actual points from surface observations.

- In the SS93 simulations, the technique is applied to try to determine the formation of the squall line that struck Florida.
- The warping technique is shown to be effective, creating the squall line, but the line is very out of place on this new model run, and is not oriented as it actually was.
- For this reason, the authors apply the “tying down” technique in which the actual surface, satellite, and radar observations are used to improve the location of the squall line on the forecast, which produces the line in an improved preciseness.

MY COMMENT: Although the technique that the authors use in this paper in which data from the SSM/I overpasses are used (as in #16) improves the model forecast and description of the squall line, it does not seem as though this technique is very effective in the way they use it. The technique that includes the lightning data, as described in #16, seems to be a vast improvement on the warping technique, as it actually provides a better advanced forecast.

