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Related Storms Article List:

This list provides a bibliography and summarization of articles related to east coast snowstorms in general, as well as articles studying specific storms. Detailed summaries are given for articles providing information on forecast improvement for specific storms.

Climate/Climatology Articles:

1. Climatology of Blizzards in the Conterminous United States
Schwartz, RM. Schmidlin, TW. 2002. Journal of Climate. **15**, pp. 1765-1772.

The article provides details on the occurrence of blizzards across the United States for 41 winters from the years 1959-2000. There were 438 blizzards over that time period, with as many as 27 (1996-97) in one year to as few as 1 (1980-81). Blizzards are most frequent in January on average, but occur more frequently in December in the Sierra's, March in the Great Plains, and April in Montana. Blizzards were also found to occur more in La Nina ENSO events than El Nino years.

2. A Climatology of winter cyclogenesis intensity in the northwest Gulf of Mexico
Hardy, Jeffrey W. Hsu, SA. 1997. National Weather Digest. **22**, pp. 3-7.

This study is a compilation of all of the extratropical storms that formed over the northwest Gulf of Mexico from 1966-1996. Through investigation of these years, a list of all of the storms and their intensities (based on central low pressure) is provided. The frequencies of both weak and strong systems is also provided in the article, and the occurrence during ENSO events is looked at. The authors find that a significantly greater number of storms form in this part of the Gulf of Mexico during El Nino years.

3. An East Coast Winter Storm Climatology
Hirsch, Matthew E., A.T. DeGaetano, S.J. Colucci, 2001. Journal of Climate, **14**, 882-899.

The purpose of this paper is to create a climatology classifying East Coast Winter Storms (ECWS) into categories based on location, strength, time of year, and causes. This is done by looking back at the storms meeting 4 criteria for the period from 1948-1997. The storms are divided into three categories, Northern, Southern, or Full Coast storms, and are then split into normal ECWS or strong ECWS based on wind speeds. The most frequent times of year for the ECWS are evaluated as are the effects of an El Nino – Southern Oscillation (ENSO) event.

- To be classified as an ECWS, an area of low pressure had to meet four requirements: :
1) Closed circulation 2) Located along the east coast of the U.S. in a quadrilateral bound by: at 45N: 65W and 70W... and at 30N: 75W and 80W 3) General movement from the SSW to NNE, and 4) Surface winds greater than 20 knots during at least a 6-hr period.
- The average position of the Gulf Stream veers sharply away from the coast near 35N, and there is an interaction of cold air and warm waters south of this point. This interaction may be the reason for explosive cyclogenesis south of 35N. The concave coastal shapes at several points along the east coast of the US also cause a pressure drop, and may promote or contribute to explosive cyclogenesis.
- Full Coast storms are defined as storms originating below 35 N, usually in the concave regions of the GA/SC/NC area or the Gulf of Mexico.
- Northern storms usually originated in the Plains or Midwest, with secondary cyclogenesis occurring over another concave section of coastline, the Delmarva peninsula.

- Southern storms stayed below the 35 degree north boundary.
- In the 48 year study, 562 low pressure systems met the criteria for an ECWS.
- Kocin and Uccellini (1990) described 23 snowstorms, all of which are ECWS in this study.
- An average of 11.8 ECWS were found per season.
- There is a general year-to-year variability, with active seasons followed by relatively inactive seasons.
- The 5 yr means for full coast storms show a relatively flat profile, describing little change in the number of full coast storms.
- There was a decline in the number of full coast storms in the 1970's but it was offset by a peak in the northern storm counts.
- The snowy winters of 93-94 and 95-96 were above average, with full coast storms counts of 9 both seasons. There was still a flat 5 year profile, which again shows the large variability year to year.
- 'Looking at 5 year means, pressures of lows have been dropping since the late 1980's, showing an increase in storm intensities.'
- 1/3 of full coast storms were strong storms (winds>45 knots), and 2/3 of all strong storms were full coast storms.
- Overall storm frequency increases during seasons to a peak in January, while the peak of strong storms is not until February.
- ENSO seasons have an average of 44% more ECWS than neutral seasons.
- Two of the four most active seasons were during ENSO events.
- Frequency of all three storm types increase during El Nino seasons , but the number of full coast storms increases the most (75%)
- During strong ENSO events, southern and full coast storms increase more, but northern storm frequencies decrease, possibly due to the stronger southern branch of the jet stream during these years.
- The ENSO events have more effect on the number of storms from December-February than on the frequencies in other months.
- There are an average of 6 northern, 1 southern, and 5 full coast storms per year.
- ECWS deepen to an average pressure of 992.7 mb.
- Sustained surface maximum winds of ECWS average 39.8 knots over 6 hrs.
- An average of 3 strong storms occur per season, with most in February.

4. Storm Following Climatology of Precipitation Associated with Winter Cyclones Originating over the Gulf of Mexico

Businger, Steven. D.I. Knapp, G.F. Watson, 1990.. Weather and Forecasting, 5, 378-403.

In this paper, there is a construction of another climatology for East Coast Winter Storms (ECWS), but instead of looking at only storms that travel the east coast, the authors look at storms originating along the Gulf Coast. There are three distinct tracks for surface lows introduced in this paper, two up the east coast and one across Florida and out to sea. The authors evaluate the moisture flow associated with each type of storm, and the source of the moisture. They also evaluate the areas of precipitation common to each storm, and the location of the precipitation. Finally, a case study is done of a storm (following the track along the east coast), from GALE in 1986.

- Storms were divided into three tracks: Track A is storms following the east coast of the US very close to the coast (most off the coast slightly). Track B is storms farther inland following the Appalachians. Track C is storms following the Gulf Coast and crossing Florida or Georgia and going out to sea.
- The maximum precipitation for the A tracks occurs over the Alabama/Georgia/Florida areas as the lows cross the Gulf Coast region. There is a second maximum when the Atlantic joins as a second moisture source over the Florida Panhandle.
- When the Gulf of Mexico is the major moisture source of the track A storms, nearly the entire southeastern US experiences light precipitation more than 10% of the time the

storm is affecting the east coast. However, as these lows travel north, the extent of precipitation diminishes.

- For Track A storms, the frequency of moderate to heavy precipitation is highest to the northeast of the storm center, with 65% chance of moderate precip in this region and 30% of heavy precipitation.
- For Track B storms, the Gulf of Mexico is the major moisture contributor during the early stages, but as the storms approach the Appalachians over Virginia, the Atlantic provides a majority of the moisture to the storm. The maximum precipitation values decrease as these storms leave the Gulf of Mexico region. (This seems to indicate that the Gulf of Mexico is a better contributor to the strength of Track B ECWS than the Atlantic).
- An interesting feature of Track B storms is that when the storms reach the TN/KY region, they can spawn cyclones along the Atlantic coast, creating a double center for these types of storms. These secondary lows formed in 42% of Track B cases. The secondary lows (usually forming from SC to VA) advect moist air from the Atlantic Gulf Stream, which contributes to Track B precipitation maxima east of the Appalachian Range.
- Track C storms have the same precipitation distribution along the Gulf Coast in general as Track A storms, but they do not veer north. Southern Mississippi, Alabama, and the Florida Panhandle receive most of the precipitation from the Track C storms.
- In the case study of a storm 2/11/86, there is the appearance of a low level jet (LLJ) between 700 and 900 mb. The LLJ was ahead of the cold front, drawing moisture ahead of the storm up the east coast from the Gulf of Mexico. **This appears to be a similar phenomenon to the LLJ that brought moisture from the Gulf of Mexico into SS93 ahead of the cold front. It could be a very frequent feature of storms following this track, as this storm and SS93 were both Track A storms.** The finding of this LLJ supports the evidence in the climatology of the importance of the Gulf of Mexico as a moisture source for storms over the Southeastern US.
- Most of the storms in this study formed over the Gulf of Mexico or the adjacent coastal region.
- The Gulf of Mexico provides a great majority of the moisture for all of the storms that initially form over the Gulf region, with greatest precipitation generally north and east of the storm center.
- The Atlantic Ocean provides little moisture early in the storm's movement, but its influence increases as the storms move north and east.
- The Appalachians play the role of locally increasing precipitation for the three storm tracks.

5. Synoptic Scale Features Common to Heavy Snowstorms in the Southeast United States.

Mote, Thomas L., D.W. Gamble, S.J. Underwood, M.L. Bentley, 1997. *Weath. And Forecasting*, 12, 5-23.

This paper studies synoptic-scale features of southeast snowstorms by creating a composite based on 18 such storms. The paper assigns a "zero hour" to each storm based on conditions in Asheville, NC, and compares the development, intensification, surface, and upper-level features of the entire composite before and after the zero-hour. The study uses the composite to try to determine features that are consistent with most or all of these Southeast storms.

- Synoptic climatological analysis completed in four separate steps: 1) Identification and mapping of heavy snowfall events 2) Determination of a zero hour (+00 hour) for each storm to produce time relevant composites 3) Construction of composites in 12 hour intervals from 72 hours before +00 to 48 hours after +00. 4) Discussion of significant features in each composite.
- Seven states included in study are: VA, NC, SC, TN, GA, AL, MS.
- The study looked at storms from January 1949 to December 1992: Heavy storm based on a loose definition: Snowfall > 10 cm in 12 hours over at least 6 square degrees: For this study, at least 10cm at 50 stations.
- 18 storms were used in the composites.

- The +00 hour was determined by the first hour of continuous snowfall at Asheville, NC.
- **Similar storms given on page 7: 2-4 March 1960, 29-30 January 1966, 25-27 December 1969, 17-19 February 1979.
- Only one storm in the study did not have the heaviest snowfall in the Appalachians or the Mississippi Valley.
- In the -48 hr composite, an arctic air mass with center of high pressure is located over northern Saskatchewan. Area of low pressure is evident over northern Mexico north to the Big Bend region (Texas). There is a developing jet streak centered over southern Indiana.
- At -36 hrs, the Canadian anticyclone is centered near Winnipeg, Manitoba. Cold Air Advection (CAA) is present throughout the great lakes, and is particularly strong from Michigan to western New York. The CAA **increases baroclinic instability near the Gulf of Mexico**. The jet streak is better defined at 250-mb, with winds > 60m/s from western KY into MD, VA, and NC.
- At -24 hrs, the Canadian anticyclone moves farther southeast, centered over northern MN with pressure of 1030. Looking at each storm indicates that the anticyclone is usually present over the Great Plains or Northeast. The jet streak remains anchored over the same region, but expands west to St. Louis.
- At -12 hrs, the anticyclone has not moved, but the arctic air mass has expanded, with the 1020 mb isobar as far south as the Gulf Coast. The 0 degree C isotherm extend from TX to SC. A strong temperature gradient is evident along the gulf coast states and northern Gulf of Mexico, with a 15 degree C difference from the TX panhandle to Brownsville, TX. A trough at 700 mb strengthens from CO to NM, backing low level flow, and enhancing warm air advection (WAA) from the Gulf of Mexico, and thus enhancing upward motion.
- At +00 hrs, the anticyclone is centered over western Wisconsin, and an inverted trough forms over the Gulf of Mexico. The 700-mb trough runs from IA to the Gulf Coast, and a region of 70%+ humidity is present from AL to MS. This time period is when snow is expected over the western area of the study region. The jet streak has moved northward into Delaware, and has intensified to 70 m/s.
- At +12 hrs, the anticyclone is moving southward across the Great Lakes. Comparing individual storms shows one center of high pressure over Kansas City, and one over Ontario. A surface low pressure is apparent forming west of Tampa Bay. The trough continues to amplify and is vertically stacked from 700-200 mb. The jet streak has moved to just east of the New Jersey Coastline. A large region of >70% humidity covers all of SC, northern GA, NC, and eastern TN at 700-mb, and this region is indicative of the area of heaviest snowfall.
- At +24 hrs, a distinct surface low is present east of the NC coast, with CLP of 1011 mb. The anticyclone has moved into the southern plains, with the high pressure located near Dallas. The trough has stopped amplifying. The area of humidity >70% has decreased in size and only covers coastal NC, while the Jet Streak has moved into the Cape Cod area.
- Low-Level Jet (LLJ) – The LLJ is evident throughout the composite, starting at -12 hrs going from the Gulf of Mexico into Texas. As the composite progresses, the LLJ moves across LA, MS, and AL, and is nearly parallel to the GA coast by +12 hrs. This jet produces upslope flow across the entire region from +00 to +12 hrs, when the maximum heavy snowfall occurs.
- The southern Appalachians are located under a region of upper-level divergence associated with the right entrance of a jet streak off the Atlantic coast, coinciding with heavy snowfall.
- The moisture that results in Southeast snowfall is carried along the LLJ and experiences adiabatic ascent. The moisture source for the LLJ is the Gulf of Mexico: Moisture rises from the surface to 700-600 mb over the Carolinas. In the eastern Appalachians, moist air from the Atlantic Ocean is also dammed up against the eastern slopes, creating more intense snowfall.

- Due to cold air damming against the Appalachians, there is often only 0 degree C temperatures in the lowest 50 mb in the Carolinas, resulting in sleet and freezing rain over much of the region.
- Most of the snowstorms develop low pressure over the Gulf of Mexico along the leading edge of the anticyclone, while some appear to redevelop as their favorable upper-level dynamics overrun the strong baroclinic zones of the Gulf Region.
- The preferred cyclone track follows the Gulf Coast, crosses over northern FL/ southern GA into the Atlantic Ocean, and follows the east coast. The location of the storms at +00 hrs is along the central Gulf Coast, with a mean CLP of 1003 mb.
- In greatest snowfall storms, cyclones move into the Gulf states before crossing into the Atlantic ocean.
- The rapid deepening of the cyclones off the Carolina coast is the result of the tight thermal gradient between cold air along Appalachians and warm air over the Gulf Stream.
- Cyclogenesis over the Gulf of Mexico occurs just preceding the onset of heavy Southeast snowfall.
- When rapid intensification occurs off the Carolina coast, and Atlantic moisture is fed into the Appalachians, the rates of evaporative cooling decrease, and sleet/freezing rain likelihood increases.
- SS93 was not included in this study for fear of very strong features significantly affecting the results.
- If SS93 was included: The +00 center was just south of Louisiana coastline. The location was similar to that of other storms, but cyclone was much deeper: 984 mb compared to 1003. The other features were the same: anticyclone dropping across the plains, amplifying trough. **In SS93, however, there was a coupling of two upper-level jet streaks, one ahead and one behind the surface cyclone. Although common to east coast snowstorms, this coupling is uncommon among southeast snowstorms. The jet streak combined with strong isentropic up-glide produced record snowfalls in the Southeast.**

6. Planetary- and Synoptic-Scale Characteristics of Explosive Wintertime Cyclogenesis over the Western North Atlantic Ocean.

Lackmann, Gary M., L.F. Bosart, D. Keyser, 1996. Mon. Wea. Rev., 124, 2672-2702.

The authors examine the planetary-scale features of explosive cyclogenesis in the North Atlantic Ocean, and their relationship to cyclone formation and cyclogenetic precursors. While previous papers have examined the synoptic-scale characteristics of these storms, this article relates the planetary- and synoptic-scale events. Particular emphasis is placed on the planetary-scale, and its interaction with synoptic-scale cyclogenetic precursors.

- The planetary- and synoptic-scale flow environments are put into a composite based on 42 western North Atlantic wintertime explosive cyclogenesis events, with the 6 days surrounding each event placed into the composite.
- The source used for the gridded data is the National Center for Environmental Prediction (NCEP) twice-daily hemispheric analysis.
- The onset of deepening is defined as a Central Sea Level Pressure (CLP) drop of 2 mb in 3 hours for 2 or more consecutive 3 hour periods.
- The 42 storms were taken over a period of 12 seasons.
- Composites of 500-mb geopotential height, geopotential height anomaly, geostrophic relative vorticity (QGPV), QGPV anomaly, as well as 200 mb heights, 250-mb winds, 850-mb temperatures, and sea level pressure (SLP) are generated. Anomalies are defined as departures of the composite fields from the monthly means. The monthly mean fields are computed from 1964-1988.

- Throughout the composites, there is a 500-mb geopotential height ridge located over the west coast of North America, and a broad trough over eastern North America.
- The axis of maximum SLP lies east of the ridge axis at 500 mb.
- The composite SLP field exhibits a large cyclone centered near the Aleutian Islands, and an anticyclone centered over western North America.
- There is a persistent geopotential height anomaly with negative values over the North Pacific and positive values over western North America.
- The negative anomaly over the Pacific indicates a southward shift of the jet stream in this region, with strengthened geostrophic flow south of the anomaly center.
- The presence of statistically significant synoptic- and planetary-scale features in the composite fields shows a preferred flow configuration associated with explosive wintertime cyclogenesis over the western North Atlantic Ocean.
- Three previously determined synoptic-scale features (Bell and Bosart 1989) are present in planetary-scale study: Predecessor trough, cyclogenetic trough, and Atlantic Ridge.
- The strongest cyclogenetic events are accompanied by movement of cold air into the cyclogenetic region.
- Consistent with Sanders and Davis (1988), there are negative 500 mb geopotential height and 850 mb temperature anomalies west of the incipient surface cyclone prior to the time of initial development.
- Both the North Pacific Ridge and the western North American ridge are “robust” features of the explosive cyclone composite.
- The western trough ridge couplet remains significant even with the removal of all events occurring in El Nino years.
- Maps and chart of the composites given from 2690-2698
- Persistent features for all storms include North Pacific trough, enhanced Pacific jet, and a prominent troposphere-deep trough over western North America.
- The Pacific trough and western ridge remain nearly stationary during the 6-day evolution of the composite.
- The 500 mb cyclogenetic trough develops over the western North American ridge, and when the trough reaches the East Coast, an associated ridge forms over the North Atlantic Ocean.
- Transient features include two predecessor troughs, one cyclogenetic trough associated with rapid surface deepening, and an upper-tropospheric jet streak west of the developing cyclogenetic trough.
- A composite of 25 **non**-explosive cyclones was done as a control.
- The Pacific trough and western ridge show only transient features in the control, whereas they are prominent in the explosive composite.
- There is no evidence of precursor disturbances in the control.
- The cyclogenetic trough is smaller in amplitude and develops later in the non-explosive composite when compared to the explosive.
- The planetary-scale features described appear to be unique to explosive cyclogenesis in the North Atlantic Ocean.
- Although some of the same features are apparent in both composites, the non-explosive composite appears to have more mobile, shorter-lived, and lower-amplitude anomalies when compared to the explosive composite.
- Planetary-scale features appear to play an important role in the occurrence of explosive wintertime cyclogenesis over the Atlantic Ocean.

7. Energy dispersion effects on explosive development of marine cyclones
 Huang, Liwen. Qin, Zenhao. 1998. *Acta Meteorologica Sinica*. **12**, pp. 486-503.

This study details how an eddy can move from a decaying cyclone and perturbate downstream, creating another disturbance. The study followed anomalies starting over the Pacific Northwest, through their development to decay, and then followed their signatures across the U.S. The authors find that in many cases of explosive cyclogenesis, the initial development is caused by the dispersion of energy from eddies thrown out of decaying cyclones upstream.

8. 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.

9. 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.

10. 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.

11. 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.

12. 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...

Oceanic Effects on Cyclogenesis

13. Impacts of waves, sea spray, and upper ocean on extratropical storms

Perrie, Will. Zhang, W. Long, Z. Andreas, EL. 2004. 13th AMS Conference on Interactions of the Sea and Atmosphere. 8-13 Aug 2004.

This article is a study on the effects that wave drag, sea spray, and upper ocean sea surface temperatures have on the development and intensity of extratropical cyclones. The authors do a study on three hurricanes that became extratropical and two winter “bombs” in January 2000 and January 2002. Results find that these factors are most prominent at the most intense point of the storm, when the highest winds occur, creating more sea spray and wave drag, thus adding to the strength of the systems.

14. The life cycle of an extratropical marine cyclone. Part I: Frontal cyclone evolution and thermodynamic air-sea interaction

Neiman, Paul J. Shapiro, MA. 1993. Mon. Wea. Rev. **121**, pp. 2153-2176.

This study details the first precursors of extratropical cyclogenesis by looking at one storm from 4-5 January 1989 that was investigated during ERICA. The authors found two main events that come before the development of the cyclone’s comma head shape: 1) a storm-relative westward development of the warm front as a bent-back front into the polar airstream and 2) the formation of a warm-core frontal seclusion in the post-cold-frontal cool air at the southwestern tip of the bent-back front.

15. Mesoscale air-sea interactions related to tropical and extratropical storms in the Gulf of Mexico

Lewis, James K. Hsu, SA. 1992. Journal of Geophysical Research. **97**, pp. 2215-2228.

This article discusses some of the main features in the Gulf of Mexico that the authors feel are important to the development of both tropical and extratropical cyclone development in that area. The study details the northwestern Gulf of Mexico, and shows several features that are primarily important for instability during the study (December 1982 – March 1983): The importance of lower level vorticity, unstable air along the shelf break in the Gulf, and effects of the Loop Current and its rings are all discussed in the paper, and the authors discuss at the end how cyclonic vorticity can be generated in the lower atmosphere by these oceanic features.

16. Numerical Simulation of a mesolow over a Gulf Stream filament

Raman, Sethu. Reddy, Neeraja C. 1996. Pure and Applied Geophysics. **147**, pp. 789-819.

This study’s purpose is to determine the importance of Gulf Stream filaments (warm areas branching from the Gulf Stream) in East Coast cyclogenesis. The study puts a filament in an area

with constant ambient wind speeds, and the area develops a circulation, then removes the filament and the simulation lacks circulation. This presents one possible cause of offshore cyclogenesis for the U.S. East Coast.

17. The Effect of Gulf Stream-induced Baroclinicity on U.S. East Coast Winter Storms.
Cione, Jospeh J., S. Raman, L.J. Pietrafesa, 1993. Mon. Wea. Rev., 121, 421-430.

This paper looks at the effect of the Gulf Stream, particularly off the East Coast of the Carolinas, in inducing strong baroclinicity in the region. This baroclinicity has been known to lead to rapid and explosive cyclogenesis in the region, and is a major focal point for the development of East Coast Winter Storms. The paper takes a composite of storms, and of Sea Surface Temperatures and coastline surface temperature to study this effect.

- Knowledge of Coastal Marine Boudary Layer (MBL) conditions is becoming apparently important to prediction of the development of “bombs”
- The MBL is a highly baroclinic zone in the Carolina region due to the proximity of the Gulf Stream to the coastline.
- During Cold Air Outbreak (CAO) periods, cold air flows offshore and encounters the warm air over the Gulf Stream environment.
- The magnitude of the MBL is a function of both distance of the Gulf Stream front (GSF) from shore and the intensity of the CAO.
- The Gulf Stream is known to move horizontally in the region north of Charleston, SC. As a result, wintertime variability in the region is pronounced.
- Only the MBL off the coast of the Carolinas and Virginia was studied (for objectivity).
- All East Coast winter storms entering the region for 6+ hours from 1982-1990 were analyzed, with trajectory information, as well as Sea Suraface Temperature (SST) analyses were retrieved from the National Climatic Data Center.
- Objective of study is to find link between horizontal baroclinicity and cyclogenetic intensification.
- Cape Hatteras and Wilmington, NC were the coastal sites used in the study.
- Near surface air temperatures were obtained at 3-hr intervals , and averaged during the 24-hr coldest period of the storms with the objective being to find the prestorm period with maximum baroclinicity.
- Storm intensification was taken to be the SLP decrease.
- The distance of the GSF at Cape Hatteras varied from 15-120 km from the coast, and a Wilmington, 100-300 km from the coast. The horizontal temperature difference from coastline to jet stream varied from 3-30 degrees C.
- Large temperature contrasts between cold continental and warm Gulf Stream environments strengthen the magnitude of thermal winds and lead to formation of a low-level jet.
- Initially, the cold continental air meeting the warm jet stream air produces moist convection and formation of shallow clouds over the Gulf Stream.
- The cold and dry continental airmass is warmed and moistened with time, increasing the depth of the MBL: This is referred to as the atmopheric preconditioning period.
- During strong CAOs, large sensible heat and latent heat fluxes occur over Gulf Stream waters: The largest values and strongest gradients of total heat flux exist offshore to the north and east of Cape Hatteras.
- During some of the wintertime CAOs, the coastal waters off VA/NC are transformed into a region of strong surface-layer heating due to the proximity of the Gulf Stream. This results in large horizontal temperature and humidity gradients, and large gradients in sensible and latent heating.
- The time of minimum air temperature coincides with the time of maximum wind speed during CAO events.
- The lag time between occurrence of maximum air-sea temperature contrast and time of most rapid storm intensification was also investigated.

- Low-level surface heating, especially latent heating, enhances the process of offshore cyclonic development.
- Stronger storms are associated with much smaller lag times than the weaker events.
- When the largest surface fluxes are located to the rear of the storm (cold advective quadrant), they do not play a major role in the storm intensification: The fluxes would not help strengthen the cyclone in these cases.
- Latent-heat release associated with deep cumulus convection acts to decrease the CLP substantially, which increases the low-level wind field and convergence pattern of the storm.
- For decreased lag time conditions (stronger storms), the region will: 1) remain highly baroclinic at low levels. 2) Still show signs of a strong offshore heat flux distribution.
- The magnitude of prestorm CAOs is substantially larger for strong storms compared to weak storms: 21 degrees C change vs 12.2 degrees C change.
- The highly baroclinic conditions present off the NC/VA shore during prestorm and development stages significantly affect local intensification rates in developing storms.
- At Cape Hatteras, the mean distance to the GSF was 56.6 km. Whereas at Wilmington it was 194.6 km.
- For air moving at the same rate, it would take cold continental air 3.3 times longer to reach the GSF at Wilmington than at Cape Hatteras.
- The Gulf Stream position may indeed affect initial deepening rates, as storm development is more intense in the Hatteras region than the Wilmington region.
- The smaller standard deviation of distance of GSF at Cape Hatteras for storm experiencing pressure drops of 3 mb/3 hrs suggests a “preferred” position of the GSF with respect to cyclogenetic intensification.
- More intense events are characterized by significantly smaller GSF-to-land distances (56.6 km to 71.4 km). These results were also found when looking at strong vs weak storms **only at Cape Hatteras**, increasing the validity of the results.
- Both GSF distance and prestorm temperature are significant factors of the rate of offshore cyclonic intensification.
- The prestorm low-level baroclinic nature of the region plays a “key role” in the eventual intensification of cyclonic events entering the study region.
- Strong storms had lag times averaging 20 hours, while weaker storms averaged about 40 hours.
- Examining all factors, the region offshore southeast VA and northeast NC is potentially a maximum intensification zone for developing cyclones south of 38 degrees N.

18. The Use of Pre-storm Boundary-layer Baroclinicity in Determining and Operationally Implementing the Atlantic Surface Cyclone Intensification Index.

Cione, Joseph J. R.A. Neuhertz, S. Raman, L.J. Pietrafesa, K. Keeter, and L. Xiaofeng, 1998 *Boundary-Layer Meteorology*, **89**, 211-224.

The authors do a follow up paper on the earlier article by Cione et al (1993) in looking at uses of the determination of the Marine Boundary Layer (MBL) along the NC/VA coastal region. By using sea-surface temperature (SST) and thus Gulf Stream Front (GSF) data, the authors attempt prediction of cyclogenesis in this region. With NOAA and North Carolina State University data, they create an operational use of the GSF data in prediction of the intensity of winter cyclones.

- Paper looks at determining the usefulness of the NWS Atlantic Surface Cyclone Intensification Index (ASCII) by looking at results from the 1994-1996 use of ASCII.
- The other possible uses of the Cione 1993 paper are discussed, and their effectiveness evaluated.
- Descriptions of the study by Cione (1993) are on 214-215.
- The ASCII is more effective now that the NOAA polar orbiting data is available twice a day. This data gives significantly more and improved data with 1.1 km resolution SST data twice daily as opposed to the prior NOAA data once or twice weekly. With this data,

highly accurate representations of the SST conditions off the NC/VA coastline are available on a routine basis.

- During the CAO periods, regional SST and surface-air temperatures were recorded, at Cape Hatteras and Wilmington, just as in the previous study by Cione.
- ASCII is a predictive index for surface cyclogenesis/re-intensification in the mid-Atlantic coastal zone.
- ASCII can produce data on intensity 24 hours before the beginning of cyclogenesis by taking into account the SST.
- Useful tool for RAH? Forecasters who make marine advisory statements.
- The method for determination and implementation of ASCII is given on pages 217-221.
- The ASCII statistical forecast technique provides “added-value” to the numerical forecasts of wintertime cyclogenesis in the mid-Atlantic region coastal region.
- The ASCII value is most significant in cases of weak to moderate cyclonic intensification, again making it especially useful for accurate marine advisories.
- The ASCII technique is used to gauge potential for cyclonic intensification due to forcing in the low-level baroclinic environment during the pre-storm period.
- “Bomb prediction”: When looking at the ASCII numerical values, when a prediction of more than 11.5 mb/12 hr decrease in CLP is forecast, the likelihood for a bomb occurring (12 mb/12 hr) increases “dramatically”.

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 (and 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).

Factors Contributing to Storm Formation and Intensification

1: Regional/Meso/Microscale: Factors Contributing to Storm Formation/Intensification

23. Mesoscale Prediction of the Surprise Snowstorm of 24-25 January 2000.

Zhang, F. C. Snyder and R. Rotunno 2001. *Month. Wea. Rev.*, **130**, 1617-1632.

This article focuses on a specific snowstorm that experienced explosive cyclogenesis off the coast of Georgia/South Carolina on January 24, 2000. The storm was not well predicted in terms of strength or precipitation by NWS forecasters, and was thus called a "Surprise" storm. This paper looks at the predictability of the storm, and what could have been improved in the NCAR-PSU MM5 model to better predict the storm, especially in terms of precipitation forecasts.

- Primary focus is quantitative precipitation forecasts out to 36-hrs.
- ETA model completely missed the precipitation of the storm over the Carolinas except for some light precipitation on the coast, when in fact a record 20 inches of snow fell in Raleigh.
- Authors use a research model, the NCAR-PSU MM5 to try to improve the precipitation forecasts in several ways: model grid resolution, overall initial conditions, and specific sounding initial conditions.
- Several studies (Orlanski, Katzfey 1987, Anthes 1983, Kocin 1985) have found the lateral boundary conditions of models increases in importance with forecast lead time.
- For model resolution, the study focuses only on 36-hr forecasts, improving resolution down to 3.3 km: Significant improvements are achieved through higher grid resolution.
- Changes in the forecasts with MM5 vs ETA are not through growth of forecast differences at the synoptic scale, but through the very rapid growth of moisture differences at the meso- and micro-scales.
- Storm: 300 hPa low formed off of GA/SC coast, moved north through NC and then onto the DC area. Ended up in New England on 26 January.
- There was a 22 mb drop in pressure in 24 hrs from 24-25 January.
- Experiments done by changing model resolution from 60 to 10 km and then from 10 to 3.3 km all show that the forecast differences between the MM5 and ETA models grow most rapidly at smaller scales, while differences at larger scales are smaller.
- Experiments show distinct mechanisms for error growth at the synoptic and meso-scales: Error growth at small scales is tied to the presence of moisture processes in the flow, while at synoptic scales the error is tied to predictability of global models.

- Both insufficient resolution and initial conditions are the cause of errors in the original models and forecasts.
- Increased resolution results in crucial changes to the model forecasts' upper-level features, while running the simulations without late-heat release show little to no dependence on the model resolution.
- Authors suggest that the planned increase of model resolution for operation forecasts to 10 km will significantly improve quantitative precipitation forecasts, but because the forecasts did not improve greatly when resolution improved to 3.3 km, any further increases in resolution will require much more justification.
- The dependence on initial conditions was evaluated by initializing the model with several different analyses.
- The MM5 model using the ETA analysis as a first guess produced the best result.
- Errors in initial conditions likely accounted for a substantial (although substantial is not really defined) portion of the operational forecast errors.
- Removal of any single sounding from the MM5 analysis produced only marginal changes to the cyclone strength, position, or precipitation forecasts (this downplays one of the theories that a couple of faulty soundings were to blame for the very poor forecasts at the onset of the storm)
- Rapid forecast-difference growth at scales smaller than 600 km is an important result reiterated many times throughout the paper. In particular, the authors demonstrate by simulations without latent-heating, the growth at small scales requires moist processes.
- Results indicate that there is inherent difficulty involved in estimating precipitation relative to other features, such as surface pressure, and small changes in initial conditions may not affect general features of the storm, but can have drastic effects on prediction of amount and location of precipitation.
- Due to the importance of initial conditions, detailed precipitation forecasts for this event may have been impossible beyond 2-3 days in advance, even with greatly improved analyses.

24. A numerical investigation of a moderate coastal storm with intense precipitation (12-14 February 1993).

Zhang, Da-Lin. MacGillivray, Karl. 1997. Atmosphere-Ocean. **35**, pp. 161-188.

This article is a study on a coastal storm on 12-14 February 1993, with an emphasis on attempting to improve the Canadian Regional Finite-element model by using more realistic physical representations than the initial model run used. By adding better moist physics, there is an improvement in the predictions of cyclogenesis, and distribution and intensity of heavy precipitation. The authors also state that from the study it is found that latent heat release accounts for 50% of the cyclone's total deepening.

25. A regional model intercomparison using a case of explosive oceanic cyclogenesis

Gyakum, John R, Et. Al. 1996. Weather and Forecasting. **11**, pp. 521-543.

This paper is an evaluation of the current (1996) regional models in an intercomparison to determine systematic errors with models. The study looks at the Canadian Atlantic Storms Experiment and the Genesis of Atlantic Lows Experiment. The results find that throughout the regional models there is a high sea level pressure bias and cold tropospheric temperature error in the oceanic regions, while there is a low sea level pressure bias and warm tropospheric temperature error in continental regions. These errors cause the models to produce systematically weaker systems than actually occur during the critical early stages of cyclogenesis.

26. The ERICA IOP-5 STORM: Mesoscale cyclogenesis and precipitation parameterization
Kuo, Ying-Hwa. Reed, Richard J. Liu, Yubao. 1996. pp. 1409-1434.

The paper assesses the performance of various subgrid-scale cumulus parameterization and microphysics scheme in the PSU/NCAR MM5 model with the objective of determining just how important latent heat release is to cyclogenesis. Emphasis in the paper and the study is on several factors of the model including intensity, distribution, and precipitation in mesoscale low pressure centers looked at in study. The study is done at grid resolutions of 20 and 60 km. In all of the cases, the important feature that was present affecting all of these factors was the presence of an upper-level PV maximum.

27. Local Energetics on explosive development of extratropical marine cyclones
Huang, Liwen. Qin, Zwnhao. Wu, Xiuheng. Zou, Zaojian. 1999. Acta Meteorologica Sinica. **13**, pp.47-63.

A diagnosis of explosive extratropical development is done in this article, with the authors breaking the development into local balance, net volume integration, and vertical distribution of potential energy. Three primary “scenarios” are responsible for explosive development. One that is specifically responsible is enhanced baroclinic instability by “eddy heat transport” and “eddy diabatic heating.” Another is that cyclogenesis is a product of strong thermal differences during the cold season.

2: Observation Improvements: Factors Contributing to Storm Formation/Intensification

28. Satellite-derived integrated water vapor and rain intensity patterns: indicators for rapid cyclogenesis.
McMurdie, Lynn A. Katsaros, Kristina B. 1996. Weather and Forecasting. **11**, pp. 230-245.

This article is trying to prove a relationship between water vapor content, rain intensity patterns, and rapidly deepening cyclones. The authors look at 12 rapidly deepening storms and 11 non-rapid cases to examine the relationship. They found that correlations (R-squared) of 0.55 to 0.70, the Special Sensor Microwave Imager indications of high water vapor anomalies and heavy precipitation predicts a case of rapid cyclogenesis, while there are secondary factors including condensations and lower atmospheric water vapor that also play a role in storm intensification.

29. Incorporation of SSM/I-derived water and rainfall rate into a numerical model: a case study for the ERICA IOP-4 cyclone
Xiao, Q. Zou, X. Kuo, Y-H. 2000. Mon. Wea. Rev. **128**, pp. 87-108.

This paper aims to improve cyclogenesis forecasts by doing a case study on the 4-5 January 1989 storm, and assimilating rain rates (RR) and precipitable water (PW) measurements into the model for the storm. The model used is the PSU/NCAR MM5 model, and the authors found the following results: The MM5 initial simulated a less intense and center-shifted storm based on NCEP analysis (from surface and radiosonde observations), the PW and RR were successfully integrated into the model for this study, and this integration significantly improved prediction of the cyclone, specifically the track of the storm.

30. Forecast skill of the ECMWF model using targeted observations during FASTEX
Montani, A. Thorpe, AJ. Buizza, R. Uden, P. 1999. Quarterly Journal of the Royal Meteorological Society. **125**, pp. 3219-3240.

In this paper, the authors are promoting the idea of adding “targeted observations” or more observations at certain places and times, in an attempt to improve initial conditions. The ECMWF model was run twice for each set of data, once with the actual observations that were included, and again for the observations included and those that were added. The improvement in the prediction errors was an average (for less than 48-hr forecasts) of 15%, with a maximum improvement of 37%.

31. Incorporating TOMS ozone measurements into the prediction of the Washington, D.C. winter storm during 24-25 January 2000
Jang, K. Zou, X. De Pondeca, MSFV. Shapiro, M. Davis, C. Krueger, A. 2003. Journal of Applied Meteorology. **42**, pp. 797-812.

This article is a specific application of an improvement to forecasting the 24-25 January 2000 “surprise” snowstorm. The suggestion is that with the incorporation of measurements for total column ozone data from the Total Ozone Mapping Spectrometer (TOMS) into the initial conditions for the model, there will be dramatic improvements in the forecasts of position and intensity of the storm. This prediction was investigated based on previously documented correlation between ozone (O₃) and vertical mean potential vorticity.

- The study finds that for this storm, when adding only ozone measurements into the initial conditions for the model, there is not an increase in performance from the model.
- Three 4DVAR experiments were then carried out on O₃ data, radiosonde data, and both combined to determine the effect on model improvement.
- The authors find that although the O₃ data and radiosonde data, by themselves, do not lead to any improvement on the models of storm development, the two combined produce a stronger, more rapidly deepening storm closer to the coast, as was the actual case.

NCEP hourly precipitation data is used a verification of the better model performance with the O₃ data included, and shows that the TOMS data is in fact a way to improve cyclone prediction.

32. Impact of assimilating SSM/I rainfall rates on numerical prediction of winter cyclones (several storms)
Chang, Simon. Holt, Teddy R. 1994. Mon. Wea. Rev. **122**, pp. 151-164.

This study details the positive effects that the assimilation of Special Sensor Microwave/Imager estimated rainfall rates (RR) can have on model accuracies. The paper focuses on two storms, one during the GALE project 26-28 January 1986 and one during the ERICA project 4-5 January 1989. The results of including the RR data in the model (Regional Analysis and Forecast System? RAFS) show that when including the RR data, there is a 50% improvement in forecast error over model runs done with no satellite data. The most improved areas with this new data were better storm track prediction and better structure forecasts.

33. 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.

Prediction Improvement Through Model Simulations

34. Linearly stable localized atmospheric features inserted into nonlinear cyclogenesis
Grotjahn, R. 2003. AMS Conference on Atmospheric and Oceanic Fluid Dynamics. 8-13 Jun 2003.

This paper studies the effect of inserting three dimensionally localized features as initial conditions into otherwise linear models. The simulations consider whether nonlinear convection favors nonmodal growth or normal mode baroclinic instability. The selected initial conditions are found to have very little nonmodal growth, and the same is true for basic flows that are tested. The new initial conditions lead to faster breakdown of localizations in the model, and initial condition tilts better develop upstream conditions consistent with observed cyclogenesis.

35. Sensitivity diagnosis of the 24-25 January 2000 storm
Kleist, DT. Morgan, MC. 2003. 10th AMS Conference on Mesoscale Processes. 22-27 Jun 2003.

This study examines the 24-25 January 2000 snowstorm from the basis of an evaluation of the model products. The paper looks at several features of the model (PSU/NCAR MM5) to determine what could be improved to improve forecasts. The features specifically focused on are: “energy weighted,” lower tropospheric circulation, horizontal frontogenesis, vertical motion, and finally a look at forecast error. The similarities and differences between models in relative vorticity and potential vorticity are also examined.

36. Mesoscale predictability estimated through explicit simulations of moist baroclinic waves
Tan, Z-M. Rotunno, R. Snyder, C. Zhang, F. 2002. 19th AMS conference on Weather Analysis and Forecasting. 12-16 Aug 2002.

This article details the study of the effect of simulations on moist baroclinic waves on better predicting the January 24-25 2000 “surprise” snowstorm. The model used in this study is the PSU/NCAR MM5 model: the simulations are done by adding an upper-level disturbance to trigger cyclogenesis. The dependence of error growth on synoptic-scale interaction initial errors is shown, and the fact that small changes in the initial conditions drastically influence small scale errors that propagate and grow quickly throughout 36-hour runs, the time out forecasts of this storm were still very poor.

37. Synoptic interpretation of adjoint-derived forecast sensitivities (24-25 January 2000)
Kleist, DT. 2002. 16th AMS Conference on Probability and Statistics in Atmospheric Sciences. 13-17 Jan 2002.

This paper is about an idea of having observing systems take more observations when forecasts are disagreeing to try and give the models better initial conditions to work with. The 24-25 January 2000 storm is looked at in particular because of poor forecasts at 36+ hours lead time. The study looks to improve the lead times and accuracies of forecasts such as this storm by convincing forecasters that better initial conditions at greater lead times adds to the accuracy of forecasts.

38. Single-vector perturbation growth in a primitive equation model with moist physics
Ehrendorfer, Martin. Errico, Ronald. Raeder, Kevin D. 1999. Journal of Atmospheric Sciences. **56**, 1627-1648.

This article looks to improve two problems with the NCAR Mesoscale Adjoint Modeling System, V2, tangent-linear description of moist physics, and design of an appropriate measure of growth. The authors emphasize the second of these two problems. They find in looking at explosive cyclogenesis and summer convection, that consideration of moisture in inexact ways can lead to faster error propagation than with only minimal consideration of moist physics.

39. Misforecasts of synoptic systems: diagnosis via PV retrodiction
Fehlmann, Rene. Davies, Huw C. 1997. Mon. Wea. Rev. **125**, pp. 2247-2264.

This article looks at a way of improving forecasts by taking into account tropopause-level features, specifically PV anomalies, and using these features to more accurately predict synoptic and sub-synoptic weather systems. The approach identifies upper-level PV errors at the forecast time, and traces them back to their initial analysis time, to identify problems. The authors find that revised simulations after improvements in forecasting PV anomalies predict the actual development of systems much more accurately. They argue that sufficient evidence exists that initial condition field improvement is needed, as are alternate forecasting strategies for PV propagation.

40. A case study of cyclogenesis using a model hierarchy
Rotunno, Richard. Bao, Jian-Wen. 1996. Mon. Wea. Rev. **124**, pp. 1051-1066.

This article uses a hierarchy of model studies for one case of cyclogenesis to attempt to confirm the fact the tropopause level perturbations are prevalent preceding cyclogenesis. The authors look at the fact that it is these perturbations that associate with baroclinic instability and form extratropical cyclones. The models are looked at in order of decreasing complexity.

41. The life cycle of the intense IOP-14 STORM during CASP II. Part II: Sensitivity experiments
Huo, Zonghui. Zhang, Da-Lin. Gyakum, John. 1996. Atmosphere-Ocean. **34**, pp. 81-102.

This article is a review of sensitivity experiments done on a storm during CASP, looking at which factors affected storm development the most. The model used was the Canadian RFE model, and the findings show that latent heat release accounted for 30% of the storm's deepening, with dry processes accounting for the rest. The explosive nature of the storm's deepening was the result of weak surface drag over the ocean, and the storm is baroclinically driven in nature, while only modulated by other physical processes.

42. Explosive marine cyclogenesis in a three-layer model with a representation of slantwise convections: a sensitivity study
Balasubramanian, G. Yau, MK. 1995. Journal of Atmospheric Sciences. **52**, pp. 533-550.

In this article, explosive marine cyclogenesis is studied using a 3-layer primitive equation model with a representation of slantwise convection. The authors create a simulation of a back-bent warm front, and its effect on explosive deepening. One of the major findings was that both enhanced vertical wind shear and weak low-level stabilities have significant impacts on explosive cyclogenesis. Stable condensation also accelerates the development of baroclinic waves in the simulations.

43. Optimal initial perturbations for 2 cases of extratropical cyclogenesis
Vukicevic, Tomislava. 1998. Tellus. Series A. **50A**, pp. 143-166.

This paper studies the effectiveness of a model (ECMWF) in creating an accurate product for cyclogenesis given optimal initial conditions for the storm, with values that should create a perfect forecast. When the optimal conditions are applied to the model, the ECMWF does not do a perfect job of creating the cyclogenesis that occurred, and still differs run to run. The result is that the model is not perfect, and only an adequate representation, only when initial conditions are almost perfect.

44. The impact of Global Positioning System data on the prediction of an extratropical cyclone: an observing system simulation experiment
Kuo, Y-H. Zou, X. Huang, W. 1998. Dynamics of Atmospheres and Oceans. **27**, pp. 439-470.

The study is an attempt to examine the potential benefits of adding Global Positioning System/meteorology refractivity data in improving model products. The PSU/NCAR MM5 model is used at 90 km resolution. The main objective of the paper was met, and the overall findings were that the GPS/MET refractivity data is extremely useful in recovering missing surface observation data, including atmospheric temperature and moisture fields, and through internal model dynamical processes, the wind fields can also be recovered. The inclusion of refractive data significantly improves model prediction of the cyclones in each case studied.

Better Data/Initial Conditions:

45. Initial Condition Sensitivity and Error Growth in Forecasts of the 25 January 2000 East Coast Snowstorm.
Langland, Rolf H. M.A. Shapiro, R. Gelaro 2002. Mon. Weath. Rev., **130**, 957-974.

This paper again details the “surprise” snowstorm to hit the east coast on 24-25 January 2000. The authors look for a way to improve the forecasts, especially at 72 hours, of the storm intensity and location. While focusing on many factors, the main focus is on the upper-air wind and temperature over the east coast before and during the storm. These are two initial conditions that are found to have the greatest negative affect on the model forecasts of the storm.

- The forecast model used in this study is the Navy Operational Global Atmospheric Prediction System (NOGAPS).
- The model is run with a spectral truncation of T79, which gives horizontal resolution of about 150 km.
- There are 18 different vertical levels used in the study, creating a range of data throughout the atmosphere.

- By modifying the initial conditions based on the spectral truncation, new 72 hour and closer-to-event forecasts are created (called OptIC).
 - The problems with the original forecasts were that this storm had forecasts combining very large error growth rates and a complex upstream flow pattern.
 - The operational forecasts used at the time were not sufficient to create accurate short and medium-range forecasts of storm position or intensity.
 - In the original NOGAPS run, the 24-48 hour forecasts contain significant errors in the cyclone position and intensity, with much worse forecasts from 72-96 hours.
 - When an “adjoint sensitivity correction” to the original initial conditions is added to the model, the forecast error for intensity is reduced by 75%.
 - The 1860 km error in the original forecast of position is reduced to 105 km.
 - These results show that more accurate initial conditions in operation numerical weather prediction, in this case and other significant storms, lead to more accurate short and medium-range forecasts of position and intensity.
 - By changing the initial conditions slightly in an ensemble run of the NOGAPS model, the authors find that initial condition error is the “leading cause” of large errors that occur in the NOGAPS 72-hr forecast.
 - Short-range forecast errors in January and February of 2000 are mainly caused by the complex upper-air ridging pattern over the Gulf of Alaska that is not well simulated by the models.
 - At 72 hours before the storm’s formation, there were relatively small, but critical errors in the “dynamically sensitive regions.” These errors grew at extreme rates, causing forecasts of storm trajectory and intensity to develop increasingly large errors.
 - Small initial condition errors over well-observed land areas in this case caused the large forecast errors...Doesn’t say why these errors over land were present.
 - The model had forecast errors of 20 m/s propagation of the trough/ridge features associated with the snowstorm, when the actual speed of these was around 5-10 m/s.
 - To make a good 72-hr prediction of the snowstorm, the authors had to improve initial conditions over the Pacific Ocean, Gulf of Mexico, the western U.S., and Canada, which they say would have been an impractical concept to do at the time of the storm.
 - Error growth in the snowstorm forecast on the synoptic scale was due to dry dynamics and instabilities in this case, rather than moist processes as is seen in many other snowstorm forecasts.
- Very large errors (cyclone position of hundreds of km) can be and were caused by small errors in wind velocity (few m/s) and temperature (few degrees).

46. The relative utility of current observation systems to global-scale NWP forecasts
 Graham, RJ. Anderson, SR. Bader, MJ. 2000. Quarterly Journal of the Royal Meteorological Society. **126**, pp. 2435-2460.

This article is a study of 20 cases of cyclogenesis to see what types of additional observations would be the most useful in improving the initial conditions in the models. The findings show that the most important observations that could be added to initial conditions into the models are: Acquire more aircraft data over the North Atlantic and Europe, deploy more surface observations (i.e. buoys), make more use of satellite pattern tracking techniques, and continue to increase “targeted” observations in critical storm development areas.

47. A case study of frontal cyclogenesis and its sensitivity to coastal initial conditions (3-4 October 1987)
 Wang, Jianjie. Zhang, Da-lin. 2000. Acta Meteorologica Sinica. **14**, pp. 173-192.

This article is a case study of a storm 3-4 October 1987 in which the most important factors of cyclogenesis are examined and the sensitivities to small changes in initial conditions are studied. The paper finds that the NESTEDgrid model used does a good job of reproducing the cyclogenesis in a strong baroclinic zone, and that the data over the baroclinic zone are essential to reproducing

this model accuracy. Latent heat release accounts for only 25% of the deepening of the storm, and the results reveal that the predictability of the storm is also strongly related to vertical coupling between the surface cyclone and the upper-level PV core, which is determined by initial offshore perturbations along the baroclinic zone.

48. 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.

Data Assimilation:

49. Four-Dimensional Variational Data Assimilation for the Blizzard of 2000.
Zupanski, Milja. Dusanaka., D.F. Parrish, E. Rogers and G. DiMego 2002. Month. Wea. Rev., **130**, 1967-1988.

This article is another examination of ways to improve the forecasts of the "surprise", poorly predicted snowstorm of 24-25 January 2000. In this paper, the authors use a new and more detailed data assimilation than that used in current (2002) operational forecasts in the U.S. They say that some version of the Four-Dimensional variational (4DVAR) data assimilation technique has been used by ECMWF since 1997, and has many advantages in accuracy over the current

3DVAR system used in the U.S. This study only looks at the prediction of the first 12 hours of the storm (at different times before the onset of the storm) to look at the effect of using the 4DVAR data assimilation technique on improving forecasts of storm strength and precipitation. The model used in this study is the NCEP regional ETA model.

- The 3DVAR data assimilation based forecast badly underforecast precipitation across the Carolinas, and did not intensify the storm as quickly as it should have.
- In this project, the 4DVAR-based forecasts do a much better job, creating a near-perfect forecast of precipitation amounts and distribution 24 hours before the event.
- The difference in the two appears to the authors to be the initial conditions. As has been mentioned in the two previous articles, the moisture processes were underestimated in the models, resulting in poor forecasts of precipitation. The 4DVAR-based forecast models were able to take into account (and create in the model) strong surface convergence and excess precipitable water flowing along the surface from Georgia into the storm.
- The initial convection responsible for the flow from Georgia was strengthened by a Low Level Jet that the 4DVAR-based model was able to recognize ahead of the storm, which resulted in deep convection throughout the troposphere.
- After running the experiments, the authors found that model errors were the main source of error in the forecasts. They create a model error adjustment to compensate for these errors, which improves the forecasts more over the initial runs. This is an area that needs vast improvement to make the 4DVAR method more accurate.
- The major failures of the 3DVAR forecasts were in precipitation amounts over the Carolinas. By using the 4DVAR method, the authors have eliminated those errors almost completely, making a notably better forecast possible, at least up to 24 hours prior to the storm.

50. Influence of the assimilation scheme on the efficiency of adaptive observations
Bergot, Thierry. 2001. Quarterly Journal of the Royal Meteorological Society. **127**, pp. 635-660.

This article compares 3-D and 4-D variable assimilation schemes for 20 cases of cyclogenesis during the Fronts and Atlantic Storm Track Experiment, to determine which scheme is more efficient in using adaptive observations in the model runs. The results of this study are that adaptive observations significantly influence model accuracy using both assimilation schemes, but the 4-D variable scheme improves the model products for the storm verification times by 10-50 % over the 3-D variable scheme.

51. Extended assimilation and forecast experiments with a four-dimensional variational assimilation system
Rabier, Florence. Thepaut, Jean-Noel. Courtier, Philippe. 1998. Quarterly Journal of the Royal Meteorological Society. **124**, pp. 1861-1887.

This paper is another comparison of a 4-D VAR assimilation scheme versus a 3-D VAR scheme. The author look at 5-day forecasts in this study to determine how much of an improvement the 4-D variable scheme creates over the 3-D variable system. The results of the paper are that the 4-D VAR outperforms the 3-D VAR assimilation by 35% in terms of precipitation and storm track forecasting, and the 4-D VAR system shows the most improvement in cases involving the tropics or mountainous areas, and with aircraft observational data.

Ensemble Forecasting:

52. Ensemble reforecasting: Improving medium-range forecast skill using retrospective forecasts
Hamill, TM. Whitaker, JS. Wei, X. 2004. Mon. Wea. Rev. **132**, pp. 1434-1447.

The value of doing ensemble forecasts is presented in this paper by looking back at 23 winter seasons from 1979-2001, and running a 15 member ensemble with a version of the NCEP medium-range forecast model. The ensemble runs are compared at the NCEP analyses for these years to determine the value of the ensemble runs to improving predictions. A model output statistics (MOS) approach was used in the ensemble forecasting, and the authors show that by using this approach, 14 day ensemble forecasts outperform the 6-10 day forecasts done without the MOS. They argue that MOS forecasting should become an integral part of medium-range prediction, even though this approach requires a very large data set to be effective. They discuss ways to compute ensemble reforecasts while minimizing impact on operational weather prediction facilities.

53. Effective use of regional ensemble data in forecasting

Grumm, RH. 2002. 16th AMS conference on prob. and stats in atmos. Sci.(AMS Conf. Prob. Stat. Atmos. Sci.) 13-17 Jan 2002.

This paper is an examination of the effectiveness of ensemble forecasting in the prediction of an east coast winter storm that occurred 3-4 January 2000. The authors compare NCEP short-range ensemble forecasts (SREF) to deterministic forecasts from the ETA model runs and the NCEP AVN model runs, and show that ensemble forecasting is effective because it gives multiple possible scenarios to forecasters. They show how effective ensemble forecasting can be in improving forecasts associated with winter storms.

54. Flow dependent background error covariance and mesoscale predictability estimation through ensemble forecasting

Zhang, F. Ham, J. Aksoy, A. 2002. 19th AMS Conference on Weather Analysis and Forecasting. 12-16 Aug 2002.

This article looks at ensemble forecasting in the 24-25 January 2000 snowstorm, and the ways that ensemble forecasting can be most effective in predicting mesoscale cyclogenesis. The authors present results of tests done using random initial perturbations, and ensemble forecasting can be effectively used for many situations: minimizing errors within 6-12 hours prior to cyclogenesis over the area of initial development, spread information for observed and unobserved variables, and determine where "targeted observations" should be made.

55. Short range ensemble forecasts during IPEX

Nelson, JA. 2002. Proceedings of the 16th AMS conference (AMS Conf. Prob. Stat. Atmos. Sci.) 13-17 Jan 2002.

This paper deals with the PSU/NCAR MM5 model and several storms during the IPEX experiment, and aims to provide evidence that short-term ensemble forecasting is an effective use of models. Operationally, ensembles are usually used in medium-range prediction, because they are not shown to be as effective at tighter model resolutions due to time consumption. The authors show that while ensemble forecasting is not as drastic an improvement over single model runs in the short-term, the ensembles still outperform only single model runs.

56. Prediction of the U.S. Storm of 24-26 January 2000 with the ECMWF Ensemble Prediction System.

Buizza, Roberto. P. Chessa 2002. Month. Wea. Rev., 130, 1531-1551.

This paper is a study of how effective a forecast for the January 24-25, 2000 snowstorm could have been created by using the European Centre for Medium -Range Weather Forecasting (ECMWF) Ensemble Prediction System (EPS). The article details the fact that "poor forecasts were due to poor model initial conditions and model uncertainties of physical representations."

The paper tests the EPS against the single run ECMWF model to look for improvements in forecasts, as well as differences.

- Errors in initial conditions quickly affect forecast accuracy in the case of a single model run.
- Model uncertainties due to discrete representations of physical equations enhance forecast error growth.
- These two sources of error lead to inconsistent deterministic forecasts, making it difficult to issue severe weather warnings.
- When these errors exist, systems capable of forecasting time evolution of probability density functions (PDF) of forecast states should be used.
- Ensemble prediction uses multiple integrations of the model equations, thus making it a useful estimator of the PDF of the forecast: ECMWF has generated ensemble forecasts since 1992.
- ECMWF EPS is designed to simulate the effect of uncertainties in the model and in the initial conditions.
- The storm was not properly forecast by ECMWF or NCEP single deterministic forecasts until 36 hours in advance, for a type of storm that occurs on average 6 times per year. (Full coast storm)
- SST plays a fundamental role in the rapid evolution of the storm, and the SST is an uncertainty that is difficult to account for in a single model run.
- The Pacific and Atlantic regions influenced by the Kuroshio Current and Gulf Stream are the areas most affected by explosive cyclogenesis. Lack of data in these areas, along with numerical approximation of moist processes and fast error growth (which is typical of explosive systems due to timing problems) are all reasons for forecast failures in predicting explosive events.
- The verification of the effectiveness of ensemble forecasting in this paper is based on mean sea-level pressure (MSLP), total precipitation, and snowfall at key times.
- The most critical period in the forecasting was the same period as the rapid development of the storm (24-25 January). For this period, single model runs at -72 and -48 hours failed to intensify the storm, failed to predict area covered by precipitation, and underestimated precipitation by a factor of 2. Even -24 hour forecasts failed to predict intensification, but did a better job with precipitation.
- -72 hr EPS forecast predicted (with uncertainty) heavy precipitation in areas that received it, and -48 hr EPS did a good job (60% probability) of predicting locations and amounts of precipitation. The -24 hr gave even higher probabilities of intensification and precipitation, up to 90%.
- Both deterministic and probabilistic predictions of storm development were more accurate with EPS.
- EPS gave indication of storm intensity/track/precip 24-48 hours before the single run forecasts.
- The authors conclude that the EPS does a better job of predicting MSLP and precipitation in advance of the single run forecasts FOR THIS STORM. They go on to say that results indicate that ensemble mean-fields are too smooth to predict severe weather events associated with a strong pressure gradient.
- Several references to other papers on EPS are given on page 1550.
- Stochastic physics has less effect on accuracy of EPS forecasts than initial perturbations, especially in sea surface temperatures.
- Errors in predicting the storm were very sensitive to moist processes.

57. Ensemble simulations of explosive cyclogenesis at ranges of 2-5 days
Sanders, Frederick. Mullen, Stephen L. Baumhefner, David P. 2000. Mon. Wea. Rev. **128**, pp. 2920-2934.

This article discusses the use of ensemble forecasting in a global model to attempt prediction of cyclogenesis. The authors find that although the model does a decent job of predicting

cyclogenesis in most cases, the prediction does not do well beyond 5 days out. The model also varies with location on Earth, including better prediction of a low pressure system near Kamchatka, and not as good prediction of a low over the central Pacific ocean.

58. Seasonal skill and predictability of ECMWF PROVOST ensembles

Brankovic, Cedo. Palmer, TN. 2000. Quarterly Journal of the Royal Meteorological Society. **126**, pp.2035-2067.

The paper looks at the forecasting skill of ECMWF ensembles in predicting tropical season cyclones and extratropical cyclones. The authors look at 120-day ensembles in both cases, and find that the ECMWF ensembles do a better job of predicting tropical cyclones than extratropical storms. They also find that the features important to the accuracy of ensemble forecasts are primarily Sea Surface Temperatures, and secondarily initial conditions in the atmosphere.

59. The dependence of ensemble dispersion on analysis-forecast systems: implications to short-range ensemble forecasting of precipitation

Mullen, Steven L. Du, Jun. Sanders, Frederick. 1999. Mon. Wea. Rev., **127**, pp. 1674-1686.

This paper is a study looking for a way past the problem of large errors due to the combination of initial condition errors and model physics errors. The suggestion is more widespread use of ensemble forecasting in cases of cyclogenesis. The results show that mixed-model ensemble systems (25 members) are the most effective in short-range prediction of precipitation associated with cyclogenesis, but the implementation of these systems is hard, because mixing ensembles tends to degrade many important features of the individual models.

60. Verification of eta-RSM short-range ensemble forecasts

Hamill, Thomas M. Colucci, Stephen J. 1997. Mon Wea. Rev. **125**, pp. 1312-1327.

This paper is looking at the problem of making effective short-range model ensembles to improve forecasts of precipitation. The authors use a 15 member ensemble, 10 from the NCEP ETA model, to try to create quantitative precipitation forecasts that are more accurate than single model runs. The performance of the ensemble is good with the assumption of perfect initial conditions, but shows problems with error propagation when the initial conditions are changed, showing the potential for a short-range ensemble system to be effective in predicting precipitation quantities.

61. Short-range ensemble forecasting of quantitative precipitation

Du, Jun. Mullen, Steven L. Sanders, Frederick. 1999. Mon. Wea. Rev., **125**, pp. 2427-2459.

This article is also trying to use short-range ensembles to provide an accurate quantitative forecast of precipitation. The authors use the PSU/NCAR MM4 model in their runs with a 25 member ensemble. The results are that when the ensemble is used for a case of explosive cyclogenesis, ensemble sizes of more than 10 can create a 90% error improvement over a single model run. This improvement increases considerably up to 10 ensemble members, and then levels off.

62. Monte Carlo simulations of explosive cyclogenesis

Mullen, Steven L. Baumhefner, David P. 1994. Mon. Wea. Rev. **122**, pp. 1548-1567.

The article is another investigation of the effect of changing initial conditions to model prediction of cyclogenesis. "Monte Carlo" simulations are performed on 10 cyclones that were generated by global models during a January simulation, and the impacts of initial condition uncertainty on short term model products are investigated. The results show the importance of initial condition uncertainty in all of the cases as a major cause of forecast variability, and also indicate a strong sensitivity to subtle differences in initial perturbation location and structure.