Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents. Part 1: A 44 Case Study Synoptic Observational Analyses

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Abstract

In this paper we describe the results of 44 case study analyses of synoptic scale data sets that define the atmospheric structure prior to the development of accident-producing turbulence. First, the 44 case studies are categorized as a function of the location, altitude, time of year, time of day, and turbulence environment, i.e., in clear air, cloudiness, convection, near mountains, or in the proximity of deep convection. It is noteworthy that this later category was much more ubiquitous than was anticipated. Second, NCEP Reanalysis data sets as well as both visible and infrared satellite imagery are employed to diagnose "predictor" fields associated with the synoptic-scale environment preceding severe turbulence. These predictor fields are calculated based on jet stream configuration, kinematic, dynamical, and thermodynamic analyses of the synoptic-scale atmosphere.

The results of these analyses indicate a prevalence of severe accident-producing turbulence within the entrance region of the polar or subtropical jet stream at the synoptic-scale. Typically, there is a region of flow curvature located just upstream within the jet entrance region, convection is present within 100 km of the accident, the vertical motion is upward typically within the curved entrance region, absolute vorticity is low, the vertical wind shear is increasing with time, and horizontal cold air advection is substantial. Not all of the 44 case studies conform to this entrance region paradigm. However, most do and the most consistent predictor of severe turbulence is upstream curvature in the synoptic-scale flow. Nearby convection is the second most ubiquitous predictor field. Upward vertical motion, low absolute vorticity, and horizontal cold air advection are all typical predictors in case studies occurring both within the entrance and exit regions of the polar or subtropical jet stream.

1. Introduction

Atmospheric turbulence is an extraordinarily challenging subject that has long been studied by aerospace engineers, computational fluid dynamics experts, and atmospheric scientists. It is of crucial interest to aviators because of the significant impact it can have on aircraft safety. According to a 1998 press release from the US Department of Transportation, in-flight turbulence is the leading cause of non-fatal accidents to airline passengers and flight attendants (U.S.D.O.T. 1998). Major airlines reported 252 incidents of turbulence which resulted in 2 deaths, 63 serious injuries, and 863 minor injuries from 1981 to 1996. Pilots often don't know when severe turbulence is about to occur because there is little warning from meteorologists. Turbulence is extremely difficult to predict due to the fact it often occurs in a microscale environment usually covering 100's of meters to 1 to 2 km^2.

Previous studies of the preturbulence environment have shown that turbulence can occur near upper level frontal zones (Reed and Hardy 1972), near mountains (Lilly and Zipser 1972; Clark et al. 2000), and in clear air (Chambers 1955). Turbulence can also occur in and near convection due to the rapidly changing upward and downward motions due to breaking gravity waves that can form in and around the convection as well as gravity waves accompanying mesoscale jet streaks (Kaplan et. al 1997, 2000; Lane et al. 2003). Roach (1970) and Reed and Hardy (1972) showed that the confluence between two different flow fields in the entrance region of a jet streak is conducive to turbulence generation. Uccellini et al. (1986) showed through observations and numerical model simulations, that at the time of the Space Shuttle Challenger accident the polar jet (PJ) and the subtropical jet (STJ) entrance regions were juxtaposed over the launch site. As noted in Uccellini et al. (1986) this condition can produce very large vertical wind shears conducive to wave breaking. Endlich (1964), Reiter and Nania (1964), Mancuso and Endlich (1966), Keller (1990), as well as Ellrod and Knapp (1992) focused on the possible relationship between frontogenesis, jet streams, wind shear, and clear air turbulence (CAT). Ellrod and Knapp (1992) observed that much of the significant CAT in their data occurred where the total deformation and vertical wind shear were both relatively large, i.e., ~>10^{-4} and ~>$10^{-2}s^{-1}$, respectively. They formulated an equation relating vertical wind shear and deformation:

$$\mathrm{TI1} = \mathrm{VWS} \bullet \mathrm{DEF} \tag{1}$$

where TI1= turbulence index#1, VWS = vertical wind shear, and DEF = total deformation. Knox (1997) examined CAT in regions of strong anticyclonic flow. He argued that the association between frontogenesis, deformation, and CAT is not appropriate in anticyclonic flows and that the CAT generated in such flows is not accounted for in conventional CAT theory. He suggested that geostrophic adjustment and inertial instability, especially in strongly anticyclonic flows could cause CAT by promoting gravity wave genesis and breaking. He proposed that future CAT indices should include inertial instability and geostrophic adjustment in their formulations.

This multi-part sequence of papers differs from the aforementioned studies in that our focus is *only* on severe *accident*-producing aircraft turbulence. An accident, in this study, indicates an event in which injuries occurred to passengers and crew, as a result of severe turbulence. It is important to emphasize the element of surprise to passengers and to the crew as the severe turbulence was totally unexpected. As such, little could be done to prevent injuries to passengers or crew. By analyzing accident-producing case studies we are endeavoring to develop better forecasting products for the prediction of these dangerous, and, hence, important hazards to commercial aviation. Furthermore, as part of this process, we are endeavoring to synthesize the sequence of dynamical atmospheric processes that lead to violent turbulence into a paradigm that is consistently useful in understanding when and where severe turbulence will occur. Existing operational turbulence forecasting algorithms, e. g., those developed by Marroquin (1998), Marroquin et al. (1998), and Sharman et al. (2000) are designed to provide forecast guidance for a spectrum of turbulence intensities, i.e., from light to severe. Our multi-part study will focus on synoptic-scale case studies and processes more likely to be associated with extremely severe (aircraft accident-producing) atmospheric turbulence whether it occurs in clear air, cloudy air, or the vicinity of moist convection. In this paper, an observational analysis of the synoptic scale meteorological conditions present in 44 cases of reported severe accident-producing turbulence is performed. The common dynamic signals in these cases are examined and a paradigm of the most prevalent atmospheric conditions is formulated. The purpose being to "set the table" for the mesoscale and microscale simulation studies to be presented in subsequent papers and to provide coarse but highly persistent and reproducible evidence of the synoptic-scale state of the atmosphere prior to severe turbulence events. When coupled with the very high-resolution simulation studies, a paradigm will emerge that will form the groundwork for the development of a potentially improved severe turbulence forecast product.

In the following section, the process by which data for the 44 cases were obtained and the way in which individual cases were classified is discussed. Background information for the cases is also provided. Section 3 discusses how the data was processed and the common synoptic meteorological signals detected. Section 4 describes several specific case study examples of the primary common synoptic observational features in the accident producing turbulence case studies. Finally, Section 5 presents a summary in the form of a synoptic-scale paradigm that serves as a logical precursor to the mesoscale and microscale issues to be discussed in subsequent papers.

2. Forty-four Case Study Categorization

a. Data Description

Data for classification of the 44 cases of severe turbulence, i.e., wherein commercial aircraft encountered severe turbulence and onboard injuries occurred, was obtained from the National Transportation Safety Board archive of aviation accident narratives. These case study accidents occurred between 1990-1996, and the list of cases was provided by the NASA Ames Research Center. NASA personnel provided the date, approximate location of the turbulence, time, height, and the probable class/cause of the turbulence. These turbulence classes were sorted into 4 primary categories: 1) CAT (clear air turbulence-defined as a typically higher altitude turbulence phenomenon, which is widely separated from mountains, occurring in cloud-free regions, associated with wind shear, particularly between the core of a jet stream and the surrounding air), 2) MTN (mountain-defined as mountain wave-induced severe or extreme clear air turbulence which can present a significant hazard to aviation), 3) TRW (thunderstorm-defined as turbulence occurring in convective storms, particularly thunderstorms, that is felt by aircraft and is caused by strong updrafts and downdraft), and 4) CLD (cloud-defined as turbulence occurring in cloud covered regions without the requirement of convection or precipitation reaching the ground). However, the only weather information, which was included in the NASA analysis, was the hourly observation at the surface aviation station at the time period closest to the accident. This information obviously falls short of a comprehensive synoptic scale analysis. Therefore, in order to thoroughly diagnose the synoptic regime present for these cases, NCEP Global Reanalysis datasets (Kalnay et al. 1996) were obtained for all 44 cases. The reanalysis data consisted of 6-hour temperature, height, wind, and mixing ratio datasets on constant pressure surfaces across the globe. The data includes observations from rawinsondes, wind profilers, satellite, radar, and surface observations assimilated onto a grid of 2.5-degree horizontal resolution for all mandatory levels (100, 850, 700, 400, 500, 300, 250, 200, 150 and 100 mb). Graphical analysis was done using GEMPAK 5.4. Also to aid in our analysis, NOAA NESDIS high-resolution 1-km visible and 4-km infrared satellite imagery was used. This was available for 43 of the 44 case studies and was useful in determining the type and distribution of clouds for the cases.

b. Classification of Turbulence Categories

After doing an in-depth analysis of the satellite data associated with 43 of the 44 cases, it became obvious that a coherant classification of the causes of turbulence was lacking. There were several case studies wherein the turbulence occurred in proximity to, but not directly within ongoing deep cumulonimbus convection, i.e., thunderstorms. Thus the turbulence may have occurred in clear air but spatially very close to TRW conditions. Therefore, a new category was created to describe thunderstorm conditions that occurred in proximity to the aircraft, but wherein severe turbulence was accompanied when the aircraft was clearly not in the convective cells. In other words, the pilots had to visually report the presence of convection, but turbulence occurred after the aircraft was out of the convective clouds. It should be noted that in this instance we are describing deep convection with at least a minimal intensity level as contoured on the manually digitized radar charts. In a more general sense, convection was ubiquitous in these case studies even when the cloud bases were in the middle and upper troposphere, unlike typical thunderstorms. This new category was named TRW* for convective storms within view of the cockpit and, therefore, noted by the pilot, but with turbulence occurring outside of the convection. An example of TRW* can be seen for a case of turbulence near South Bend, Indiana (SBN) that occurred at 2159 UTC 7 July 1994. Fig. 1b shows the GOES visible satellite imagery of the accident location near SBN at 2201 UTC 7 July 1994 and Fig. 1a shows the NTSB narrative for the incident. Upon examination of the NTSB report, it can be seen that the pilot did not mention flying directly in convection within the area and therefore NASA personnel classified this case as CAT. It is apparent, however, that widespread convection existed very close to SBN, and the pilot did note that radar was used to avoid "weather"; the implication being that the pilot was *near* but not *within* deep convection at the time of the accident.

The addition of the TRW* category led to a change in the breakdown of the probable causes of the turbulence for the 44 case studies. Table 1 shows the numeric distribution of the weather categories for the 44 cases based on the original NASA turbulence classification. Table 2 depicts the numerical redistribution of case studies from their original classification to the TRW* category. Note that the TRW* category constitutes 13 of the 44 cases and is the second largest classification. Additional analysis using satellite imagery showed that 9 of the cases that were originally classified CAT and 2 that were classified as MTN were actually within 30 km of deep convection, but no convection was noted in the pilot reports. These cases were not added to the TRW* category because the pilot failed to note convection. Nevertheless, this seemed to indicate that proximity to convection was an important consideration for these cases. Additionally, the 44 case studies were categorized as a function of geographical location, time of year, time of day, and altitude. The findings include the following:

1) the location where severe turbulence was most often encountered was the southeastern U.S., followed by the south-central U.S. and the tropical oceanic regions, all of which account for more than half of the total (note Table 3),
2) the time of year most common was the warm season with more than 40% of the case studies occurring in summer, with June and July being the most frequent months and the combined spring and summer periods accounting for more than 70% of the total (note Table 4),
3) the preferred time of day was between 1700 and 0000 UTC, wherein more than half of the case studies occurred (note Table 5),
4) the preferred altitude range (not including case studies reported as descent, final approach, or climb out) was between 9 and 12 km with nearly 40% of the case studies occurring in this range. The 6-9 km range accounted for nearly half of the remaining case studies with an average elevation of ~7.3 km for all case studies (note Table 6), and
5) TRW* case studies were more numerous than TRW case studies and nearly as numerous as CAT case studies, which is consistent with the first four findings, all of which highlight the importance of convection, which was within 100 km of the

turbulence in 86% of the case studies (note Table 10). The proximity to convection was likely more important than the existence of a very strong jet stream, which occurred in a minority of case studies. Typically the jet was in proximity to the accident but not notably strong, i.e., not significantly greater than 50 ms^{-1} .

3. Diagnoses of the Synoptic Paradigm

a) Calculation of the Synoptic Predictor Fields

In an effort to determine the most prevalent synoptic scale atmospheric configuration associated with the severe turbulence reports, nearly two-dozen predictor fields from the NCEP reanalyses datasets and the available satellite imagery were calculated. By predictor fields we mean fields unambiguously associated with the location and time of the turbulence accident event. No in depth statistical analyses were performed on the fields due to the small sample size of case studies belonging to each turbulence category. Predictor fields were composed of kinematic, dynamic, and thermodynamic fields (e.g., vertical wind shear, static stability, vorticity, divergence, and vertical motions, etc.) (note Table 9). By calculating the predictor fields, we can determine whether or not these specific dynamical fields tended to be relatively large or small compared to average synoptic flow conditions or in a certain configuration when and where severe turbulence occurred, therefore determining their relative usefulness in predicting turbulence. By doing this for many different dependent variables and derived fields, we could build a synoptic model of the atmospheric environment favorable for severe accident-producing turbulence. Since in-depth statistical analyses were not possible, the predictor status is intended to suggest utility as a potential forecasting tool.

These calculations of the predictor fields where performed using the 6-hourly NCEP reanalysis dataset and satellite imagery closest to the reported time (typically within 4-8 minutes) of the accident in the NTSB database. They were also calculated at the constant pressure level closest to the altitude of the accident. Furthermore, the calculations were centered in space on the location of the accident. Horizontal and vertical cross sections were constructed in an effort to derive 3D predictors centered in space and closest to the available analyses/satellite data time. Vertical cross sections were calculated both along and normal to the jet stream axis centered on the accident location as well as tangential to the flight path of each accident flight starting at the origin and ending at the flight's destination. Tables 7-9 depict lists of these horizontal and vertical cross section fields as well as the specific predictor fields.

b. Primary Signals in the Synoptic Predictor Fields

The synoptic predictor fields listed in Table 9 represent standard derived quantities often associated with turbulence in the meteorological literature (e.g., Keller 1990; Ellrod and Knapp 1992; Knox 1997). These predictor fields were first calculated and then the magnitudes were compared to the location, elevation, and time of the accident. From these comparisons, we were able to derive simple numerical indicators of the most and least useful predictor fields for determining when and where severe accident-producing turbulence should be occurring. Table 10 shows the 5 most meaningful predictors from all 44 case studies based on their proximity in space and time to the accidents: 1) an upstream trough/ridge axis in the height field less than 500 km from the accident (occurring in 43 of the 44 cases), 2) convection less than 100 km away (occurring in 38 of the 44 cases), 3) upward vertical motion within the curved jet entrance region, 4) layer averaged absolute vorticity <= $10^{-4}s^{-1}$, as well as 5) the jet stream entrance region (occurring in 34 of the 44 cases). While there are slight variations for each individual category of turbulence (as can be seen depicted in Tables 11-15), the most persistent signals across the various categories are the existence of: 1) upstream flow curvature, 2) convection, 3) upward vertical motion, 4) low relative or absolute vorticity, 5) the entrance region of a jet streak, and 6) horizontal cold air advection in the mid-upper troposphere.

4. Synoptic Signals In Individual Case Studies

We now briefly describe seven case study examples from several categories, including TRW*, TRW, CAT, and CLD, which indicate the preferred synoptic regime for severe turbulence and emphasize the redundancy of so many of the synoptic predictor fields. As can be seen from Table 10, most of the case studies share all (or most) of the key characteristics to be described in these seven representative case studies. These seven case studies are highly representative of the majority of the case studies as they all occur within a curved flow regime, within the entrance region of a jet streak, with upward vertical motion in the entrance region of a jet streak, low relative vorticity, cold air advection, and nearby convection. All occurred relatively close to a minimum value in the vertical variation of the Richardson number, although the coarse 3-dimensional resolution of the data produced Richardson number values which varied considerably and which were relatively large in magnitude, i.e., >>1.0. We also examine a case study that violated this paradigm and discuss common factors in ~20-25% of the case studies which served as significant outliers.

a. South Bend, Indiana - TRW (July 7, 1994)*

Figure 1 describes the NTSB narrative for this accident, indicating the presence of nearby convection but no mention of the aircraft being in a convective cell during the turbulence event, which occurred in between 500 and 400 mb. Figure 2 depicts the 500 mb flow regime in which a moderately strong jet core was located downstream of SBN over Quebec, with the accident location occurring in the right entrance region of the jet. The ageostrophic flow was directed towards the left and there was a definite anticyclonic to cyclonic variation in flow curvature. Absolute vorticity values were less than the Coriolis parameter, indicating negative relative vorticity. An along-stream variation of ascent indicated the curved structure of the flow with SBN still in the upward motion at the time of the observations (not shown). Additionally, weak cold air advection was occurring near and just upstream of the accident location. There was no relative Richardson number minimum near the level of the accident.

b. Alma, Georgia - CAT (March 16, 1995)

While this was categorized as a CAT case study because the pilot did not mention nearby convection (refer to Figure 3a), deep convective cells were obviously near the aircraft's flight path as can be seen from the satellite imagery (Fig. 3b). Figure 4 indicates that the accident occurred within the left entrance region of a moderately strong ~ 200 mb jet streak centered just east of southern Florida. The ageostrophic flow was directed to the left of the stream and there was neutral-weak cold air advection. Substantial flow curvature existed as the accident was located between a relatively short wavelength ridge to the east and trough upstream (and within) the upward motion region. Absolute vorticity values were slightly larger than the Coriolis parameter, indicating that the left entrance region was not a locus of large cyclonic vorticity, i.e., the vorticity maximum was more closely aligned with the cyclonic curvature just upstream. There was no relative Richardson number minimum near the level of the accident.

c. Granite, Colorado – CAT (June 22, 1996)

This case occurred near 400 mb in proximity to deep convection. However, as in the previous case study, the lack of a mention of convection by the pilot enabled it to be classified as CAT (Fig. 5a). The accident occurs in the right entrance region of a moderately strong jet streak (Fig. 6). The upstream flow curvature is significant. The ageostrophic flow is directed to the left, the absolute vorticity is approximately equivalent to the Coriolis parameter, there is cold air advection, and the vertical motion is transitioning from sinking to rising motion at the synoptic scale. However, the presence of multiple convective cells imply numerous subsynoptic scale regions of ascent. The Richardson number was <1.0 through a deep layer, including the accident level.

d. Miami, Florida – TRW (July 14, 1990)

This event occurred within deep convection (Fig. 7) at a relatively low elevation of ~4 km. A weak jet core was centered northeast of Florida, with its right entrance region located over Miami (MIA) (Fig. 8a). Strong flow curvature existed just south of the accident location wherein upward vertical motion and cold air advection was occurring. Absolute vorticity values were considerably less than the Coriolis parameter, indicating negative relative vorticity. The ageostrophic flow was directed to the left of the stream. A relative Richardson number minimum was observed near the accident elevation.

e. Fort Myers, Florida – CAT (July 18, 1990)

In this event the aircraft was, technically speaking, in clear air, however, as can be seen from Fig. 9 it was getting very close to convection over the airport at Fort Myers

(FMY). No mention of convection was found in the NTSB narrative, so it was classified as a CAT case study even though the aircraft was very close to deep convection. The 300 mb winds (Fig. 10) indicate two jet streaks, one moderately strong westerly wind maximum over the Carolinas and a weak easterly maximum over the Bahamas. FMY was located in the right entrance region of the northernmost streak. A comparison with the flow at 200 mb (not shown) indicates that the accident level was located in the transition zone between the two jet streaks at ~250 mb. The flow curvature maximum was again just south of the accident location and the absolute vorticity was considerably less than the Coriolis parameter in magnitude. Ageostrophic flow was directed towards the northernmost jet and into its entrance region. Weak cold air advection and upward vertical motion were both occurring at the accident location. A relative Richardson number minimum slightly <1.0 was observed at the accident location.

f. East Hampton, New York – TRW (June 29, 1994)

In this case the aircraft was in cloud and there were nearby thunderstorms. It was difficult to decipher exactly where the aircraft was relative to the convection at the time of the severe turbulence (based on the narrative depicted in Fig.11, which utilized both convection and visual meteorological conditions). The satellite imagery indicated abundant nearby convection. The event occurred on the right flank and very close to the entrance region of a moderately strong 300 mb jet streak centered to the north of the accident location with leftward-directed ageostrophic flow (note Fig. 12). There was a pronounced upstream flow curvature maximum with strong cold air advection, upward vertical motion, and the absolute vorticity was much less than the Coriolis parameter. A relative minimum in the Richardson number could be found just below the altitude of the accident location.

g. Grand Rapids, Michigan – TRW (August 4, 1995)*

In this case, while the pilot reported no convection, the weather logs of the airline indicated that convection was nearby during the turbulence event as can be seen in Fig. 13a. The satellite imagery indicated convection very close to the location of the accident (Fig. 13b). The accident occurred just below 300 mb where a fairly weak jet core was located over the northern Great Lakes and south-central Canada (Fig. 14a). The accident occurred in the right entrance region of the streak with leftward-directed ageostrophic flow indicating a balanced straight jet entrance region. Cold air advection, upward vertical motion, and very low absolute vorticity existed where the accident was reported. Curvature was weaker than most case studies but still existed upstream. A relative minimum of Richardson number could be found at the level of the accident.

h. Counterpoint Case Studies

While approximately 75-80% of the 44 case studies closely share the aforementioned dynamical characteristics, ~20-25% are clearly not similar in many aspects of the precursor synoptic environment. These anomalies come from all five turbulence categories. An example of these “anomalies” is depicted in Fig. 15. A TRW case study accident occurred near Buffalo, New York (BUF) on March 23, 1991 at ~250 mb. Nothing about this case study conforms to the previous seven except that there was significant curvature and cold air advection. This accident occurs in the left exit region of a highly curved jet streak with sinking motion and rightward-directed ageostrophic flow. Accidents in the right entrance region with ascending leftward-directed ageostrophic flow were much more typical. The vorticity is much greater, rather than less than the Coriolis parameter as was the case in the previous seven case studies and the majority of the other case studies. There is no obvious relative minimum in the vertical profile of the Richardson number. Only a small portion of these 10 anomalous case studies differs so drastically from the other 34 case studies. In fact, all but two of these ten case studies have significant cold air advection, all but one has a highly curved jet streak, and all but seven have very low absolute vorticity. One could infer that when the classic jet streak structure, i.e., entrance region location of the accident, associated upward vertical motion, or low absolute vorticity is missing, the cold air advection and flow curvature increases considerably. The inference being that since cold air advection follows a cold front, particularly if flow curvature is significant, hence, *some combination of curvature and solenoidal/cold frontal structure is the key to understanding what establishes an environment predisposed to turbulence*. The paradigm seems strongly weighted towards inertial-advective adjustments in a baroclinic zone as curvature implies cold air advection by the ageostrophic wind if the values of radii of curvature are significant and differential horizontal cold air advection can be frontogenetical as is typical in a confluent jet streak entrance region. Hence, ageostrophic frontogenetical processes are likely important in the turbulence accident environment. This clearly indicates, however, that signals at the synoptic scale are only a partial indicator of the possibility of severe turbulence and that mesoscale and microscale processes may refine the probability of how favorable or unfavorable a synoptic environment will be for producing turbulence. Additional research may very well yield a mesoscale and/or microscale synthesis that distills the common signals among all 44 case studies?

5. Summary and Discussion

The first in a sequence of papers on severe accident-producing turbulence has shown the atmospheric, geographical, and seasonal commonalities typically observed in 44 cases of severe turbulence. NCEP reanalysis data was obtained for the 44 cases and used in the analysis. The data indicates that for these 44 cases, the most common time and location for severe turbulence to occur was in the summer at a flight level between 9 km and 12 km across the southeastern United States. Also, by using satellite data to aid in our analysis it was determined that convection played a key role in the severe turbulence reports in this set of data, with a majority of the cases (86%) occurring within 100 km of moist convection. It was also shown that the most important synoptic signals pointed to an environment where convection coincided with a curved jet streak entrance region, upward vertical motions, low relative vorticity, horizontal cold air advection, and leftward-directed ageostrophic flow. A 3D conceptual model of this process would indicate that the curved jet entrance region is a preferred zone of subsynopticscale ageostrophic confluence and cold frontogenesis. As the cold front aloft intensifies and isentropic surfaces become deformed, convection develops producing an accelerating jet entrance region flow, reduced static stability and increased vertical wind shears. However, it was also apparent that relative minimum values of Richardson number calculated from *synoptic*scale observations are not well-correlated with reported incidents of severe turbulence, probably due to the lack of vertical detail in the observational data sets. In addition, the strength of the jet stream was less clearly associated with turbulence accidents than was the presence of convection, jet streak curvature, upward vertical motion and cold air advection. These features were relatively similar across all five turbulence categories. When all five predictors were not present, strong signals of flow curvature and cold air advection were still evident, indicating that these two processes, or what these processes do to the mesoscale and microscale environments, such as producing mesoscale streamwise cold fronts aloft, somehow are critical to understanding why turbulence develops. The synoptic evidence points towards the juxtapositioning of inertial-advective forcing (large horizontal curvature and low vertical vorticity) and cold air advection in an environment that supports moist convection. The aforementioned type of environment would be favored by a confluent jet entrance region or regions where curved flow supports highly ageostrophic ascending motions, frontogenesis inferred from nonuniform cold air advection, and moist convection. In subsequent papers these findings will be compared with numerous additional cases of severe accident-producing turbulence, including convective and clear air case studies. All of these additional case studies share the same synoptic signals as described in the 44 case study analysis presented here. The analysis in the subsequent papers will focus on meso-β and meso-γ scale signals derived from numerical simulations occurring at the same location as the severe turbulence.

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11. Best predictors for CAT accident case studies (% of 16).

12. Best predictors for TRW* accident case studies (% of 13).

13. Best predictors for TRW accident case studies (% of 8).

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