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SURFACE WIND CONVERGENCE AS A SHORT-TERM PREDICTOR OF CLOUD-TO-GROUND LIGHTNING AT KENNEDY SPACE CENTER: A FOUR-YEAR SUMMARY AND EVALUATION

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ABSTRACT

Since 1986, USAF forecasters at Kennedy Space Center (KSC) have had available a surface wind convergence technique for use during periods of convective development. In Florida during the summer, most of the thunderstorm development is forced by boundary-layer processes. The basic premise is that the life cycle of convection is reflected in the surface wind field beneath these storms. Therefore the monitoring of the local surface divergence/convergence fields can, in most cases, be used to determine timing, location, longevity, and specifically, the lightning hazards which accompany these thunderstorms. This study evaluates four years of monitoring thunderstorm development using surface wind convergence, particularly the average over the area. Cloud-to-ground (CG) lightning is related in time and space with surface convergence for 346 days during the summers of 1987 through 1990 over the expanded wind network at KSC. The relationships are subdivided according to low-level wind flow and midlevel moisture patterns. Results show a one in three chance of CG lightning when a convergence event is identified. However, when there is no convergence, the chance of lightning is negligible. By itself, the convergence nowcasting technique is a very good simple technique. But when used with other observational platforms, the convective forecast is greatly enhanced. The 1990 deployment of a 5 direction finder (DF) network with a positive flash option is also examined and related to surface convergence and convective development.

1. INTRODUCTION

The responsibility for thunderstorm prediction as well as all other weather support at the Kennedy Space Center (KSC) rests with USAF forecasters. The USAF forecasters are responsible for issuing weather advisories with 30-minute lead times for numerous locations at KSC and Cape Canaveral Air Force Station CCAFS. They are required to provide weather information for NASA, USAF, U.S. Navy, and commercial launches. This responsibility demands that the forecasters continue to provide a more timely and improved forecast product. In 1988, during the four convective summer months, the percent of man-hours lost due to lightning warnings within 5 miles of Complex 40 and 41 was 9.2% (Maj. A. Dye, private communication). A preliminary study of shuttle processing time lost during the four summer months of 1988 indicated that for each hour during which negative ground flashes were observed within 5 miles of Complex 39 by the lightning mapping system, there were, on the average, 13 hours of warning duration (R. Bentti, private communication).

Watson *et al.* [1 and 2] have shown the feasibility of using surface wind convergence as a short-term predictor of thunderstorms, especially cloud-to-ground (CG) lightning. These recent studies examined the ability of surface convergence in a relatively small network to anticipate the onset as well as the cessation of lightning in this network. Much of the convection in Florida during the summer is triggered by processes in the boundary layer. The life cycle of these thunderstorms is likely to be reflected in the surface wind field beneath the storms. This assumption, however, does not always hold true for thunderstorm development in a more midlatitude environment [3] or during other seasons in Florida. The convergence technique presented here uses surface convergence, particularly the average over the area, to identify the potential for new, local thunderstorm growth, which can be used to specify the likely time and location of lightning production during the life cycle of the convection.

In 1987, NASA expanded the surface wind network onto the mainland west of KSC. The network area increased from near 800 km^2 to over 1600 km^2. This study reports the results of this expansion using four years of wind and lightning information collected during June, July, August, and September of 1987-1990.

2. DATA AND ANALYSIS

The wind-tower locations and the 1600-km^2 analysis area are shown in Figure 1. Although individual towers have varying instrumentation, this study used winds sampled mainly at 16.5 m (54 ft), which is the highest available level for all the sites and is above all the vegetation. The wind data were recorded in increments of 5-min averages. The analysis area

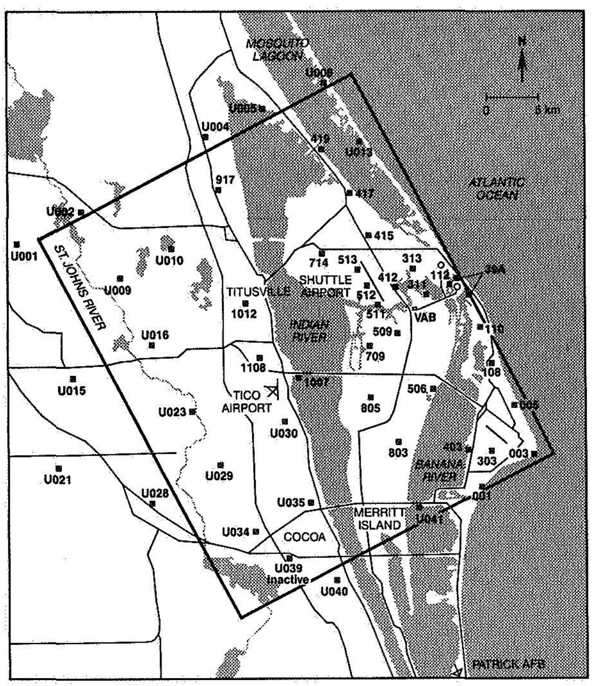

Figure 1. Kennedy Space Center and Cape Canaveral Air Force Station area. The rectangle marks the wind mesonetwork boundary. Solid squares indicate meteorological stations.

was divided into a 13-by-17 grid of equally spaced (2.8 km) points. The divergence quantities were then computed using an objective analysis scheme [1, 2, and 4].

CG lightning information was obtained from a medium gain network of three direction finders (DF) with a mean distance between DFs of 69 km. Only flashes recorded in the analysis area shown in Figure 1 were considered. Krider *et al.* [5 and 6] described the lightning location system, Mach *et al.* [7] described network performance, and López and Holle [8] described the lightning data processing. Unfortunately, only negative flash information (i.e., lightning lowering negative charges to the ground) was available for the three DF network. In 1990, data from the Melbourne, Florida DF were unusable, reducing the system to a two DF network. Considering the baseline problems which resulted over the northern half of the KSC wind network, the data could not be used.

Fortunately, a new five-DF low-gain lightning location network came on-line in 1990 with a mean distance between DFs of 45 km. Processing of the raw DF information was performed using a Passi and López [9] algorithm which calculates site errors and optimizes the flash position using information from all DFs detecting the flash. Since many more flashes seem to be detected with this network, this flash information was only used in examining positive flashes.

3. DIVERGENCE-LIGHTNING RELATIONSHIPS

If conditions in the middle troposphere are favorable, thunderstorms are likely to develop and be sustained in the sea-breeze zone and, through the process of downdrafts and outflows, produce new flanking convection which may migrate into other areas. Planetary boundary-layer convergence initiates these convective events.

TOTAL-AREA DIVERGENCE

Total-area divergence is a term coined by Cunning *et al.* [10] for area-averaged divergence, that is, the sum of the divergence values at gridpoints divided by the total number of gridpoints. It is equivalent to the line integral of the normal component of the wind around the domain boundary divided by the area. In a region the size of the KSC network, the value of total-area divergence quantifies the amount of horizontal mass into or out of the network boundaries, which approximates the average vertical motion in the region. Total-area divergence senses the prestorm environment as well as the formative, mature, and dissipation stages of convective development.

Figure 2 shows profiles of total-area divergence and 5-min CG flash totals in the network for 10 July 1988. Two relatively strong convergence-divergence couplets are shown with associated lightning. The convergence-divergence couplets in the total-area-divergence time series occur repeatedly as a sign of convective development. In the stages of convective development described by Byers and Braham [11], the cumulus or *formative* stage is characterized by updrafts throughout the cloud or cell. In the total-area divergence profile, the *formative* stage is from beginning convergence to maximum convergence, when there is predominantly inflow into the developing storm. The *mature* stage has both updrafts and downdrafts occurring throughout the thunderstorm. In the total-area divergence profile, this stage begins at maximum convergence and continues to maximum divergence. Throughout this period, convergence and divergence zones coexist in the network. Convergence begins to decrease while

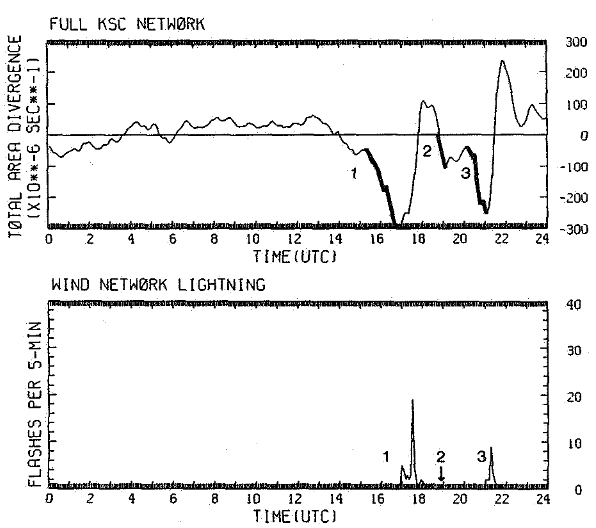

Figure 2. Time profiles (5-min resolution) of (top) total-area divergence, and (bottom) CG lightning for the KSC network on 10 July 1988. Bold lines identify convergence events.

downdrafts and precipitation cause increasing divergence. Finally, the *dissipation* stage is characterized by downdrafts. This stage begins at maximum divergence and ends when the total-area-divergence time series returns to near zero values as the downdrafts weaken and precipitation ceases.

CG lightning begins a short time before maximum convergence as convective clouds, in response to boundary-layer convergence, become deep and vigorous enough to support electrical discharges. Peak lightning occurs in the middle of the mature stage near the cross-over from convergence to divergence, which is described by Watson *et al.* [1]. CG lightning ends after peak total-area divergence as divergence settles back to quiescent values.

The magnitudes in the convergence-divergence couplet in the total-area divergence profile vary considerably from case to case. Because of the position of convective development in the network, one stage or another may be lost as cells move in or out of the network. Complicated patterns may form because of clashes of intersecting outflows. Signal may be lost because of the inhomogeneity of the station spacing (Fig. 1), and smaller-scale development may be lost until sensed by several sites because only the network average of divergence is being considered. Convergence-lightning episodes are usually not as dramatic as in Fig. 2. Figure 3 depicts an average day (21 June 1989) where convective development is weak.

POSITIVE CG FLASHES AT KSC

In 1990 a low-gain CG flash detection network was installed at KSC which detects positive as well as negative CG flashes. The old lightning network did not contain the positive flash option. Therefore, there was little known about the concentration of positive flashes during convective development in the immediately vicinity of KSC and their association to surface convergence.

Positive CG flashes are considered to constitute a small fraction of the total number of flashes. Positive flashes are generally considered to have large currents and charge transfers. A literature review of positive flashes can be found in López *et al.* [12].

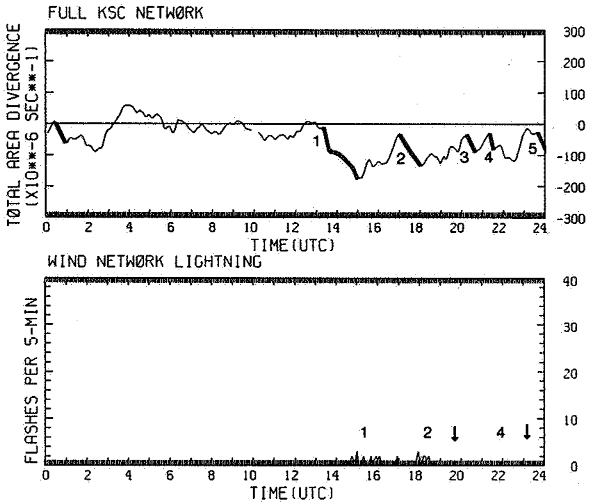

Figure 3. Same as Fig. 2, except for 21 June 1989.

Figure 4 shows time profiles of total-area divergence, total CG flashes, and positive flashes in the KSC wind network on 24 July 1990. A convergent/divergent couplet begins at 1600 UTC and ends near 2200 UTC. Network flashes begin at 1745 UTC immediately before the minimum in total-area divergence (convergence peak). The lightning peak occurs just before the peak in divergence during convective maturity as stated in the last section. Lightning ends at 2140 UTC as total-area divergence slips back towards zero. During the nearly 3 hours of CG flashes, positive flashes occur only for one hour and a half, peaking with 5 flashes in 5 minutes at maximum flash intensity with 8% of the flashes being positive. It appears that the majority of positive flashes occur during the mature stage of convective development in this example.

In a second example (Fig. 5), another strong convective event occurred on 17 August 1990. Development begins after 1600 UTC. CG flashes begin in the network at 1830 UTC, nearly 45 minutes before maximum convergence. Peak lightning occurs at the cross-over from convergence to divergence, that is, during the mature portion of the convective event. Positive flashes again straddle peak lightning activity. Main CG activity ends at 2010 UTC. Several flashes occur later as weak convergence occurs at 2130 UTC. Again, it is evident that most of the positive flashes exists in the mature stage of the convection. Figure 6 shows the surface situation at

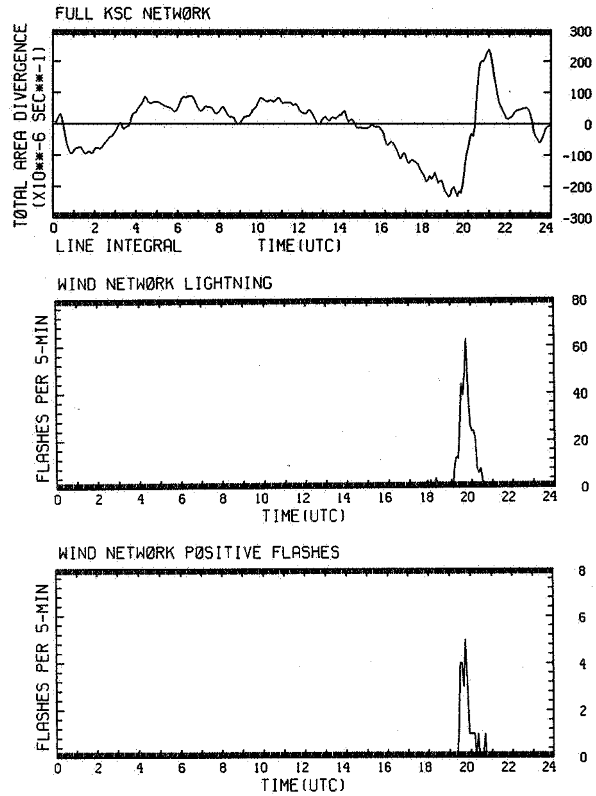

Figure 4. Time profiles (5-min resolution) of (top) total-area divergence, (middle) total CG flashes, and (bottom) positive CG flashes in the KSC wind network on 24 July 1990.

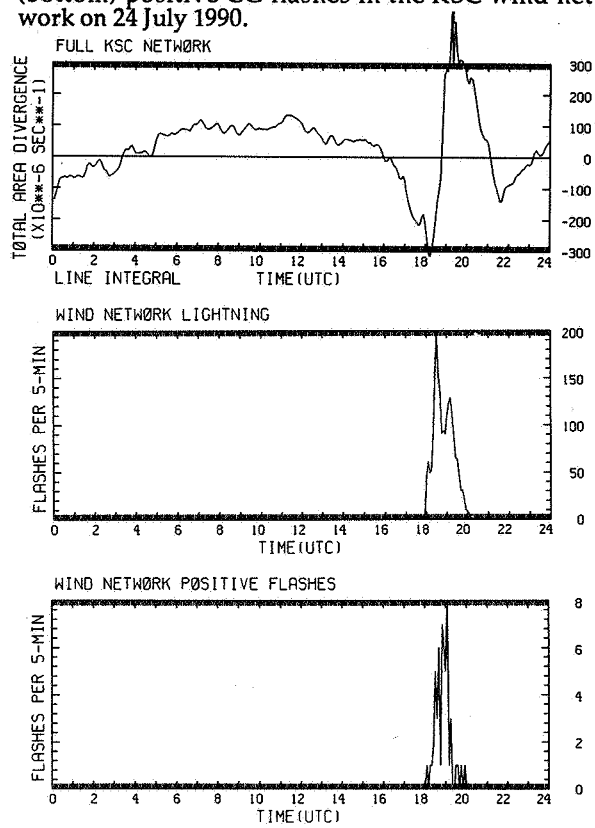

Figure 5. Same as Fig. 4, except for 17 August 1990.

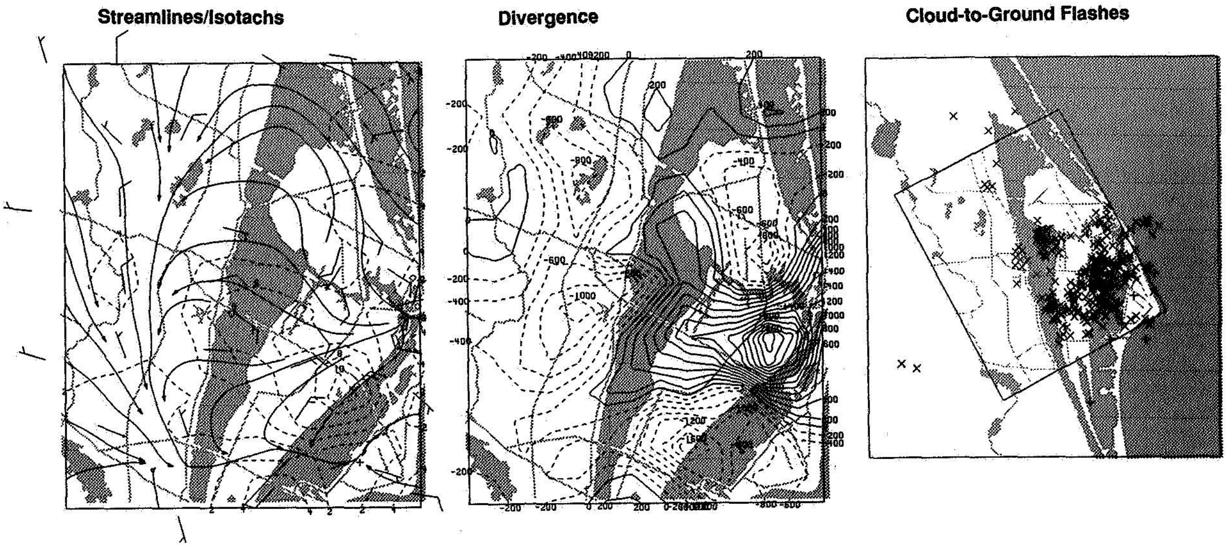

Figure 6. KSC mesonetwork analyses for 5-min period beginning at 1830 UTC (1330 EST) on 17 August 1990. Left: streamlines and isotachs (m s^{-1}). Center: divergence (10^{-6} s^{-1}). Right: Larger area view of 10-min CG flashes centered at 1830 UTC.

maximum convective development.

What about these positive flashes? Are these positive flashes lowering intense positive charges to ground? The variation of signal strength versus distance from the center of the lightning DF array is shown in Fig. 7. Notice that the majority of these flashes are weak and are attenuated very quickly with range. These weak positive CGs have also been reported in analysis of Colorado flash structure [12].

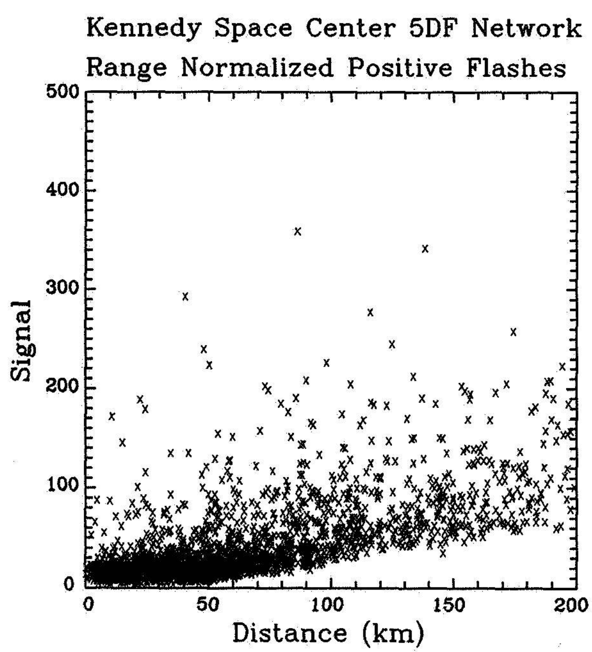

Figure 7. Variation of positive flash signal strength with distance during July and August 1990.

A CONVERGENCE EVENT

The nearly monotonic drop in total-area divergence during the formative stage occurs before the onset of precipitation or CG lightning (see Fig. 2). Therefore, this increase in convergence can be used to anticipate convective development and production of precipitation or lightning during the mature and dissipation stages.

Watson *et al.* [1 and 2] developed convergence-event criteria for relatively small (280-km^2 and 800-km^2) KSC networks. Their assumptions were that flow must be into the network, which can be converted into upward vertical motion. Therefore, the total-area divergence profile must be at zero or less. To filter noise from the total-area divergence profile, a three-point running mean (15-min average) is applied. For the expanded KSC network, an event is then defined as a sustained or monotonic drop in total-area divergence exceeding 50 x 10^{-6} s^{-1} (called 50 units hereafter) for more than 10 minutes. Slight hesitations in this drop in divergence are ignored.

A LIGHTNING EVENT

To statistically relate lightning to convergence events, a lightning-event criterion must also be developed. A lightning event is defined as the occurrence of one or more negative CG lightning flashes within the limits of the mesonetwork. An individual lightning event must be separated from previous or future lightning events by at least 30 min without flashes. Figure 2 shows three lightning events on 10 July 1988 associated with three convergence events. Figure 3 shows five convergence events, three of which have related lightning. Two lightning events (arrows) have no associated convergence.

4. IMPORTANCE OF WIND DIRECTION

The patterns and locations of Florida convection are directly related to the synoptic wind field [13]. This and other studies emphasized the importance of the interaction between the synoptic wind field and the sea-breeze circulation in determining the timing and location of convective activity across the Florida peninsula. López and Holle [14] have also shown that the spatial CG lightning distribution in central Florida is determined in large part by this interaction.

The sea-breeze circulation assumes different characteristics depending on whether the prevailing wind has an onshore or offshore component. The larger-scale flow can accelerate or impede the daily progress of the sea breeze inland; the same is true for convection. Onshore flow along the Gulf coast normally produces vigorous convection inland. This convection may then drift eastward across KSC. Onshore flow along the Atlantic coast usually generates less vigorous convection, which results in less lightning. If convection occurs, it usually develops by midmorning and drifts westward across the state.

To estimate sea-breeze and thunderstorm motion, a mean vector wind [1,14], V_{0-3}, from the surface to 3 km (10,000 ft) was computed each day using the Cape Canaveral sounding released daily between 0900 and 1300 UTC. Five wind-regime classes were selected, depending on V_{0-3}. One class was calm for $V_{0-3} \leq 2$ m s^{-1}, and the other four classes were mutually exclusive 90° sectors centered on the average Florida east coastline in the vicinity of KSC; these classes were northeasterly (NE), 023°-113°; southeasterly (SE), 113°-203°; southwesterly (SW), 203°-293°; and northwesterly (NW), 293°-023°.

Table 1 gives the distribution of daily CG flashes in the KSC wind network for the study period, June-September 1987-1989, based on the mean vector wind V_{0-3}. SW flow contributes 66% of the total network flashes. NE and NW flow have the smallest percentage of flashes. The percent of regime days with lightning ranges from 30% (NE) to 73% (SW).

Table 1. Distribution of CG flashes in KSC wind network for June-September 1987-1989.

Flow Regime	Regime Days	% Days with Ltg.	Avg. No. of Flashes	Peak Daily Flashes	Total Flashes	% of Network Flashes
All	346	55	132	982	25223	100
NE	71	30	14	121	303	1
SE	101	63	64	823	4077	16
SW	103	73	221	982	16583	66
NW	19	42	58	189	464	2
Calm	52	44	165	657	3796	15

5. EFFECT OF MIDLEVEL MOISTURE

In south Florida studies, Burpee [15] found greater amounts of midtropospheric moisture on rainy sea-breeze days than on dry sea-breeze days. Watson and Blanchard [16] found better surface convergence-convective rainfall relationships when midlevel moisture was more abundant. Figure 8 presents the distribution of midlevel relative humidity (RH) averaged in the 700-500-mb layer from the morning sounding over the KSC region for the total ensemble and for the five low-level wind directions. Box-and-whisker plots depict the distributions of relative humidity on days when lightning and no lightning were reported in the KSC network. For the total set, midlevel moisture was greater for the lightning cases than for the cases of no lightning in the network; the corresponding median values of relative humidity were 46% and 67%, respectively. The no-lightning days in the NE regime were the driest, and the lightning days in the SE wind regime were the wettest. Each wind regime held true; the greater the midlevel relative humidity, the more likely the chance for lightning. Precipitable water (not shown) for the entire atmospheric column also shows similar differences. However, low-level moisture (below 700 mb) was always present and therefore shows no correlation.

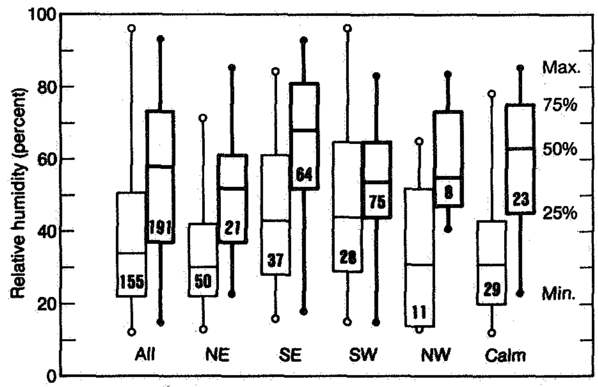

Figure 8. Distribution of midlevel RH (700-500 mb) according to low-level wind direction. Box-and-whisker plots represent the distributions of RH on days when lightning (bold boxes) and no lightning were reported in the KSC wind network. Rectangles represent the middle 50% of the sample; lines within the rectangles indicate the median; the extreme dots represent the maximum and minimum. Numbers in the boxes indicate the number of days in each sample.

6. VERIFICATION SUMMARY

Criteria for convergence and lightning events were given in Section 3. All convergence events were determined only by the total-area-divergence time series. No distinction was made as to how convergence cells were situated in the network.

CONVERGENCE-LIGHTNING EVENT SUMMARY

Table 2 summarizes the convergence-lightning event results. There were 545 convergence events; 185 of these events had lightning. There were 140 lightning events with no related convergence; 63 of these misses had only one flash. The associated summary measures testing predictability are also provided in Table 2 and in tables which follow. These summary measures include the probability of detection (POD), the false alarm ratio (FAR), the critical success index (CSI), and true skill statistic (TSS). The TSS is presented formally by Doswell and Flueck [17]. The TSS is provided because it uses all the information contained in a 2 x 2 contingency table, and provides a measure of the observed skill to perfect skill. It has a fixed range of -1 to +1, where TSS = +1 is perfect skill, and TSS = 0 shows zero correlation between the observed and predicted values.

EFFECT OF LOW-LEVEL WIND DIRECTION AND MIDLEVEL MOISTURE

Table 2 also subdivides the convergence-lightning event summary according to low-level wind direction. SW flow is the major lightning producer; NE flow has the lowest lightning output. POD and TSS are highest under Calm and SW flow. False alarms are greatest under NE flow with only 17 lightning events occurring with 97 convergence events.

Table 3 separates the convergence-lightning event summary according to midlevel relative humidity. The morning midlevel RH values (700-500 mb) for the period were separated into quartiles, ranging from RH < 41%, 41-52%, 53-67%, and RH > 67%. For the driest conditions (RH < 41%), the FAR is very (.81). Only 24 lightning events occurred with 128 convergence events. As RH increases, so does TSS.

In the following Tables (4 and 5), the low-level wind regimes are subdivided accord-

Table 2. Total-area divergence versus CG lightning, based on 1987-1989 KSC wind network for a convergence-event threshold of 50 x 10^{-6} s^{-1} separated according to low-level wind direction.

	Regime Days	Related Conv. Events	Related Ltg. Events	Avg. Total Flashes	Ltg. Misses	Avg. Total Flashes/Miss	POD	FAR	CSI	TSS
All	346	545	185	121	140	17	.57	.66	.27	.43
NE	71	97	17	11	17	6	.50	.82	.15	.39
SE	101	194	56	58	56	12	.50	.71	.22	.35
SW	103	147	74	208	47	18	.61	.50	.38	.49
NW	19	23	6	61	8	14	.43	.74	.19	.33
Calm	52	84	32	100	12	54	.73	.62	.33	.59

Table 3. Total-area divergence versus CG lightning, based on 1987-1989 KSC wind network for a convergence-event threshold of $50 \times 10^{-6}\ s^{-1}$ separated according to midlevel relative humidity.

	Regime Days	Related Conv. Events	Related Ltg. Events	Avg. Total Flashes	Ltg. Misses	Avg. Total Flashes/Miss	POD	FAR	CSI	TSS
All	346	545	185	121	140	17	.57	.66	.27	.43
RH < 41%	125	128	24	184	25	8	.49	.81	.16	.35
RH (41 - 52%)	68	111	40	94	34	19	.54	.64	.28	.38
RH (53 - 67%)	74	140	53	123	34	25	.61	.62	.30	.43
RH > 67%	79	166	68	114	47	15	.59	.59	.32	.50

ing to midlevel RH. As found in Table 2, SW flow is the major lightning producer. When SW flow is subdivided according to midlevel RH (Table 4), the POD increases as RH increases, FAR decreases as RH increases, and TSS increases as RH increases.

Calm flow (Table 5) may be the most important regime for the convergence technique, since convection develops in place (i.e., little movement) under this regime. Again, the FAR is high during dry conditions but decreases as RH increases. The TSS is quite good throughout the RH classes. Notice the one large lightning "bust" in RH (53-67%).

The remaining directions are not present due to space limitations. A summary is given instead. The NE wind regime is the weakest lightning producer. Under the two driest quartiles, there is little chance for a lightning event to occur with convergence. However, as midlevel RH increases, the chance for lightning improves. The summary measures (POD, etc.) also improve as RH increases. The RH values under SE flow provide some puzzlement. The usual situation under low RH values appears consistent with other directions, i.e., low POD, high FAR, and low TSS. The lack of skill (low TSS) at higher RH values may be attributed to more disturbed conditions when there is less association between surface convergence and lightning as convection develops by other means than surface heating. The NW regime had too few samples to be meaningful.

When compared to the 2-year study of Watson *et al.* [2] encompassing the smaller 800-km^2 network, the forecast statistics have decreased in skill. The TSS has dropped approximately 0.2 in nearly all cases. The principal reason is that many small storms are imbedded in a large network. The encouraging aspects are that the statistics appear most favorable for calm flow, which is the most difficult wind regime, since extrapolation and persistence techniques do not work when development occurs in place. In the case of calm flow, the TSS has increased by 0.05 to 0.59. The probable cause for this is that much of the entire life cycle of convection occurs within the boundaries of the larger network. The use of the convergence-lightning

Table 4. Total-area divergence versus CG lightning, based on 1987-1989 KSC wind network for a convergence-event threshold of $50 \times 10^{-6}\ s^{-1}$ separated according to midlevel relative humidity for the SW wind regime.

SW Flow	Regime Days	Related Conv. Events	Related Ltg. Events	Avg. Total Flashes	Ltg. Misses	Avg. Total Flashes/Miss	POD	FAR	CSI	TSS
	103	147	74	208	47	18	.61	.50	.38	.49
RH< 41%	29	37	14	247	12	15	.54	.62	.29	.39
RH (41 - 52%)	23	36	17	138	16	28	.52	.53	.33	.37
RH (53 - 67%)	30	43	22	250	13	11	.63	.49	.39	.48
RH > 67%	21	31	21	196	6	17	.78	.32	.57	.70

Table 5. Total-area divergence versus CG lightning, based on 1987-1989 KSC wind network for a convergence-event threshold of 50×10^{-6} s^{-1} separated according to midlevel relative humidity for the Calm wind regime.

Calm Flow	Regime Days	Related Conv. Events	Related Ltg. Events	Avg. Total Flashes	Ltg. Misses	Avg. Total Flashes/Miss	POD	FAR	CSI	TSS
	52	84	32	100	12	54	.73	.62	.33	.59
RH < 41%	26	30	5	179	3	2	.63	.83	.15	.48
RH (41 - 52%)	7	12	6	116	4	7	.60	.50	.38	.46
RH (53 - 67%)	8	18	10	38	1	595	.91	.44	.53	.75
RH > 67%	11	24	11	113	4	6	.73	.54	.39	.55

technique as a nowcasting tool is a very good simple single rule. In practice, the technique is not used alone, but should be combined with other platforms such as radar, satellite, lightning maps, visual observations, etc.

7. SUMMARY

During the three summers of data collection, 25,223 flashes were detected in the KSC wind network covering 1600 km^2. The convergence-lightning technique accounted for 89% of the network flashes in 185 convergence events. Synonymous with dry conditions was NE flow; there was little chance for lightning under these conditions. There also were high false alarm rates with NE flow as moderate onshore flow produced implied convergence at coastal wind sites which oscillated at times to create convergence events.

More midlevel moisture was available on days when lightning was reported in the KSC wind network than on days when no lightning was reported. Overall, as midlevel RH decreased, the less the chance for lightning. As RH increased, the greater the chance for lightning to occur with convergence.

The summer of 1990 provided the first opportunity to study the relationship of positive CG flashes to the life cycle of convection as viewed through the surface total-area divergence profile. Most positive CG flashes were found to be weak and occurred during the mature stage of convective development. After reviewing several months of convergence and lightning (both positive and negative CG flashes) for 1990, it can be concluded that due to the small percentage of positive flashes (3.7% in wind network) and their time of occurrence (convective maturity), little has been lost in previous years' convergence-lightning summaries which did not contain positive flashes, because the positives always occurred during peak negative activity, and not at the end of the storm.

The technique is currently implemented at KSC for use by USAF forecasters and has met with great success. However, the technique cannot be used in a vacuum; it must be incorporated into a total mesoscale observing and forecasting system. The likelihood of thunderstorms must be determined from the synoptic situation. Monitoring the total-area divergence time series and horizontal fields is but one aid that will help the forecaster determine the timing, longevity, and possibly, the intensity of the lightning episode.

8. ACKNOWLEDGMENTS

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