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VISIBILITY TRENDS FOR COASTAL REGIONS

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1. INTRODUCTION

Increased biomass burning (e.g., forest fires, controlled burns, etc.) and anthropogenic emissions into the earth's atmosphere in the past century have led to much debate with regard to greenhouse gases, atmospheric carbon buildup, aerosol increases, and global warming. Atmospheric aerosols are linked to reduced air quality and visibility (V) in many parts of the world. In south-central South Carolina visibility reduction has been responsible for traffic fatalities on public highways, with resulting lawsuits against governmental entities.

Congress passed the Clean Air Act in 1963, with amendments in 1970, 1977, and 1990 to improve air quality. The actual implementation of the Clean Air Act has been an intermittent process because of litigation over some provisions of the Act. However, it is reasonable to assume that visibility has improved in the U.S. over the past decades due to implementation of the Clean Air Act's provisions.

In this study visibility data have been acquired for seven weather stations along or near the U.S. East Coast (Table 1) to study how conditions have changed from the 1980s to the 1990s. During this time period a number of aerosol related emission compounds have decreased, including volatile organic compounds; NO_X, and SO_2 (Rising, 2002); national total particulate emissions including PM_{10} (USEPA, 1994 and USEPA, 2001), and ozone (USEPA, 2003). For an interesting comparison, a region with fewer clean air implementation initiatives, but a somewhat similar geographical area to the U.S. East coast was found in East Asia (Table 2) and was examined in a similar fashion.

*Table 1: East coastal cities in the United States used in this study with station identifier. *Norfolk was only used for the 1990s data set since its visibility observations were limited to 11 km in the 1980s. +Jacksonville was only used for the 1980s data set since its visibility observations were limited to 10 km in the 1990s.*

City	State\ Dist.	Latitude (°N)	Longitude (°E)	Station ID
Boston	MA	42.37	-71.01	BOS
New York	NY	40.77	-73.89	LGA
Washington	DC	38.85	-77.02	DCA
Norfolk*	VA	38.28	-76.39	ORF
Wilmington	NC	34.27	-77.91	ILM
Charleston	SC	32.90	-80.02	CHS
Jacksonville+	FL	30.50	-81.69	JAX

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2. METHOD

Visibility measurements are normally available only at primary weather stations in the U.S. and other parts of the world, which complicates the investigation of this problem. Meteorological data including visibility were extracted for major weather stations in U.S. cities on the East Coast including Boston (BOS), New York (LGA), Washington (DCA), Norfolk, VA (ORF), Wilmington, NC (ILM), Charleston, SC (CHS), and Jacksonville, FL (JAX) (Fig. 1) from 1980 to 1983 and from 1990 to 1994. These cities experience climatic influences from the nearby Atlantic Ocean. Most of these stations are influenced by land/sea breeze air exchange during diurnal cycles.

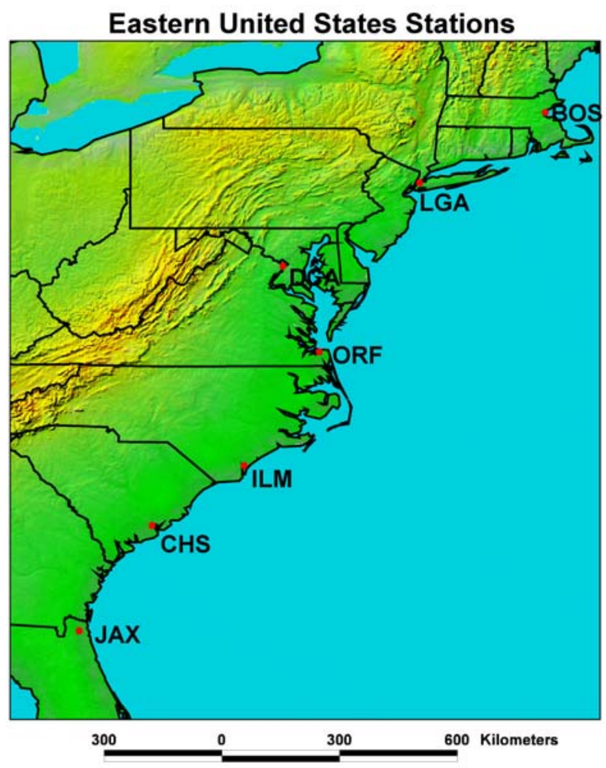

Figure 1: Stations used for studying visibility along the U.S. East Coast. This region was divided into a northern sector including BOS, LGA, and DCA; and southern sector including ORF, ILM, CHS, and JAX.

The first four-year time period represents an earlier time during which efforts were made to improve air quality and visibility, while the second five-year period represents a later time which should reflect efforts to improve *V* due to the Clean Air Act. A more recent time period (from the mid-1990s to present) for the U.S. was avoided due to changes in visibility data collection mainly due to installation of Automated Surface Observing Stations (ASOS). Note that the data for JAX was not used in for the 1980s and ORF data were not used in the 1990s. This is due to visibility limits of < 15 km (no reports exceeded 15 km) for both locations during the respective periods.

For the East Asia comparison study, data were taken for Shenzhen, Shantou, Fuzhou, Wenzhou, Ganyu, Qingdao, Tianjin, and Dalian, China; and Incheon, South Korea (Fig. 2, Table 2) from 1980 to 1983 and from 1998 to 2002.

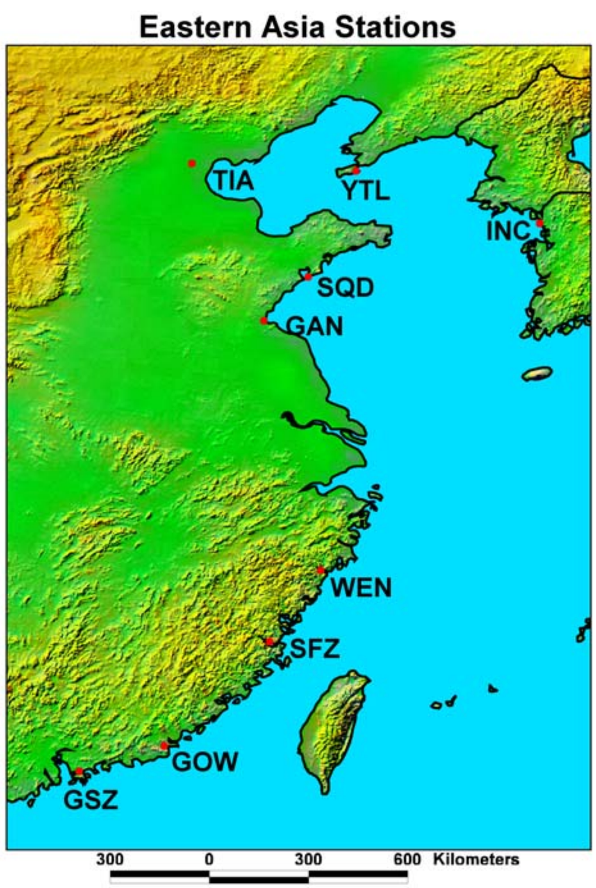

Figure 2: Stations used for studying visibility along the East Asia Coast. This region was divided into a northern sector including GAN, SQD, TIA, YTL, and INC; and a southern sector including GSZ, GOW, SFZ, and WEN.

All the visibility data from both regions have been filtered to eliminate influences due mainly to ongoing precipitation following criteria similar to those used by Husar, et al. (2000). These filters excluded data with a temperature - dew point difference of less than 2.2 degrees C, and present weather codes between 20 and 99 (except for the codes between 30 and 35 whenever the temperature – dew point difference was greater than 4 degrees C) (WMO, 1995).

Table 2: East Asian coastal cities used in this study with station identifier. (No Official Station ID was available (except WMO number) so a three-letter designator was assigned for convenience.)*

City	Country	Latitude (°N)	Longitude (°E)	Station ID
Shenzhen	China	22.55	114.10	GSZ
Shantou	China	23.24	116.41	GOW
Fuzhou	China	26.08	119.28	SFZ
Wenzhou	China	28.02	120.67	WEN*
Ganyu	China	34.83	119.13	GAN*
Qingdao	China	36.02	120.33	SQD
Tianjin	China	39.10	117.17	TIA*
Dalian	China	38.90	121.63	YTL
Incheon	S. Korea	37.48	126.63	INC*

The primary aim of this study was to examine differences in visibility in the two regions during the period when the Clean Air Act reduced emissions that affect *V* for the U.S.

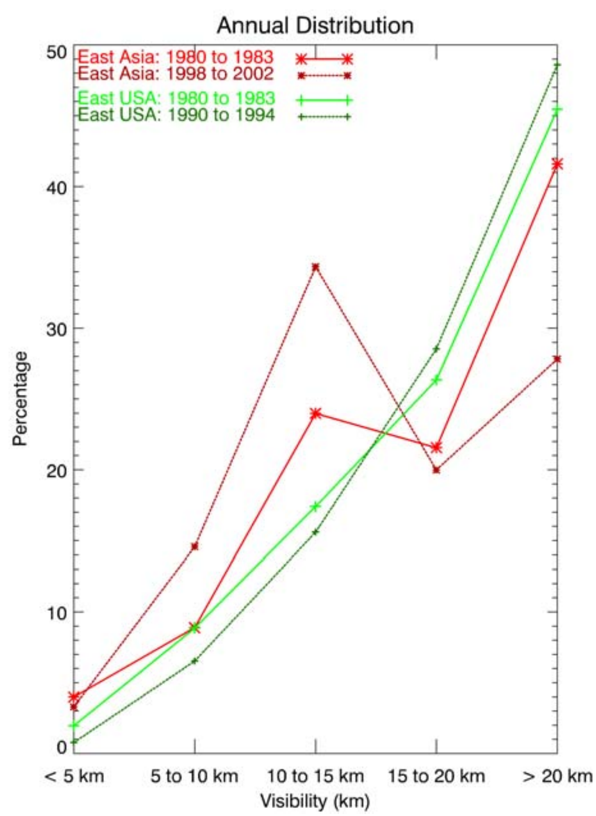

Figure 3: Annual average of visibility bins (5-km increments) for the Eastern United States compared with Eastern Asia. Green lines denote the United States, while red lines denote Eastern Asia.

3. ANNUAL AVERAGES

Annual averages of the visibility were computed for both regions and Fig. 3 shows the results. The averages over the 4 or 5 year period reveal an increase in high *V* ($\geq$20 km) for the U.S. stations and a decrease for the East Asian stations. On the other hand, low visibility occurrences ($\leq$5 km) decline in the U.S. and increase in East Asia. Improvements in the U.S. are not as dramatic as the declines in East Asia.

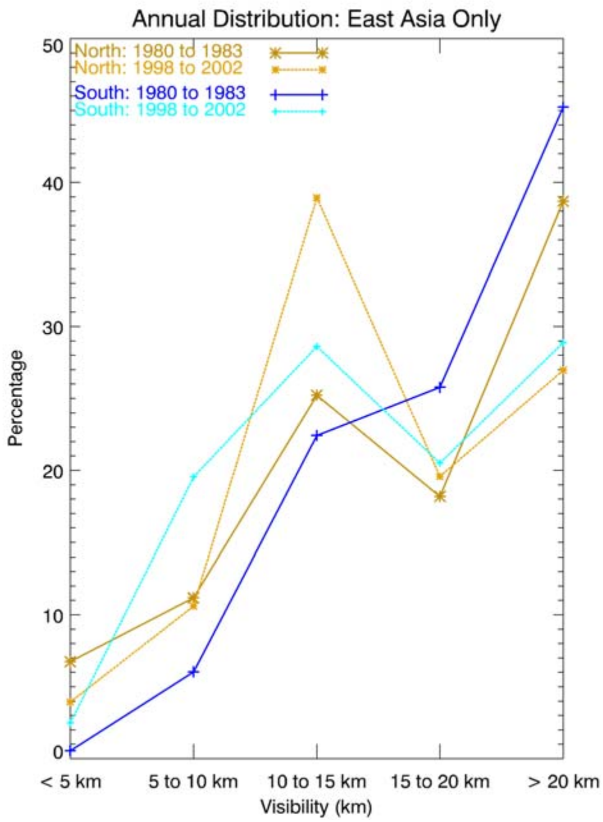

Figure 4: Annual average of visibility bins (5-km increments) for Eastern Asia comparing northern and southern sectors and for the early and late time periods. Brown lines denote the northern sector while blue lines denote the southern sector.

The largest visibility declines in East Asia occurred along the southern part of the region. This is demonstrated in Fig. 4 by breaking up the distributions into a northern sector (GAN, SQD, TIA, YTL, and INC) and a southern sector (GSZ, GOW, FSZ, and WEN). Although the inclusion of both sectors demonstrates a decline in *V*, it can be seen that the decline is much more dramatic in the southern sector.

4. SEASONAL VARIATIONS

Averaging was also performed by season (Mar. to May, Jun. to Aug., Sep. to Oct., and Dec. to Feb.) representing, spring, summer, autumn, and winter (as has been done in previous work, cf. Husar, et al. 2000). The results are presented in Table 3. These results show that the visibility has increased for the East U.S. coastal cities from 1980-83 to 1990-94 for all seasons whereas the visibility has decreased for the East Asian coastal cities from 1980-83 to 1998-2002.

The visibility tended to be lowest for the U.S. in the summer, while *V* in East Asia was highest in summer and autumn. These results are consistent with studies performed by Schichtel, et al. (2001) and Husar, et al. (2000). The differences in visibility show that the greatest improvement in the U.S. has been in the autumn and the least in the spring. For East Asia, the greatest decrease in visibility has been in the autumn and the least in the winter.

Table 3: Seasonal change of visibility (km) for the U.S. from the period from 1980-83 (an earlier period in Clean Air Act history) to 1990-94 (a later period in Clean Air Act history). Also shown are the seasonal changes in visibility for East Asia for the period from 1980-83 to 1998-2002. The difference between the visibility for the later period and the earlier period for each region is also shown.

Region/ Period	Spring (km)	Summer (km)	Autumn (km)	Winter (km)
East US/ 1980-83	20.1	16.2	20.1	20.7
East US/ 1990-94	21.0	17.3	22.7	22.4
Difference	**+0.9 4.5%**	**+1.1 6.8%**	**+2.6 12.9%**	**+1.7 8.2%**
East Asia/ 1980-83	16.3	19.2	18.5	15.1
East Asia/ 1998-2002	14.6	16.2	15.3	14.1
Difference	**-1.7 10.4%**	**-3.0 15.6**	**-3.3 17.8%**	**-1.0 6.6%**

There were several thousand visibility observations (a range of 5,500-21,000) for each seasonal group in Table 3. The large number of observations will help ensure that the differences in visibility are statistically significant even though there is a degree of statistical correlation among the observations.

5. DIURNAL VARIATIONS

Averaging was performed for six periods of the diurnal cycle (01 to 04 LST, 05 to 08 LST, 09 to 12 LST, 13 to 16 LST, 17 to 20 LST, 21 to 00 LST, representing 'midnight:MD', 'pre-sunrise:PR', 'post-sunrise:PS', 'afternoon:AF', 'early evening:EE', and 'late evening:LE'). The results are presented in Table 4 for the six periods of the diurnal cycle.

For the U.S. in the earlier period, the best *V* occurred in the late evening, while the worst *V* occurred post-sunrise. For the U.S. in the later period, the best *V* occurred in the late evening while the worst *V* occurred in the afternoon. For East Asia in the earlier period, the best *V* occurred in early evening, while the worst *V* occurred post-sunrise. For East Asia in the later period, the best *V* occurred in early evening, while the worst *V* occurred post-sunrise. This seems to indicate a correlation of *V* with atmospheric stability for both regions since the best *V* occurs during the evening and nighttime hours and vice versa.

The differences in visibility show that for the U.S. the greatest increase in *V* has been in the late evening and the least in the afternoon. Also for East Asia, the greatest decrease in visibility has been in the early evening and the least in the post-sunrise.

Table 4: Diurnal change of visibility (km) for the U.S. from the period from 1980-83 (an earlier period in Clean Air Act history) and 1990-94 (a later period in Clean Air Act history). Also given is the diurnal change of visibility for East Asia for the periods 1980-83 and 1998-2002. (05 to 08 LST, 09 to 12 LST, 13 to 16 LST, 17 to 20 LST, 21 to 00 LST, 01 to 04 LST, representing 'pre-sunrise: PR', 'post-sunrise: PS', 'afternoon: AF', 'early evening: EE', 'late evening: LE', and 'midnight: MD'). The difference between the visibility for the later period and the earlier period for each region is also shown.

Regn/ Period	PR 05-08 (km)	PS 09-12 (km)	AF 13-16 (km)	EE 17-20 (km)	LE 21-00 (km)	MD 01-04 (km)
US/ 80-83	19.1	18.1	18.8	19.3	20.6	19.8
US/ 90-94	21.6	20.1	19.9	20.8	23.9	21.5
Diff.	**+2.5 13.1%**	**+2.0 11.0%**	**+1.1 5.9%**	**+1.5 7.8%**	**+2.9 14.1%**	**+1.7 8.6%**
Asia/ 80-83	16.3	13.2	16.3	19.0	17.2	17.7
Asia/ 98-02	14.1	13.0	14.5	16.4	15.3	14.4
Diff.	**-2.2 13.5%**	**-0.2 1.5%**	**-1.8 11.0%**	**-2.6 13.7%**	**-1.9 11.0%**	**-2.3 13.0%**

In order to focus on the periods for the best and worst *V* for each season and part of the diurnal cycle, the visibility data were divided into two sections, north and south, for each part of the world. The southern section for the U.S includes CHS and ILM. The northern section includes DCA, LGA, and BOS. The southern section of East Asia includes GSZ, GOW, SFZ, and WEN. The northern section of East Asia includes GAN, SQD, TIA, YTL, and INC. These visibility values are shown in Tables 5 and 6. Note that in general, the two regions tend to be opposite one another, i.e., the best *V* in the U.S. is in autumn and winter whereas the best *V* in East Asia is in summer and conversely. Also note that within the U.S. the northern sector tends to have the best visibility overall whereas the southern sector tends to have the worst. On the other hand, in Eastern Asia, the situation tends to be reversed.

Tables 5 and 6 also give one the opportunity to examine a specific region's change in *V* for a given season and time of day in order to determine the amount of increase or decrease for the given categories.

6. VISIBILITY ROSES

Results were also demonstrated using 'visibility roses' showing the frequency of the wind direction and the corresponding visibility. By examining the visibility roses one can see more details in the overall pattern of *V* and better appreciate the consistencies and inconsistencies.

The best *V*s in both sections for the U.S. occur in late evening of spring, winter, and autumn. These are also seasons and times of day corresponding to lower relative humidity. Fig. 5 shows some examples of visibility roses.

It is also worth noting that in autumn in the U.S. there are frequently high pressure systems centered over the Great Lakes or over the northern Appalachians. Visibility in high pressure systems is typically enhanced and the air is drier than for low pressure systems in the same region. The summer corresponds to the worst visibility conditions for both regions of the U.S. The summer is often dominated by high pressure systems centered off the U.S. East Coast (the Bermuda High) and the winds are often in the directions shown in Fig. 5. It is probably the case that the air in the early evening summer hours on average has higher relative humidity and produces hazy conditions (USEPA, 2003).

For the lower latitudes of East Asia (Fig. 6) in the summer there are typically low pressure systems over the land mass which can draw air from the ocean toward the land. Also, typically, sea breezes will have been ventilating the southern stations during the afternoon. Thus the best visibility may be due to a combination of these two factors.

The worst visibility conditions for East Asia are in the north region particularly post-sunrise (for all seasons). This is probably due to fumigation conditions (the mixing of heavily polluted air near the surface up to the top of the shallow early morning boundary layer as the sun warms the

Table 5: Visibility averages for the U.S. from the periods 1980-83 (an earlier period in Clean Air Act history) and 1990-94 (a later period in Clean Air Act history) by sector (S), season, and period of the day (DP). The U.S. was divided into two regions, south; including CHS and ILM, and north; DCA, LGA, and BOS. Periods of the day are defined as in Table 4. The lowest visibility by sector is italicized while the highest visibility by sector is underlined. The final column is the change in V from the earlier to the later period for that sector and diurnal period.

1980-1983				1990-1994				
S	Season	DP	*V* (km)	S	Season	DP	*V* (km)	(±%)
S	*SUM*	*PR*	*10.4*	*S*	*SUM*	*PR*	*12.2*	*(17)*
S	SUM	MD	11.6	S	SUM	MD	12.5	(8)
S	SUM	LE	11.6	S	SUM	LE	13.4	(15)
S	SUM	PS	12.7	S	SUM	PS	13.6	(7)
S	SUM	EE	13.0	S	SUM	EE	14.0	(8)
S	SUM	AF	13.4	S	SUM	AF	14.6	(9)
S	SPR	PR	14.4	S	AUT	MD	15.8	(-1)
S	AUT	PS	14.8	S	SPR	MD	16.5	(7)
S	AUT	PR	14.9	S	SPR	PS	16.6	(6)
S	SPR	MD	15.3	S	AUT	PS	16.6	(12)
S	SPR	PS	15.7	S	SPR	PR	16.7	(16)
S	WIN	PS	15.7	S	AUT	EE	16.9	(1)
S	SPR	LE	15.8	S	WIN	MD	17.5	(7)
S	WIN	LE	15.9	*N*	*SUM*	*PS*	*17.5*	*(-1)*
S	AUT	MD	16.0	S	WIN	PS	17.6	(12)
S	WIN	MD	16.3	S	AUT	PR	17.7	(19)
S	WIN	PR	16.4	S	AUT	AF	17.7	(4)
S	SPR	EE	16.5	S	AUT	LE	17.8	(7)
S	AUT	LE	16.6	S	SPR	EE	17.9	(8)
S	WIN	AF	16.7	S	SPR	LE	18.1	(14)
S	AUT	EE	16.8	N	SUM	AF	18.3	(1)
S	AUT	AF	17.0	S	SPR	AF	18.4	(6)
S	WIN	EE	17.0	S	WIN	PR	18.5	(13)
N	*SUM*	*PR*	*17.2*	N	SUM	PR	18.5	(8)
S	**SPR**	**AF**	**17.3**	S	WIN	EE	18.5	(9)
N	SUM	PS	17.6	S	WIN	AF	18.6	(12)
N	SUM	AF	18.2	**S**	**WIN**	**LE**	**19.5**	**(23)**
N	SUM	EE	18.8	N	SUM	MD	19.5	(3)
N	SUM	MD	19.0	N	SUM	EE	19.6	(5)
N	SUM	LE	19.8	N	SUM	LE	21.9	(10)
N	AUT	PR	21.2	N	SPR	AF	22.0	(1)
N	AUT	AF	21.3	N	AUT	AF	22.3	(5)
N	AUT	MD	21.6	N	WIN	AF	22.7	(5)
N	WIN	AF	21.7	N	SPR	PR	22.9	(4)
N	SPR	AF	21.8	N	SPR	MD	23.2	(3)
N	SPR	PR	22.0	N	SPR	EE	23.5	(2)
N	WIN	PS	22.5	N	WIN	MD	23.9	(3)
N	SPR	MD	22.6	N	AUT	MD	24.0	(11)
N	AUT	PS	22.6	N	WIN	EE	24.8	(7)
N	SPR	PS	22.8	N	WIN	PR	25.0	(6)
N	AUT	EE	22.9	N	AUT	PR	25.2	(19)
N	SPR	EE	23.0	N	SPR	PS	25.7	(12)
N	WIN	EE	23.1	N	AUT	EE	26.0	(14)
N	WIN	MD	23.3	N	WIN	PS	27.7	(23)
N	WIN	PR	23.6	N	SPR	LE	28.5	(15)
N	SPR	LE	24.7	N	WIN	LE	29.2	(17)
N	WIN	LE	25.0	N	AUT	PS	31.4	(39)
N	**AUT**	**LE**	**25.5**	**N**	**AUT**	**LE**	**32.2**	**(26)**

Table 6: Visibility averages for East Asia for the periods 1980-83 and 1998-2002 by sector (S), season, and period of the day (DP). Asia was divided into two regions, south; including GSZ, GOW, SFZ, and WEN; and north; including GAN, SQD, TIA, YTL, and INC. Periods of the day are defined as in Table 4. The lowest visibility by sector is italicized while the highest visibility by sector is underlined. The final column is the change in V from the earlier to the later period for that sector and diurnal period.

1980-1983				1998-2002				
S	Season	DP	*V* (km)	S	Season	DP	*V* (km)	(±%)
N	*WIN*	*PS*	*8.7*	*N*	*SUM*	*PS*	*11.2*	*(-8)*
N	SPR	PS	11.7	N	SPR	PS	12.1	(3)
N	AUT	PS	11.8	*S*	*WIN*	*MD*	*12.1*	*(-23)*
N	SUM	PS	12.2	N	WIN	PS	12.5	(43)
N	WIN	AF	12.5	N	SUM	PR	12.8	(-17)
N	SPR	AF	14.5	N	AUT	PS	13.0	(9)
N	WIN	LE	14.6	S	SPR	PS	13.0	(-20)
N	WIN	EE	15.1	S	SPR	MD	13.0	(-26)
N	AUT	AF	15.4	S	WIN	PR	13.1	(-16)
N	WIN	PR	15.4	S	WIN	LE	13.2	(-16)
N	SUM	AF	15.4	N	SUM	AF	13.3	(-13)
N	SUM	PR	15.5	S	AUT	MD	13.4	(-33)
N	SPR	PR	15.6	S	AUT	PR	13.5	(-30)
S	*WIN*	*PR*	*15.6*	S	WIN	AF	13.6	(-18)
S	WIN	LE	15.7	N	WIN	AF	13.6	(9)
S	WIN	MD	15.8	S	SPR	PR	13.7	(-20)
N	WIN	MD	16.2	N	SPR	AF	13.7	(-5)
N	SPR	LE	16.2	S	WIN	PS	13.9	(-18)
S	SPR	PS	16.2	S	SPR	AF	14.0	(-18)
S	WIN	AF	16.5	N	SPR	PR	14.1	(-10)
N	SUM	LE	16.7	S	SUM	MD	14.3	(-36)
N	SPR	EE	16.7	S	AUT	PS	14.3	(-26)
N	AUT	PR	16.8	N	WIN	PR	14.4	(-6)
S	WIN	PS	16.9	N	WIN	EE	14.6	(-3)
S	SPR	PR	17.0	N	SUM	MD	14.7	(-20)
N	SPR	MD	17.1	N	WIN	LE	14.7	(1)
S	SPR	AF	17.1	N	AUT	AF	14.7	(-4)
S	SPR	MD	17.7	N	AUT	PR	14.7	(-12)
N	AUT	LE	17.9	N	WIN	MD	14.9	(-8)
S	SPR	LE	18.0	S	AUT	LE	14.9	(-23)
S	WIN	EE	18.2	N	SUM	LE	14.9	(-11)
N	SUM	MD	18.3	S	SPR	LE	15.2	(-16)
N	SUM	EE	18.3	S	WIN	EE	15.2	(-17)
S	SUM	PS	18.6	N	SPR	LE	15.2	(-6)
N	AUT	EE	18.7	N	SPR	EE	15.2	(-9)
N	**AUT**	**MD**	**18.9**	N	SUM	EE	15.3	(-16)
S	AUT	PR	19.3	N	SPR	MD	15.3	(-10)
S	AUT	LE	19.3	N	AUT	MD	15.8	(-16)
S	AUT	PS	19.4	N	AUT	LE	15.8	(-12)
S	SPR	EE	19.9	S	AUT	AF	15.8	(-24)
S	AUT	MD	19.9	S	SUM	PS	16.1	(-13)
S	AUT	AF	20.8	**N**	**AUT**	**EE**	**16.1**	**(-14)**
S	SUM	AF	21.7	S	SPR	EE	16.9	(-15)
S	SUM	PR	22.1	S	SUM	PR	17.0	(-23)
S	SUM	MD	22.3	S	AUT	EE	18.1	(-21)
S	AUT	EE	22.9	S	SUM	AF	18.3	(-16)
S	SUM	LE	23.7	S	SUM	LE	19.1	(-19)
S	**SUM**	**EE**	**25.8**	**S**	**SUM**	**EE**	**22.1**	**(-14)**

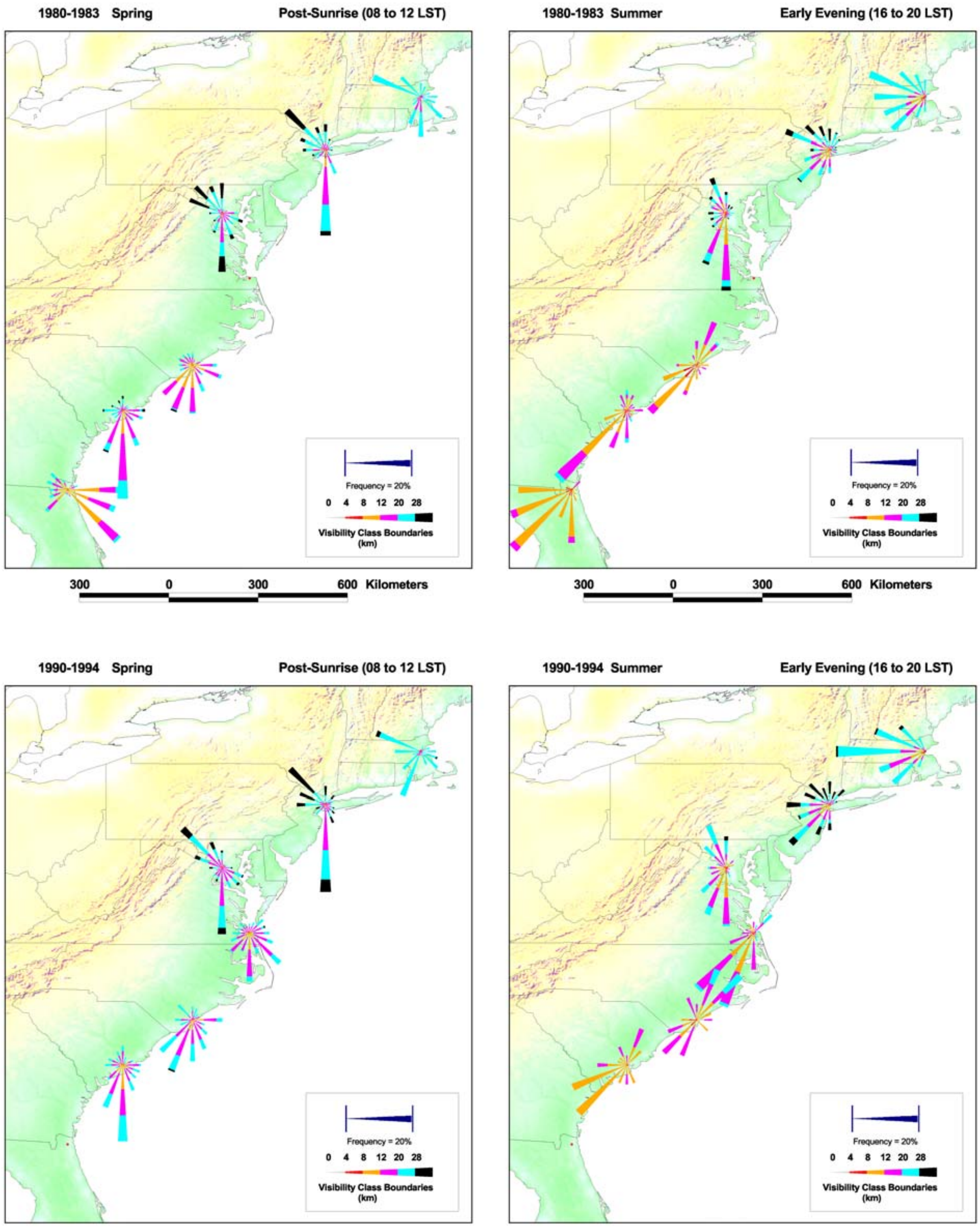

Figure 5: Example Visibility Roses for the Eastern United States: (a) 1980s, good visibility (spring, post-sunrise), (b) 1980s, poor visibility (summer, early evening), (c) 1990s, good visibility (spring, post-sunrise), and (d) 1990s, poor visibility (summer, early evening).

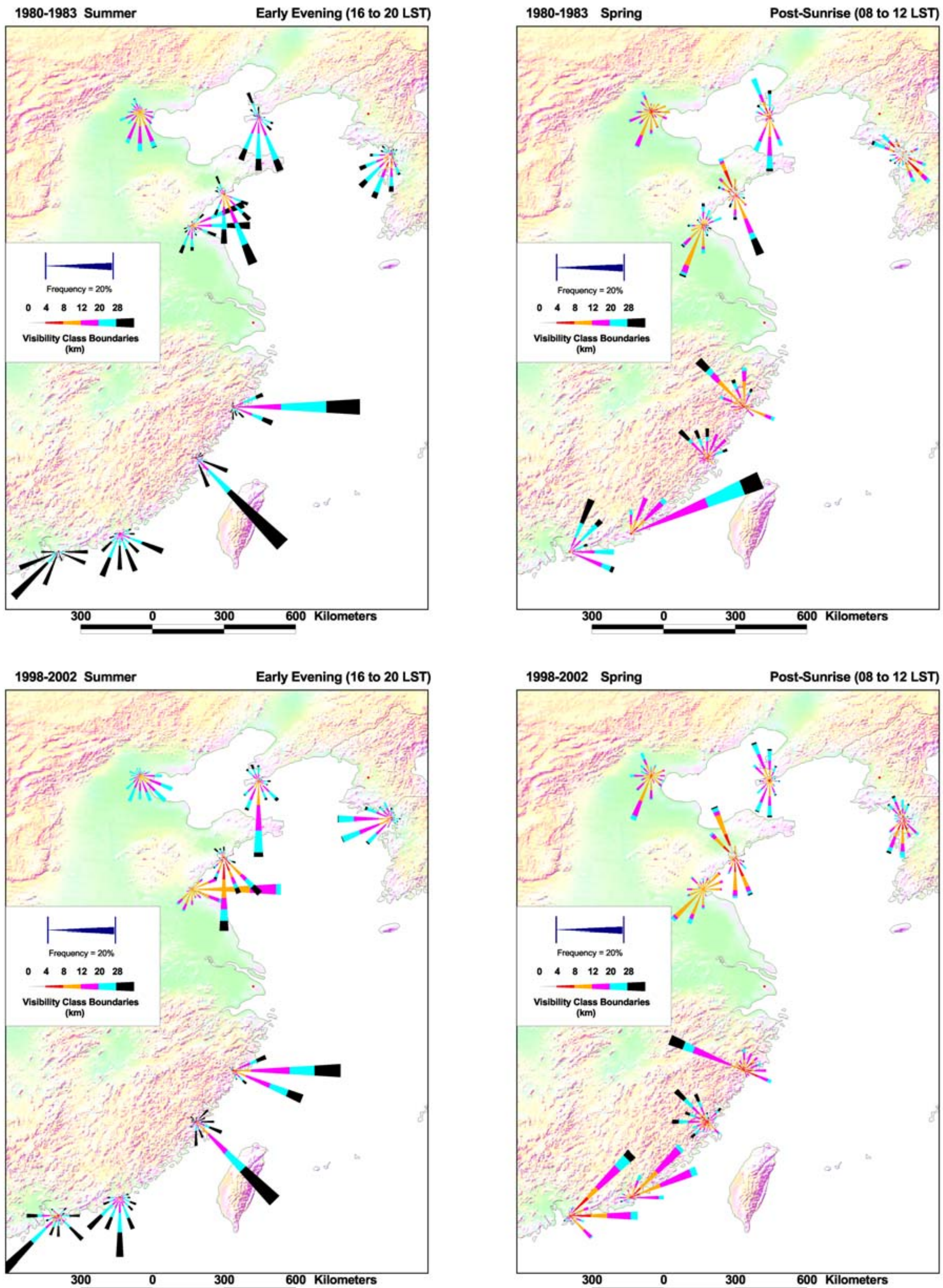

Figure 6: Example Visibility Roses for the Eastern Asia: (a) 1980s, good visibility (summer, early evening), (b) 1980s, poor visibility (spring, post-sunrise), (c) 2000s, good visibility (summer, early evening), and (d) 2000s, poor visibility (spring, post-sunrise).

surface).

There is also the issue of dust storms originating from the Gobi Desert blowing easterly toward the stations in the northern sector of East Asia in the spring (Schneider, 1996). According to Arakawa (1969) the worst visibility conditions for East Asia occur primarily in the north during the winter after sunrise.

7. DISCUSSION/CONCLUSIONS

The two coastal regions of the U.S. and East Asia have more differences than similarities. The reduced emissions resulting from the Clean Air Act are probably related to enhanced visibility for the U.S. East Coastal cities between 1980-83 and 1990-94. One can at least say that the measured *V* has increased by a significant percentage in most instances. In East Asia the *V* has decreased between 1980-83 and 1998-2002.

There are regional differences for both continents when one breaks the two coasts into northern and southern sectors. The northern sector of the U.S. has greater *V*, while the southern sector has lower *V* at least for the small subset of stations considered here. Conversely, the southern sector of East Asia has greater *V*, while the Northern sector has lower *V*. The reasons for these differences (which could be due to relative humidity and sulfate concentration, as suggested by USEPA, 2003, and Husar, et al., 1981) should be investigated further. Seasonal trends indicate better *V* in the U.S. in the cooler seasons (autumn and winter) while *V*s in East Asia are better during the summer. The seasonal differences in *V* in the U.S. found here are consistent with other investigators and climatological summaries dating back to the 1960s (Arakawa, 1969; Husar, et al, 2000; Schichtel, et al., 2001).

An advantage of this investigation is that it was accomplished relatively quickly using standard meteorological observations available to anyone. This study is also unique in that it provides information over a full diurnal cycle (i.e. Tables 4 to 6), whereas previous studies have focused on daily arithmetic averages. Visibility based on this study tends to be best in the early or late evening hours while the worst *V*s are in the hours around sunrise (for both locations). The concept of the visibility rose plotted on a geographical map is also useful in that it provides a quick way to examine directionality in visibility for multiple locations.

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