Classification of Annual Great Lakes Ice Cycles: Winters of 1973–2002*

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ABSTRACT

Annual seasonal average ice cover from 1973 to 2002 and associated dates of first ice, last ice, and ice duration are presented and discussed. The annual seasonal average ice cover of each Great Lake is used to define three ice cycle classes: mild, typical, and severe. About half of the severe ice cycles occurred from 1977 to 1982 and about half of the mild ice cycles occurred from 1998 to 2002. The seasonal progression of daily lake-averaged ice cover, spatial differences in ice cover, and differences among the Great Lakes for mild, typical, and severe ice cycles are discussed within the context of lake bathymetry and winter air temperatures. Seasonal average ice cover is larger on Lakes Superior, Erie, and Huron relative to Lakes Michigan and Ontario, because of shallower depths (for Erie and Huron) and lower air temperatures (for Superior) relative to Lakes Michigan and Ontario. This ice cycle classification scheme can be used to compare future Great Lakes ice cycle severity with this 30-winter benchmark.

1. Introduction

The annual cycle of ice formation and loss on the Laurentian Great Lakes of North America affects physical processes within the lake and in the adjacent atmospheric boundary layer, which in turn affect the economy of the Great Lakes region and the ecology of the Great Lakes. Lake ice is an index of winter regional climate and climate change (Assel and Robertson 1995; Magnuson et al. 2000). The timing, duration, and extent of ice formation affect the flora (e.g., Vanderploeg et al. 1992) and fauna (e.g., Brown et al. 1993) of the winter lake ecosystem. In past studies, the annual maximum ice cover (AMIC) each winter was used to quantify ice cycle severity (Assel et al. 2003; Assel and Quinn 1979). The AMIC, while important, does not contain information on the duration of ice cover. A recent 30-winter climatology of Great Lakes ice cover (Assel 2003) includes daily lake-averaged ice cover for each Great Lake. The daily lake-averaged ice cover is used in this study to calculate a seasonal average ice cover. In the case where the AMIC is similar for a given lake for two winters, the seasonal average ice cover is a useful tool for evaluating the relative severity of the two ice cycles, as it is an index of the time-integrated ice cover extent over the entire ice cycle. Thus, the seasonal average ice cover is a better metric of ice cycle severity then the AMIC.

Annual ice cycles over a 30-winter base period (1973–2002) are analyzed to estimate seasonal average ice cover and ancillary data for each winter for each lake. The seasonal average ice cover is classified into mild, typical, and severe categories to provide a scientific benchmark for the evaluation of the severity of past and future Great Lakes ice cycles relative to ice cycle severity of the 30-winter base period. This information is pertinent for analysis of climate change during the twenty-first century (McCarthy et al. 2001) and on the potential impact of climate change on the Great Lakes aquatic system (Magnuson et al. 1997). The class limits for each Great Lake are presented. The median values of extreme and typical ice cycle classes are quantified, and the general relationship of the class median value differences among the five Great Lakes is discussed within the context of winter air temperature and lake depths. The temporal distribution of the extreme

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TABLE 1. Lake-averaged ice cover (%) on Julian dates of first and last observed ice charts. Bold figures indicate ice cover over 5%.

	First	Erie	Superior	Michigan	Huron	Ontario	Last	Erie	Superior	Michigan	Huron	Ontario
1973	354	0.0	**12.4**	4.5	**21.2**	0.6	461	0.0	1.4	0.0	**6.5**	0.0
1974	365	2.8	**8.4**	1.1	**8.2**	1.4	489	0.0	0.0	0.0	0.0	0.0
1975	367	1.1	1.7	1.6	2.0	1.1	479	0.0	2.2	3.2	**10.2**	0.0
1976	357	**7.4**	5.1	5.5	**24.8**	2.3	475	0.2	2.3	0.4	5.4	0.0
1977	350	**22.4**	**14.4**	**15.9**	**26.1**	1.7	489	0.4	1.0	0.0	1.5	0.0
1978	355	5.5	2.0	2.6	**6.8**	1.1	488	1.7	1.9	0.0	2.6	0.0
1979	352	3.1	2.0	2.5	4.7	0.3	499	0.0	**8.7**	0.0	0.0	0.0
1980	367	**10.7**	5.5	3.5	**8.5**	0.7	471	1.3	**6.2**	1.5	**7.2**	0.0
1981	358	**15.6**	4.8	**9.5**	**16.7**	0.5	470	2.6	3.0	0.0	5.1	0.0
1982	355	0.0	1.6	1.1	0.3	0.0	502	0.7	0.0	0.0	0.0	0.0
1983	355	0.0	1.7	0.0	0.0	0.0	488	0.0	0.8	0.0	0.0	0.0
1984	354	1.8	**10.3**	5.0	**13.7**	0.0	488	1.0	1.0	1.0	1.2	1.0
1985	356	0.0	1.8	0.1	0.4	0.0	482	2.4	0.9	0.0	0.0	0.0
1986	348	4.4	3.8	2.2	3.9	2.6	478	0.1	0.9	0.0	0.0	0.0
1987	361	0.0	2.1	2.7	1.8	0.0	460	0.0	2.1	0.2	5.7	0.0
1988	368	**6.9**	1.7	2.5	2.7	0.0	472	2.2	0.5	0.6	**6.1**	1.0
1989	348	1.9	0.9	0.9	3.6	0.0	493	0.0	0.3	0.0	0.0	0.0
1990	347	4.7	1.5	1.5	2.3	0.0	482	0.0	0.5	0.0	0.0	0.0
1991	362	0.3	0.9	0.6	0.5	0.0	486	0.0	0.2	0.0	0.0	0.0
1992	340	0.0	4.1	2.1	0.5	0.0	496	0.0	0.4	0.0	0.0	0.0
1993	348	0.0	0.4	0.0	0.0	0.0	490	0.0	0.3	0.0	0.0	0.0
1994	337	0.0	0.8	0.0	0.0	0.0	501	0.0	0.0	0.0	0.0	0.0
1995	339	0.0	0.1	0.0	0.0	0.0	507	0.0	0.0	0.0	0.0	0.0
1996	321	0.0	0.0	0.0	0.0	0.0	516	0.0	0.1	0.0	0.0	0.0
1997	330	0.0	0.3	0.0	0.0	0.0	498	0.0	0.9	0.0	0.1	0.0
1998	336	0.0	0.0	0.0	0.0	0.0	479	0.0	0.0	0.0	0.0	0.0
1999	349	0.0	0.2	0.0	0.0	0.0	489	0.0	0.0	0.0	0.0	0.0
2000	337	0.0	0.0	0.0	0.0	0.0	483	0.0	0.0	0.0	0.0	0.0
2001	335	0.0	0.4	0.0	0.0	0.0	488	0.0	1.1	0.0	0.0	0.0
2002	337	0.0	0.0	0.0	0.0	0.0	494	0.0	0.0	0.0	0.0	0.0

winters is briefly examined. The seasonal and spatial progression of ice cover for each ice cycle class is presented and discussed.

2. Seasonal average ice cover

The data used in this study are the daily lake-averaged ice cover, obtained from Assel (2003). The daily spatial average ice cover for each Great Lake was calculated from daily grids. Daily grids were generated by linear interpolation of observed ice cover grids between adjacent dates for a given winter season from the date of first ice chart to date of last ice chart (Assel and Norton 2001). Lake-averaged ice cover prior to date of first ice chart and after date of last ice chart was assumed to be zero.

The daily lake-averaged ice cover on each Great Lake is used to calculate the seasonal average ice cover. The seasonal average ice cover is the sum of the daily lake-averaged ice cover over a winter divided by 182 (the number of days between 1 December to the following 31 May). The seasonal average ice cover is calculated for days when the lake-averaged ice cover was greater than or equal to 5%. The 5% criteria was used because lake-averaged ice cover for most winters was 5% or less on the date of the first and date of the last observed ice charts (Table 1). The seasonal average ice cover was likely underestimated for some of the Great Lakes (primarily Lakes Huron, Erie, and Superior) for some winters (1973, 1974, 1976, 1977, 1980, 1981, 1984, and 1988) because the lake-averaged ice cover was more than 5% on the first ice chart (Table 1).

The seasonal average ice cover is an index of the severity of an annual ice cycle. Ancillary ice cycle variables calculated for each winter are the Julian dates that the first and last observed lake-averaged ice cover was greater than or equal to 5% and the duration of the ice cover, that is, the difference between dates of last and first ice.

3. Ice cycle classification

Correlation analysis shows that ice cycle duration is significantly correlated ($\alpha = 0.001$) with seasonal average ice cover (Table 2). The date of first (last) ice is also correlated with the seasonal average ice cover. Corre-

TABLE 2. Correlation coefficient for seasonal average ice cover. All are significant at the 1% level; Lake Ontario dates of first and last ice for 2002 are not included because seasonal average ice cover was zero that year

	Erie	Superior	Michigan	Huron	Ontario
First ice	−0.68	−0.50	−0.59	−0.58	−0.60
Last ice	0.90	0.83	0.68	0.72	0.61
Duration	0.92	0.84	0.78	0.79	0.80

lation coefficients indicate that as the seasonal average ice cover increases, the duration of the ice cycle increases, the dates of last ice cover increase (become later), and the dates of first ice cover decrease (become earlier). This is consistent with the observed seasonal pattern of daily lake-averaged ice cover for the Great Lakes. Thus, it seems plausible to use the seasonal average ice cover to classify the annual Great Lakes ice cycles.

The seasonal average ice cover for each lake was ranked from lowest to highest. Ice cycles were classified as mild, typical, and severe using the upper and lower 20% of the cumulative frequency distribution as a first estimate of class boundaries, and then these boundaries were adjusted up or down to account for large differences between adjacent observations above or below the original class limits to define final class boundaries (Fig. 1). In some cases, class limits stayed the same. Lakes Michigan, Ontario, and Erie had large differences between the last one to three observations, that is, difference between ranks 28–29 or differences between ranks 29–30 of the seasonal average ice cover. These differences were not used to choose class limits as they would have been too restrictive, that is, they

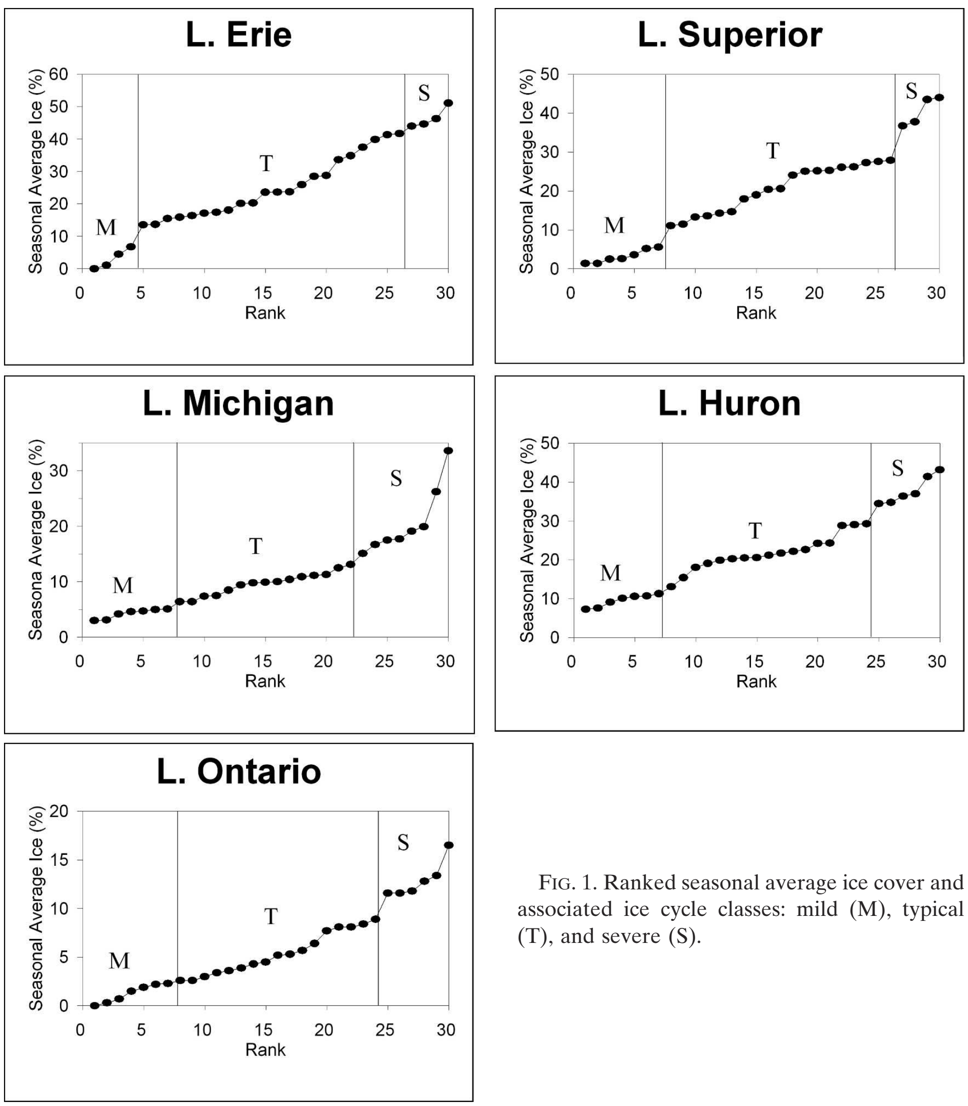


FIG. 1. Ranked seasonal average ice cover and associated ice cycle classes: mild (M), typical (T), and severe (S).

would have produced a class with only one or two members.

The paired ice cover class medians (mild and typical, typical and severe, and mild and severe) were tested (Ferguson 1976) and found to be statistically significantly different ($\alpha \geq 0.05$). This was also the case for the class limits defined exclusively by the upper and lower 20% of the cumulative frequency distribution and a preliminary analysis showed that the results described and discussed below would not have been much different had the class limits determined exclusively by the cumulative frequency distribution been used. The seasonal average ice cover for each lake, associated date of first (last) reported ice, ice duration, and median values of all variables for mild, typical, and severe ice cycle classes is summarized in Table 3.

4. Mild, typical, and severe ice cycle comparisons

a. Median seasonal average ice cover

Lakes Erie and Huron have the largest seasonal average ice cover for the typical ice cycle (Fig. 2) because they are the shallowest of the Great Lakes, with mean depths of 19 and 58 m, respectively. Lakes Erie and Superior have the largest range of ice cover between severe and mild ice cycles. Lake Erie with its shallow depth is more sensitive to changes in interannual atmospheric variability, while Lake Superior, farthest to the north and deepest of the Great Lakes (mean depth 148 m), usually forms an extensive ice cover because it is exposed to the lowest air temperatures. However, during mild winters, its ice cover extent is low. Lake Ontario has the second mildest winter air temperatures and second-to-highest mean lake depth (86 m), resulting in the lowest seasonal average ice cover. Lake Michigan with a similar mean depth (85 m) also has a low range of ice cover because, in all but some of the severe winters, the southern half of the lake is not exposed to low air temperatures for sufficiently long periods to form extensive ice cover.

b. Median dates of first ice, last ice, and ice cover duration

The Great Lakes have sufficiently large shallow areas (less than 20 m) to respond rapidly to low air temperatures in early winter, and once the ice is formed it usually remains in the shallow areas (e.g., bays and shoals) until the spring. Thus, the median duration of ice cover for typical ice cycles (Fig. 2) are skewed toward the medians for severe winters. For typical ice cycles, the median dates of first ice are earliest (Fig. 2), and dates of last ice are latest (Fig. 2) on Lake Huron giving this lake the greatest typical ice cycle duration (Fig. 2). The difference between mild and severe ice cycle dates of first ice is also the lowest on Lake Huron relative to the other Great Lakes. The same is true of dates of last ice and ice duration. This is because Lake Huron has large shallow areas (North Channel, Georgian Bay, and Saginaw Bay) that are exposed to relatively low winter air temperatures, so that lake-averaged ice cover of 5% or more forms earlier and lasts longer on this lake for most winters. Lake Superior has the next longest median ice duration for the typical ice cycles, due to a combination of second earliest date of ice formation and second latest date of last lake-averaged ice of 5%. Lake Superior is exposed to the lowest winter air temperatures, but because of its great depth and lower proportion of shallow waters (4.7% and 14.8% of lake depth less than 10 m for Superior and Huron, respectively; Table III of Assel et al. 2003), ice cover forms slower and deteriorates faster. Dates when Lake Superior lake-averaged ice is first greater than 5% are later than they are for Lake Huron. Dates when lake-averaged ice in spring is less than 5% are earlier than Lake Huron's because of a large proportion of Lake Superior's ice cover being in waters of greater depth where the action of winds, waves, and upwelling can cause more rapid deterioration and loss of ice cover. The large difference in ice duration between mild and severe winters on Lake Superior (Fig. 2) is due primarily to large differences in dates of last ice (Fig. 2). Lake Michigan has the third longest median ice duration for the typical ice cycles, after Lakes Huron and Superior (Fig. 2). The median date of first ice cover in Lake Michigan is about the same as Lake Erie (Fig. 2), but its date of last ice (lake-averaged ice cover of 5%) in spring is later than it is for Lake Erie because of large shallow areas in the northern half of the lake where air temperatures are lower later in spring. Lake Erie's shallow depth makes it highly sensitive to interannual variations in air temperature, an important climatic variable affecting ice formation and loss. Thus, the difference of Lake Erie median ice duration (and dates of first and dates of last ice) for mild and severe ice cycles is largest of any of the Great Lakes. Lake Ontario, because of its large mean depth and relatively mild winter air temperatures, has the shortest median ice duration for typical ice cycles (Fig. 2), latest median dates of first ice (Fig. 2), and earliest date of last ice (Fig. 2) for typical ice cycles. Lake Ontario also has a large difference in median date of ice duration (and dates of first and dates of last ice) between mild and severe ice cycles. This is because shallow lake depths at the northeast end of the lake and along the northern shore respond rapidly to low air

Table 3. Seasonal average ice cover and ancillary data for mild, typical, and severe ice cycles. The seasonal average ice cover is ranked in descending order. The mild (severe) ice cycles for each lake are the winters with bold entries.

Lake Erie					Lake Superior					Lake Michigan					Lake Huron					Lake Ontario				
	Date[a]		Dur[b]	Ice		Date		Dur	Ice		Date		Dur	Ice		Date		Dur	Ice		Date		Dur	Ice
Winter	First	Last	days	(%)	Winter	First	Last	days	(%)	Winter	First	Last	days	(%)	Winter	First	Last	days	(%)	Winter	First	Last	days	(%)
1998	**388**	**388**	**1**	**0.0**	**2002**	**395**	**454**	**59**	**1.4**	**2002**	**396**	**454**	**58**	**3.0**	**2002**	**368**	**474**	**106**	**7.3**	**2002**	**—**	**—**	**0**	**0.0**
2002	**366**	**414**	**48**	**1.1**	**1998**	**379**	**412**	**33**	**1.4**	**1998**	**378**	**445**	**67**	**3.1**	**1998**	**366**	**454**	**88**	**7.6**	**1998**	**394**	**410**	**16**	**0.3**
1983	**378**	**424**	**46**	**4.5**	**1987**	**369**	**441**	**72**	**2.5**	**1995**	**389**	**449**	**60**	**4.2**	**1983**	**377**	**461**	**84**	**9.1**	**1987**	**388**	**440**	**52**	**0.7**
1991	**371**	**437**	**66**	**6.8**	**1999**	**372**	**443**	**71**	**2.6**	**1987**	**362**	**447**	**85**	**4.6**	**1999**	**362**	**464**	**102**	**10.1**	**1975**	**397**	**432**	**35**	**1.5**
1987	380	436	56	13.6	**2000**	**378**	**427**	**49**	**3.6**	**2000**	**374**	**439**	**65**	**4.7**	**2000**	**363**	**450**	**87**	**10.6**	**1983**	**387**	**420**	**33**	**1.9**
1975	379	443	64	13.7	**1995**	**378**	**456**	**78**	**5.2**	**1983**	**379**	**442**	**63**	**5.0**	**1987**	**379**	**460**	**81**	**10.7**	**1999**	**369**	**437**	**68**	**2.2**
1992	382	446	64	15.5	**1983**	**365**	**456**	**91**	**5.6**	**1999**	**367**	**446**	**79**	**5.1**	**1995**	**372**	**464**	**92**	**11.3**	**1989**	**409**	**451**	**42**	**2.3**
1974	366	443	77	15.9	1975	375	469	94	11.1	1992	381	461	80	6.4	1991	371	472	101	13.1	1991	373	429	56	2.6
1973	368	436	68	16.4	2001	363	468	105	11.5	1991	371	451	80	6.4	1975	375	479	104	15.4	1995	403	441	38	2.6
2000	361	431	70	17.2	1976	357	471	114	13.3	1993	372	460	88	7.4	1973	354	461	107	18.1	2000	384	426	42	3.0
1999	367	446	79	17.4	1973	354	450	96	13.6	1973	355	439	84	7.5	2001	345	474	129	19.1	1976	368	450	82	3.4
1995	370	449	79	18.1	1993	362	465	103	14.3	1975	376	473	97	8.5	1992	358	485	127	19.9	1992	388	455	67	3.6
1989	371	449	78	20.2	1992	342	468	126	14.7	1988	369	457	88	9.4	1976	357	475	118	20.3	2001	368	448	80	3.9
1990	349	444	95	20.3	1988	369	461	92	18.0	2001	352	462	110	9.8	1988	369	473	104	20.5	1997	388	463	75	4.3
1997	365	459	94	23.6	1980	367	471	104	19.0	1989	366	472	106	9.9	1980	367	472	105	20.6	1993	399	460	61	4.5
1976	357	447	90	23.7	1991	371	463	92	20.4	1976	357	464	107	10.0	1974	365	484	119	21.2	1974	366	442	76	5.2
1993	381	463	82	23.8	1990	351	467	116	20.6	1980	375	464	89	10.4	1993	359	479	120	21.7	1980	396	455	59	5.3
1980	367	466	99	26.0	1978	359	481	122	24.1	1984	354	466	112	10.9	1989	360	483	123	22.2	1988	370	454	84	5.7
1988	368	469	101	28.5	1984	354	481	127	25.1	1974	366	476	110	11.1	1990	349	474	125	22.6	1996	370	457	87	6.4
1985	365	465	100	28.8	1981	359	468	109	25.2	1997	364	476	112	11.3	1997	364	491	127	24.2	1990	351	445	94	7.7
2001	347	469	122	33.7	1985	357	463	106	25.3	1990	351	458	107	12.5	1985	361	477	116	24.3	1973	368	434	66	8.1
1981	358	465	107	34.9	1989	361	480	119	26.1	1985	365	458	93	13.1	1981	358	470	112	28.8	1984	366	459	93	8.1
1979	366	461	95	37.5	1982	368	488	120	26.2	**1981**	**358**	**461**	**103**	**15.1**	1984	354	484	130	29.1	1981	359	425	66	8.4
1994	362	474	112	39.9	1997	365	490	125	27.3	**1996**	**358**	**480**	**122**	**16.7**	1986	349	473	124	29.3	1985	367	451	84	8.9
1982	370	474	104	41.4	1986	352	466	114	27.6	**1982**	**371**	**475**	**104**	**17.5**	**1982**	**365**	**493**	**128**	**34.5**	**1986**	**363**	**452**	**89**	**11.6**
1996	343	474	131	41.7	1974	365	483	118	27.9	**1986**	**350**	**463**	**113**	**17.7**	**1979**	**361**	**480**	**119**	**34.8**	**1979**	**374**	**444**	**70**	**11.6**
1984	**355**	**477**	**122**	**44.0**	**1996**	**369**	**502**	**133**	**36.8**	**1978**	**359**	**471**	**112**	**19.1**	**1996**	**343**	**488**	**145**	**36.4**	**1982**	**377**	**462**	**85**	**11.8**
1986	**349**	**469**	**120**	**44.7**	**1994**	**362**	**486**	**124**	**37.8**	**1994**	**363**	**469**	**106**	**19.9**	**1978**	**355**	**484**	**129**	**37.0**	**1994**	**366**	**464**	**98**	**12.8**
1977	**350**	**466**	**116**	**46.3**	**1977**	**350**	**482**	**132**	**43.5**	**1979**	**362**	**478**	**116**	**26.2**	**1994**	**361**	**483**	**122**	**41.4**	**1978**	**361**	**466**	**105**	**13.4**
1978	**355**	**478**	**123**	**51.1**	**1979**	**363**	**499**	**136**	**44.0**	**1977**	**350**	**473**	**123**	**33.6**	**1977**	**350**	**485**	**135**	**43.2**	**1977**	**358**	**475**	**117**	**16.5**
Median[c] values for mild, typical, and severe ice cycle classes																								
Mild	**375**	**419**	**47**	**2.8**	**Mild**	**378**	**443**	**71**	**2.6**	**Mild**	**378**	**446**	**65**	**4.6**	**Mild**	**368**	**461**	**88**	**10.1**	**Mild**	**388**	**432**	**35**	**1.5**
Typical	367	454	92	23.7	Typical	361	468	114	20.6	Typical	366	462	97	9.9	Typical	359	475	119	21.2	Typical	370	450	75	5.2
Severe	**353**	**473**	**121**	**45.5**	**Severe**	**363**	**493**	**133**	**40.7**	**Severe**	**359**	**472**	**113**	**18.4**	**Severe**	**358**	**485**	**129**	**36.7**	**Severe**	**365**	**463**	**94**	**12.3**

[a] The Julian day the ice cover first and last exceeds 5% each winter, e.g., day 366 is 1 Jan.
[b] Dur: duration. The difference between first and last date of ice. If the first and last days are the same, ice duration is 1 day.
[c] Rounded to nearest day for first (last) ice and ice duration; rounded to nearest tenth for seasonal average ice cover.

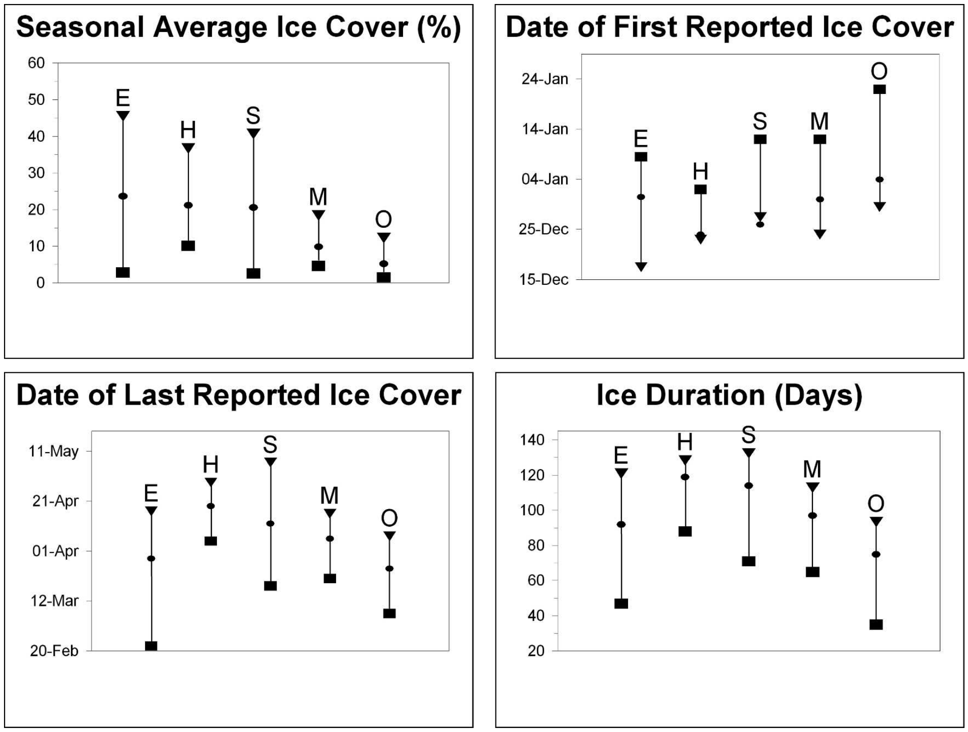


FIG. 2. Median seasonal average ice cover (%), dates of first ice, dates of last ice, and ice cover duration for severe (▼), typical (●), and mild (■) ice cycles for Lakes Erie (E), Huron (H), Superior (S), Michigan (M), and Ontario (O).

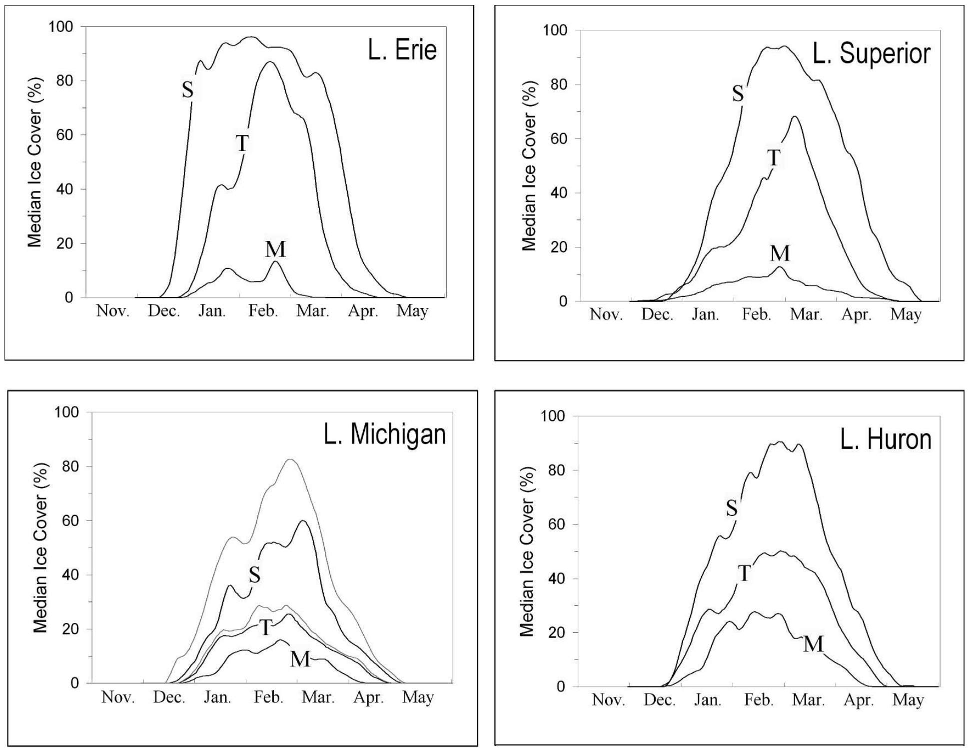
temperatures, and the median date of first ice in severe winters is near the end of December. However, during mild winters, median dates of ice formation do not occur until the last half of January.

c. Temporal distribution of mild and severe ice cycles

There is a total of 150 lake winters (5 lakes × 30 winters). The total number of mild lake winters (Table 3) is 32 (4 for Lake Erie, and 7 each for Lakes Superior, Michigan, Huron, and Ontario). Seventeen of the 32 mild ice cycles (i.e., approximately 53%) occurred between 1998 and 2002. The total number of severe lake winters is 28 (4 each for Lakes Superior and Erie, 6 each for Lakes Huron and Ontario, and 8 for Lake Michigan). Seventeen of these 28 severe winters (i.e., approximately 61%) occurred between 1977 and 1982 (Table 3). These results are in agreement with Assel et al. (2003), who examined trends in annual maximum ice cover on the Great Lakes from 1963 to 2001. These temporal biases coincide with phase variations in two atmospheric oscillations, the Pacific decadal oscillation (PDO) and the El Niño–Southern Oscillation (ENSO). Rodionov and Assel (2003) found that a shift to a warm PDO regime in 1977 accompanied by an absence of strong warm ENSO events resulted in an amplification of the ridge–trough system over North America. This amplified longwave pattern is associated with an increase in mederional (north to south) atmospheric circulation, cold air advection to the Great Lakes, and a series of unusually cold winters (from 1977 to 1982). Strong warm ENSO events are related to below-average Great Lakes ice cover (Assel 1998) and typically a strong zonal (east to west) atmospheric circulation pattern over the North Pacific (Rodionov et al. 2001). Starting in 1983, the frequency of warm ENSO events increased and was accompanied by a trend for more frequent mild winters in the Great Lakes in the 1980s, 1990s, and early 2000s relative to the late 1970s and first few years of the 1980s.

d. Seasonal progression of the daily median lake-averaged ice covers for severe, typical, and mild ice cycles

The temporal pattern of an ice cycle consists of a period of ice formation and increasing ice cover, a period when the ice cover is near its seasonal maximum coverage (this period can be a few days or several



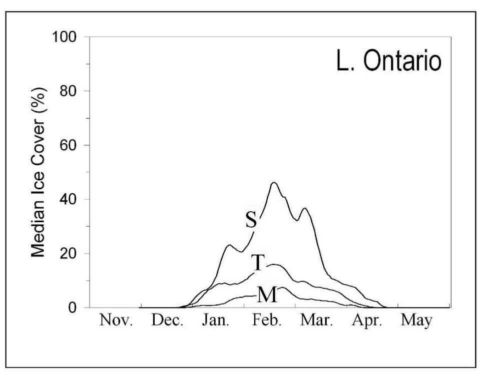


FIG. 3. Daily median ice concentration for mild (M), typical (T), and severe (S) ice cycle classes for each Great Lake. The curves are 7-day running averages of the lake-averaged daily ice cover concentration. The two additional gray lines for Lake Michigan show the median ice cover for the two most severe winters, 1977 and 1979, and for the typical winters if winters 1981, 1996, 1982, 1986, 1978, and 1994 were moved from the severe to the typical winter class.

weeks, and in some winters a lake can be near it maximum ice extent more than once because of a mild winter or episodic high winds followed by cold, calm conditions), and a period of ice deterioration and ablation ending in the final loss of the ice cover. The lake-averaged value of the daily median for the severe ice cycles, the daily median for the mild ice cycles, and the daily median for the typical ice cycles are illustrated for each Great Lake in Fig. 3. The frequency distribution of the daily lake-averaged ice cover for typical ice cycles is skewed toward the severe ice cycles for Lakes Superior and Erie, and skewed toward the mild ice cycles for Lakes Michigan and Ontario as evidenced by a comparison of the medians for the severe, typical, and mild ice cycles (Fig. 3). This was also found to be the case for the annual seasonal maximum ice cover (Assel et al. 2003). Assel et al. (2003) explained this in terms of the combination of lake heat storage and climatic potential for heat loss for each Great Lake. Lake Erie forms an extensive ice cover almost every winter because of its shallow mean water depth (19 m), while Lake Superior also forms an extensive ice cover most winters, because of its exposure to much lower air temperatures than the other Great Lakes. Lakes Michigan and Ontario have relatively large mean depth (85 and 86 m, respectively) but more moderate winter air temperatures relative to Lake Superior, and as a result, do not form extensive ice covers most winters. There is a decline in the ice covers on some of the Great Lakes near the end of January (Fig. 3), more pronounced on Lakes Erie (typical and mild ice cycles), Michigan (severe ice cycle), and Ontario (severe ice cycle). This may be a manifestation of the "January thaw[1]" phenomenon (Huschke 1959).

1) Severe ice cycles

The severe ice cycle ramp-up period leading to the seasonal maximum ice cover occurs in December and January for Lake Erie and in December, January, and February for the other Great Lakes. The period near maximum ice extent lasts longest for Lake Erie (ice cover on Lake Erie is in excess of 80% from early January to mid-March). Ice cover near-seasonal maximum extent (in excess of 80%) is about a month shorter in duration (early February to mid-March) on Lakes Superior and Huron. Ice cover is near its seasonal maximum extent on Lakes Michigan and Ontario near the end of the first week of February to the end of the first week of March (50%–60% Lake Michigan; 35%–50% Lake Ontario). As a comparison, the median ice cover for the two extremely severe winters for Lake Michigan (1977 and 1979) ranged from 70% to 83% during this time (Fig. 3). The ice dissipation period starts in March, and by the end of that month, ice cover on Lake Superior is near 60%, on Lake Huron is near 44%, on Lake Erie is near 40%, on Lake Michigan is near 15%, and on Lake Ontario is near 8%. By the end of April, ice cover is less than 10% on Lake Superior, less than 5% on Lake Huron, and less than 2% on Lakes Erie, Michigan, and Ontario.

2) Typical ice cycles

The typical ice cycle ramp-up period for Lakes Erie, Huron, Michigan, and Ontario occurs in January to the first week of February, and for Lake Superior it occurs in January to early March. Lakes Michigan and Ontario are near their seasonal maximum ice extent (22%–28% for Michigan; 12%–16% for Ontario) during the month of February. Lake Erie is near its seasonal maximum ice cover (in excess of 80%) from the end of the first to the end of the third week of February. Lake Huron is near its seasonal maximum ice extent (45%–52%) from the end of the first week of February through the end of the first week of March. Lake Superior is near its seasonal maximum ice extent (60%–72%) from the last week of February to the end of the first week of March. The ramp-down period starts in late February (Lakes Erie, Michigan, and Ontario) to the end of the first week in March (Lakes Huron and Superior). By the end of that month, Lakes Superior and Huron are approximately 22% ice covered, Lake Michigan about 9%, Lakes Erie near 5%, and Lake Ontario approximately 2%. By mid-April, the ice covers for Lakes Huron and Superior are less than 10%, ice cover on Lake Michigan is approximately 1%, and ice cover on Lakes Erie and Ontario is less than 1%.

3) Mild ice cycles

The ramp-up period for mild ice cycles ends in January on all the Great Lakes. The median ice cover for Lake Erie mild ice cycles is near its maximum extent the end of the third week of January, decreases from the last week of January to the middle of the second week of February, and is at its annual maximum ice extent (12%–16%) in the third week of February. Lakes Huron, Michigan, and Ontario are near their median daily seasonal maximum ice extent from the last week of January to the last week of February (20%–30% for Huron, 11%–18% for Michigan, and 4%–8% for Ontario). Lake Superior is near its maximum ice extent (8%–15%) the entire month of February. By mid-March ice covers range from approximately 15% for Lake Huron to less then 1% for Lake Erie, with Lakes Michigan, Superior, and Ontario having approximately 9%, 6%, and 3% ice cover, respectively. By the end of March, Lake Erie is ice free, Lakes Ontario and Michigan have approximately 1% ice cover, Lake Superior has less than 4% ice cover, and Lake Huron has 8% ice cover.

e. *Ice cover spatial distribution differences for early, mid-, and late winter*

The spatial distribution patterns of ice cover for early winter (mid-January), midwinter (mid-February), and late winter (mid-March) for specific winters [1977, 1985, and 1983, all taken from ice chart data given in Assel (2003)] are used to illustrate real-world spatial patterns of ice cover distribution for severe, typical, and mild ice cycles (Fig. 4). Computer animations of the daily spatial distribution pattern of ice cover from 1 December to 31 May for winters from 1973 to 2002 are available in Assel (2003).

1) Early winter patterns

During the first half of January of a severe ice cycle, ice cover distribution patterns are sometimes not substantially different than they are for typical ice cycles. The severe 1977 ice cycle is an exception. Extensive ice cover formed in the midlake areas of Lakes Superior, Michigan, and Huron (Fig. 4a) a month or more earlier than in a typical ice cycle. The 12 January 1977 ice cover is similar to a typical midwinter pattern (Fig. 4e). This

[1] Mild weather that occurs in late January in the northeastern United States; it may be caused by southerly winds from anticyclones offshore of the southeastern United States.

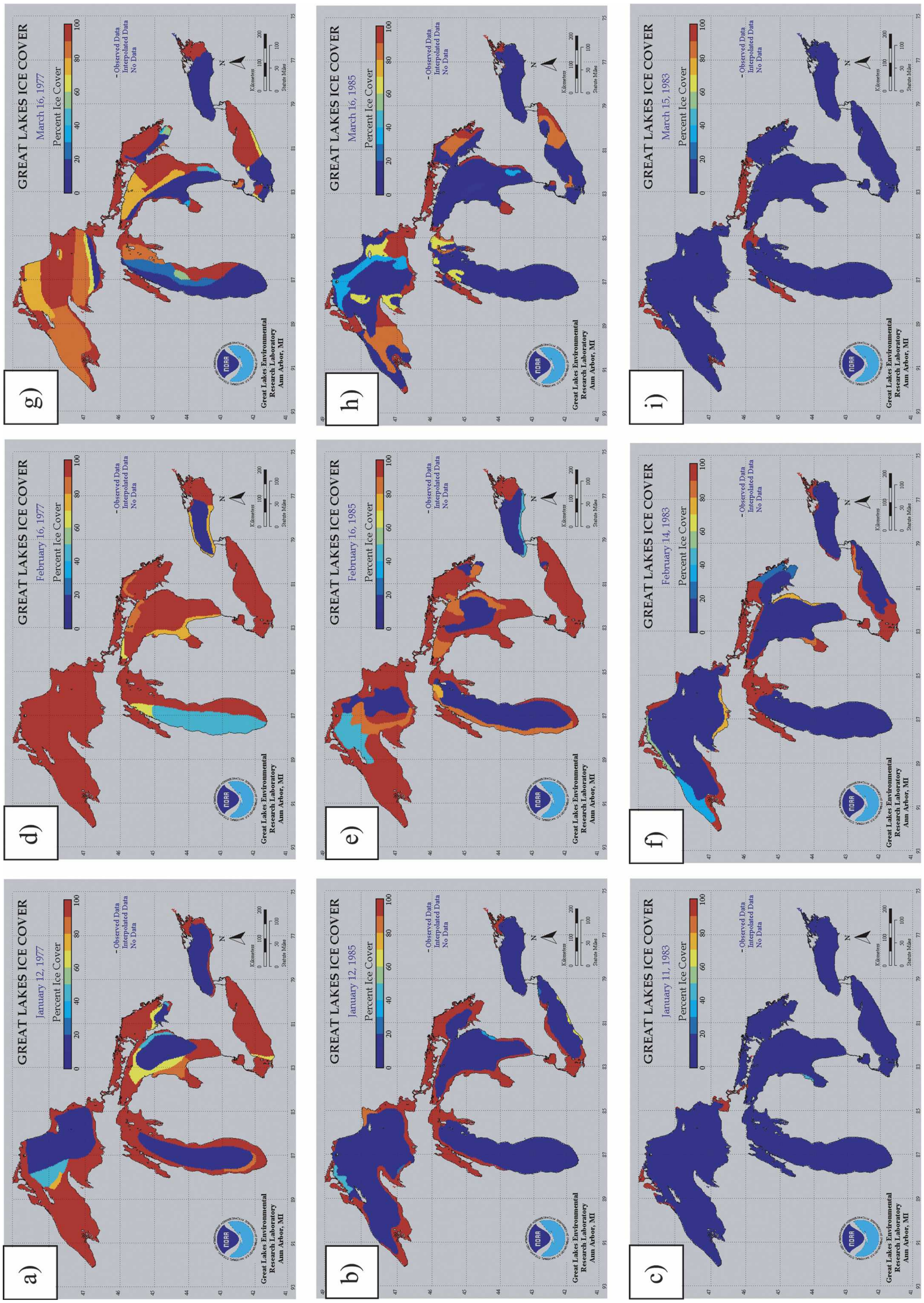


FIG. 4. Ice cover distribution patterns for early winter [(a) severe, (b) typical, and (c) mild], midwinter [(d) severe, (e) typical, and (f) mild], and late-winter [(g) severe, (h) typical, and (i) mild] ice cycle classes, respectively.

is the result of record-breaking low air temperatures starting in mid-October 1976 [see Quinn et al. (1978) and Assel and Quinn (1979) for more information]. January 1985 portrays early winter ice cover during a typical winter (Fig. 4b). Ice cover the second week of January that winter is limited to the shore regions and relatively shallow areas of the Great Lakes. It should be noted that Lake Erie could develop extensive ice cover during the first half of January in a typical winter because it is so shallow compared to the other Great Lakes. Winter 1981 provides a good example; Lake Erie was in excess of 80% ice covered by the end of the first week of January 1981 (Assel 2003). In early winter of a mild ice cycle, ice cover is primarily in the shallowest areas of the Great Lakes and is less extensive than during typical winters. In the mild 1983 ice cycle, even most bays were ice free (Fig. 4c).

2) Midwinter patterns

During midwinter of a typical ice cycle, ice forms in the deeper areas of Lakes Superior, Michigan, and Huron as ice cover approaches its seasonal maximum extent and coverage (Fig. 4e). However substantial open water areas remain due to heat storage in the deeper waters and the action of winds. Lake Erie is over 80% ice covered in a typical ice cycle in mid-February. Lake Ontario has extensive ice cover lining its shore and extending well out into the lake from its northeast shore. In a severe winter (Fig. 4d), Lakes Superior, Michigan, and Huron can have over 80% of their surface ice covered by mid-February, and Lake Erie can have over 90%. In 1977, Lake Superior also had over 90% ice cover by mid-February. At the other extreme, midwinter mild ice cycles only have ice cover extending out from the shore and in shallow areas with the midlake areas being virtually ice free (Fig. 4f), similar to or less than early winter ice cover for the typical 1985 ice cycle (Fig. 4b).

3) Late-winter patterns

Starting in early to mid-March, the ice cover begins to recede from its seasonal maximum extent. Interannual differences in mid-March ice extent can be large because the ice cycle is in transition from near or at its seasonal maximum extent to loss of all ice cover. During a severe winter, the Great Lakes can still have extensive ice cover over midlake areas and the eastern portion of lakes in late winter (Fig. 4g). In the typical 1985 ice cycle, Lakes Superior, the northern bays in Lake Michigan, the Straits of Mackinaw at the northern ends of Lakes Michigan and Huron, bays in Lake Huron, the eastern part of Lake Erie, and the northeast bays of Lake Ontario still had substantial ice cover in late winter (Fig. 4h). Mild ice cycle late-winter ice cover is usually limited to bays and shallows of the Great Lakes. Lake Erie can be virtually ice free as it was in 1983 (Fig. 4i) or have substantial ice cover as it did in 15 March 1995. Lake Ontario ice cover is limited to shore areas, primarily at the northeast end of the lake; this area can be virtually ice free in mild ice cycles by mid-March as it was in 1983.

5. Concluding remarks

The ice cycle classification scheme described here is useful for quantifying extreme ice cycles over the 30-winter base period. It also provides a metric and a reference base period by which the severity of past and future Great Lakes ice cycles can be evaluated. The frequency of mild ice cycles over the five winters from 1998 to 2002 is notable. Over half of the mild ice cycles of the 30 winters under study occurred during those five years. If this trend continues, "typical" ice cycles in the twenty-first century may be similar to the winters classified as having "mild" ice cycles in this paper. However, it is still too early to say with certainty if we are entering into a new, milder ice cover regime relative to the 1973–2002 base period. An update of the current Great Lakes ice cover climatology (Assel 2003) over the next 10 yr will provide a more definitive answer.

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