DEVELOPMENT OF A LAKE BREEZE FORECAST METHODOLOGY FOR NORTHERN MICHIGAN

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Abstract

It is important for operational forecasters to accurately predict when lake breezes will occur, since lake breezes can have a large impact on temperature, wind direction, and the development of precipitation. Lake breezes form in response to land/water temperature differences, which occur frequently on spring and summer days. The magnitude of the temperature difference and the strength and direction of the low-level synoptic flow help determine whether or not a lake breeze will form.

In this study, lake breezes that formed along the Lake Michigan and Lake Huron shorelines in northern lower Michigan from April through August of 1998 and 1999 were examined. Several variables related to lake breeze formation were evaluated, including average water temperature near the shoreline, inland maximum temperature, the temperature difference between land and water, forecast 950-mb winds, and whether a lake breeze actually formed.

Forecast diagrams were generated showing lake breeze occurrence as a function of land/water temperature difference and Eta model forecast 950 mb wind speed. These plots reveal that a relatively light wind is more important than a large land/water temperature difference when forecasting lake breezes. While lake breezes occurred with a wide range of land/water temperature differences, lake breeze development tended not to occur when forecast 950 mb wind speeds exceeded approximately 12 to 18 knots, depending on study site. These results can be used by operational forecasters to improve forecasts of spring and summer lake breezes near the Great Lakes.

1. Introduction

Lake breezes are common along the Great Lakes during spring and summer. These winds form along coastal regions in response to temperature differences that frequently develop during the day between the land and water. The lake breeze and its impact on coastal areas has been the subject of considerable research. Many authors have documented that the inland penetration of the lake breeze front is accompanied by an abrupt wind shift, decrease in temperature, increase in relative humidity and enhanced surface convergence (Estoque 1962; Frizzola and Fisher 1963; Moroz 1967; Ryznar and Touma 1981). The ability of lake breezes to alter summertime precipitation patterns has also been noted (Moroz and Hewson 1966). Due to the impact lake breezes have on local weather, it is important for operational forecasters to be able to accurately predict lake breeze formation.

In this study, lake breezes that form over northern lower Michigan along the Lake Huron and Lake Michigan shorelines are examined. The primary goal of the study is to develop basic, easily applied guidelines that operational forecasters can use to more accurately predict whether a lake breeze will form, given the prevailing meteorological conditions. Improved lake breeze forecasts should lead to improved spring and summer forecasts of temperature, clouds, wind, and precipitation near the Great Lakes.

2. Lake Breeze Characteristics

The generally accepted explanation for the development of the lake breeze is depicted in Fig. 1 (adapted from Simpson 1994). When the sun shines during a typical spring or summer day, the land quickly becomes warmer, while the water temperature remains nearly constant. Convection currents develop over land in response to the rising temperatures, which causes heat near the surface to be redistributed vertically through the lowest several thousand feet above the ground.

As air over the land is warmed, the air expands and becomes less dense. This produces a decrease in surface pressure over the land. Meanwhile, the pressure over the water remains nearly constant. The pressure difference (or gradient) between land and water causes air over the water near the shoreline to move inland. This is the lake breeze. Weak subsidence over the water and a return flow aloft directed from land to water completes the lake breeze circulation. Appendix A shows a sequence of surface weather observations associated with the passage of a lake breeze front at Manistee, Michigan (KMBL), located 3 miles from the Lake Michigan shoreline. Note the wind shift and temperature decrease that occurred at 1835 UTC with the passage of this lake breeze.

Lake breeze circulations develop most frequently during mid morning, several hours after sunrise. Lyons (1966), studying lake breezes on the southeast shore of Lake Michigan, found that the lake breeze circulation began at the shoreline around 0800 local time. Moroz and Hewson (1966) found that the initial onshore flow along the east shore of Lake Michigan started between 0900 and 1030 local time. Wind speeds associated with lake breezes generally average around 10 knots. Inland penetration of the lake breeze often varies, though it can occasionally exceed 30 miles depending on meteorological conditions (Simpson 1994).

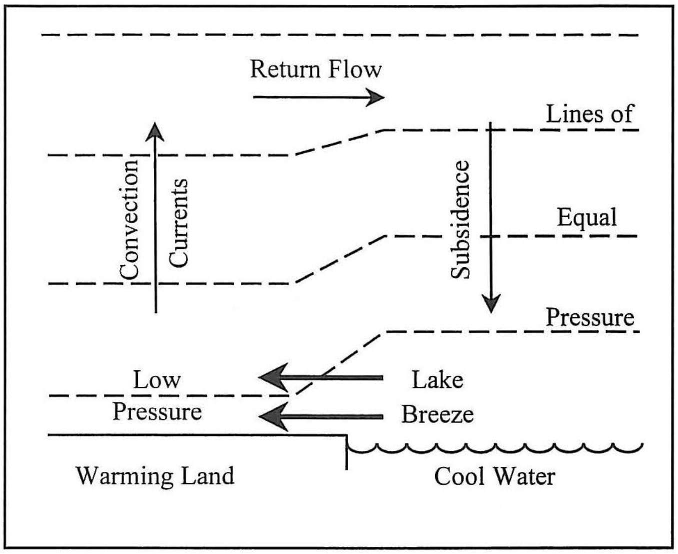

Fig. 1. Conceptual model showing the development of a lake breeze.

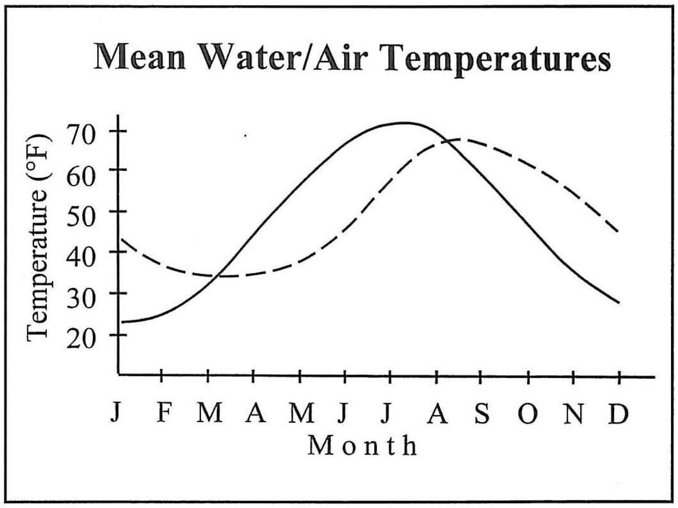

Fig. 2. Mean water temperature (dashed line) and mean air temperature over land (solid line) for central Lake Michigan and Muskegon, Michigan, respectively.

Mean annual water and air temperatures for central Lake Michigan and Muskegon, Michigan, respectively, are shown in Fig. 2. Note that the annual water temperature cycle lags the air temperature cycle. Whereas average air temperature peaks in mid summer, average water temperature does not reach its maximum until late summer. This temperature lag can be attributed to the difference in heat capacity between land and water, and results in about a five month period (roughly April through August) when the average air temperature is higher than the average water temperature. It is during this time period (spring and summer) that lake breezes are most common.

In addition to the temperature contrast between the water and adjacent land, another factor that helps determine whether a lake breeze forms is the strength and direction of the prevailing low level wind. For example, a lake breeze may not develop even with a large land/water temperature difference if the low level flow is strong and offshore, since this wind would oppose the onshore wind of a lake breeze. Conversely, a lake breeze may form even with a small land/water temperature difference provided the opposing offshore low level flow is relatively weak. Frizzola and Fisher (1963) found that the maximum wind speed that would permit a sea breeze to form near New York City ranged from 9 to 18 mph. Hall (1954), studying lake breezes near Chicago, found that offshore wind speeds of 10 to 15 mph at 2000 feet above the surface were the maximum that would allow lake breeze development. Watts (1955) noted that sea breeze formation on the southern coast of England depended on both the temperature contrast and the low level wind direction and speed. He found that on a calm day, a temperature difference of 1 °C between land and water was large enough for a sea breeze to form, but to overcome an offshore wind as strong as 8 m s^{-1} (approximately 16 knots) a temperature difference of 11 °C was needed.

3. Methodology

This study was conducted using data from April through August of 1998 and 1999. Pertinent data related to lake breeze formation were collected for several sites in northern lower Michigan (Fig. 3). In 1998, the lake breeze study sites included Alpena, Manistee, and Oscoda, Michigan. In 1999, the study sites included Alpena, Manistee, and Traverse City, Michigan. Selection of these study sites was based primarily on their proximity to one of the Great Lakes, and the availability of surface observational data.

For each day of the study, several variables related to lake breeze development were assessed:

- Average water temperature (°C) within approximately 20 miles of the shoreline for each site. This information was collected using the satellite derived water temperatures depicted on the Great Lakes Environmental Research Laboratory's Great Lakes Surface Environmental Analysis.
- Inland maximum temperature (°C). Due to its proximity to the center of northern lower Michigan, the maximum temperature at Houghton Lake (Fig. 3) was considered representative of the inland maximum temperature for each site.
- Difference (°C) between the water temperature and the inland maximum temperature for each site.
- Forecast 950 mb wind speed (knots) and direction (to the nearest 10°) valid at 1500, 1800, and 2100 UTC for each site. This information was collected from the 1200 UTC cycle of the Eta model.
- The existence of a surface front or other surface boundary not associated with a lake breeze in northern Michigan between 1200 and 0000 UTC.
- The existence of convection in the vicinity of northern Michigan that may have altered surface winds between 1200 and 0000 UTC.
- Observed hourly wind direction at each site between 1200 and 0000 UTC (used to determine whether an onshore wind associated with a lake breeze occurred).

For the purpose of this study, a wind was considered onshore if it fell within 70° of a line perpendicular to the

Table 1. Percentage of days identified as potential lake breeze days, percentage of potential lake breeze days on which a lake breeze occurred, and the percentage of all days on which a lake breeze occurred.

Study Site	Years	% of Days identified as Potential Lake Breeze days	% of Potential Lake Breeze days on which Lake Breeze occurred	% of All days on which Lake Breeze occurred
Alpena (APN)	1998/99	50% (152/306)	52%	26%
Manistee (MBL)	1998/99	30% (92/306)	74%	22%
Oscoda (OSC)	1998	53% (81/153)	67%	35%
Traverse City (TVC)	1999	30% (46/153)	28%	8%

shoreline for a particular study site. In order to ensure that an onshore wind that developed at a site was associated with an actual lake breeze, *only potential lake breeze* days were considered. A *potential lake breeze* day was defined as a day on which all of the following occurred at a study site:

1) 950 mb winds were not forecast to be onshore at 1500, 1800, or 2100 UTC

2) A surface front or other surface boundary was not located within northern Michigan between 1200 and 0000 UTC

3) Convection in the vicinity of northern Michigan was not altering surface winds between 1200 and 0000 UTC

This set of criteria helped ensure that an onshore wind resulting from another meteorological process did not provide the false indication of a lake breeze. *Therefore, a lake breeze was considered to have occurred at a study site only if the observed surface wind became onshore between 1200 UTC and 0000 UTC on a day defined as a potential lake breeze day.*

4. Results and Operational Implications

Table 1 shows the percentage of days identified as potential lake breeze days, the percentage of potential lake breeze days on which a lake breeze occurred, and the percentage of all days on which a lake breeze occurred. Note that Oscoda and Alpena had the highest percentage (53% and 50%, respectively) of days identified as potential lake breeze days. This result stems from these site's being situated on Lake Huron's western shore. Here the climatologically favored west wind tends to minimize the number of days with an onshore synoptic flow (and therefore increases the number of potential lake breeze days).

Of those days identified as potential lake breeze days, lake breezes actually occurred most frequently at Manistee and Oscoda (74% and 67%, respectively). This finding can be attributed to the proximity of these sites to their respective lake. Oscoda (2 miles from Lake Huron) and Manistee (3 miles from Lake Michigan) are relatively close to the shore, whereas Alpena (6 miles from Lake Huron) is farther inland. Though Traverse City is only 2 miles south of Lake Michigan, the city borders Grand Traverse Bay. This bay is small (relative to Lake Michigan) and has an irregularly shaped shoreline, suggesting that lake breezes that form at Traverse City are likely more complex than those that form at the other study sites. Overall, lake breezes occurred most frequently at Oscoda (35% of all days) and Alpena (26% of

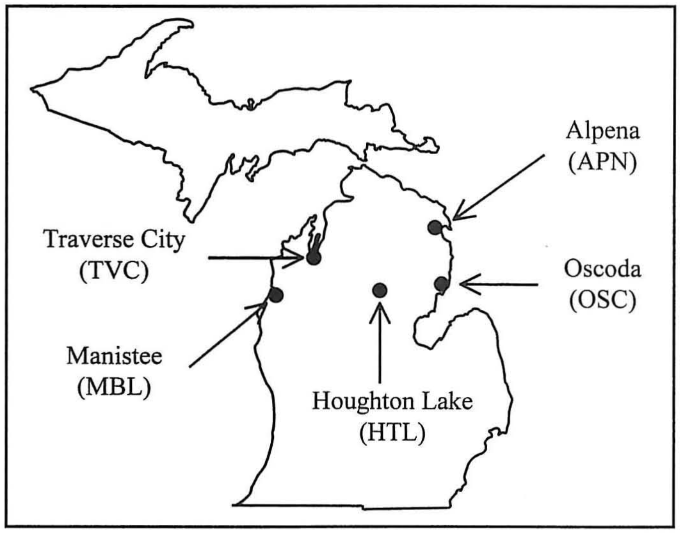

Fig. 3. Sites in Michigan where lake breeze data was collected. Surface observations from Houghton Lake were used for the inland maximum temperature for all study sites.

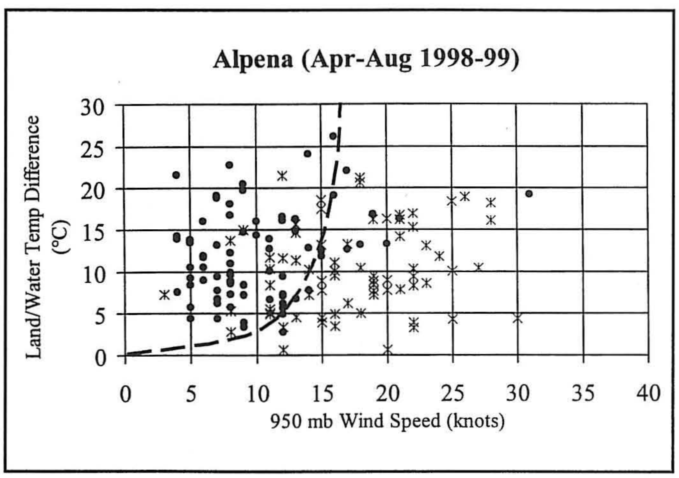

Fig. 4. Scatterplot showing the combination of land/water temperature difference and Eta model forecast 950 mb wind speeds (valid at 1800 UTC) resulting in days with lake breezes (dots) and days without lake breezes (stars) at Alpena, Michigan. Dashed line represents subjective delineation between days with lake breezes and days without. Only potential lake breeze days are plotted. Total sample size is 152.

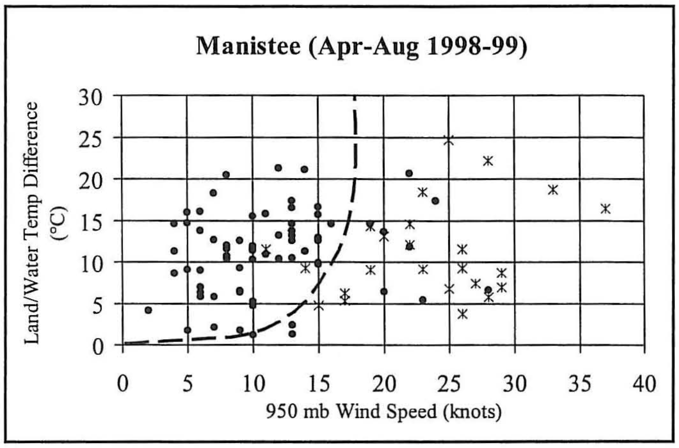

Fig. 5. Same as in Fig. 4., except for Manistee, Michigan. Total sample size is 92.

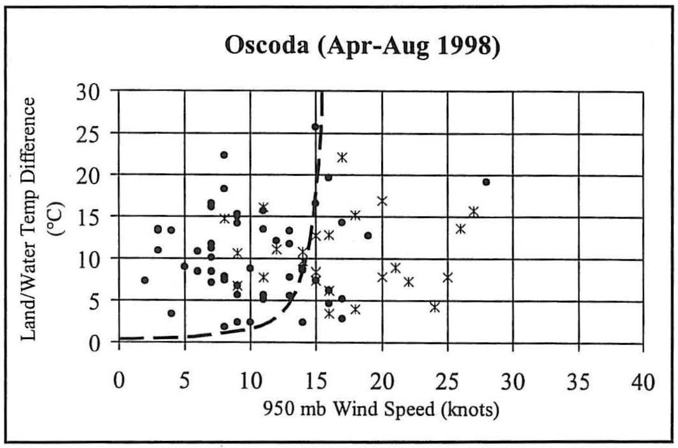

Fig. 6. Same as in Fig. 4., except for Oscoda, Michigan. Total sample size is 81.

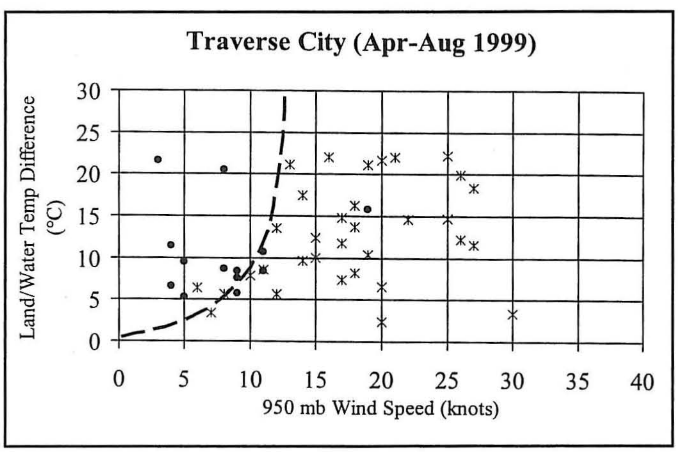

Fig. 7. Same as in Fig. 4., except for Traverse City, Michigan. Total sample size is 46.

all days), and least frequently at Traverse City (8% of all days).

Figures 4-7 show lake breeze occurrence and nonoccurrence for each study site as a function of land/water temperature difference and Eta forecast 950 mb wind speed valid at 1800 UTC. These figures include potential lake breeze days only. In each figure, a dot indicates that a lake breeze occurred on a potential lake breeze day, while a star indicates that a lake breeze did not occur on a potential lake breeze day. The curved, dashed line in each figure delineates the combinations of land/water temperature differences and forecast 950 mb wind speeds that are favorable for lake breezes (left of the curved line) from those that are not favorable for lake breezes (right of the curved line). These "best fit" curved lines were drawn subjectively and assume that a positive temperature difference (land warmer than water) is required to generate a lake breeze. The fact that some data points fall on the wrong side of the "best fit" lines can be attributed to a number of factors, including inaccurate inland maximum temperature, inaccurate assessment of water temperature, inaccurate 950 mb forecast wind speed, and other small scale weather interactions (like mesoscale boundaries and terrain induced winds).

As previously noted, both the contrast in temperature between land and water, and the strength and direction of the prevailing low level synoptic flow help determine whether a lake breeze forms. Conceptually, a light wind speed and/or a large temperature contrast should favor the development of a lake breeze. Figures 4-7 suggest, however, *that a relatively light (forecast) 950 mb wind speed is more important than a large land/water temperature contrast when forecasting lake breeze development.* Note that lake breezes occurred at each study site with a broad range of land/water temperature differences. With the exception of Traverse City, lake breezes even occurred with a temperature contrast as low as 2-3 °C. As the forecast 950 mb wind speed increased, however, lake breeze frequency at each site showed a clear decrease. Figures 4-7 suggest that the maximum forecast 950 mb wind speed associated with a lake breeze ranged from approximately 12 knots at Traverse City to about 18 knots at Manistee. These values are consistent with the findings of Frizzola and Fisher (1963), Hall (1954), and Watts (1955).

With forecast responsibility along portions of Lake Superior, Lake Michigan, and Lake Huron, meteorologists at the National Weather Service (NWS) in Gaylord, Michigan, routinely consider lake breezes when issuing several types of forecasts during spring and summer. Forecasters at NWS Gaylord reference Figs. 4-7 when deciding on the likelihood of lake breezes, and have found the diagrams to be a valuable source of forecast guidance. When lake breezes are anticipated, forecasters coordinate and reference the resulting onshore wind in all appropriate forecasts (Zone Forecasts, Nearshore Marine Forecasts, and Aviation Forecasts). Appendix B shows examples of these NWS forecasts on a day when lake breezes are expected.

5. Summary

Lake breezes are common along the shores of the Great Lakes during spring and summer. These circulation patterns develop in response to land/water temperature gradients that form when the land is warmer than the adjacent water. Whether or not a lake breeze forms is a function of the magnitude of the land/water temperature difference, and the strength and direction of the low level synoptic flow.

In this study, lake breezes that formed along the Lake Michigan and Lake Huron shorelines during April through August of 1998 and 1999 were examined. Study sites included Alpena, Manistee, Oscoda, and Traverse City, Michigan. The goal of the study was to develop guidelines that operational forecasters could easily use to more accurately predict the occurrence of lake breezes. For each study site, several variables related to lake breeze development were assessed, including average water temperature near the shoreline, inland maximum temperature, the temperature difference between land and water, forecast 950 mb winds, whether convection and/or boundaries were affecting northern Michigan, and observed wind directions.

Forecast diagrams were generated for each study site showing how lake breeze occurrence depended on land/water temperature difference and forecast 950 mb wind speed. These plots indicated that a relatively light (forecast) 950 mb wind speed was more critical than a large land/water temperature difference when forecasting lake breeze development. While lake breezes were found to occur within a broad range of land/water temperature differences, an upper limit of forecast 950 mb wind speeds was found to be associated with lake breeze development. This upper limit ranged from approximately 12 to 18 knots, depending on study site.

Results from this study can be used by operational forecasters to improve forecasts of spring and summer lake breezes near the Great Lakes. Improved lake breeze forecasts will subsequently lead to improved forecasts of temperature, cloud, wind, and precipitation in the vicinity of the Great Lakes.

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Author

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Appendix A

Sequence of surface weather observations from Manistee, Michigan, associated with the passage of a lake breeze:

METAR KMBL 091335Z AUTO 14007KT 10SM FEW017 FEW041 SCT055 14/10 A2966 RMK A01
METAR KMBL 091435Z AUTO 14008KT 10SM FEW095 16/09 A2966 RMK A01
METAR KMBL 091535Z AUTO 12004KT 10SM FEW110 15/08 A2968 RMX A01
METAR KMBL 091635Z AUTO 12005KT 10SM CLR 16/08 A2968 RMK A01
METAR KMBL 091735Z AUTO 12009KT 10SM CLR 16/08 A2968 RMK A01
METAR KMBL 091835Z AUTO 29012G19KT 9SM SCT038 13/07 A2964 RMK A01
METAR KMBL 091935Z AUTO 30008KT 8SM SCT001 SCT033 OVC041 13/08 A2971 RMK A01
METAR KMBL 092035Z AUTO 31009KT 7SM SCT001 BKN042 12/09 A2971 RMK A01
METAR KMBL 092135Z AUTO 30009KT 10SM FEW090 13/09 A2968 RMK A01
METAR KMBL 092235Z AUTO 17009KT 10SM FEW075 FEW090 12/07 A2966 RMK A01

Appendix B

Excerpts of public, marine, and aviation forecasts issued by NWS Gaylord, Michigan, on a day when lake breezes were expected:

Zone Forecast Product (ZFP):

.TODAY ... SUNNY AND WARM. HIGHS NEAR 85 ... COOLER NEAR LAKE HURON. WEST WINDS AROUND 10 MPH BECOMING ONSHORE.

Nearshore Marine Forecast (NSH):

.TODAY ... WEST WINDS AROUND 10 KNOTS BECOMING ONSHORE. SUNNY. WAVES ONE FOOT OR LESS.

Aviation Forecast (TAF):

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KAPN 151135Z 151212 25004KT P6SM SKC
       BECMG 1415 27012KT
     FM1700 11010KT P6SM FEW060
     FM0000 20007KT P6SM SKC
       BECMG 0203 VRB03KT=
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