"Tea Kettle" Effect Snow

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ABSTRACT

"Tea kettle" effect snow is a type of lake effect snow caused by the interaction of a land breeze and gradient flow. This particular type of land breeze induced snow occurs when the land breeze and gradient flows directly oppose each other and are of equal strength. When this balance occurs the resulting convergence can create enough vertical motion for snowfall. Snow resulting from "tea kettle" events has a low water content with typical accumulations of 2-8cm. Snowfall is heaviest along the shoreline with a rapid decline with distance inland.

This paper describes the general causes and characteristics of "tea kettle" effect snows and describes two case studies near Oswego, New York.

INTRODUCTION

This paper describes the general causes and characteristics of "tea kettle" effect snows and describes two case studies near Oswego, New York (Figure 1).

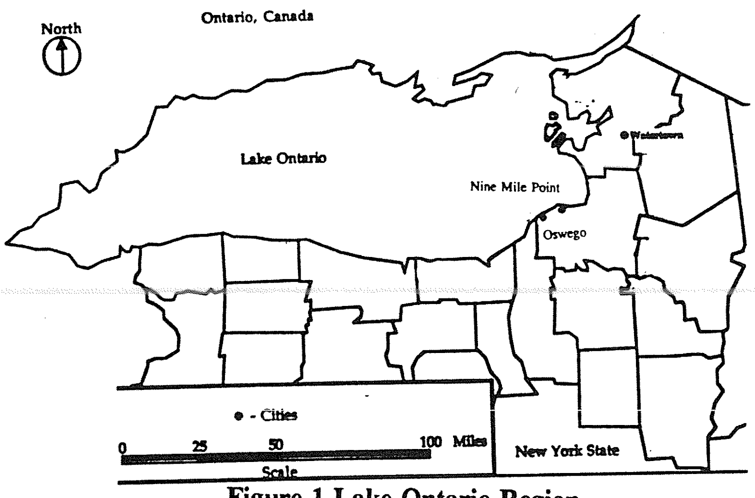

Figure 1 Lake Ontario Region

The authors have been unable to trace the origin of the term "tea kettle" or "tea pot" effect snows. The first published reference found (Sykes et al. 1971) was only a passing reference in the discussion of land breeze generated lake effect snows in the vicinity of Oswego. It may that this is a regional term used only in that area. This paper is the first focused description of this type of storm using this terminology, but it is not the original use of the term.

Also note that land breeze induced snowfalls have been studied in detail elsewhere. Passarelli and Braham (1981) have summarized the role of the land breeze on lake effect snow over all the Great Lakes. Murphy (1989) discussed land breeze lake effect snow on the northwestern shore of Lake Ontario.

"Tea kettle" effect snow is a particular type of lake effect snow caused by a balanced interaction of a land breeze and gradient flow. The name was apparently coined because the phenomenon has a "lid" and a "plume" of convection much the same as a tea kettle. The "lid" occurs when subsidence in a high pressure system balances convection in the unstable surface layer formed as air flowing over the lake warms from the surface. The "plume" forms when the on-shore gradient flow rises over the cold dome of air along the shoreline created by the land breeze. This physical rising motion coupled with thermal instability in the layer of air warmed by the lake counteracts the regional sinking motion enough to make the whole layer unstable, water vapor condenses into clouds and snow falls at the shoreline.

Snow resulting from the "tea kettle" effect is very fluffy and has a low water content. Typical snow totals are 2-8cm, but totals of up to 21cm have been observed. These snow events usually last from 1 to 6 hours in the early morning hours when the land breeze is strong. Observers in the Oswego NY area have only observed these storms in the winter months. Snowfall is heaviest along the shoreline with a rapid decline with distance inland. The clouds and associated snowfall can migrate inland in bands parallel to the shoreline.

Because Lake Ontario rarely develops significant ice cover there usually is a significant temperature difference between the relatively warm lake and cold land in the winter. Whenever the gradient winds are light and temperature difference between land and lake is greater than 10° C, a sufficient pressure differential develops between lake and land to form an off-shore flow or land breeze on the SE shoreline of Lake Ontario (Caiazza et al., 1989). Land breezes normally form when radiational cooling produce the temperature difference needed to create the pressure differential, which means that most land breezes occur at night and several hours into the morning. However, land breezes can also occur when an intensely cold air mass is advected into the region, so it is possible to have a land breeze any hour of the day. Although lake-effect snow can be associated with either type of land breeze, "tea kettle" snow is a result of radiational cooling induced land breezes.

When the land breeze forms, a microscale front develops which separates warmer and moister gradient air from the colder and drier dome of air along the shoreline. In order for "tea kettle" snow to form, the strength of the land breeze and the gradient flow must be balanced. If the gradient flow isn't strong enough, the air modified by the lake will not overrun the land breeze. If the land breeze is not strong enough, then the dome of cold air will not become deep enough to trigger precipitation. It also appears that the gradient flow and land breeze flow must be nearly opposite each other to trigger enough rising motion to cause condensation and snowfall. It is also possible that these events may be enhanced at Nine Mile Point ($\approx$ 10 km northeast of Oswego) because it is near the SE corner of Lake Ontario where the land breezes from the eastern and southern shores converge. This would tend to build a larger dome of air.

OBSERVATIONS

The Empire State Electric Energy Research Corporation (ESEERCO) is sponsoring a year long (10/91 - 10/92) field study of the mesoscale features of the southern shore of Lake Ontario particularly as they affect air pollution. The field project includes a 915 MHz wind profiler and Radio Acoustic Sounding System (RASS) which operated during the winter of 1991-1992 at Nine Mile Point. In addition, the meteorological network of Nine Mile Point Nuclear Station includes a Doppler acoustic sounding system (sodar) and three instrumented meteorological towers. These instruments offered a unique observing system to study "tea kettle" snow.

The 915 MHz wind profiler is a clear air radar which detects fluctuations in density caused by differences in atmospheric temperature and moisture. The fluctuations in the index of refraction are used as a tracer of the mean wind. These profilers transmit a strong microwave pulse upward into the atmosphere and monitor the phase change of the signals between pulses. The phase change is converted to velocity using the Doppler relation. An array of 3 transmitters is used to develop a 3-dimensional wind field.

The RASS combines an acoustic signal with the microwave technology to generate a virtual temperature profile. This is accomplished by making use of the temperature and moisture dependence of the speed of sound. Microwaves from a profiler are "bounced" off the acoustic energy wavefronts produced by an acoustic source having a wavelength half the radar wavelength and the change in speed of the wave determined. This speed change is, in turn, used to determine virtual temperature in each of the specified range gates.

The sodar operates much the same as the wind profiler. However, it uses a sound signal rather than a microwave signal. The sodar has a more limited range than a wind profiler. At Nine Mile Point, sodar winds are typically collected between 60m and 400m. The wind profiler typically collects data between 200m and 1500m. While wind profiler data collection generally improves during precipitation, sodar data collection typically deteriorates.

CASE STUDY: 19 DEC. 1991

The "tea kettle" snow event of 19 December 1991 was a classic. The heaviest snowfall (50mm) occurred at the shoreline and there was no snow measurable 4 km inland. The very dry snow started at 7:00 AM and ended at 10:00 AM.

The synoptic situation favored an intense land breeze. A strong high pressure system was centered over western NY and PA with clear skies over most of the region. However, the high pressure system was located such that there were light surface gradient winds from the NW. Strong downward vertical velocities were predicted over the region so a "lid" was in place.

Surface conditions (Table 1) show the influence of the land breeze and the lake on 12/19/91. Kingston, Ontario data represent the "upwind" temperature and winds. Note how the winds and temperatures changed at Nine Mile Point once the land breeze went through. Also note the temperature difference between Kingston and Nine Mile Point temperature. Air flowing over the lake spent around 6 hours over the 4 to 5°C lake which seemed to modify the air as much as 7 to 10°C.

Table 1: Surface Conditions, 19 December 1991.

Location	Time (EST)	Wind Speed (m/s)	Wind Dir. (°)	Temp. (°C)
Kingston	0700	3	360	-22
Nine Mile	0500	1.8	349	-10
Nine Mile	0600	2.2	134	-13
Nine Mile	0700	2.7	125	-14
Nine Mile	0800	2.2	120	-14
Nine Mile	0900	2.2	133	-14
Nine Mile	1000	2.2	132	-14
Nine Mile	1100	1.8	131	-12

Remote sensing using the sodar, wind profiler and RASS offer interesting clues to the structure of the "tea kettle" system. Figure 2 lists Nine Mile sodar data at 0400 and 0900. Figure 3 displays the ESEERCO wind profiler data in a different format. The display shows winds at each level using a wind barb oriented to show direction with speed shown by the shape. RASS data combined with tower data are displayed as a temperature vs height plot (Figs. 4 & 5). This display assumes that the virtual temperature measured by the RASS is for practical use approximately equal to the ambient temperature in this dry cold air (Hsu, 1988). In addition, there was no correction for vertical motion in the virtual temperature data. RASS data for 0400 (Figure 4) show the temperature profile before land breeze modification. This profile also represents expected conditions over the lake. Note the intense warming in the surface layer. Sodar data at this time show a simple structure. Data collection is poor, but low-level returns indicate northerly flow.

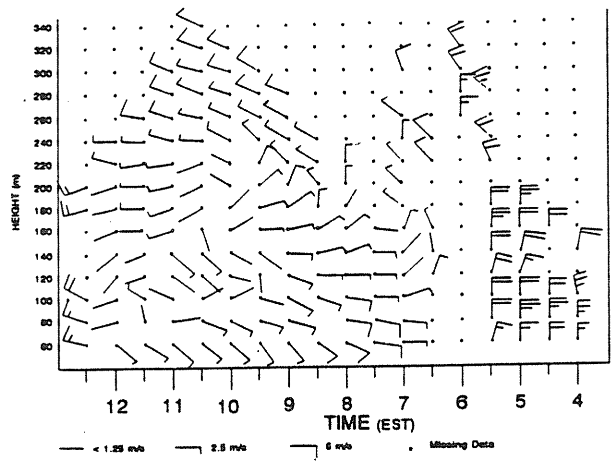

Figure 2
Nine Mile Point Sodar Data
December 19, 1991

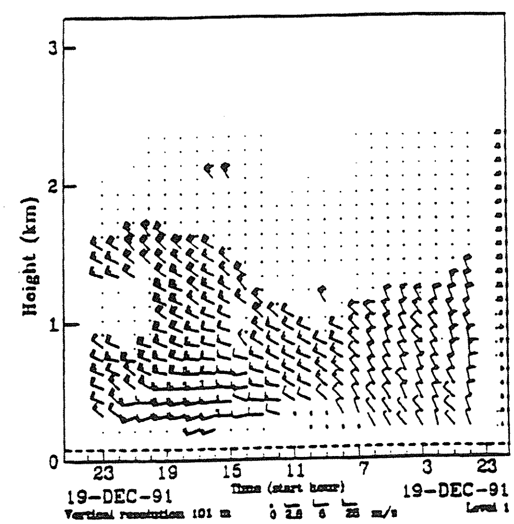

Figure 3
Nine Mile Point 915 MHz
Wind Profiler - Dec. 19, 1991

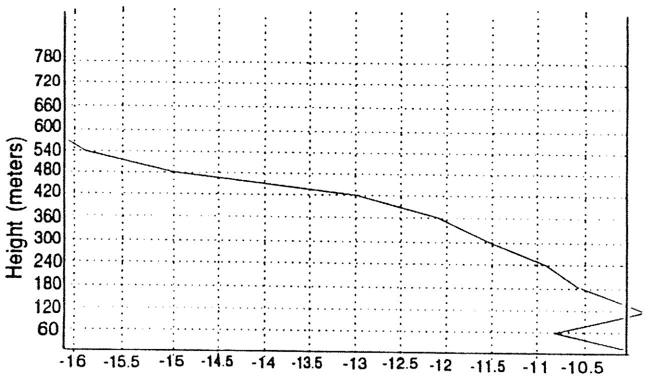

Figure 4
Nine Mile Point RASS and Tower Temperature Profile Dec. 19, 1991 (0400 EST)

At 0900 the land breeze is active over Nine Mile Point. The sodar data show the off-shore flow associated with the land breeze extends from the surface up to 120m. This corresponds to the height of the microscale inversion shown in the RASS data (Fig. 5) where temperature peaks at -13.4°C. The sodar data also show that there is a land breeze return flow between 180m and 250m. This corresponds to an isothermal region in the RASS data. Above that level both the sodar and wind profiler show gradient winds from the NW. The RASS shows that there is another inversion from 250m to 370m where the temperature increases from -13.6 to -12.9°C.

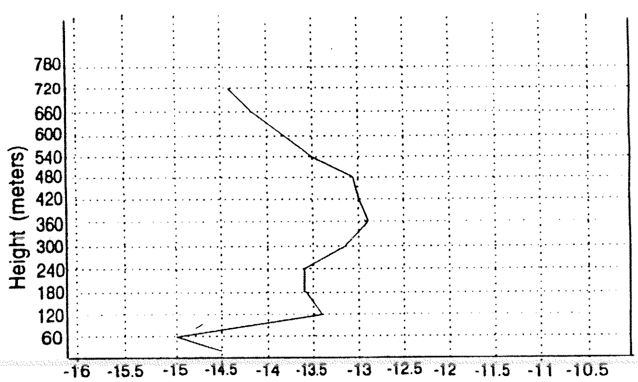

Figure 5
Nine Mile Point RASS and Tower Temperature Profile, Dec. 19, 1991 (0900 EST)

This structure reveals a classic tea kettle situation. The "lid" is the layer below the subsidence inversion where sinking air balances the unstable layer formed due to the lake. Within this layer we estimate the temperature change with height to be -10 to -13°C. This air is unstable, but no clouds form until the gradient flow forces this layer over the land breeze circulation system. This cracks the "lid" of the kettle and generates the convection necessary for snow.
Figure 6 graphically illustrates this structure. Region 1 is the cold dome of air below the microscale inversion caused by the land breeze. Cross section A-B corresponds to the temperature profiles shown in Figure 5. Region 2 is the onshore return flow of the land breeze marked by isothermal air caused by mixing with air rising over the lake. Region 3 is the warm and humid onshore gradient lake air which has been lifted from the lake surface to a height of 350m to 400m because of the land breeze circulation. Region 4 is the convergence region where the onshore gradient flow and the land breeze off-shore flow meet. The upward motion here creates the mechanism that causes convection and precipitation of the conditionally unstable lake air.

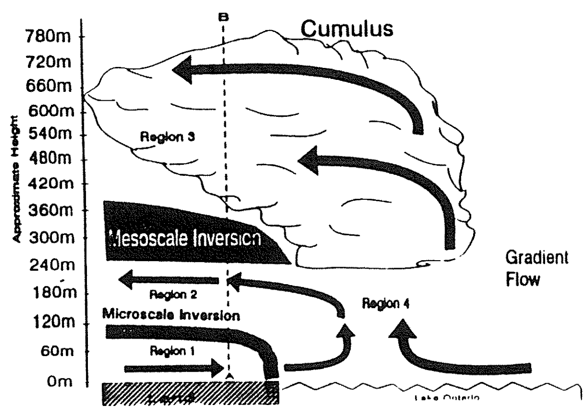

Figure 6
Tea Kettle Effect Structure December 19, 1991 (0900)

CASE STUDY: 12 FEB 1992

In contrast to the classic event of 19 December 1991, the "tea kettle" event of 12 February 1992 was very weak. Only 7mm of very dry snow fell between 0800 and 1000. The sun was visible at all times during the event.

The synoptic situation appeared similar. A strong high pressure system was centered over western NY and PA with clear skies over most of the region. In addition, the high pressure system was located such that there were light surface gradient winds from the NW. Strong downward vertical velocities were observed over the region so a "lid" was in place. Overall the situation was similar to the 19 December case study.

Surface conditions are listed in Table 2. Kingston, Ontario data represent "upwind" conditions and Nine Mile Point data show conditions before and after the land breeze went through. Also note the temperature difference between Kingston and Nine Mile Point temperature. Air flowing over the lake spent about the same time over the lake as the other case study and the lake was only 2 or 3°C cooler in this case. Again, remote sensing offers interesting clues to the structure of the "tea kettle" system. Figure 7 lists Nine Mile sodar data at 0900 and Figure 8 displays the ESEERCO wind profiler data. RASS data are displayed in Figs. 9 & 10.

Table 2: Surface Conditions, 12 February 1992.

Location	Time (EST)	Wind Speed (m/s)	Wind Dir. (°)	Temp. (°C)
Kingston	0700	3	360	-22
Nine Mile	0500	5.4	358	-17
Nine Mile	0600	4.0	006	-17
Nine Mile	0700	2.7	021	-18
Nine Mile	0800	3.1	092	-20
Nine Mile	0900	2.7	116	-20
Nine Mile	1000	2.2	133	-19
Nine Mile	1100	2.2	136	-17

RASS and tower data (same assumptions as in Case 1) for 0500 (Fig. 9) show the temperature profile before land breeze modification. Sodar data from this time period show light winds, but the data quality and continuity are poor.

At 1000 the land breeze is active over Nine Mile Point. The sodar data show the off-shore flow associated with the land breeze extends up to 120m. The RASS data (Fig. 10) shows the corresponding microscale inversion where the temperature peaks at -19.8°C. The sodar data also show the return layer from 360 to 400m. Above that level the wind profiler shows gradient winds from the WNW at 5 to 15 m/s. The RASS data show a weak mesoscale inversion from 420 to 540m. Note that the RASS picks up the synoptic subsidence inversion starting at 720m. This only leaves the region between 540m and 720m for the conditionally unstable air modified by the lake. The structure is shown graphically in Figure 11.

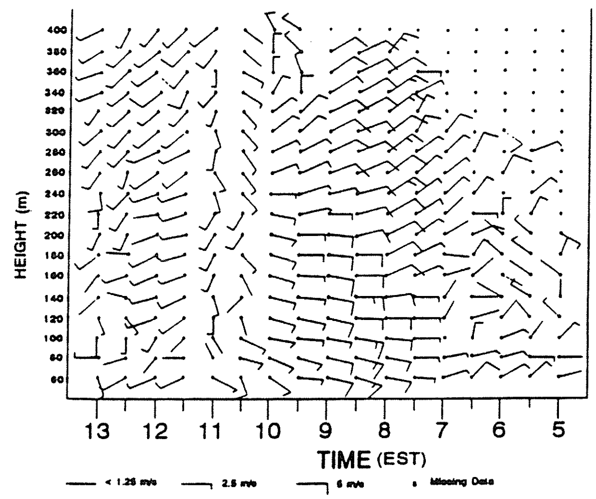

Figure 7
Nine Mile Point Sodar Data
December 19, 1991

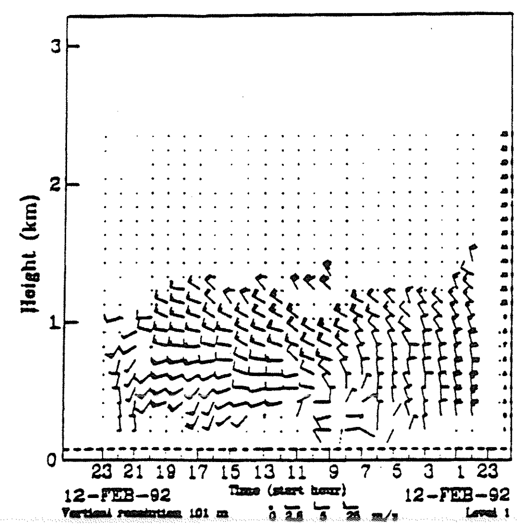

Figure 8
Nine Mile Point 915 MHz
Wind Profiler Data
February 12, 1992 (0500 EST)

The synoptic situation in the two cases appear to be similar. Nonetheless, the 19 Dec 1991 case was stronger than the 12 Feb 1992 case. There are a number of possible reasons for this difference. In the 12 Feb 1992 case the synoptic-scale subsidence inversion extended well below 1000m. Also, the thickness of the conditionally unstable air between the land breeze and synoptic inversion layer was only 180m. The gradient flow in this case was stronger than the first case, so there was less time for modification of the air by the lake. Although the mesoscale inversion was weak, the land breeze was much stronger and deeper on 12 Feb which could have kept the region of snowfall out over the lake. Finally, the lake was colder by a two or three degrees C in the February case.

Figure 9
Nine Mile Point RASS and Tower Temperature Profile

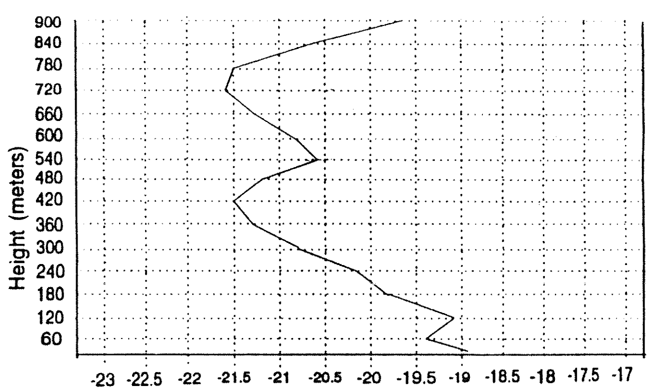

Figure 10
Nine Mile Point RASS and Tower Temperature Profile
February 12, 1992 (1000 EST)

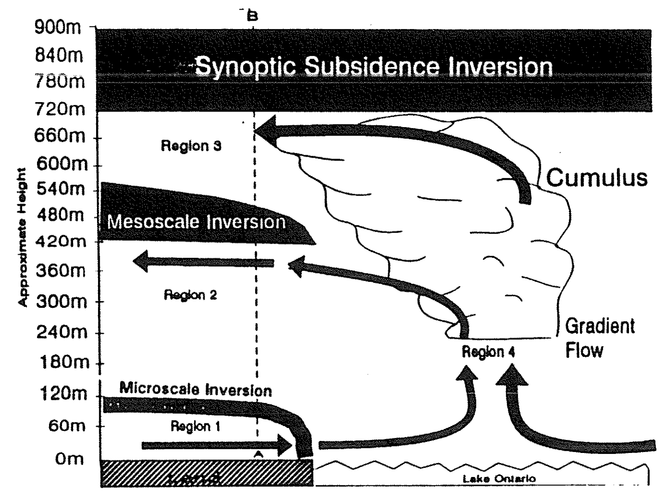

Figure 11
Tea Kettle Effect Structure
February 12, 1992 (1000 EST)

Conclusion

"Tea kettle" effect snow is a local-scale storm caused by the interaction of a land breeze and gradient flow. Remote sensing equipment offered a unique opportunity to study two cases.

Although the synoptic situation and surface conditions were similar, the 19 Dec 1991 case was much stronger than the 12 Feb 1992 case. These differences indicate that a "tea kettle" effect event forms under a limited set of conditions.

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