15 January 2009: Lake Champlain Sea Smoke, Steam Devils, and Waterspouts

Exotic Whirls in Arctic Air

Figure 1. Video capture of a waterspout over Lake Champlain at approximately 10:30am EST on 15 Jaunary 2009. Steam fog is also faintly evident near the water surface. View is from Essex, New York looking to the east toward Vermont. Air temperature was approximately -5^{0}F and water temperature was near freezing.

I. Overview

No fewer than five waterspouts were observed over the southern portion of Lake Champlain during the mid-morning hours on Thursday, 15 January 2009. Smaller low-level whirls (sometimes referred to as *steam devils*) were also abundant, originating from the arctic sea smoke or steam fog near the water surface. Documented waterspout activity over Lake Champlain is rare.

The video images shown herein are courtesy of Mr. Andy MacDougal of Essex, New York, who was out filming events over the lake around 10:30am EST that morning. The images appear here with Mr. MacDougal's kind permission for the scientic record and for educational purposes.

II. Video Captures
Below are image captures from video provided by Andy MacDougal. The video was taken from along the Lake Champlain shoreline in Essex, New York around 10:30am (1530z) on 15 January 2009.

a. Sea Smoke and Steam Devils

Arctic Sea Smoke with narrow steam devil at 45^{o} angle.

Arctic Sea Smoke with several weak steam devils.

Arctic Sea Smoke with several weak steam devils.

b. Waterspouts

Waterspout #1.

Waterspout #2.

Waterspout #3. Others possible, but faintly visible in image.

Well-developed waterspout from ragged cloud base (#4).

Twin waterspouts (#4 and #5).

Interaction of twin waterspouts (#4 and #5).

III. Definitions

Arctic Sea Smoke or *Steam Fog* develops when very cold (arctic) air moves across relatively warm, open water. Strong upward fluxes of latent heat from the water surface result in water vapor quickly condensing as it is mixed and cooled with the adjacent cold air. Since the air adjacent to the water surface is also convectively unstable, the arctic sea smoke or steam fog will be seen rising in turbulent plumes associated with shallow convective overturning of the very unstable air over the water (Lake Champlain in this case). Upon further upward mixing, the fog will eventually evaporate and dissipate in the dry arctic air, on the order of 10 meters above the water surface. As such, arctic sea smoke is a relatively shallow phenomenon.

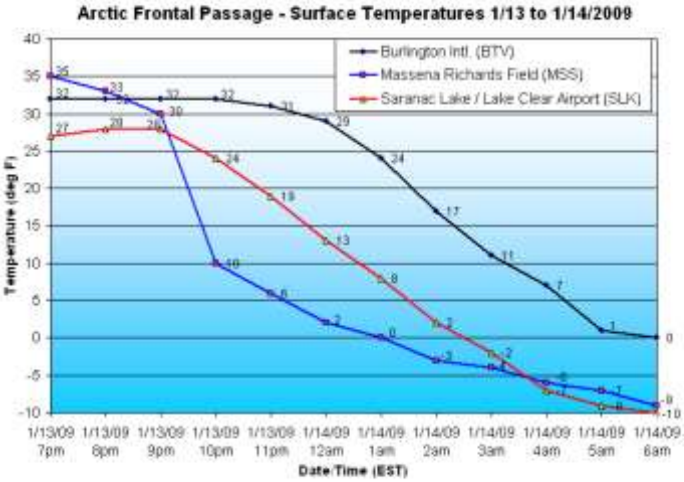
A *waterspout* (Figure III-1) is a narrow, rotating column of air that forms over water, and appears as a condensation funnel which extends from the water surface to a cumuliform cloud above. Formation typical requires a surface convergence line over the water, with some source of low-level rotation along the line that can be stretched vertically and strengthened by the convective cloud updraft itself. Waterspouts are generally of lesser intensity than a tornado, and similar to the strength of a dust devil. The formation mechanism is also thought to be similar to a class of weaker tornadoes observed over land referred to as landspouts. Waterspouts are most common in tropical environs (e.g., near the Florida Keys), but have been documented in arctic air masses. Unlike tornadoes - which typically develop with supercell thunderstorms - waterspouts are commonly observed from just modest lines of cumulus congestus clouds, as occurred over Lake Champlain on 15 January 2009.

Figure III-1. A mature tropical waterspout near the Florida Keys on 10 September 1969 (from the NOAA Photo Library).

A *steam devil* is similar in nature to a waterspout in arctic air. However, we might differentiate between a steam devil and waterspout by whether or not the condensation funnel is deep and strong enough to be attached to a convective cloud above. Deeper convective motions and vertical stretching extending from the water surface to the convective cloud base would generally result in a stronger, longer-lived feature (waterspout) as compared with a shallower, shorter-lived feature (steam devil). We might expect the vertical depth of a waterspout to be on the order of hundreds of meters, while the vertical extent of a steam devil is on the order of tens of meters.

IV. Weather Conditions

This section reviews weather conditions associated with the Lake Champlain waterspouts on 15 January 2009.



An arctic cold front pushed eastward through the North Country during the late evening hours on January 13th and into the early morning hours on January 14th, approximately 30-36 hours prior to the Lake Champlain waterspouts. Temperatures dropped 30^{o}F to 40^{o}F across the area in the hours following the frontal passage (Figure IV-1). By the morning hours on January 15th (the day of the waterspout activity), the arctic boundary had pushed south of New England. The *Daily Weather Map* for 15/12z (7 am EST) is shown in Figure IV-2.

Figure IV-1. Surface temperature versus time for ASOS stations at Burlington International Airport (BTV), Massena Richards Field (MSS), and the Saranac Lake / Lake Clear Airport (SLK). Time period covers January 13th at 7pm through January 14th at 6am.

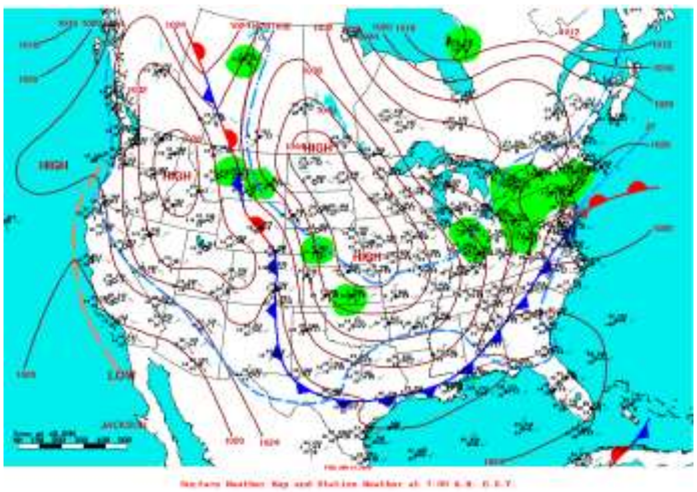
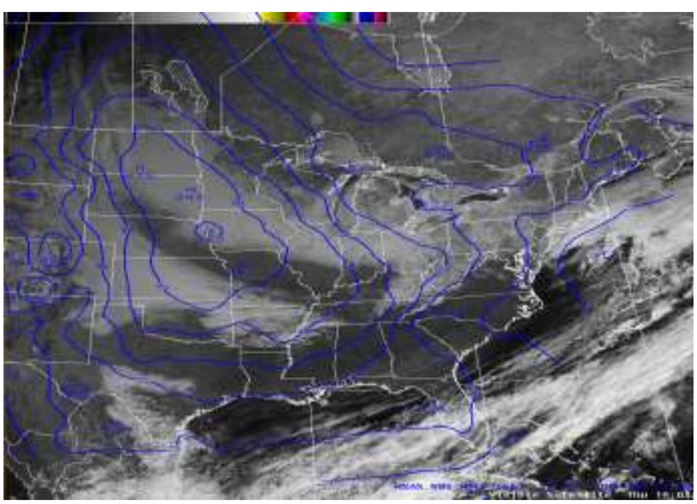


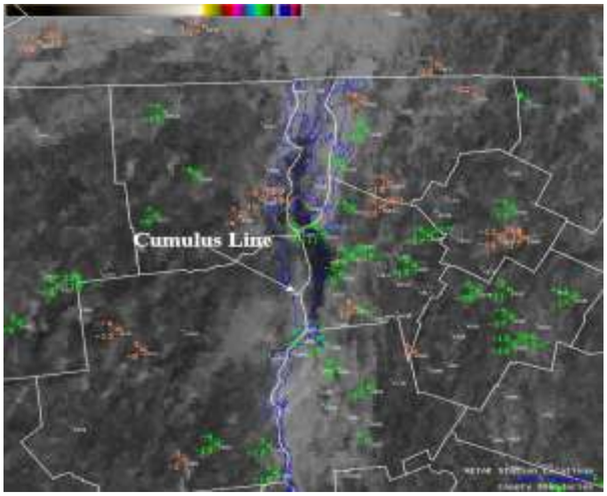
Figure IV-2. *Daily Weather Map* for 12z (7am EST) on 15 January 2009. The dashed-dot line through Vermont and Northern New York represents the 0^{o}F isotherm.



In the visible satellite imagery at 15/16z (11 am EST, Figure IV-3), a wave of low pressure was moving eastward south of New England along the surface boundary. Meanwhile, a strong arctic ridge was centered over the upper Missouri River Valley (maximum pressure around 1049mb). An extension of the surface ridge extended northeast of the Great Lakes region along the international border region between New York and Ontario/Quebec. The presence of this ridge axis to the northwest contributed to a north-northeasterly surface wind flow across Lake Champlain during the early to mid-morning hours on the 15th.

Figure IV-3. Visible satellite imagery at 1601z with sea-level pressure isobars overlaid (blue solid lines, every 4mb) at 16z, on 15 January 2009.

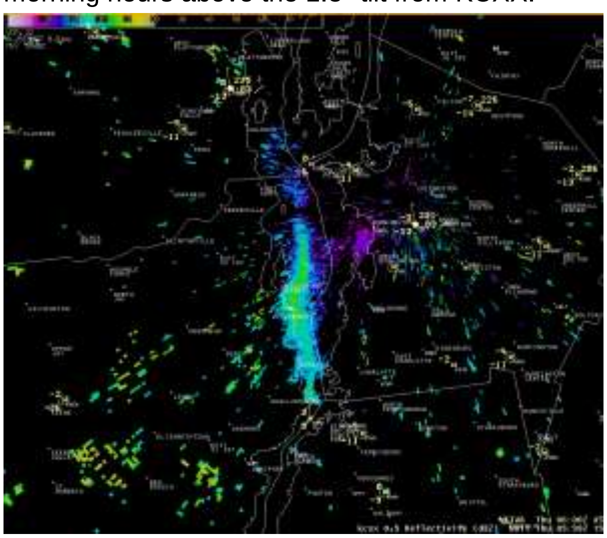
A close inspection of 15/1515z visible satellite imagery (Figure IV-4) with the surface observations at 15/15z (10am EST) shows a line of instability induced cumulus congestus clouds over the broad portion of Lake Champlain from near Colchester Reef (CRF) southward to near the Essex, NY shoreline. The northern portion of the lake was ice covered, especially east of Grand Isle. The surface observations indicated a 15/15z (10 am) temperature of -4^{o}F at BTV, and generally 0 to 5 below in the immediate Champlain Valley. The temperatures at the over-lake stations were -2^{o}F and +1^{o}F at Colchester Reef and Diamond Island, respectively. Winds over land were calm to light from the north-northeast at speeds up to 5 kt.



The flow was somewhat stronger and more veered over the water; Colchester Reef (KCRF) had winds of 060^{o}/10kts at 1508z (1008 am EDT), while Diamond Island (KDMD) reported 030^{o}/14kt. The northeast flow likely forced the low-level convergence zone over the lake toward the western shoreline (i.e., toward the New York side); a westward displacement of the lake induced cloud band is evident in satellite imagery and in radar reflectivity (discussed below). This may be somewhat atypical, based on the greater occurrence of lake effect snow showers along the southeast rather than the southwest lake short with similar occurrences of north flow over the lake with arctic air.

Figure IV-4. Visible satellite imagery with surface observation over the Champlain Valley and adjacent areas at 15/1515z (1015am EST).

The sequence of KCXX 0.5^{o} radar reflectivity images (Figure IV-5) show a long-lived north to south band of enhanced reflectivity (5 to 15 dBz) over the broad portion of Lake Champlain associated with convective cloudiness and light snowfall. The lake reflectivity band is displaced toward the western half of the lake. The most intense and higher echo tops were located near the southern portion of the lake where residence time of air moving from north to south across the lake was longest. The echo tops in the highest reflectivity region over the southern portion of the lake were generally between 2500 and 3000 feet AGL based on 1.5^{o} reflectivity (not shown). No reflectivity returns were observed during the morning hours above the 1.5^{o} tilt from KCXX.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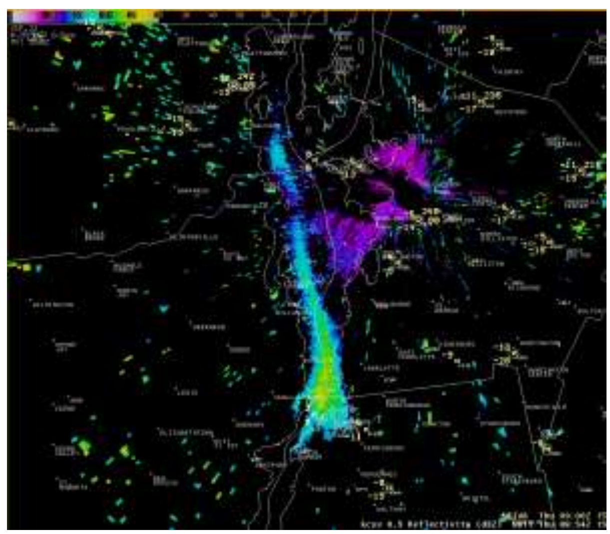
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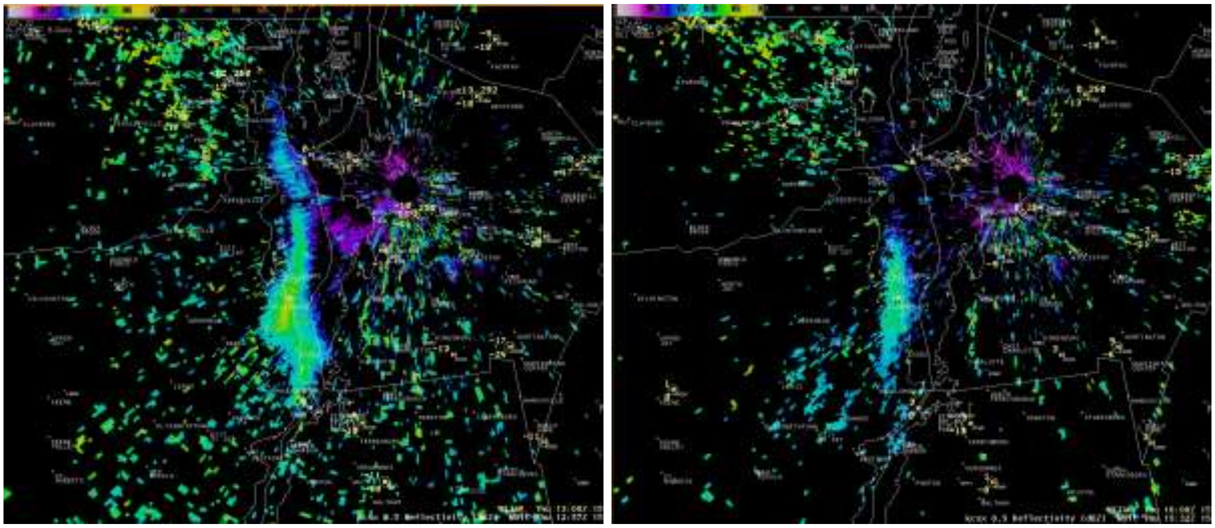
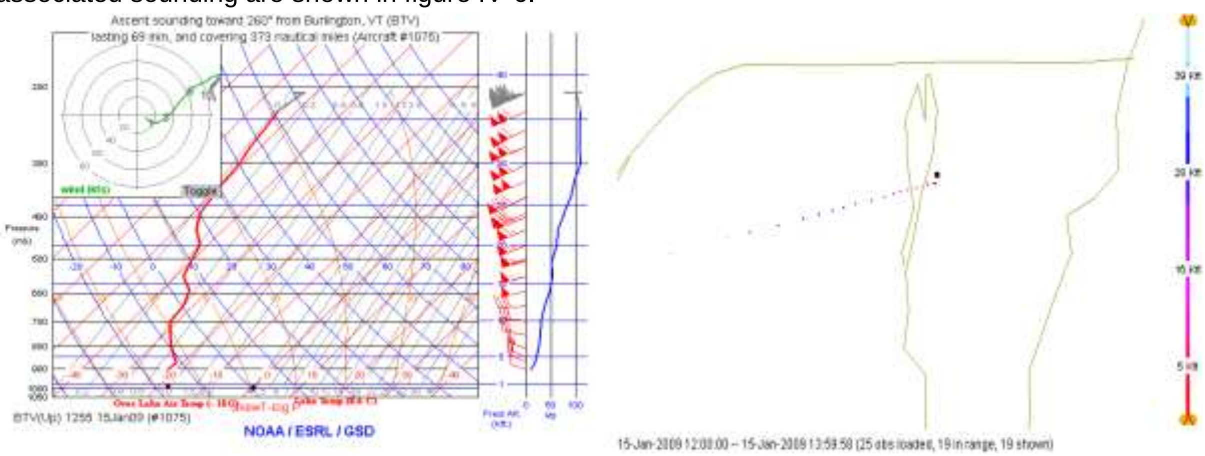


(c) (d)

Figure IV-5. Base reflectivity (0.5 deg elevation angle) from KCXX for (a) 15/0559z, (b) 15/0854z, (c) 15/1257z, (d) 15/1532z. Reflectivity values low-end color enhanced from -20 dBz to + 20dBz. Radar was in VCP 32 (clear-air mode). Surface observations are also shown.

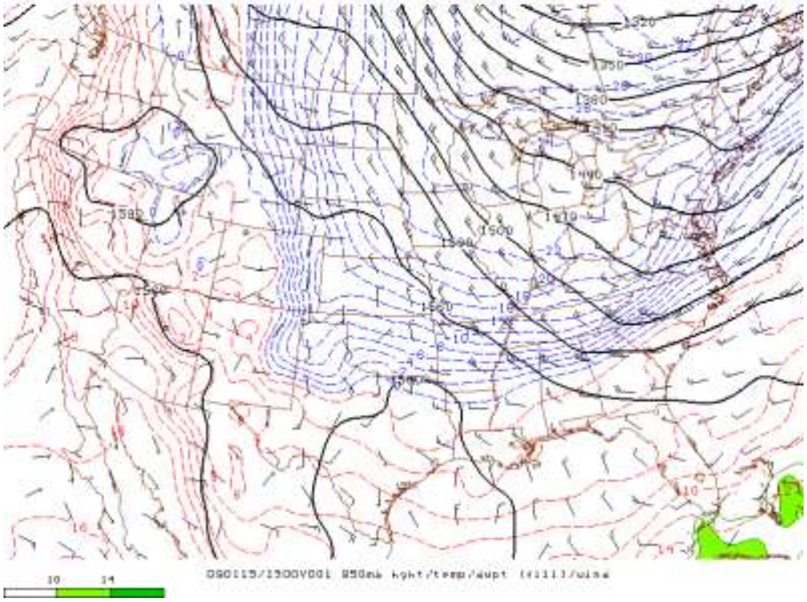
Fortuitously, an aircraft instrumented with temperature and wind sensing equipment departing Burlington for Chicago passed over the southern end of Lake Champlain around 15/13z (~8am EST). The flight path of the aircraft and associated sounding are shown in figure IV-6.



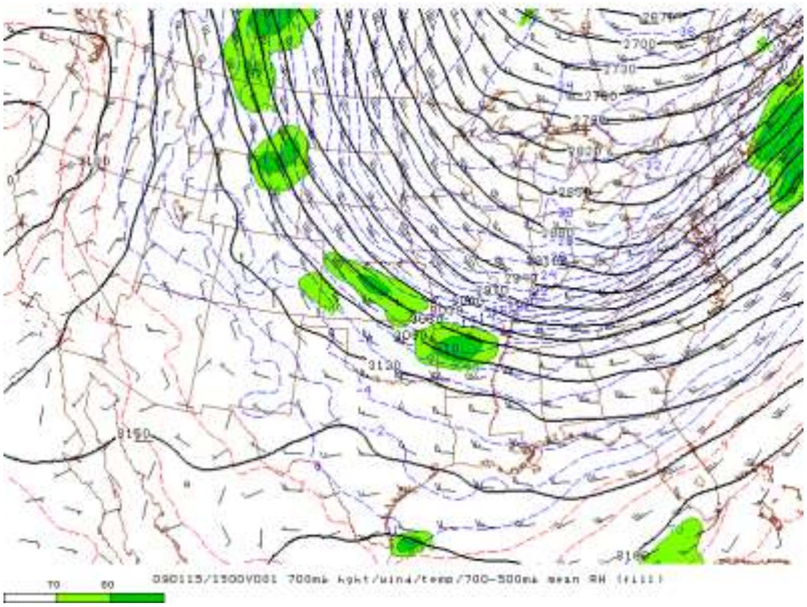
(a) (b)

Figure IV-6. In (a), ACARS sounding taken during aircraft departure from BTV at 15/1255z (755 am EST). Black circles represent air and water temperatures over Lake Champlain as labeled. In (b) map showing departure route and sounding sample points; the aircraft passed over the southern portion of Lake Champlain during ascent.

At the King Street ferry dock in downtown Burlington, the lake temperature the morning of the 15th was 33^{o}F (0.6C). The air temperature over the southern portion of Lake Champlain was around 0^{o}F (-18C). Thus, the vertical temperature difference in the first few meters above the lake was near 19C. This contributed to the arctic sea smoke or steam fog, and the steam devil activity. Based on the 15/1255z (7:55am EST) ACARS sounding, the lake to 850mb temperature difference was 23C. The 1-h Rapid Update Cycle (RUC) forecast (Figure IV-7) valid at 15/15z indicated a lake-to-850mb temperature difference closer to 25C. The lake to 700mb temperature difference was 32C based on the ACARS profile and around 31C based on the 1-h RUC forecast. This resulted in extremely unstable low-level conditions over the lake. The convective overturning resulted in ascent over the lake, and associated convergence from adjacent land areas to the east and the west. The deeper-layer instability and convective updrafts likely contributed to waterspout formation.



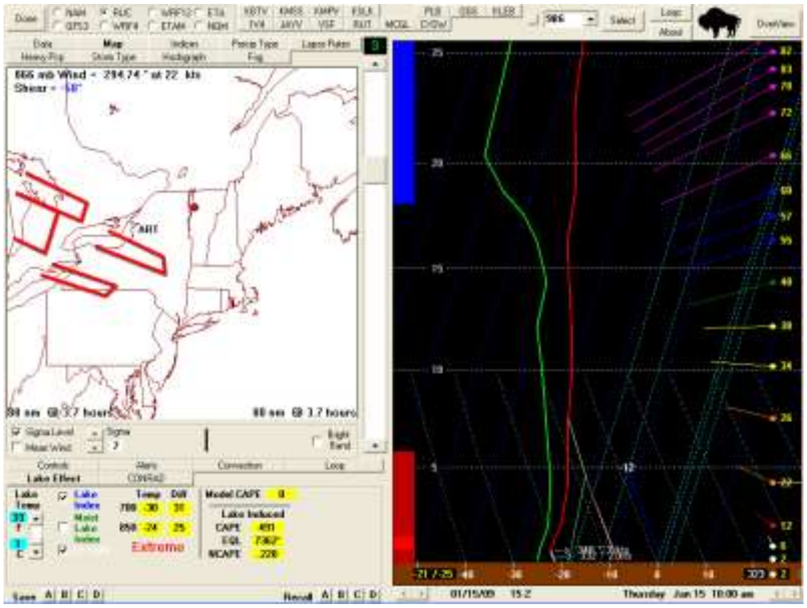
(a)



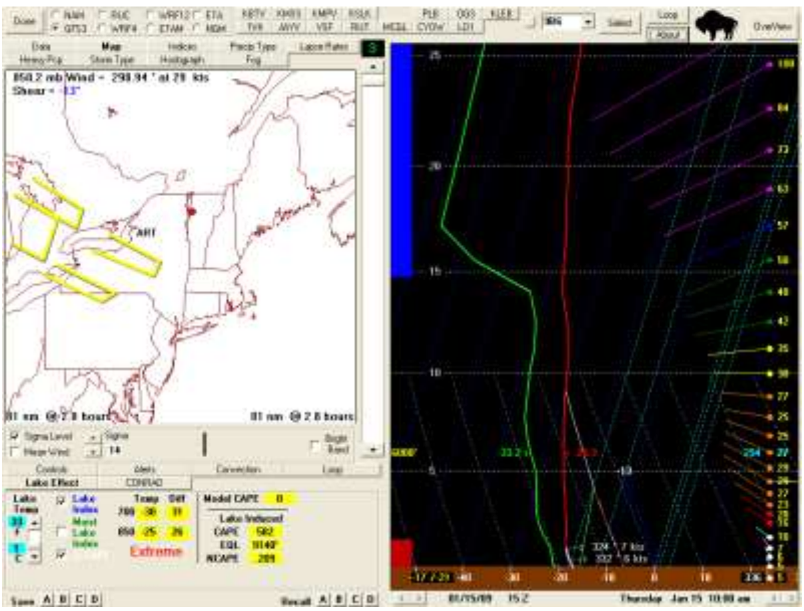
(b)

Figure IV-7. The (a) 850mb and (b) 700mb analysis valid at 15z on 15 January 2009, based on the 1-hr forecast from the Rapid Update Cycle (RUC) model. Analyses from the NCEP/Storm Prediction Center mesoanalysis archive.

The Rapid Update Cycle (RUC) and Global Forecast System (GFS) model vertical profiles (Figure IV-8) showed west-northwesterly winds of 15-30 kts from 2 to 5 kft. Winds below 2 kft were generally less than 10 kts. Assuming lifted parcels over the lake are roughly the average of the lake and near-surface temperature, lake induced convective available potential energy (CAPE) values were around 500 J/kg. The model profiles suggested equilibrium levels between 7000-9000 ft. Because the observed echo tops were only around 2500 ft, it appears this methodology for determining the lifted parcel temperature results in the parcel being too warm compared to reality. The 0h RUC sounding at BTV is also available for viewing here. If we assume a temperature over the lake of 0°F and a dewpoint of -5°F, the lifting condensation level is around 1100 ft. This seems reasonable, and would suggest cloud depths of 1000-1500 ft within the waterspout producing lake cloud band.



(a)



(b)

Figure IV-8. The 3-hour (a) RUC and (b) GFS forecast soundings valid at 15z on 15 January 2009 for KBTV. Lake temperature is set at 33°F with lake induced CAPE values of 491 J/kg and 582 J/kg, respectively based on lifted parcel temperature around -8C.

One question is why only two documented cases of winter waterspouts exist over Lake Champlain (see historical section for details on 12 February 1954 case). Typically, arctic frontal passages and northerly winds across the open waters of Lake Champlain will occur several times each winter. While lake effect snow showers or flurries are not uncommon (especially along the southeastern shore of the lake), the occurrence of waterspouts is seemingly far more infrequent. First, it is likely that some events simply go unreported. Also, it could be that some waterspouts and steam devils are obscured by falling lake effect precipitation. The sub-cloud layer was generally free of any significant precipitation in this case, suggesting sub-cloud RH may be important from the standpoint of observing these features. Also, the cloud depths were relatively shallow in this case (probably less than 2000 feet). It is possible that the degree of low-level convergence was enhanced due to northeast flow at the surface across the lake (owing to the position of the surface ridge to the west), while winds at 3000 feet were nearly westerly (per the ACARS and model soundings). This may have enhanced the magnitude of the near-surface convective updrafts compared to other similar events. Because waterspouts are such small features in time and space, it is not possible to measure the presence of cyclonic convergence along the lake convergence zone that is generally necessary in the incipient stages of a waterspout. The strength of the convergence zone along with the extreme instability over the lake due to the arctic air were certainly favorable factors for the development of waterspout activity. However, it appears that it would be difficult to differentiate between similar events with or without waterspout activity on the basis of data that forecasters would typically have available.

V. Historical Arctic Waterspouts

While the observance of winter waterspouts is relatively rare on any water body, there was one other notable occurrence on Lake Champlain back on February 12, 1954. The weather on this date was very similar to that of this past January 15th, in which strong arctic high pressure was building southward into the eastern half of the country and moderate northerly surface winds were observed in the Champlain Valley (see Figures V-1 and V-2). One notable difference between the two cases was that north winds were gusting up to 27 mph at Burlington during the 1954 case, while winds were only about 5 mph from the north-northeast during the 2009 case. On this day the local weather observer in downtown Burlington noted:

> *"Scattered clouds at 800 feet, scattered clouds at 1500 feet, barometer 1025.3 mb., temperature -8°F, dew point -21°F, wind north at 18 mph, gusts to 27 mph. Series of funnel-shaped clouds over Lake Champlain mostly extending from clouds to surface and moving from north to south. Funnels appear to be small tornadoes forming then moving southward a few hundred yards, dissipating, then new ones forming at the north end of cloud cover just west of station."*
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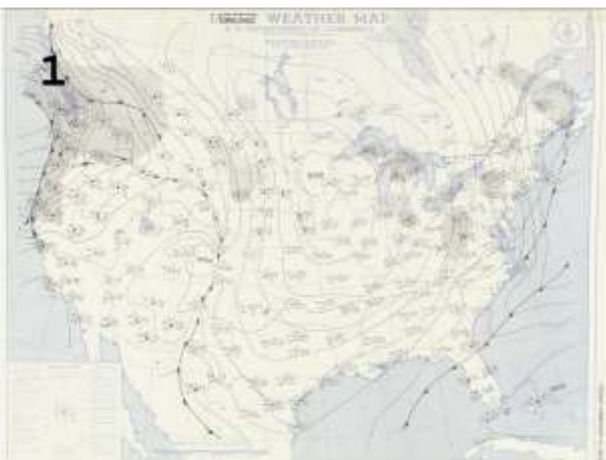
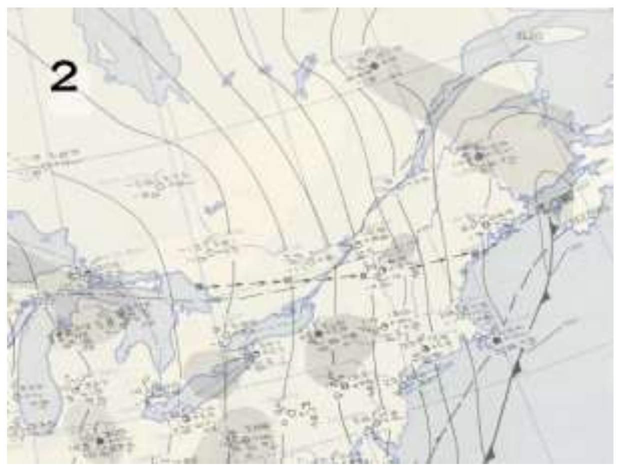
> **- excerpt from *Weatherwise*, April 1955**





Figures V-1 and V-2. *Daily Weather Maps* from 130 AM EST on the morning of February 12, 1954 showing cold arctic high pressure (centered across the northern plains) building southward into the eastern half of the country. Note the northerly gradient wind across the Champlain Valley.

With a surface air temperature of -8°F and the lake in the vicinity of Burlington unfrozen at the time of observance, the temperature difference between water and air was quite large and would certainly allow the lake to steam heavily. Given steep low level lapse rates and localized convergence over the lake, conditions were favorable for the formation of winter waterspouts. In addition to the case noted above, winter waterspouts (or snowspouts) have also been observed in other parts of the world, including Antarctica, Scandinavia, and Canada. In the latter case, a large spout was observed just offshore of Whitby, Ontario over Lake Ontario on January 26, 1994 (see Figure V-3 below). In this instance the spout was considerably larger, having a well-defined column extending upward into the cloud base. In the picture, you can clearly see the lake steaming along with the convective parent cloud elements indicative of an unstable lower atmosphere.

Interestingly the ambient low level flow was westerly (as opposed to northerly) on this day, or along the long axis of the lake. There has been some suggestion that the formation of spouts is more likely if winds align down long lakes such as Ontario and Champlain when low-level convergence is enhanced. However, with only a limited number of cases identified, further study is needed on this topic.

Figure V-3. Photo of large winter waterspout off Whitby, Ontario on January 26, 1994. (Source: *Environment Canada*, non-commercial use only)

Another old, but well documented case occurred offshore of Buffalo, NY back on February 11, 1907. An excerpt from the official *Weather Bureau* forecaster stated:

> *"The cloud had all the characteristics of a well-defined tornado funnel, or waterspout, appearing to be from 30 to 50 feet in diameter at the base and spread out to about 100 feet at the top. It retained its funnel shape as it advanced over the ice, licking up the snow as it went, until about a quarter of a mile off the south shore, when it began to waver and slowly vanish, breaking away at the bottom first."* **- from *Monthly Weather Review*, February 1907**

Given the ephemeral and relatively weak nature of these phenomena, it could be surmised that an observer would have to be in the "right place at the right time" in most cases to make a visual confirmation. Thus the formation of winter waterspouts may be more common than current thinking suggests and additional research is needed on this topic to fully ascertain the physical and dynamical processes involved in their formation.