WATERFALL MIST PLUMES: Niagara Falls, USA

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Introduction
The mist generated by Niagara Falls often propagates downstream in the Niagara Gorge, but periodically rises vertically, reaching heights up to 1km (Fig. 1). The 30 million who visit Niagara Falls each year have experienced more misty days over the past 15 years, with ensuing rainy conditions and poor viewing unfavorable for tourism, especially in Niagara Falls, ON. Water mixes with air at the base of the falls. It is hypothesized that the direction of flow of the mixture is due to contrasting water and ambient air temperatures where waterfall mist that is considerably warmer than the air develops a buoyant plume and a cooler aerosolized mixture drives denser downstream currents.

Methods
At nights of varying water-air temperature difference (ΔT), meteorological data and IR footage was taken of the American Falls from Luna Island at the top of the falls or from The Crow’s Nest at the base of the falls.

THERMAL IMAGES & MетеROLOGICAL DATA
- IR video footage was taken to visualize temperatures and mixing of air and water in different parts of the falls. (Figs. 2, 3, 4)
- Ambient temperature, humidity, pressure, horizontal wind direction, and both vertical and horizontal wind speed were recorded.

Results

UP AND DOWNDRAFTS WITH TEMPERATURE
In Fig. 5, positive Vv values were predominantly positive, reflecting updraft-dominated winds. These result from ΔT > +9.8°; air colder than water by 9.8° or more.
In Fig. 6, negative Vv indicate downdraft-dominated winds. ΔT < -11.5° corresponds to air consistently warmer than water. In Figs. 4 & 5, gusts of sustained heightened Vv regardless of draft direction, coincided with large changes in ΔT.
In Fig. 7, Vv values of 0 imply no significant vertical wind component. Slightly positive ΔT values show air marginally cooler than water, varying by less than 0.25°. (Fig. 4)

HORIZONTAL WIND MOVEMENT AND DIRECTION
In Fig. 8, relative wind directions were mostly negative, indicating winds blowing away from the falls. Vv of these winds (max. ~7m/s) were much faster than wind moving toward the falls (max. ~2.5m/s).
In Fig. 9, relative wind directions were all positive, denoting wind predominantly headed for the falls. Velocity spikes and drops correlated to sharp change in wind direction.
In Fig. 10, Vv < 0.5m/s at their peak. These low velocities correlated with highly variable wind direction. (Fig. 4)

Data

ΔT AND VERTICAL WIND VELOCITY (Vv)
ΔT is the temperature of the mist subtracted by the ambient air temperature (ΔT= Tmist- Tair). Negative velocity values are downdrafts, positive Vv values denote updrafts.

WIND DIR. (WD) & HORIZONTAL WIND VELOCITY (Vv)
WD values are relative to location: 1 is the direction of airflow toward the falls, -1 indicates the reverse. At The Crow’s Nest, positive WD values correspond to wind blowing either at the falls or down the Niagara River.

Conclusion

BUOYANT PLUME
It was expected that rising mist plumes generated by the falls are due to thermal buoyancy which is driven by the temperature difference between water warmer than the surrounding air (+ΔT), causing contraction and increase in density. The sinking of the resulting density current would cause downdrafts (-Vv) as more fresh air is pulled down toward the gorge/falls to fill space left by sinking/settling mist (+WD).

The data from March 2nd (Figs. 5, 8) meet these parameters for plume rise: positive ΔT, and predominant wind updrafts/lateral movement away from the falls. Fig. 3, recorded on the same night, shows evidence of a warm mist plume rising up and above the edge of the waterfall.

DOWNSTREAM DENSITY CURRENT
It was theorized that a denser current of mist created by the falls is due to mixing of colder water with warmer air (-ΔT), causing contraction and increase in density. The sinking of the resulting density current would cause downdrafts (-Vv) as more fresh air is pulled down toward the gorge/falls to fill space left by sinking/settling mist (+WD).

Data from March 27th (Figs. 6, 9) meet the conditions for density current propagation: negative ΔT, and dominating downdrafts and lateral air flow toward the falls. Fig. 2, recorded on a night with similar ΔT, shows a cooler, misty density current sinking below the edge of the waterfall.

Implications
Based on the results of this project, we can determine better times for certain activities at Niagara Falls. When the air temperature is much warmer than the water, the sinking of the mist plume is better for viewing the falls clearly while also staying relatively dry above the gorge. (Fig. 12)

Misty and rainy conditions (Fig. 13) are caused by the plume rising above the top of the gorge when the water is much warmer than the air. This would be most likely to occur in early mornings, due water’s relatively slow rate of heat loss overnight.

Because mist curtain geometry at Niagara Falls is dependent only on the difference in temperature rather than on the value of the temperatures themselves, the frequency of predominately misty days cannot be entirely constrained to seasonal variability.

The reason for the heightened frequency in misty days at the falls over the last 15 years is not known.

Fig. 11 (TripAdvisor, 2015, Table Rock Welcome Centre) Photo of the Horseshoe Falls under misty conditions from the Table Rock Welcome Center, ONT

Fig. 12 (Lu, 2015, Google Maps Imagery: Table Rock Welcome Centre) Photo of the Horseshoe Falls on a non-misty day from the Table Rock Welcome Centre, ONT