On the Influence of the Vertical Wind Structure on Convective Precipitation

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ABSTRACT

This study investigates whether part of the variability of rain rates not explained by the thermodynamic parameters could be explained by the vertical wind structure as revealed by standard aerological sounding observations. The correlation found between rain rates and vertical wind structure is at most marginally significant. Moreover, given the high degree of interdependence between the thermodynamic parameters and rain rates, the somewhat more significant correlation observed between the dynamic and thermodynamic variables may induce an automatic correlation between wind profiles and rain rates.

1. Introduction

In recent years, attempts have been made to relate the observed convective precipitation characteristics to wind field variables on the one hand and to the thermodynamic variables on the other hand.

Ulanski and Garstang (1978) found good correlation between the surface convergence field of the wind and storm rainfall amounts on the convective scale using a ground network fine-scale of observations of wind and precipitation characteristics. Thomas and Houghton (1979), using standard surface observations stations, found a lesser degree of correlation, though statistically significant, between the surface vorticity field of the wind and precipitation. Marwitz (1972) gave an indication of a possible relation between the mean vertical gradient of the wind through individual clouds and precipitation efficiencies. Klazura and Pritchard (1980) also found a correlation between high altitude winds and intensities of storm systems as observed with radar on the mesoscale.

In a study of the relation of precipitation to the thermodynamic variables on the mesoscale, Zawadzki and Rô (1978), hereafter called I, have shown that 60% of the storm-to-storm variability in maximum rainfall rates can be related to the convective static (parcel) energy. In a later study, Zawadzki *et al.* (1981), hereafter called II, established a similar result for average rainfall rates. They also found that the time evolution of rain rates follows hour-by-hour the variation of the static energy. These results have been corroborated by the analysis of independent data: one additional year for the correlations between maximum rain rate and maximum static energy (studied in I) and three additional days for the hour-by-hour relationship (studied in II). The results here were as positive as in I and II.

In an attempt to integrate the influence of the thermodynamic and the kinematic variables on precipitation, the present study was made to investigate whether part of the variability of rain rates not explained by the thermodynamic parameters could be explained by the vertical wind structure as revealed by standard aerological sounding observations.

The influence of the wind profile on convection can be quite complex: wind shear generated turbulence will erode and dilute convective elements and, in this way, it will inhibit the early development of deep convection; strong high level winds will increase the upper level water outflow and decrease the storm efficiency; on the other hand, wind shear tilting of updrafts in well developed storms helps to unload liquid water from the updrafts and therefore favors a more sustained vertical motion. Nevertheless, it is interesting to see if a simple effect of wind parameters on precipitation intensity results from this complex interaction.

2. Data and methodology

Two groups of well documented precipitation events were treated. One of them consists of 54 storm systems for which maximum 5 min rainfall rates $R_{\max}$, maximum convective static energy $E_{\max}$ and maximum surface wet bulb potential temperature $\theta_{w\,\max}$ reflecting the surface condition were known from I. The other group consists of 80 storm systems for which the mean rainfall rate $\bar{R}$, the mean convective static energy $\bar{E}$ and the mean surface wet bulb potential temperature $\bar{\theta}_w$ were also known from II.

TABLE 1. Correlation coefficients for the average rate sample. Threshold value for significance at the 5% level is $\rho = 0.22$. There are 77 observations in the sample.

	ΔV_{90-30}	ΔV_{90-50}	ΔV_{50-30}	ΔV_{55-50}	ΔV_{50-45}
$\bar{R}$	−0.25	−0.15	−0.18	−0.24	−0.21
$\bar{E}$	−0.18	−0.13	−0.18	−0.20	−0.27
$\bar{\theta}_w$	−0.14	−0.14	−0.12	−0.16	−0.23

TABLE 3. Partial correlation coefficients between ΔV_{85-80} and the indicated variables. Heading notation: $a \cdot bc$ means correlation between variable ΔV_{85-80} and variable a after eliminating the influence of variable(s) at the right of the dot. Threshold value for significance at the 5% level is $\rho = 0.27$.

	$R_{\max} \cdot E_{\max}$	$R_{\max} \cdot \theta_{w\max}$	$R_{\max} \cdot \theta_{w\max} E_{\max}$
ΔV_{85-80}	0.04	0.21	0.19

All these storm systems occurred in the Montreal region in the summers of 1969 and 1970. All systems had convective cells, in many cases imbedded in widespread precipitation. Rainfall rates were obtained from a network of raingages and all the sounding data (temperature and wind profile) were extracted from the Maniwaki record, the nearest one to Montreal. Details of the network of observations and the methodology of data processing and selection are described in I and II.

The following wind profile variables were considered:

1) The wind speed at each standard level.
2) The direction of wind velocity at each standard level.
3) The change in direction of wind velocity over layers of 5 kPa, 20 kPa, 40 kPa, 60 kPa at various levels.
4) The change in wind speed over layers of 5 kPa, 20 kPa and 60 kPa.
5) The norm of the vector change of wind velocity over the layers.
6) The temperature advection in the layers.
7) The Richardson number in the layers.

Correlation analysis was performed between the R, E, θ_w variables and all the wind variables described. It was found that the best correlations were obtained with the wind profiles extracted from the soundings nearest in time to the observed occurrence of the precipitation event (previous or simultaneous to it).

3. Results

The wind variable showing consistently the largest degree of correlation with the R, E, θ_w variables appeared to be the vector change in the wind velocity $\Delta V_{ij} = \|\mathbf{V}_i - \mathbf{V}_j\|$ over layers of varying depths ij.

TABLE 2. Correlation coefficients for the maximum rate sample. Threshold value for significance at the 5% level is $\rho = 0.27$. There are 49 observations in the sample.

	ΔV_{90-30}	ΔV_{90-50}	ΔV_{90-70}	ΔV_{85-80}	ΔV_{80-75}
$R_{\max}$	−0.16	−0.25	−0.17	−0.31	−0.31
$E_{\max}$	−0.17	−0.30	−0.35	−0.44	−0.43
$\theta_{w\max}$	−0.39	−0.43	−0.37	−0.55	−0.52

Table 1 shows best values for the correlation coefficients between $\bar{R}$, $\bar{E}$, $\bar{\theta}$ and ΔV_{ij} over different layers.

Table 2 shows similar data for the $R_{\max}$, $E_{\max}$, $\theta_{w\max}$ group. In the best of cases, the correlations found between the wind variables and the rainfall rates just reach the threshold of significance with a confidence limit of 5%.

One should notice that a correlation of at least as much significance is found between the wind variables and the thermodynamic parameters E and θ_w, probably reflecting the interaction between the dynamic and the thermodynamic fields. Since R is highly correlated with E and θ_w ($\rho = 0.75$), an automatic correlation could be induced between a precipitation variable and a wind variable. In our case, partial correlation between these wind variables and the rainfall rate after elimination of the influence of E and/or θ_w often brings the coefficient under the threshold of significance. Table 3 offers an example of this.

In an attempt to account for the different effects the wind could have on convection of different depths, correlations were made taking into account the cloud bases and cloud tops. The lifting condensation level was used as an estimate of the cloud base. The intersection of the pseudoadiabat defined by the surface $\theta_{w\max}$ and the sounding was used as an estimate of the cloud top. The following variables were then defined:

PLCL	the pressure level at the base of the cloud
PTOP	the pressure level at the top of the cloud
VLCL	the interpolated wind speed at the base of the cloud
VTOP	the interpolated wind speed at the top of the cloud
ΔH	the thickness of the cloud [ln(PLCL/PTOP)]

TABLE 4. Correlation coefficients for the maximum rainfall rate sample versus variables related to the cloud structure. Threshold value for significance at the 5% level is $\rho = 0.27$. There are 49 observations in the sample.

	VTOP	VLCL	ΔV	G	ΔH	PTOP	PLCL
$R_{\max}$	0.35	0.17	0.27	−0.27	0.76	−0.67	−0.03
$E_{\max}$	0.30	0.02	0.27	−0.27	0.79	−0.73	−0.08
$\theta_{\max}$	0.19	0.16	0.13	−0.49	0.85	−0.80	−0.21

TABLE 5. Partial correlation coefficients between $R_{\max}$ and speed variables VTOP, VLCL, ΔV, G after eliminating the influence of $E_{\max}$ or ΔH. Notation: $(ab \cdot c)$ is the correlation coefficient of a with b after elimination of c.

$R_{\max} V_{\mathrm{TOP}} \cdot \Delta H$: 0.08	$R_{\max} V_{\mathrm{TOP}} \cdot E_{\max}$: 0.20
$R_{\max} V_{\mathrm{LCL}} \cdot \Delta H$: 0.03	$R_{\max} V_{\mathrm{LCL}} \cdot E_{\max}$: 0.24
$R_{\max} \Delta V \cdot \Delta H$: 0.05	$R_{\max} \Delta V \cdot E_{\max}$: 0.10
$R_{\max} G \cdot \Delta H$: 0.11	$R_{\max} G \cdot E_{\max}$: −0.05

ΔV the net change of wind speed through the cloud (VTOP − VLCL)

G the mean gradient of the wind through the cloud ($\Delta V/\Delta H$).

Table 4 shows the results of the correlation analysis that was performed between these variables related to the cloud structure and $R_{\max}$, $E_{\max}$, $\theta_{w\,\max}$. The correlation coefficients are highest between the thickness of the cloud ΔH and all thermodynamic and precipitation variables. Such a degree of correlation between ΔH and $E_{\max}$, $\theta_{w\,\max}$ stems out of the definition of ΔH; correlation between ΔH and $R_{\max}$ then reflects the strong relation existing among $R_{\max}$, $E_{\max}$, $\theta_{w\max}$. The pressure level defining the top of the cloud PTOP is strongly correlated with ΔH ($\rho = -0.97$) which explains the degree of correlation observed between PTOP and the thermodynamic variables and $R_{\max}$.

The wind variables VTOP, VLCL, ΔV show less correlation with the thermodynamic variables and $R_{\max}$. The coefficients of correlation between VTOP and $R_{\max}$, $E_{\max}$ are still significant at the 5% level. The net change ΔV is strongly correlated with VTOP ($\rho = 0.95$). VLCL shows the weakest correlations. The mean vertical wind gradient G has a coefficient of correlation that barely reaches the threshold of significance at the 5% level with $R_{\max}$ and $E_{\max}$. It correlates significantly with $\theta_{w\,\max}$ ($\rho = -0.49$), despite the fact that all the speed variables (VTOP, VLCL, ΔV) reveal no significant correlation with $\theta_{w\,\max}$, reflecting the strong correlation found between $\theta_{w\,\max}$ and the thickness ΔH of the cloud.

Partial correlation analysis reveals that no significant correlation between $R_{\max}$ and any of the speed variables VTOP, VLCL, ΔV, G remains after eliminating the influence of ΔH or $E_{\max}$ (Table 5). This interdependence is confirmed if one performs multiple regression analysis between $R_{\max}$ and some combination of thermodynamic and wind speed variables. The addition of wind speed variables increases the coefficient of determination of $R_{\max}$ by no more than a few percent. As a matter of fact, a combination of several thermodynamic variables alone (among $E_{\max}$, $\theta_{w\,\max}$, ΔH, etc. . .) can bring this coefficient of determination from 60 to 70%. (Table 6).

4. Discussion

Globally, our results do not confirm our expectations to the effect that features of the vertical wind profile, as determined by standard aerological soundings, constitute an independent parameter partly accounting for the unexplained variability of rain rates.

The considered features of the wind profile revealed at most a marginally significant correlation with the rain rates. Partial correlation analysis tends to indicate that the wind profile is somewhat better correlated with the thermodynamic parameters of the convection. The excellent correlation between these thermodynamic parameters and the rain rates could induce the correlations observed between the wind profile and the rain rates.

Failure to recognize this could lead to wrong conclusions. For example, the scattergram of Fig. 1 shows a persistent feature found in our analysis; there seems to exist a limiting relationship between ΔV_{ij} and rain rate. For Fig. 1, this leads to a correlation coefficient of $\rho = 0.25$. However, the partial correlation, with θ_w held constant, brings ρ well below the level of significance and thus indicates that the limiting effect of ΔV_{ij} on $R_{\max}$ could be induced by the correlations of $\theta_{w\,\max}$ with $R_{\max}$ ($\rho = 0.74$) and $\theta_{w\,\max}$ with $\Delta V_{90\text{-}50}$ ($\rho = -0.43$).

Wind variables related to the vertical cloud extent should also be considered with caution. Speed vari-

TABLE 6. Stepwise regressions with $R_{\max}$ as the dependent variable and diverse combinations of thermodynamic and speed variables as independent ones. The value ρ_{I} is the individual correlation coefficient of the variable with $R_{\max}$ and ρ_{M} is the multiple regression coefficient at the current step.

Step	ρ_{I}	ρ_{M}	ρ_{I}	ρ_{M}	ρ_{I}	ρ_{M}	ρ_{I}	ρ_{M}	ρ_{I}	ρ_{M}
1	$E_{\max}$		$E_{\max}$		$\theta_{w\,\max}$		ΔH		$\theta_{w\,\max}$	
	0.76	0.76	0.76	0.76	0.77	0.77	0.76	0.76	0.77	0.77
2	VLCL		VTOP		$E_{\max}$		PTOP		$E_{\max}$	
	0.17	0.77	0.35	0.77	0.76	0.81	−0.67	0.81	0.76	0.81
3	ΔV		G		VTOP		$E_{\max}$		ΔH	
	0.27	0.78	−0.27	0.79	0.35	0.82	0.76	0.83	0.76	0.82
4	G		ΔV		G		VLCL		PTOP	
	−0.27	0.79	0.27	0.79	−0.27	0.82	0.17	0.84	−0.67	0.84

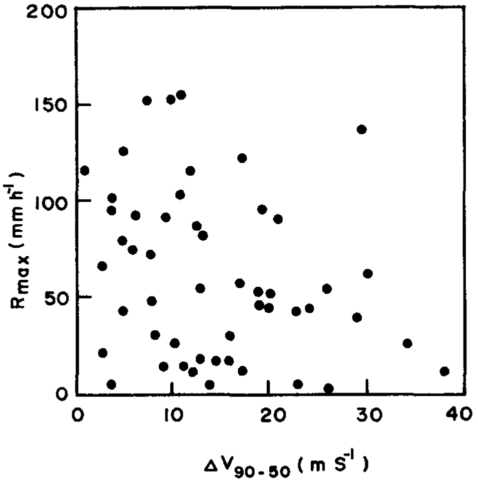

FIG. 1. Scattergram of the maximum rainfall rate R_{max} versus the norm of the vector change of wind velocity ΔV_{90-50} over the layer 90 kPa–50 kPa.

ables that incorporate the thickness of the cloud in their construction either directly (such as the mean shear) or indirectly (such as the wind velocity at the cloud top) are liable to lead to significant correlation with rain rates as a consequence of the relation that exists between the depth of the convection and the precipitation parameters.

Marwitz (1972) studied the relation between the vertical gradient of the wind through the cloud depth and the storm efficiency and found excellent correlation between these variables ($\rho = -0.83$). Despite the small number of storms considered (14), his results are statistically significant. In our case, a similar degree of correlation would exist between the inverse of the convection depth ($1/\Delta H$) and the rate although it would not reflect any property of the wind. The argument, however, is not intended to invalidate Marwitz's findings as he addressed himself to very deep convective storms, therefore presumably insuring a fairly large and uniform value of the thickness parameter through his sample. The variance he observed in the wind gradient would then reflect a property of the wind profile. If the efficiency is considered proportional to rain rate, Marwitz's results then are consistent with the persistent feature illustrated in Fig. 1, that is, large vertical wind shear inhibits large rainfall rates, although in our case this seems to be an indirect effect.

Klazura and Pritchard (1980) found higher values for the correlation coefficients between features of the wind profile and radar measured precipitation. If these good correlations were to be verified on a larger and independent sample, the differences with our findings should be attributed to differences of storm type.

Whether the vertical wind structure, as determined from standard observations, has an influence on the convective development, as determined by observations of precipitation, is uncertain. If any clear effect of the wind profile on convection is present for a particular type of storm, as Marwitz's results seem to indicate, this effect is not apparent in general and its use in a parametrization scheme as in Fritsch and Chappel (1980) is not justified.

It is quite likely that the complexity of the interaction between the wind and convection precludes any simple relationship between the two. On the other hand, the time and space scales of standard observations may not be fine enough to reveal these possible relationships.

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