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Aircraft encounters with strong coherent vortices over the boreal forest

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Abstract. A number of intense low-level vortices were encountered at a height of 30 m over the boreal forest by a Twin Otter atmospheric research aircraft. They imposed strong vertical and lateral accelerations on this aircraft: the most energetic had an updraft speed in excess of 11 m s^{-1}, only 20 m above the forest. All were associated with large sensible heat fluxes, low wind speeds, and deep boundary layers.

1. Introduction

From May to September 1994 the NRC Twin Otter (FT) atmospheric research aircraft was flown as one of the trace gas flux-measuring aircraft during the Boreal Ecosystem/Atmosphere Study (BOREAS) [*Sellers et al.*, 1995]. The aircraft was fully instrumented to measure the mean and turbulent components of atmospheric motion, the vertical fluxes of sensible and latent heat, momentum, CO_2, and ozone, as well as supporting meteorological and radiometric data [*MacPherson*, 1996; *MacPherson et al.*, 1992]. A total of 57 project flights were flown in the vicinity of Prince Albert Park, Saskatchewan (Southern Study Area (SSA), 53.5°N, 105°W), and Thompson, Manitoba (Northern Study Area (NSA), 56°N, 98°W), and on transects between these sites. The terrain was relatively flat (variations generally <50 m) but very varied in coverage, featuring forested areas of aspen, black spruce, and jack pine, burnt-over areas, lakes, fens, and beaver ponds. The majority of the FT flux-measuring runs were flown in the lowest portion of the mixed layer, at radioaltimeter heights of 30–50 m, at an air speed of approximately 55 m s^{-1}. Over 16,000 km of wind, turbulence, and flux data were collected at these altitudes during this program.

During these flights the aircraft encountered a significant number of strong, coherent vortices, one of which produced a vertical gust of 11.4 m s^{-1}, the largest measured by this aircraft in 20 years of research flying. Consequently, on completion of the field phase of BOREAS, all of the FT gust data were scanned for gusts in which the vertical component exceeded a threshold of 6 m s^{-1}. Nine events were found. This paper presents the structure of these events and comments on their role in the surface energy exchange over the Boreal forest.

2. BOREAS Gust Events

Table 1 summarizes the large gust events encountered by FT during BOREAS. Four were measured in the Southern Study Area (SSA), and five occurred in the Northern Study Area (NSA). Events 3 and 4 were experienced within a half-hour period on the same flight. Videotapes from the undernose camera on FT were reviewed to identify terrain features and type of vegetation in the vicinity of the gust events. Most of the events occurred in areas in which BOREAS data (aircraft and tower) usually showed elevated sensible heat fluxes (e.g., over spruce-covered areas, and over jack pine, which grows in sandy soil with a relatively high albedo). The videotapes generally showed some sort of surface discontinuity in the vicinity of the gust events, for example, a gravel pit for event 2, a logged clearing for event 3, a rocky outcropping for event 5, the edge of a cloud shadow for event 6, and a 5–10 acre burned area for event 9. Event 4 occurred over a spruce-covered hillside.

Figure 1 shows analog traces of the north, east, and vertical wind components measured by the aircraft during event 2. The vertical gust velocity of 11.4 m s^{-1} resulted in an upward vertical acceleration increment of 1.42 G, the largest ever measured by this aircraft. The aircraft was on a southerly heading (198°), so the peak-to-peak change in the lateral (east-west) wind component of almost 20 m s^{-1} in ~35 m (a shear of 0.57 s^{-1}) produced a sideslip angle in excess of 15° and a surprising lateral acceleration of −0.65 G. At the time of this encounter, the aircraft was less than 20 m above the jack pine.

Figure 2 illustrates plan and elevation views of the aircraft-measured wind vectors at an interval of 1/16 s (approximately 3.5 m) along the ground track of the aircraft. It reveals a feature common to at least eight of the nine gust events, i.e., a strong coherent vortex structure. This indicates that the aircraft encountered the forest equivalent of a dust devil, with a diameter, in this case, of approximately 150 m. The other cases showed diameters ranging from 200 to 300 m. Event 8 showed a less intense singular event, as it was measured in a more turbulent background associated with higher mean winds. Five of the events had cyclonic or counterclockwise rotation, while the remaining four were anticyclonic. *Sinclair* [1969] has reported that for all dust devils he studied, large or small, there appeared to be no preferred direction of rotation. None of the events showed evidence of a central downdraft in the core of the updraft, as seen in the tower-measured dust devil reported by *Kaimal and Businger* [1970], possibly because the aircraft did not penetrate the absolute center of the vortices.

Table 2 shows run-mean and peak fluxes as well as boundary layer depth for each of these events. Preliminary analysis shows that the gust events were associated with deep atmospheric boundary layers (ABLs) formed in the late morning after the

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Table 1. Summary of Gust Events

Event	1994	Location	Time, LT/UT	Alt, m	Temp, °C	Mean Wind, deg/m s^{-1}	Peak Gust, Vert m s^{-1}	Peak Az, Up/Down Gust	Peak Ay, Gust	Max Shear, s^{-1} Long	Max Shear, s^{-1} Lat	Max Shear, s^{-1} Vert	Rotation
1	June 4	SSA spruce	1253 1853	30	21.9	140/1.2	6.7	0.31 −0.55	0.21	0.43	0.33	−0.32	*A*
2	June 10	NSA jack pine	1234 1734	20	26.4	310/1.7	11.4	1.42 −0.53	−0.65	−0.71	0.70	0.95	*C*
3	July 26	SSA grid jack pine	1236 1836	30	23.4	310/0.9	7.1	0.53 −0.44	−0.32	−0.80	0.61	0.89	*C*
4	July 26	SSA spruce, hill	1303 1903	43	23.1	260/3.4	6.2	0.52 −0.55	0.45	0.58	−0.66	0.38	*A*
5	July 28	NSA grid mixed, rocky	1137 1637	40	21.1	055/3.2	6.7	0.41 −0.75	0.33	−0.93	−0.63	−0.50	*A*
6	Aug. 08	NSA grid dry, shadow	1227 1727	43	16.4	255/3.5	7.5	0.50 −0.31	−0.22	−0.72	1.53	0.91	*C*
7	Aug. 31	NSA grid mixed	1304 1804	40	17.1	315/1.5	7.0	0.53 −0.26	0.17	0.52	−0.66	0.64	*A*
8	Sept. 6	NSA grid aspen	1217 1717	35	14.1	290/7.5	7.0	0.75 −0.37	0.32	0.65	0.53	−0.76	*C*
9	Sept. 17	SSA spruce small burn	1226 1826	25	24.9	260/3.2	7.8	0.61 −0.29	−0.26	0.60	0.46	−0.51	*C*

Column 8 shows the peak vertical (vert) gust velocity. Altitude (alt) is from radioaltimeter; Temp is air temperature at flight level, and Az and Ay represent the vertical and lateral accelerations measured by the aircraft. The maximum shears (m s^{-1}/m) are for the longitudinal, lateral, and vertical wind components in aircraft axes. Column 14 indicates the rotation of the vortex, C for counterclockwise or cyclonic and A for anticyclonic. SSA, Southern Study Area; NSA, Northern Study Area.

breakthrough into the deep adiabatic layer, preexisting from the previous day. Figure 3 shows a sequence of three soundings of potential temperature for the NSA spanning the time of the most severe gust event 2 on June 10, 1994. The sounding at 1517 UT shows a shallow ABL with a top around 400 m above ground level (agl), beneath a deep preexisting ABL topped at 2200 m agl. By 1718 UT, the surface has warmed sufficiently for the two ABLs to merge. This rapid deepening phase to a single mixed layer 2200 m deep occurred just before the severe gust recorded at 1734 UT.

Other general observations of the meteorology associated with these gust events are as follows:

1. They occur in low wind regimes, with the exception of event 8. Figure 4 depicts the run-mean winds recorded during the nine gust events superimposed on the histogram of winds measured for all 1127 flux runs flown by FT in BOREAS. This is consistent with observations of dust devils [*Sinclair*, 1969], the majority of which occurred at wind speeds of 0.5–5 m s^{-1} (quoted in his paper as 1–10 mph). High winds cause an increase in the vertical mixing in the boundary layer and a weakening of the superadiabatic lapse rate driving the dust devil. Event 8 occurred in mean winds of 7.5 m s^{-1} and may be more representative of topographically caused turbulence.

2. They are associated with little ABL cloud cover. Event 8 is again an exception, with three tenths stratocumulus, as is event 1 where bands of cumulus congestus were forming. Net

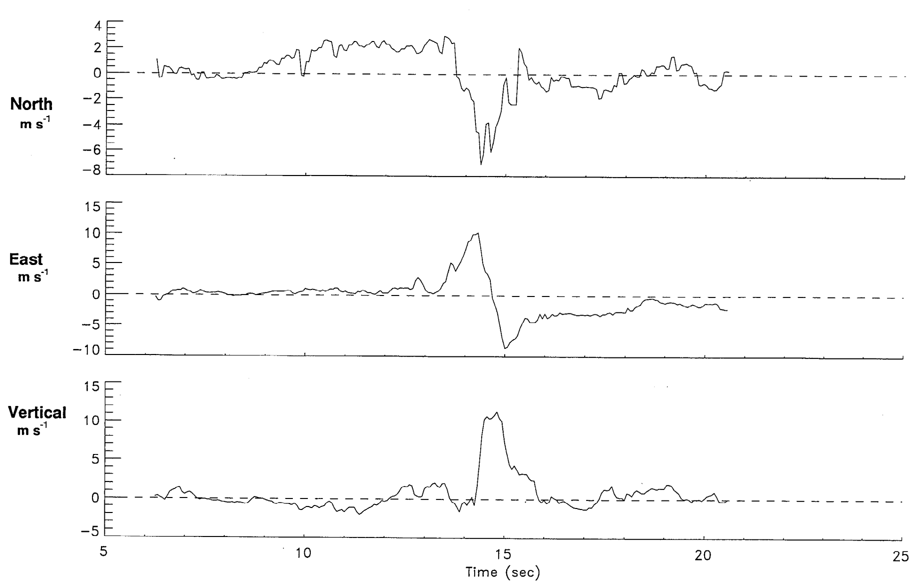

Figure 1. North, east, and vertical wind components for record gust event 2.

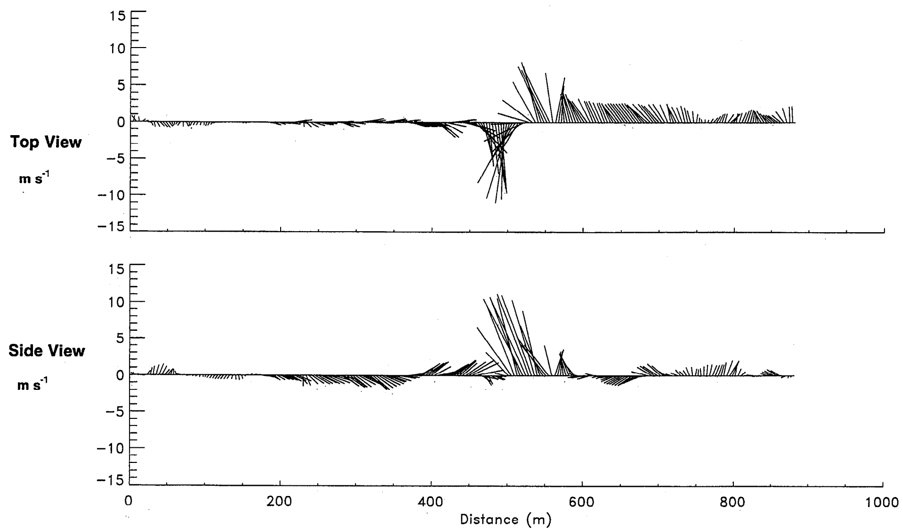

Figure 2. Plan and elevation views of wind vectors for gust event 2 relative to aircraft track (198°).

radiation measurements in Table 2 show that event 8 was recorded in a mostly sunny patch, while it was mostly cloudy for event 1. There were a few scattered cumuli for event 6, which was encountered near the edge of one of the cloud shadows.

3. They were all encountered in the two hours before local solar noon in deep boundary layers (1100–2200 m).

4. The two strongest gusts in terms of the vertical gust velocity were measured at the two warmest air temperatures (Table 1).

5. Typically, surface energy fluxes were high with net radiation >450 W m^{-2}.

3. Discussion

We conclude that the mechanism for the generation of these vortices is similar to that for dust devils [*Sinclair*, 1969; *Kaimal and Businger*, 1970] and for steam devils over water [*Bluestein*, 1990; *Grossman and Betts*, 1990]; that is, they are driven by strong surface fluxes in deep ABLs. Their rotation comes from the concentration of shear vorticity by thermals. Over the forest they are not visible and may not have been reported previously. Gust event 1 may involve some coupling with the cloud layer, as cumulus congestus lines were developing, and event 8 may be of a different structure in a stronger sheared flow and higher winds.

The vertical acceleration of air to updraft speeds of 10 m s^{-1} at elevations as low as 20 m requires an organized dynamic system. In a rotating vortex, such as the dust devil, the strong central pressure gradient accelerates the air off the surface. These dynamic systems may be able to draw on the potential energy of the deep boundary layer. We might estimate representative vertical velocities in these rotating updrafts from the simple available convective potential energy relationship:

$$w^2 \sim gh(\Delta\theta/\theta)$$

A vertical velocity $w \sim 10$ m s^{-1} is consistent with a mean excess potential temperature in a rising plume $\Delta\theta \sim 2$°K and ABL depth h of 1500 m. A typical observed potential temperature difference across the superadiabatic layer, between the forest canopy radiometric temperature and the air temperature above the canopy, based on near-surface mesonet observations, was 2° to 3°K.

The peak vertical fluxes for sensible and latent heat, CO_2, and momentum given in Table 2 show that these coherent structures can be responsible for transporting a significant pro-

Table 2. Net Radiation, Boundary Layer Depth, and Run-Mean and Peak Vertical Fluxes for Sensible Heat (H), Latent Heat (LE), CO_2, and momentum (UW)

			Run Mean		Peak Vertical Flux			
Event	Net R, W m^{-2}	ABL Depth, m agl	H, W m^{-2}	LE, W m^{-2}	H, W m^{-2}	LE, W m^{-2}	CO_2, mg m^{-2} s^{-1}	UW, N m^{-2}
1	218	1700	138	93	4500	1390	−7.2	14
2	546	2200	484	262	16300	8750	−48.2	−114
3	582	1500	218	231	12900	12500	35.6	−45
4	525	1600	179	201	4700	2900	−18.9	28
5	523	1100	166	210	6800	7700	−27.8	39
6	483	1750	196	150	7800	4800	−14.2	36
7	487	1500	232	153	6500	5700	−17.1	−11
8	456	1300	158	106	1800	1450	−11.0	−38
9	476	1600	131	135	3600	2650	−10.2	−17

The positive (upward) peak CO_2 flux for event 3 was between two negative peaks of −24 mg m^{-2} s^{-1}, with net downward transport of CO_2.

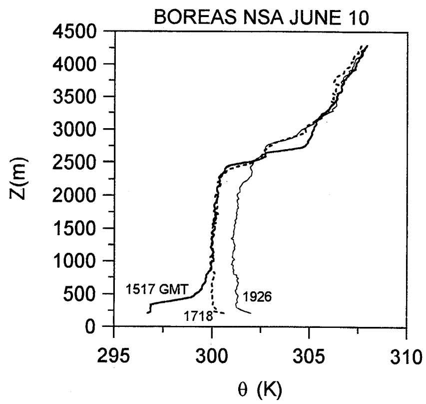

Figure 3. Soundings of potential temperature for the Northern Study Area spanning time of event 2.

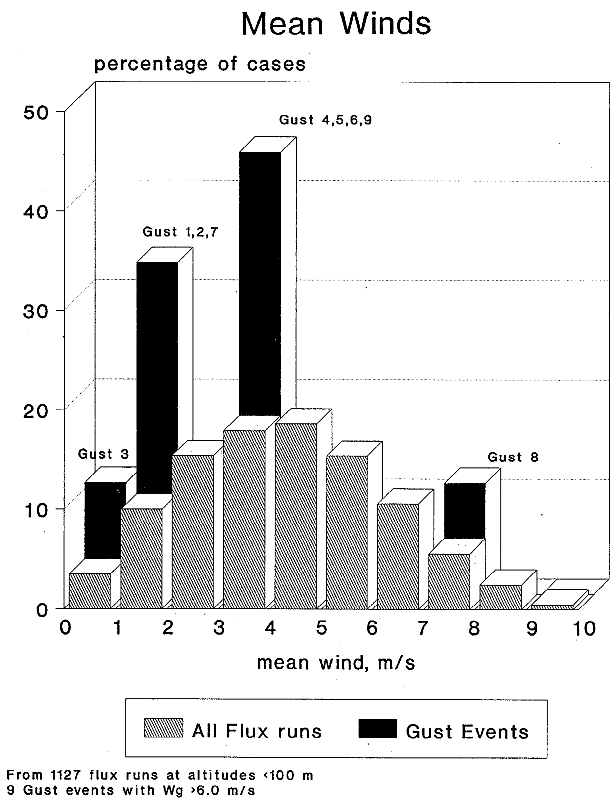

Figure 4. Comparison of run-mean winds for the nine gust events and all 1127 flux runs flown in the Boreal Ecosystem/Atmosphere Study.

portion of the energy and trace gases in the lower boundary layer on some aircraft legs. Peak H, LE, and CO_2 fluxes during the gust events were typically 30 to 60 times the run averages. Both positive and negative momentum fluxes were observed, some with very high peak values.

Finally, the study of these gust events is interesting from an aeronautical perspective. During the low-altitude flux runs in BOREAS, FT encountered vertical gusts >6 m s^{-1} at an average rate of approximately once per 1800 km. They resulted in significant vertical and lateral accelerations to the airframe, as well as pitch, roll, and yaw excursions that required prompt corrective control inputs by the pilot. The hazard potential of these coherent structures is a function of flight altitude as well as the aircraft's wing loading (aircraft weight over wing area); aircraft with lower wing loadings would respond more violently to these rotating gusts. The fact that these vortices are generally invisible over the forest suggests that pilots of low-altitude flux-measuring aircraft, pipeline patrol aircraft, etc., should be prepared to occasionally experience such encounters.

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