NOTES AND CORRESPONDENCE

Impact of Boundary-Layer Clouds—A Case Study of Cover Hours

ROLAND B. STULL

Boundary Layer Research Team, Department of Atmospheric and Oceanic Sciences, University of Wisconsin, Madison, Wisconsin

26 June 1991

ABSTRACT

Cover hours are defined as the cloud-cover fraction times the number of hours those clouds are observed. Case study statistics of cover hours during 1990 for nonprecipitating low clouds at Madison, Wisconsin, indicate the potential for climatic impact by boundary-layer clouds. A total of 1476.6 cover hours by all low clouds are observed, of which the subset of scattered boundary-layer clouds contributes 33%. The subset of low clouds that are turbulently coupled to the ground contributes 1199.1 cover hours, which is 81% of the total observed and 13.7% of the total possible 8760 hours per year.

1. Location and climate

Although scattered cumulus clouds are often perceived by the general population as signs of fair weather and sunshine, their coverage and radiative characteristics make them a significant modulator of the earth-system energy budget. To address the significance, a case study of nonprecipitating boundary-layer clouds at Madison, Wisconsin, is presented for the year 1990.

The continental climate in Madison is typical of interior North America, with large annual and diurnal temperature ranges. Located at 43°08.3'N, 89°20.8'W, midlatitude cyclones and anticyclones are frequently blown by the prevailing westerly winds across the region. Continental polar air masses from Canada in winter and modified maritime tropical air masses from the Gulf of Mexico in summer are most common. Snow is typical in winter, and thunderstorms are common in summer. Lake Michigan, which is about 100 km east of Madison, rarely influences the Madison weather. Lake Mendota (area 39 km^2) is about 3 km west of the National Weather Service (NWS) Office at Madison's Truax Field airport (MSN) and occasionally influences the local cloudiness.

During 1990, the annual weather at Madison was well within the range of normal climate variations. That year was neither excessively wet nor dry, and summer temperatures were not as exceptionally hot as the previous two summers. The only extraordinary event was a blizzard in December.

Corresponding author address: Dr. Roland B. Stull, University of Wisconsin, Department of Atmospheric and Oceanic Sciences, 1225 W. Dayton St., Madison, WI 53706-1695.

2. Cloud observations and groups

The NWS-MSN office keeps a record of cloud type, base height, coverage, and precipitation every hour, and segregates clouds into low, middle, and high categories. The low clouds observed during 1990 were: cumulus (cu), stratocumulus (sc), stratus (st), towering cumulus congestus (tc), cumulonimbus (cb), cumulus fractus (cf), and stratus fractus (sf). The following weather elements were also included in the NWS record, but are excluded from this case study: fog, obscurations, nimbostratus clouds, and all cloud observations during those hours that rain was observed.

To separate the scattered nature of some boundary-layer clouds from overcast clouds, two groups of clouds were also formulated. Group A represents scattered clouds and includes all cumulus, towering cumulus, cumulus fractus, and only those stratocumulus observations of 7/10 coverage or less. Group B consists of (nearly) overcast clouds and includes stratus and only those stratocumulus observations of 8/10 or more. Note that the NWS definition of broken clouds (6/10 to 9/10) has been split down the middle and added to groups A and B. Neither stratus fractus nor cumulonimbus are included in groups A or B.

A third group, C, is defined similar to group A, except that it includes all stratocumulus clouds. All of the clouds in this group show the lumpy structure typical of turbulent boundary layers and indicate a strong coupling of the clouds with the surface. Although stratus clouds are low clouds, they frequently are caused by upslope advection over a frontal surface and are thus not caused by, or tied to, the underlying surface. Stratus are not really boundary-layer clouds for that

TABLE 1. Monthly summary of cover hours at Madison, Wisconsin (MSN), 1990. Groups: A = cu + tc + cf + (sc ≤ 0.7); B = st + (sc ≥ 0.8); C = cu + tc + cf + sc

Month	cu	tc	cb	cf	sc ≤ 0.7	sc ≥ 0.8	st	sf	A	B	C	Total	Days of A
Jan	0.8			0.1	14.3	90.6	16.3	2.0	15.1	106.9	105.7	124.0	15
Feb	1.4			1.8	23.2	59.9	9.9	1.1	26.4	69.8	86.3	97.3	16
Mar	5.2	1.4		0.1	22.9	64.2	32.2		29.6	96.4	93.8	126.0	19
Apr	15.5	4.7		0.2	26.4	90.6	15.1	4.2	46.7	105.7	137.3	156.6	27
May	13.1	6.2			28.4	52.2	29.4		47.7	81.6	99.9	129.2	22
Jun	22.2	6.1	1.5	7.8	27.3	45.4	5.4		63.2	50.8	108.6	115.5	29
Jul	14.5	22.9	4.6	0.1	26.3	20.0	2.9	0.1	63.8	22.9	83.8	91.3	28
Aug	29.0	11.0	2.5	0.1	27.7	48.5	22.0	1.0	67.7	70.5	116.2	141.6	26
Sep	16.2	2.5	3.1	1.0	28.4	87.5	33.6		48.0	121.1	135.5	172.2	24
Oct	6.0	1.1	0.1	1.3	25.9	55.0	2.2		34.2	57.2	89.2	91.5	21
Nov	1.9			4.7	17.5	45.6	11.8	9.1	24.1	57.4	69.7	90.6	19
Dec	2.5			0.1	16.9	54.0	56.9	10.7	19.5	110.9	73.5	141.1	15
Total	127.8	55.8	11.7	17.1	285.0	713.5	237.7	28.2	485.6	951.2	1199.1	1476.6	261

reason. Thus, group C is based on turbulent dynamics, rather than on coverage.

3. Definition of cover hour

To quantify the impact of boundary-layer clouds, "cover hours" are tabulated as the number of hours multiplied by the fractional cloud coverage. For example, 3 hours of cumulus clouds of 4/10 coverage contribute 1.2 cover hours. The NWS hourly observations of cloud cover are assumed to apply to the whole hour, even though their official observations are usually made during an interval of just a few minutes. This assumption does not appear too bad, because diurnal changes in cloudiness were often gradual and were well documented by the hourly observations.

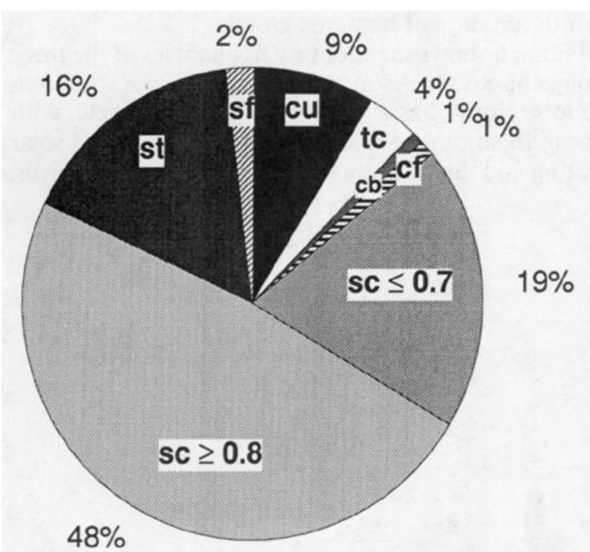

FIG. 1. Relative contributions of nonprecipitating low-cloud types to the observed total of 1476.6 cover hours during 1990 at Madison, Wisconsin; cu: cumulus, tc: towering cumulus, cb: cumulonimbus, cf: cumulus fractus, sc: stratocumulus, st: stratus, and sf: stratus fractus. The stratocumulus clouds are split by coverage into "scattered" (7/10 or less), and "overcast" (8/10 or more).

Sometimes the NWS reported more than one type of low cloud during any one hour. All reported low clouds except those excluded above are included in the cover hour tabulation.

When clouds were observed with a coverage less than 1/10, this was recorded by the NWS as 0/10 of some particular cloud type. For the purpose of this case study, we assume that a report of 0/10 coverage corresponds to 5% cloud cover. Note that when there were no low clouds, the NWS did not record even 0/10 in their record; thus, there is no confusion about few clouds versus no clouds.

4. Cover hour results

Table 1 lists the monthly summary of each of the eight individual cloud types, the three groups of clouds, the total clouds, and the number of days during which clouds of group A were observed. Note that the "total"

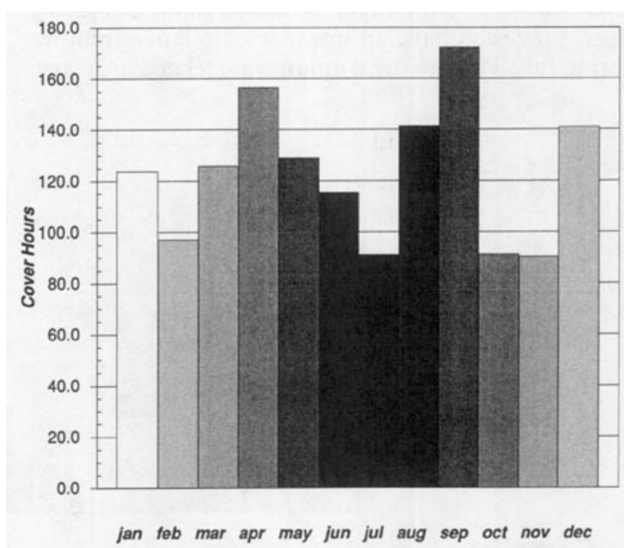

FIG. 2. Total cover hours of all nonprecipitating low clouds segregated by month during 1990.

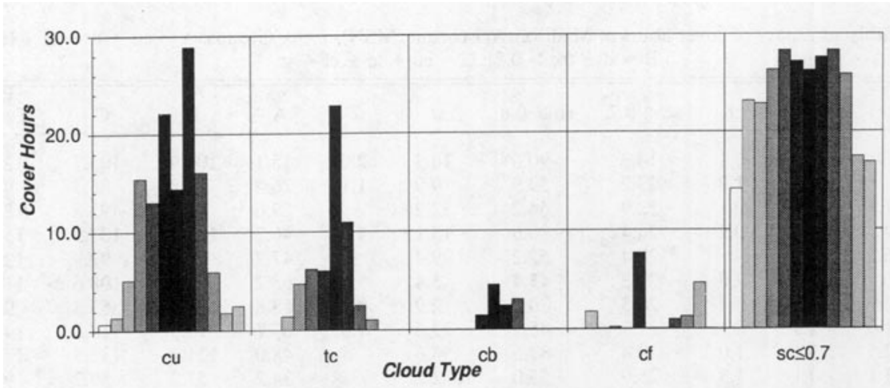

FIG. 3. Monthly contributions to cover hours by individual cumuliform cloud types and by scattered stratocumulus clouds. Shading of monthly bars corresponds to that in Fig. 2.

column represents the sum of the eight individual cloud types. The three groups of clouds (A, B, C) include overlapping cloud types and do not sum to the listed total. All numbers in that table are rounded to the nearest tenth of a cover hour.

Figure 1 shows the relative contributions of each cloud type to the 1476.6 cover-hours total (from the bottom row of Table 1). Stratocumulus clouds dominate—making up over two-thirds of the total cover hours. The overcast subset of stratocumulus are the major contributor to this total, with 48%. Scattered clouds, including the portion of stratocumulus clouds of 7/10 coverage or less, contribute 33% of the total. Total cover hours exhibit peaks in April, September, and December, as shown in Fig. 2. On the average, 123 cover hours are observed each month during 1990.

The monthly variation of cumuliform clouds and scattered stratocumulus clouds are shown in Fig. 3. Although both cumulus and scattered stratocumulus clouds have a broad maximum of cover hours during the summer months as expected due to the increased solar heating and thermal convection in the boundary layer, they each have an unexpected relative minima during July. Perhaps these minima are related to greater instability during July, which allows many cumuliform clouds to grow to greater depths, as indicated by the sharp maximum in towering cumulus and cumulonimbus. As will be seen later, the sum of all scattered clouds does not have a relative minimum in July.

Cover hours contributed each month by stratus, overcast stratocumulus, and stratus fractus clouds are shown in Fig. 4. During January, April, and September there are major cover hour peaks in stratocumulus, while the major stratus peak is in December.

Scattered boundary-layer clouds (group A) are observed 261 days during the year and contribute a total of 485.6 cover hours. Figure 5 shows the number of days during each month that any "scattered" boundary-layer cloud within group A is observed. Group A clouds are most frequent during the summer months June through August and occur on the average 28 out of 31 days of each month. During winter, about half of each month has days of scattered clouds.

Figure 6 shows the monthly frequencies of the three groups of clouds. As mentioned earlier, the scattered-cloud group A has a well-defined annual cycle, with a peak in summer associated with the increased solar heating and thermal convection in the boundary layer.

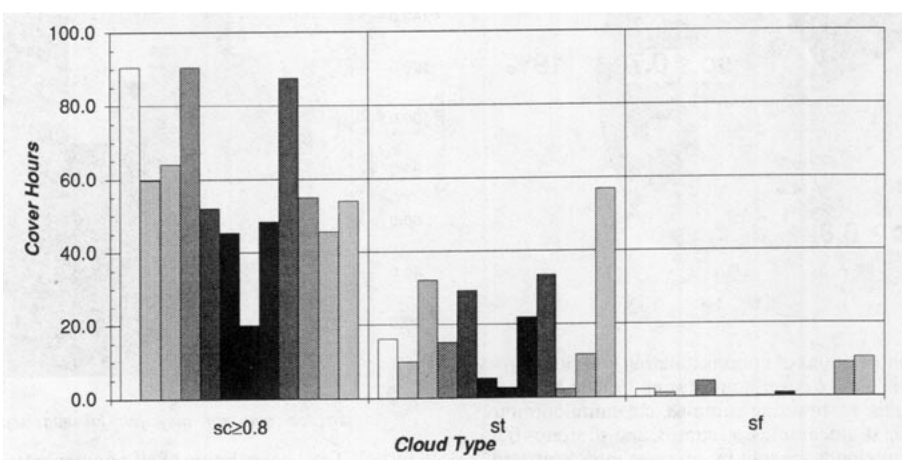

FIG. 4. Same as Fig. 3, except for individual stratiform types and overcast stratocumulus.

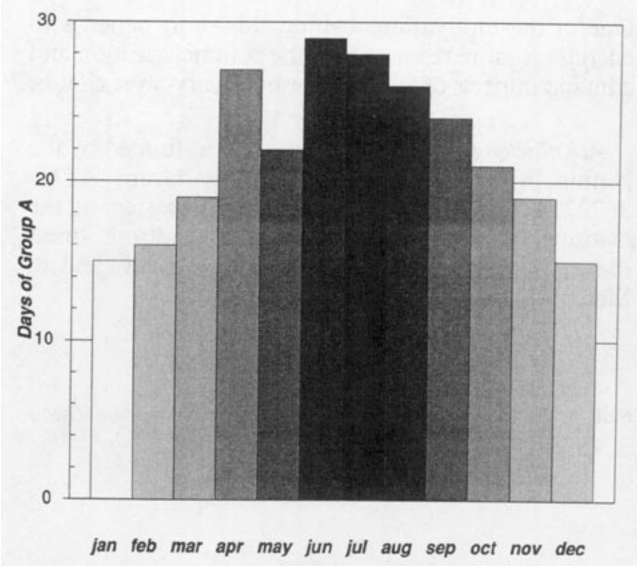

FIG. 5. Number of days each month that any type of scattered boundary-layer clouds were observed.

This distribution is well approximated by a sine curve: (cover hours per month) = $40 + 25 \sin[2\pi(i - 4)/12]$, where i is the month index ($i = 1$ for January, 2 for February, etc.).

Group C in Fig. 6, which is associated with strong boundary-layer turbulence and coupling to the underlying surface, has major peaks in April and September associated mostly with overcast stratocumulus. April is climatologically the windiest month in Madison, so perhaps the enhanced mechanical turbulence caused by wind shear is supporting the April peak of stratocumulus. The September peak is more difficult to explain. Climatologically the frequency of arctic airmass incursions from Canada begins to increase in autumn. During these events, cold air advects over warmer land, causing vigorous boundary-layer convection. This leads to the frequent observation of stratocumulus clouds behind cold fronts, which perhaps explains the September cloudiness peak.

The overcast clouds of group B in Fig. 6 show a noticeable minimum in July. During the summer, most of the cyclones and associated stratiform clouds pass well north of Madison. Even when stratus and stratocumulus clouds do form, the solar heating is often strong enough to enhance boundary-layer growth and turbulence to the point where the cloud decks break up during the day.

5. Discussion and conclusions

The reason why scattered stratocumulus clouds, cumulus, and towering cumulus clouds are grouped together is because they are different manifestations of a common dynamical process. Namely, the first rising thermals that reach their lifting condensation level in the late morning are often rather shallow, and as such would be morphologically classified as stratocumulus. As this same cloud field evolves and surface heating continues, the clouds can grow to sufficient depth to be classified as cumulus clouds. In some cases, the cloud tops can penetrate above their level of free convection and continue to grow vertically into towering cumulus. This dynamic classification of cumulus clouds has been discussed by Stull (1985).

All boundary-layer clouds (group C) contributed 1199.1 cover hours during this case study year, which is 13.7% of the total possible 8760 hours per year. Because the weather during 1990 was basically typical, it is suggested that these cover hour statistics, albeit a

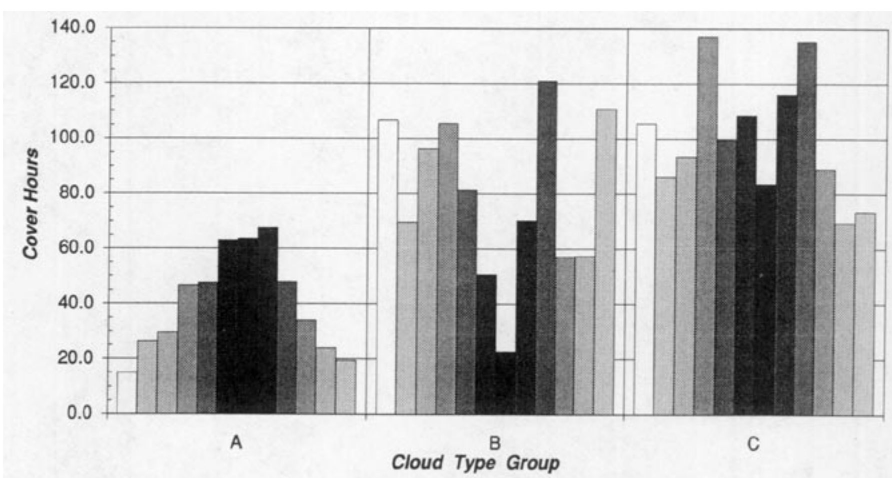

FIG. 6. Monthly contributions to cover hours by groups of clouds. Group A represents "scattered" boundary-layer clouds, including cu, tc, cf, and scattered sc. Group B represents "overcast" low clouds, including st and overcast sc. Group C are all low clouds that are turbulently coupled with the surface, including all of group A plus overcast sc.

limited sample, are representative of other years and perhaps of other locations in central North America. When viewed as a relative impact on climate, the relative contribution of boundary-layer clouds compares in magnitude with those of other physical processes receiving attention in climate models.

Fair-weather cumulus clouds and other scattered boundary-layer clouds (group A) contribute more to the total cover hours than perhaps many people realize, as suggested in section 1. Namely, 33% of the cover hours are associated with group A, while 48% is associated with overcast stratocumulus decks for this case study. The overcast stratocumulus problem has been receiving increased study during the past decade, but less attention has been given to fair-weather cumulus. One of the motivations behind this short paper is to encourage more research into the parameterization and climatic impacts of fair-weather boundary-layer clouds.

Acknowledgments. This research was funded by the National Science Foundation under Grant ATM-8822214. Special thanks go to the forecasters at the National Weather Service office in Madison: Brian Pierce, Ted Stimach, and Margaret Mooney, and to Meteorologist in Charge Gene Przekurat.

REFERENCES

Stull, R. B., 1985: A fair-weather cumulus cloud classification scheme for mixed-layer studies. *J. Climate Appl. Meteor.*, **24**, 49–56.