551.515.41 (54)

Note on the mechanism of Nor'westers of Bengal

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(*Received 8 August 1950*)

In a recent note, Desai[1] amplified the theory of formation of Nor'westers given by Desai and Mal[2] in 1938. Some of the important conclusions reached by these authors have been verified by recent work of the United States Weather Bureau Thunderstorm Project[3] and others. For example:

1. Desai and Mal[2] concluded that the fall of dry and wet-bulb temperature observed with most Nor'westers is due to the downflow of continental air from above the transition layer separating the dry northwesterly air from the lower moist southerly current, and evaporative cooling of this in rain. Stommel[4] and Byers and Braham[5] have shown that the way this actually happens in a thunderstorm is by the entrainment of lateral drawing-in of outside unsaturated air into the thunderstorm cells from their environment. This relatively dry air is mixed inside the thunderstorm, part of the liquid water in the cloud being used to cool it by evaporation. The dry air from higher levels is thus enabled to descend all the way to the earth's surface, mixed partly with air in the cloud which had previously ascended from lower levels in updrafts.

2. Desai and Mal[2] also state that the force of thundersqualls depends partly upon the original horizontal velocity of the descending air. Since the air entrained into a downdraft in higher levels must retain its horizontal momentum in the absence of outside forces, this statement also appears to be verified.

3. Desai[1] mentions that although Nor'westers start at different times over different places, time sequences for some thunderstorms at different places on the same day are also found. Desai suggests, following Chatterjee and Sur[6], that outflowing cold air from a parent thunderstorm could act as a trigger for formation of new convective storms. Photographs of radar echoes of thunderstorms taken by the Thunderstorm Project[3] show that this effect really is important.

In Nor'westers and other similar type thunderstorms, there seem to be preferred directions for the movement or propagation of the thunderstorm area, and the most violent thunderstorms are generally found on the side of the rain area toward which it is moving. The mechanism causing the greater spreading out of the cold air in some directions than in others, although implied in point (2) above, does not appear to be fully understood in so far as its effects upon further thunderstorm formation are concerned. An article recently written by the author of this note on the "squall line" of North America[7] may have some bearing on this problem, and seems to fit in with the theory of Desai and Mal. From the figure given by Desai[1], schematic diagram is shown sketched in Fig. 1. For simplicity in discussion, it has been assumed that the dry current is from the NW, the moist current from SE.

When a thunderstorm breaks through the separation layer in Fig. 1, the air within the updraft, originally moving from SE, acquires horizontal momentum partly representative of the upper current (NW), through entrainment and dynamic interaction with the environment which is moving at a velocity different from that of the cloud. The air from this part of the cloud then descends in a downdraft, carrying with it part of the NW momentum of the upper levels. Byers and Braham[5] have shown that the typical thunderstorm is actually an aggregate of coexistent updrafts and downdrafts. With this in mind, the thunderstorm area can be regarded as a region of vertical mixing of the property horizontal momentum through the alternate carrying upward of SE momentum and downward of NW momentum.

The net effect of this is to decrease the vertical shear of the horizontal wind inside the cloud below the shear observed in its environment. Malkus[8] and Byers and Battan[9] have presented data showing that this effect is really observed (see also Thunderstorm Project[3]). Measurement of movements of thunderstorm radar echoes by the latter authors indicated that, on the average, shear within the thunderstorm is about 3/4 that outside the cloud. This value is higher than that which could be explained by entrainment of momentum alone, showing that dynamical interaction or "impact forces" between winds in the cloud and in the environment must be important.

Fig. 1 shows the hypothetical result of such a process in the case of a Nor'wester thunderstorm (arrows are drawn so that length is proportional to velocity of wind inside and outside cloud). In consequence of the vertical interchange of horizontal momentum, regions of horizontal divergence and convergence must develop in the vicinity of different parts of the cloud boundary as indicated in Fig. 1. As a result of convergence in lower levels on the SE side of the cloud, upward accelerations are produced on that side (considering the principle of continuity and the fact that vertical motion must be zero at the ground). This is aided by divergence above the same region in the upper part of the cloud boundary. The convergence through a deep layer (presumably as much as half the cloud depth) acts, along with the outflow of cold air as described by Desai [1], as a powerful trigger for the release of convective instability and causes the formation of new thunderstorm cells on this side.

Similarly, the lower-level divergence coupled with upper-level convergence on the NW side of the thunderstorm favors only downward-directed currents, and dissipation of the cloud in lower levels on that side. By propagation of new cells on the SE side and dissipation of old ones on the NW side, the thunderstorm region as a whole would move toward SE at a rate greater than the velocities of the individual cells.

This process can, of course, only operate once an initial thunderstorm has formed and broken through the separation layer, as discussed by Desai and Mal [2]. Although original thunderstorm formation occurs mostly during the hottest part of the afternoon as described by Desai and Mal, the process described here can continue to operate as long as the aggregate of thunderstorms moves along in a region possessing convective instability and a proper type of vertical wind shear of sufficient strength.

Since, according to Byers and Braham [5], the most violent vertical motions are found in relatively young thunderstorms, the convergence patterns discussed above would be most pronounced on the SE side. The greater spreading out of cold air in the surface layers toward SE than in other directions, as discussed by Desai [1], is partly understood from the fact that the downdrafts bring down northwesterly momentum. To the horizontal velocities of the descending air are added other components due to the extremely rapid divergence of the downdraft in the surface layers (see Thunderstorm Project [3]). Since the strong downdrafts are found on the SE side of the cloud system, and are prevented from spreading toward NW by the large cold-air region beneath older thunderstorms on that side, the divergence can take place most readily toward SE and produces the strong NW winds observed with the onset of the storm.

The direction of propagation of the thunderstorms, and the effectiveness of this mechanism, will of course differ according to the directions and relative strengths of the dry and moist currents.

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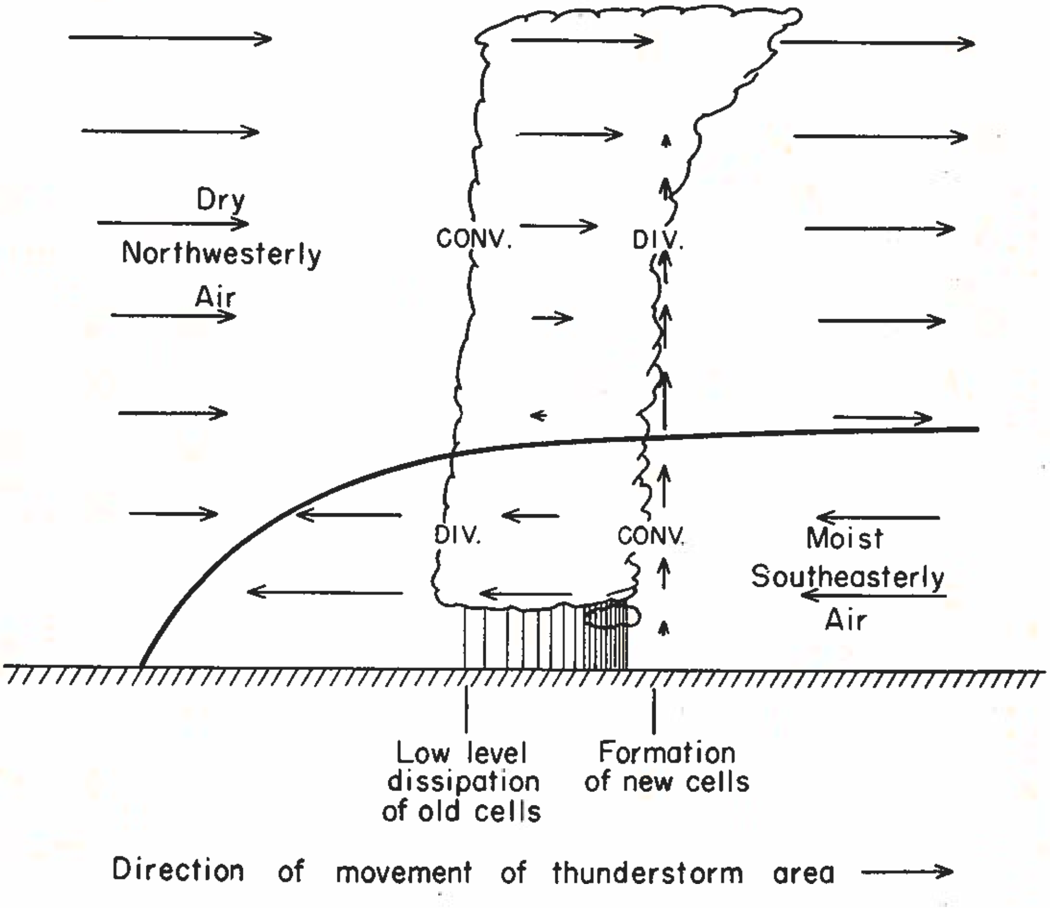

Fig. 1. Schematic diagram of Nor'wester thunderstorm. Horizontal vectors are proportional to wind velocity at different heights inside and outside cloud mass (vectors inside cloud represent mean horizontal velocity over whole cloud region. Individual downdrafts would have stronger horizontal component from NW; updrafts from SE). Regions of horizontal convergence or divergence caused by vertical interchange of horizontal momentum are indicated at different parts of cloud boundary. On SE side of cloud, vertical vectors of different lengths indicate forced vertical accelerations resulting in turn from horizontal divergence field.