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Flash Flood-Producing Convective Storms: Current Understanding and Research

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Abstract

Flash floods have achieved the dubious distinction in the U.S. of being the weather disaster that year in and year out produces the most casualties. Lightning is responsible for even more deaths, but the fatalities from lightning typically occur as isolated events, and the storm producing the lightning may not be severe in any other way. Flash floods result from the concatenation of special meteorological and hydrological conditions. Heavy convective precipitation is not a sufficient condition for a flash flood, but it is necessary.

The physical processes associated with heavy convective precipitation are generally well understood, but the conditions which produce them often involve subtle signatures an can challenge the best meteorological science can offer. With some exceptions, most flash flood-producing convection is from more or less unremarkable thunderstorms, where multiple convective cells pass over a confined regions, with successive cells reaching forming, reaching maturity, and dissipating at about the same locations. The result is a quasi-stationary convective rain system: such events can produce flash floods in 2 h or less, depending on antecedent rainfall and other hydrological conditions. By the time such a storm is recognized as a threat, the system itself can be dissipating. In some cases, of course, the heavy precipitation continues for many hours. In the U.S., most such events occur at night, apparently abetted by the nocturnal increase in the poleward flow at the top of the surface boundary layer.

Recent research has suggested that, contrary to earlier beliefs, supercells occasionally can be prolific precipitation producers. Since supercells can process enormous amounts of moist air through their powerful, persistent updrafts, tend to move relatively slowly and have long lifetimes, they can become a heavy precipitation threat at times. Supercells have received the greatest amount of attention from numerical cloud modelers, whereas ordinary thunderstorms have not been the topic of much modeling research. It appears that on the scale of the convective cell, most flash flood-producing convection is not very noteworthy. What appears to be of greatest interest are the mesoscale processes that organize ordinary thunderstorms into quasi-stationary convective rain systems. Research in this area is hampered by the intermediate scale of the problem; an important unresolved issue is how important it is in modeling to describe convection explicitly.

1. Introduction

Flash floods are a world-wide problem, from the tropics to the subpolar regions. Virtually by definition, a flash flood is a hydrometeorological event: an event that depends on both hydrological and meteorological factors. Flash floods are distinguished from "ordinary" floods by the time scale of the event. Whereas floods occur over periods of several days and it is possible to attempt damage mitigation (like sandbagging), flash floods occur much too rapidly for such preparations. One hopes merely to save lives through preparation and warnings. The worst of the event can develop in periods of hours or less, which makes flash floods particularly dangerous in terms of human casualties. In North America, flash floods have become the weather-related disaster which year in and year out produces the greatest number of casualties.[1]

[1] Lightning-caused fatalities often exceed flash flood deaths, but lightning fatalities almost always occur individually. No fatality is trivial, but isolated deaths from lightning probably don't qualify as disasters.

As noted, hydrology plays a major role in the occurrence of flash floods. Of particular significance to flash floods are: (1) antecedent precipitation, (2) terrain, and (3) surface runoff characteristics. A particular rain event may produce little or no effect in one situation and a comparable event in another situation will cause a disaster. In this discussion, the hydrological issues will not be discussed. This does not deny their importance, but my focus is on the clearly necessary (but not sufficient) condition of heavy precipitation. Moreover, my remarks will deal only with convectively-produced heavy rainfalls, since by far the majority of flash flood-producing rainfalls are associated with convection.

In spite of growing recognition of the importance of flash floods, there is as yet no consistent record of flash flood events in the United States, comparable to that for severe thunderstorms and tornadoes. Therefore, it is somewhat difficult to develop a comprehensive climatology of flash floods. In view of the difficulties in defining a flash flood, it might make more sense to develop a climatology of heavy precipitation events. To my knowledge, no such comprehensive record exists for this, either. This is an unfortunate gap in our knowledge, which should be addressed in the future.

2. Processes governing heavy precipitation

A complete understanding of heavy rainfall necessarily involves complex microphysical topics: formation of cloud droplets on condensation nuclei, cloud droplet spectra, ice formation, the Bergeron-Findeisen mechanism, drop growth via coalescence, and so on. These are topics of no small importance, and yet there is perhaps less knowledge by far than is needed for a comprehensive understanding. One important contribution to ignorance about microphysical processes is that the necessary observations to understand the role of microphysics in precipitation process are not obtained routinely. We simply have no information about microphysical effects unless a special observing program happens to be ongoing. Polarimetric radars and other remote sensing techniques (see, e.g., Jameson 1991; Zrnic' et al. 1993) offer some promise for the future, but this remains to be seen, at least in a practical, operational sense.

What we do have are the routine observations used to forecast the weather operationally. These observations allow answers only to some quite basic issues associated with precipitation. In very simple terms, heavy precipitation falls where high rainfall *intensity* is combined with relatively long *duration*. This statement seems almost too obvious to be of value, but it allows us to focus on issues that can be addressed with the coarse data of operational forecasting.

a. Rainfall intensity

The intensity of rainfall clearly is dependent on the rate at which a storm processes water vapor. As already noted, convective storms are associated with the vast majority of flash floods simply because they process large amounts of water vapor in a short time. It is a simple exercise to show that a convective cell with a liquid water density of one g m^{-3} (not a particularly high value) that is 18 km deep and 10 km in radius contains about 5.75×10^{12} g of condensed water. If one assumes that this water is all converted to precipitation (an issue to be discussed shortly), and falls out of the convective cell during its typical life cycle of 20 min, this amounts to a precipitation rate of about 18×10^6 metric tons per hour. Assuming that the cell spreads this amount of water uniformly over the area it covers in 20 min when it moves at a speed of 10 m s^{-1}, then this rainfall rate is about 13 mm hr^{-1}. While this is not a particularly high precipitation intensity, it does represent a prodigious amount of condensed water. Generally, a precipitation rate of about 25 mm hr^{-1} is considered marginally heavy, and flash floods often result from rainfall intensities much greater than that value. It is difficult to achieve this sort of rainfall rate from non-convective processes; they simply don't process water mass fast enough.

A major factor in water mass flux through a convective storm clearly is the moisture content of the inflowing air. Obviously, the higher the mixing ratio, the greater the water vapor mass flux, for a given updraft speed. Just as obviously, a convective storm with a strong updraft has higher water vapor mass flux than a convective storm with a weak updraft. Both of these aspects of a convective storm can be inferred from the environmental conditions in which convection develops. To a certain extent, updraft speed is closely associated with the environmental Convective Available Potential Energy (CAPE), where

$$\mathrm{CAPE} = g\int_{LFC}^{EL} \frac{T_v' - \overline{T}_v}{\overline{T}_v}\,dz\,, \qquad (1)$$

where g is the acceleration due to gravity, T_v is virtual temperature (in °K),[2] the prime denotes a property of an updraft parcel, an overbar denotes a property of the convective environment, LFC denotes the Level of Free Convection and EL denotes the Equilibrium Level for the updraft parcel. In other words, CAPE is the integrated net buoyancy of the updraft parcel.

It should be clear that CAPE and the inflowing air's mixing ratio are closely related; the higher the mixing ratio, the more likely a convective storm will have large CAPE. This is because as low-level mixing ratio increases, the difference between the moist and dry adiabatic lapse rates also increases. Simple parcel theory predicts that the maximum updraft speed is related to CAPE via the formula:

$$w_{max} = \sqrt{2\,\mathrm{CAPE}}\,, \qquad (2)$$

so it can be seen that a moderate updraft speed of 10 m s^{-1} only requires a CAPE value of 50 J kg^{-1}. With moderate values of CAPE (say, $\geq$ 1500 J kg^{-1}), updraft speeds exceeding 50 m s^{-1} are theoretically possible. An updraft that strong can process a lot of water vapor.

Precipitation efficiency is defined as the ratio of the water vapor ingested into the storm to the water deposited as precipitation. This ratio is not meaningfully evaluated as an instantaneous value: at the start of a convective storm, no precipitation is falling, so the ratio's denominator is zero, whereas at the end of the storm, precipitation can continue to fall after the updraft (and associated influx of water vapor) has dissipated (Fig. 1). Therefore, this quantity only makes sense as a time integral over the lifetime of the convective system (Fankhauser 1988). Simple basic considerations suggest that of the water vapor that passes through a convective storm, what doesn't fall out as precipitation must evaporate. Given the height of a typical convective storm, virtually none of the input water vapor should fail to condense, although it might be that some microphysical process could inhibit condensation; this seems unlikely. Therefore, the prime factor affecting precipitation efficiency has to be the environmental relative humidity.[3] A near-saturated environment reduces evaporation, a dry environment encourages evaporation. Clearly, precipitation efficiency can only approach 100% , although it appears that in many flash flood situations, it may well be quite close to this ideal.

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[2] In most cases, the virtual correction is very small and can be neglected, so that a very good approximation to CAPE can be obtained simply from the temperatures.

[3] There have been some studies suggesting that environmental vertical wind shear is a factor in precipitation efficiency (e.g., Marwitz 1972; Foote and Fankhauser 1973), but these works have not been comprehensive, nor have they been borne out by more recent studies (Fankhauser 1988). It is not clear by what mechanism vertical wind shear affects precipitation efficiency, although it has been suggested that entrainment is enhanced by vertical wind shear. This hypothesis remains unvalidated.

In simple terms, then, the rainfall rate is the product of water vapor mass flux times the precipitation efficiency. A given rainfall rate can result from extremely high water vapor mass flux, from high precipitation efficiency, or both.

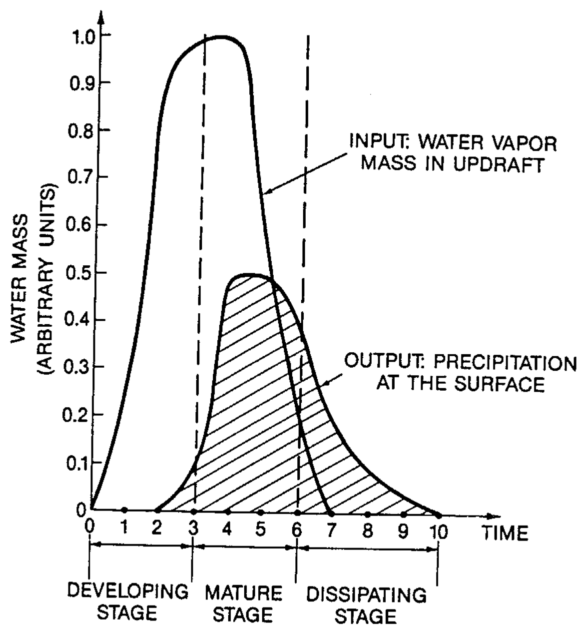

Figure 1. Schematic diagram showing the time history (in arbitrary time units) of water vapor input and precipitation output (hatching) for a convective storm system. The ratio of the areas under the two curves is the precipitation efficiency.

b. Rainfall duration

The basic building block of most convection is the so-called convective cell. As already noted, the convective cell typically has a lifetime of about 20 min. If follows, then, that any convective storm lasting more than about 20 min[4] is made up of more than one cell. If rainfall is to persist long enough to have flash flood potential, the convective storms must be multicellular in character (although this does not preclude supercell storms, as discussed below). In general, most convection is multicellular, so this is not a particularly useful notion; flash floods usually come from ordinary thunderstorms. What makes ordinary thunderstorms dangerous from the standpoint of flash flood potential is that they become quasi-stationary. This can arise in a variety of ways, but the basic elements are always the same: convective storms form repeatedly in about the same location, and follow each other in succession, reaching maturity (and maximum rainfall rate) at about the same location. Such a series of convective cells results in the so-called "train effect." The dominant role played by this process in determining rainfall duration forces attention to be paid to the question of convective *storm motion.*

Considerable value can be gained by understanding that convective storms are not objects, but processes. That is, an object is tangible and relatively unchanging (neglecting quantum processes) so that if it is embedded in a flow, it simply will be carried along by that flow; in meteorological terms, its movement will be the result solely of *advection.*

[4] A useful definition of a *convective* time scale is the time it takes for a parcel to rise from its LFC to its EL, which for a moderate updraft is about 20 min. It is no coincidence that a convective cell lasts for a single convective time scale, when that scale is defined in this way. Of course, microphysical contributions (e.g., condensation/freezing nucleus populations) could affect precipitation efficiency, but these are not observable.

However, a convective storm is made up of a succession of parcels which flow *through* it; it is a *process*, not an object. As a process, it can move by formation and dissipation. What we see as a continuous convective storm can be the result of new cells forming on one flank of preceding cells, eventually becoming "the storm" as the older cells dissipate. The movement of convective storms arising from this formation and dissipation of new cells is called the *propagation* contribution. A convective storm's movement, then, is the sum of advection and propagation effects.

As noted by Chappell (1986), at times the advective and propagative effects can come close to canceling, so the resulting storm's motion becomes quite small; when this occurs the storm becomes a Quasi-stationary Rain System (QRS). This cancellation between advection and propagation can arise from processes operating on a variety of scales. Note that the development of such a situation does *not* require the windflow in which the storms are embedded to be weak; QRSs are not uniquely associated with weak flow in the troposphere. Quite to the contrary, it is difficult to develop persistent heavy rainfall in weak wind flow regimes because the convection tends to stabilize its immediate environment. If new moisture and instability is not brought in to replace that processed in convection, the storms will cease, perhaps to develop elsewhere but not forming a QRS. Figure 2 shows an example of how systems might become quasi-stationary.

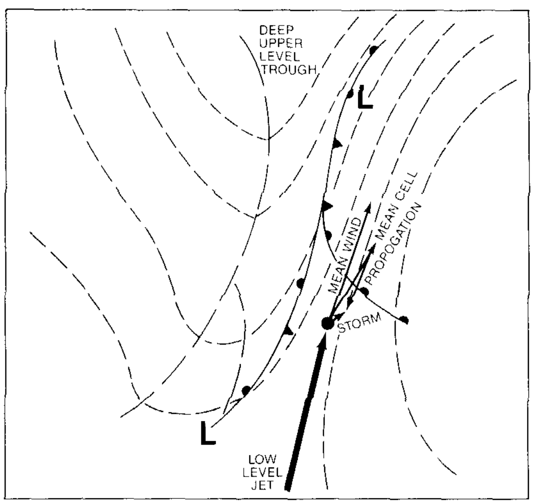

Figure 2. Schematic illustration of how a Quasi-stationary Rain System might develop in a strongly forced synoptic setting. Frontal symbols are conventional, dashed lines show upper level (say, 500 mb) contours, and the vectors show the mean wind, the mean cell motion, the contribution to system motion from propagation, and the resulting storm motion (from Chappell 1986).

Again in simple terms, then, the total rainfall is simply the product of the average rainfall rate times its duration. Heavy precipitation can be the result of high rainfall rates, or long rainfall duration, or both.

3. Supercells and heavy precipitation

For many years, it was thought that supercells were not likely to have much flash flood potential because it was felt that they were not very efficient rainfall producers. In fact, they typically do not have particularly high precipitation efficiency, in general. Original studies of supercells focused on storms during tornado outbreaks, which generally are considered to be mostly classic supercells (see Doswell and Burgess 1993). Supercells typically are characterized by considerable evaporation, which plays a major role in the production of tornadoes (Brooks et al. 1994; Davies-Jones and Brooks 1993). Nevertheless, the very strong updrafts which typify supercells (often exceeding 40-50 m s^{-1}) make them prodigious processors of water vapor. As suggested above, the rainfall rates from supercells can still be quite high. Furthermore, Moller et al. (1990) have developed a preliminary conceptual model of a *high-precipitation* form of supercell storm, which is characterized by a mesocyclone thoroughly wrapped in precipitation. Despite the high rate of evaporation of precipitation in such storms, they nevertheless are quite capable of developing flash flood-producing rainfalls, albeit with low efficiency.

Whereas classical supercells in tornado outbreaks move quickly owing to the high wind speeds in their environments, it has long been known that supercells tend to move more slowly than ordinary storms in the same environment. This reduced translation speed has been known to be the result of propagation (see e.g., Charba and Sasaki 1971). Since slow movement can be an important contributor to rainfall, it is somewhat surprising that the flash flood potential of supercells has not been given much emphasis. The changing perception of supercells as a flash flood threat has been due to the recognition that not all supercells arise in classic tornado outbreaks, and not all supercells produce tornadoes. With the growth in recognition of storms as supercells in cases where they may previously not have been identified as such, the occurrence of flash floods with such storms (e.g., Belville et al. 1980) has raised the awareness of supercell flash flood potential.

4. Mesoscale convective systems

Although the understanding that convection can become organized into mesoscale systems has been around for quite some time (e.g., Fujita 1955), the geostationary satellite brought this aspect of convection into clear focus. Maddox (1980) first pointed out the existence of what he called the Mesoscale Convective Complex (MCC). Subsequent study (Houze et al. 1989) has indicated that MCCs are simply the largest members of a spectrum of Mesoscale Convective Systems (MCSs), a group of organized convective systems that also includes convection organized into linear structures, as well as the more nearly circular patterns associated with MCCs. To some extent, the geometry of convective organization is influenced by the observing system; it often turns out that radar sees the precipitation patterns within an MCC as linear, even though the cold cloud shield at the anvil level is nearly circular. MCCs and MCSs in general are the dominant form of convection. Truly isolated convection is a relatively rare event and typically does not produce flash flooding very often (although such events can occur, especially with supercells, as on 4 June 1980, near Grand Island, Nebraska; see Maddox and Doswell 1982). Much of the warm season rainfall in many places is associated with MCSs (Fritsch et al. 1986).

A typical structure of an MCS is to have most of the deep convection organized into a line along the leading edge of the outflow. Many times, a region of so-called "stratiform" precipitation is present behind this leading deep convection. Some typical patterns of this organization are shown in Fig. 3. The passage of the system includes a relatively brief episode of heavy rain followed by a much linger period of moderate rain. The combination of these two components can result in substantial rainfalls of 200 mm or more, with the partition between "convective" and "stratiform" precipitation being roughly equal. In some cases, the synoptic scale processes can favor the passage of a succession of MCSs over a location, in a sort of "super train effect," with MCSs playing the role of individual convective cells! Clearly, in such cases, the passage of the first system leaves the ground nearly saturated, thereby increasing run-off (and, therefore, flash flood potential) for the MCSs that follow. Recent events is the north-central plains of the United States were associated with a persistent synoptic pattern such that this "training" of MCSs occurred over a period of months.

In view of the ways in which heavy convective precipitation occurs, it is not surprising that monsoonal circulations can result in tremendous rainfalls. Such persistent circulations are typical of the tropics, where the complications associated with baroclinic disturbances are absent and a persistent re-supply of the ingredients for deep convection by the monsoonal circulation results in daily convective episodes. In mid-latitudes, such a persistent structure is infrequent, thereby distributing the precipitation over a much broader area.

Naturally, in cases of persistent convection, flash floods contribute to a "regular" flooding, in many cases being the primary way in which such floods produce casualties. Even in a flood situation, the short time scale of embedded flash flood events is the primary threat to humans.

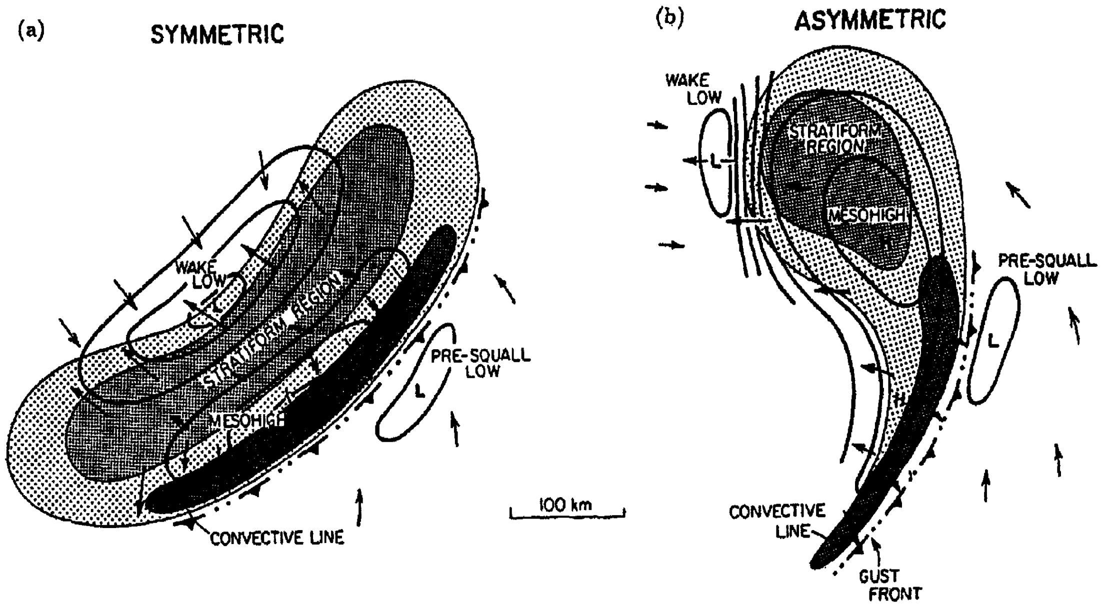

Figure 3. Schematic depictions of the low-level radar reflectivity structure of MCSs. On the left is a symmetric system (a), whereas the system on the right is asymmetric (b). Solid lines are surface isobars, the barbed dash-double-dot line is the gust front, shading denotes weak, moderate, and strong reflectivity, and arrows suggest surface windflow (from Loehrer and Johnson 1993).

Many flash flood events in North America occur during the night, a time when one might expect a convective minimum. The occurrence of MCSs and flash floods at night is not coincidental; rather the two are connected by the nocturnal boundary layer wind maximum (Doswell 1985; Maddox 1985). Warm season nocturnal convection typically develops during the day as relatively isolated convective storms, perhaps including supercells. As the sun sets and the diurnal heating diminishes, the boundary layer mixing driven by insolation decreases, and the surface layer is de-coupled from the mixed layer above it. Theory (Blackadar 1957) and observations (Means 1954; Bonner and Paegle 1970) all suggest that this de-coupling promotes the development of an inertial oscillation that yields an elevated nocturnal boundary layer wind maximum. This promotes the sustenance of convection that has developed during the day in the poleward flowing moist unstable boundary layer air that feeds convection. It is a common factor in MCCs (Maddox 1983) and other MCSs and certainly is a factor in the nocturnal frequency of flash floods, promoting strong, sustained convection.

5. Summary and discussion

The heavy rainfalls that produce flash floods are the result of high rainfall rates that persist. In turn, the high rainfall rates are caused by high water vapor mass flux through convection, coupled with high precipitation efficiency. Because mass flux can compensate for relatively low precipitation efficiency, some supercell storms can develop dangerous rainfalls. Similarly, even a moderate rainfall rate can result in threatening rainfalls if it persists long enough. Thus, the rainfalls that trigger flash floods can arise in a variety of situations. The conditions that distinguish a flash flood event from one with non-threatening heavy rain are subtle and can be missed by forecasters; in convective situations the potential for *severe* thunderstorms (damaging convective winds, hail, and tornadoes) may be a distracting factor (Schwartz et al. 1990).

Since antecedent precipitation can play an important role in the danger level, forecasters must be aware of the changing hydrological factors. A rainfall that is concentrated within a single, "flashy" drainage basin (i.e., one with a known tendency to develop flash floods) may be vastly more dangerous than when the same meteorological event is distributed among several basins, or within a basin with a large capacity to absorb rainfall. Although this paper mainly has ignored the contributions from hydrology, this cannot be done in a forecasting environment.

Forecasters are generally reluctant to forecast the large rainfall amounts that characterize flash floods. Even when they recognize the potential for flash floods, they have a notable tendency to underestimate the maximum point rainfall amounts by a factor of two or more. In the unfortunate circumstance that forecasters have not anticipated the heavy rainfall potential in a situation, the likelihood that they will react properly as the event unfolds is quite small. In my experience, in reviewing forecaster performance during flash floods, when forecasters have *not* recognized the flash flood threat *before* convection commences, they will spend a great deal of effort trying to understand what is happening *during* the flash flood and so they will do an inadequate job of issuing warnings. Given the short time scales associated with flash floods, there simply isn't time to spend trying to figure out what is going on; by the time that can be done, the event often is over.

With the challenges to forecasting associated with flash floods, it is natural to inquire about the role that could be played by numerical models. The current operational numerical models are basically synoptic-scale models, no matter how fine their grid meshes (or the spectral equivalent) become. This is due to two different issues: (1) only coarse data are available for initialization and mesoscale detail is needed to have consistent success in mesoscale forecasting, and (2) not very much is known about the mesoscale processes of relevance. Whereas synoptic-scale prediction is simplified by the relative dominance of the rather well-understood baroclinic instability process and quasigeostrophic balance, mesoscale meteorology is much more complex. Most current mesoscale models parameterize convection but it appears that no paramterization is yet available to treat convection properly in all contexts. Evaluation of convection with explicit physics over mesoscale domains is still not practical, in terms of computational resources needed. Therefore, major challenges to the application of numerical prediction models for flash flood forecasting remain in these two areas, as well as some others (see Brooks et al. 1992).

Humans find themselves involved with flash floods to an ever greater extent as populations push into new areas. Establishing residences and commerce in flash flood-prone locations is an invitation to disaster. There are commercial pressures to "develop" flash flood-prone areas that are very hard to resist, and buyers (and even developers) may be ignorant of the threat. Insurance is hardly a solution to the dangers posed by flash floods: buyers and developers need to accept the responsibility for their errors in judgment, and insurance creates the appearance of not having to accept that responsibility. Of course, society as a whole then pays for the mistakes of a few, through increased insurance premiums.

Increased use of flash flood-prone areas for recreation is another factor putting people at risk. In some sense, when people are on vacation, they are even less likely than normal to appreciate the inherent dangers in certain hydrological circumstances. Building vacation homes along scenic streams makes good sense only if one ignores the potential of a stream valley to experience flash floods. It is not a matter of *whether* flash floods will occur in such locations, it is only a matter of *when* and *how bad*. By building and vacationing in such places, the gamble is that the big event will not occur during the time one is there.

Perhaps this is a good calculated risk, but when the decision is made in ignorance, the danger is high that preparation will be minimal.

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REFERENCES

Belville, J.D., G.A. Johnson, A.R. Moller, and J.D. Ward, 1980: A synoptic and mesoscale analysis of the Palo Duro canyon flash flood and associated severe weather. Preprints, 2nd Conf. Flash Floods (Atlanta, GA), Amer. Meteor. Soc., 30-37.

Blackadar, A.K., 1957: Boundary layer wind maxima and their signficance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.*, **5**, 283-290.

Bonner, W.D., and J. Paegle, 1970: Dirunal variations in boundary layer winds over the south-central United States in summer. *Mon. Wea. Rev.*, **98**, 735-744.

Brooks, H.E., C.A. Doswell III, and R.A. Maddox, 1992: On the use of mesoscale and cloud-scale models in operational forecasting. *Wea. Forecasting,* **7,** 120-132.

______, ______, and R.B. Wilhemson, 1993: The role of midtropospheric winds in the evolution and maintenance of low-level mesocyclones. *Mon. Wea. Rev.*, **122**, (in press).

Caracena, F. and J.M. Fritsch, 1983: Focusing mechanisms in the Texas Hill Country flash floods of 1978. *Mon. Wea. Rev.*, **111**, 2319-2332.

Chappell, C.F., 1986: Quasi-stationary convective events. *Mesoscale Meteorology and Forecasting*, Amer. Meteor. Soc., 289-310.

Charba, J.P., and Y. Saaski, 1971: Strucutre and movement of the severe thunderstorms of 3 April 1964 as revealed from radar and surface mesonetwork data analysis. *J. Meteor. Soc. Japan*, **49**, 191-213.

Davies Jones, R., and H.E. Brooks, 1993: Meoscyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (Geophys. Monogr. 79), Amer. Geophys. Union, 105-114.

Doswell, C.A. III, 1985: The Operational Meteorology of Convective Weather. Vol. II: Storm Scale Analysis. NOAA Tech. Memo. ERL ESG-15, Available from the author at National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069, 240 pp.

______, and D.W. Burgess, 1993: Tornadoes and tornadic storms: A review of conceptual models. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (Geophys. Monogr. 79), Amer. Geophys. Union, 161-172.

Fankhauser, J.C., 1988: Estimates of thunderstorm precipitation efficiency from field measurements in CCOPE. *Mon. Wea. Rev.*, **116**, 663-684.

Foote, G.B., and J.C. Fankhauser, 1973: Airflow and moisture budget beneath a northeast Colorado hailstorm. *J. Appl. Meteor.*, **12**, 1330-1353.

Fritsch, J.M., R.J. Kane, and C.R. Chelius, 1986: The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. *J. Clim. Appl. Meteor.*, **25**, 1333-1345.

Fujita, T., 1955: Results of detailed synoptic studies of squall lines. *Tellus*, **4**, 405-436.

Houze, R.A., S.A. Rutledge, M.I. Biggerstaff, and B.F. Smull, 1989: Interpretation of Doppler weather radar displays of midlatitude mesoscale convective systems. *Bull. Amer. Meteor. Soc.*, **70**, 608-619.

Jameson, A.R., 1991: A comparison of microwave techniques for measuring rainfall. *J. Appl. Meteor.*, **30**, 32-54.

Loehrer, S.M., and R.H. Johnson, 1993: The surface pressure features and precipitation structure of PRE-STORM mesoscale convective systems. Preprints, *17th Conf. Severe Local Storms* [St. Louis, MO], Amer. Meteor. Soc., 481-485.

Maddox, R.A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374-1387.

______, 1983: Large-scale conditions associated with mid-latitude, mesoscale convective complexes. *Mon. Wea. Rev.*, **111**, 1475-1493.

______, 1985: The relation of diurnal, low-level wind variations to summertime severe thunderstorms. Preprints, *14th Conf. Severe Local Storms* (Indianapolis, IN), Amer. Meteor. Soc., 202-207.

______, C.F. Chappell, and L.R. Hoxit, 1979: Synoptic and meso-□ scale aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115-123.

______, and C.A. Doswell III, 1982: An examination of jet stream configurations, 500 mb vorticity advection and low level thermal advection patterns during extended periods of intense convection. *Mon. Wea. Rev.*, **110**, 184-197.

Marwitz, 1972: Precipitation efficiency of thunderstorms on the High Plains. *J. Res. Atmos.*, **6**, 367-370.

Means, L.L., 1954: A study of the mean southerly wind-maximum in low levels associated with a period of summer precipitation in the middle west. *Bull. Amer. Meteor. Soc.*, **35**, 166-170.

Moller, A.R., C.A. Doswell III, and R. Przybylinski, 1990: High precipitation supercells: A conceptual model and documentation. Preprints, *16th Conf. Severe Local Storms* (Kananaskis Park, Alberta, Canada), Amer. Meteor. Soc., 52-57.

Schwartz, B.E., C.F. Chappell, W.E. Togstead, and X.-P. Zhong, 1990: The Minneapolis flash flood: Meteorological analysis and operational response. *Wea. Forecasting*, **5**, 3-21.

Zrnic', D.S., V.N. Bringi, N. Balakrishnan, K. Aydin, V. Chandrasekar, and J. Hubert, 1993: Polarimetric measurements in a severe hailstorm. *Mon. Wea. Rev.*, **121**, 2223-2238.