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The Practical Realities of QPF

Charles A. Doswell III and Robert A. Maddox*
NOAA/Environmental Research Laboratories
Weather Research Program
Boulder, CO 80303

I. Introduction

Quantitative precipitation forecast (QPF) products come in a variety of forms: predicted precipitation isohyets, a probability distribution with respect to expected amounts, a flash flood watch, agricultural forecasts, etc. In principle, all can be derived from a set of predicted isohyets, provided those isohyets represent what would be observed in a gage measurement. This is not a trivial point, because not all predicted isohyets are intended to fulfill this requirement. Another seemingly minor point is that true QPF products must be issued before the precipitation is to fall. How long before? For this discussion, the lead time must exceed the characteristic period of natural variability associated with the process producing the precipitation. For convective processes, this might be a few hours; for synoptic-scale events, it might be as long as a day or two. Finally, we wish to distinguish between forecasts made before precipitation events have begun from those issued after precipitation has commenced, since distinctly different forecasting methodologies are involved.

Some forecasts require one to combine hydrology with meteorology -- flash flood forecasts are the most obvious example. Nowhere is QPF more essential to the process than in issuing a flash flood watch (the warning is more of a "nowcast", although this should not be construed to mean it is easy). Flash flooding and heavy precipitation are not synonymous, since hydrology plays such an important role. If the hydrologist has predicted isohyets available, this makes the job of predicted stream flows and, hence, flash floods more or less straightforward. Unfortunately, those isohyets must be correct in a very detailed sense for this hydrological forecast to be correct. In order to be worthy of the adjective "quantitative" the predicted isohyets must give an accurate prediction of the total precipitation distribution, at least down to the scale of drainage basins. The basins of interest in flash flood prediction are those of the tributaries rather than the main channels, so the scale down to which we require accurate precipitation forecasts is quite small. This also implies small time scales -- an entire event can begin, mature, and decay within three hours (e.g., the recent Cheyenne, WY flash flood).

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*Present Affiliation: National Severe Storms Laboratory, Norman, OK 73019

II. Scale interaction and QPF

Weather events are the result of meteorological processes. To be more precise, they arise through the interaction of a number of processes. For example, thunderstorms develop when the large-scale environment has evolved to bring together moisture, instability, and small-scale lifting mechanisms (fronts, drylines, upslope flow, etc.). The presence of thunderstorms can, in turn, modify that large-scale environment to make other processes (e.g., extratropical cyclogenesis) more (or less) likely. The formation of precipitation within clouds depends on other processes on scales above and below that of the precipitation formation region. Therefore, as a matter of principle, it is not hard to see that QPF requires one to know a great deal about a rather intimidatingly large number of processes.

The science of meteorology is best equipped to give insights to large-scale weather systems of middle latitudes (i.e., extratropical cyclones). There is a fair amount of knowledge about convective processes, although this is based on research data sets not generally available. There is relatively little known about mesoscale processes -- operating in, say, the size range between 1000 km and 10 km. Thus, the circumstances by which the potential for precipitation (created by synoptic-scale systems) comes to fruition in convective precipitation may be rather elusive and hard to anticipate. By implication, large-scale QPF is relatively easy, but the large-scale isohyets which one produces do not represent what one would measure with a gage. Instead, such large-scale QPF shows an *average* precipitation over a large-scale domain (say a large fraction of the area of a midwestern state). While such a product can be reasonably accurate in this limited interpretation of accuracy, it does not necessarily meet the needs of a forecaster concerned with flash floods.

In the discussion of QPF, we should distinguish between forecasting and nowcasting (a distinction to which we have already alluded). For a statement about the weather to qualify as a true forecast, some lead time is required, as mentioned above. By lead time we mean the difference between the statement's issue time and the time the event begins. When precipitation is already underway, one has to predict whether or not the event will *continue*. For precipitation events not in progress at forecast issue time, one must predict whether or not precipitation will *develop*.

In the latter case, this cannot be done directly by linear extrapolation, since one does not use linear extrapolation for events which are not yet occurring. Of course, one may be able to employ linear extrapolation successfully for prediction of the large-scale features which make precipitation *possible*. Non-convective precipitation forecasting usually depends on large-scale processes, so large-scale methods (objective and subjective) can be used to *formulate* a prediction of non-convective precipitation. The most difficult QPF problem is *convective* QPF, because there is so little quantitative knowlege about the relationship between the synoptic weather systems and convection. This paper focuses on convective QPF for two reasons. First, intense precipitation events are almost invariably convective in nature. Second, we wish to consider the effect of the ignorance of mesoscale processes which dominates meteorology.

III. Convective precipitation events

At this stage in the science of meteorology, it is just marginally feasible to consider forecasting mesoscale processes a few hours in advance. In order to do so, one must exploit the limited data to their fullest (and perhaps a bit beyond), requiring continuous diagnosis of the data with a wide range of qualitative and quantitative models (see Doswell and Maddox, 1986). A complete and detailed prediction of the storm-scale evolution is a virtual impossibility, which means that one is really incapable of forecasting rainfall isohyets on the storm scale. While a qualitative forecasting approach may make it possible to improve upon the large-scale QPF products, it must be recognized that any QPF product the science of meteorology can produce, now or in the foreseeable future, does not purport to predict actual gage measurements. Nevertheless, we believe that isohyets which represent mesoscale averages are possible, as are estimates of the absolute maximum precipitation within that mesoscale area. Under the right conditions (see Doswell, 1986), mesoscale diagnosis and prognosis can be used successfully to identify mesoscale areas of high flash flood threat (when combined with hydrological input, of course), but one must recognize that the meteorology may put the greatest threat one drainage basin over from where it actually occurs. Perhaps the meteorology leads one to put the threat area into two basins, whereas the event materializes in one basin and not the other. Even the most diligent forecaster is unlikely to hit every such mesoscale "QPF" with enough accuracy and lead time to satisfy the hydrologist's needs. To ask for mesoscale QPF which provides accurate isohyets predicting actual gage measurements is simply beyond the capacity of meteorological science, no matter how desirable it is to have such predictions.

A concept of some interest to mesoscale convective QPF is the *precipitation efficiency*. This usually refers to individual convective cells, although it could be applied to larger, mesoscale entities. It may be possible to estimate the current amount of water substance within a volume rather easily and, with some effort, to estimate the net flux of moisture into that same volume. The important issues about how much of that moisture gets converted into precipitation, over what space and time it will fall, etc. are rather difficult to forecast. Precipitation efficiency can range from zero to over 100% and it is hardly straightforward to forecast it from case to case, or even from time to time within the same event.

IV. Centralized QPF Guidance

Much of the actual QPF available today is produced centrally. This is the result of the lack of dispersion of resources within the operational forecasting system. QPF may represent the single most challenging task confronting a forecaster, and it seems apparent that the forecasting system has, by choice or by accident, put most of the resources for addressing the QPF problem into a few specialized offices. We hope to indicate why this approach may not be the optimum strategy.

The current generation of numerical weather prediction (NWP) models, as well as the next generation, are essentially large-scale models. The convective process, which is the primary mechanism for producing heavy precipitation, is *parameterized* in NWP models rather than being calcuated explicitly. That is, the contribution of convection to model-generated precipitation forecasts is derived from large-scale processes. Thus, those forecasts are most appropriately thought of as large-scale, area-averaged precipitation and not what one would observe with a dense network of gages. Particularly when convection is involved, the local observations of precipitation will depart substantially (by one or more orders of magnitude) from model-generated values. To the extent that the parameterizations are successful in predicting the rainfall input from convection, the model forecasts may be rather good, in the limited sense just described. The problem is that the models are unlikely to perform consistently well (in a quantitative sense) when truly unusual convective events are happening. That is, the models are least likely to have captured the magnitude of the threat from heavy precipitation at just those times when it is most important.

Besides parameterization, another strategy for QPF has evolved to go from large-scale models to actual sensible weather events. This is the *statistical* approach, with the so-called Model Output Statistics (MOS) being the most common statistical technique used in operations today. This paper is not an appropriate forum for a detailed treatment of MOS (see Glahn and Lowry, 1972), but we can generalize by saying that there is always some important residue of real events which remains untreatable via statistical methods. Once again, this residue is mainly composed of events which are not typical in a statistical sense. As with direct model output, the likelihood that the objective forecasts from MOS will be seriously inadequate is greatest when the magnitude of the event is unusually high; i.e., when the forecaster needs the most help. Note that objective statistical methods are usually cast in terms of probabilities, rather than the apparently desirable isohyets. This is not necessarily bad.

V. Qualitative Methods

If one accepts the idea that large-scale model-generated objective guidance is inadequate for truly important heavy convective precipitation events, the continuing need for QPF must be met by subjective methods. However, the tough task of QPF may be overlooked or given less than full attention in the local office. As with severe thunderstorms, it can be argued that a specialized team at a central location (i.e., the Heavy Precipitation Branch, or HPB, at the National Meteorological Center), concerned only with a single forecasting problem, can be more effective at that task than a local forecaster. That this argument can be disputed is not important in this paper. However, it is clear that a subjective HPB product is not intended to provide the detailed isohyets on the tributary watershed scale that seems desirable. While one might want to have some additional focusing done at the HPB level, they themselves do not claim to be attempting what we already have said is not feasible. Given the data and analysis tools at their disposal, it is unlikely that the sub=jective QPF guidance provided by HPB will become much more detailed than it currently is.

We have asserted that local QPF is difficult, resource-intensive, and may require more time than is available (as in a combined heavy precipitation and severe weather event). In spite of these problems, some local offices have made serious attempts to refine their QPF products (e.g., Belville *et al.*, 1978). Such efforts entail considerable cost to the local offices, in that they are not given formal support within the organization. The work has to be taken "out of hide", which necessarily limits its scope and rigor. To the extent that these programs have contributed positively to the office's forecasting effort, that cost may be worthwhile. However, the cost factor virtually ensures that detailed validation and documentation of the local QPF techniques will not be done expeditiously, if at all. Thus, if some local office develops a QPF scheme, that scheme may never be given a *rigorous* test. Documentation of essentially unvalidated work can stimulate interest in the schemes outside of where they were developed, but it is not obvious that one office's technique can be transferred as is to another office. Further, successful schemes should manifest themselves by improved verification, but even this (by itself) does not provide the detailed validation that one needs. For instance, a scheme may work better in some situations than in others and those who wish to employ that scheme at another location need to know about such aspects of the technique.

VI. Prospects for the Future

Although the current era is one of great technological and scientific change, it is not clear that this turmoil has resulted in any fundamental change in the way forecasters go about their business. The means of accomplishing the desired ends are rapidly moving out of the "pencil and paper" phase (in which modern meteorology has its roots), and into one where computers are heavily employed. New remote sensing systems are emerging from the laboratories and into testing and evaluation for eventual operational implementation. The science of meteorology is gaining new insights into the processes which produce precipitation, in no small way through using these new technologies.

However, it is not yet obvious how to proceed with the operational employment of all this new hardware, data, and knowledge. Reasons for this situation are rooted in the notion of the "learning curve". That is, new tools require new modes of thought, which must somehow be integrated into older, traditional approaches -- products must still go out while the transition is taking place. Training and education of forecasters have not kept pace with this explosive growth in science and technology, exacerbating the conflict between old and new. Implementation of new tools requires experimenting with different strategies and validating the results of the experiments. This trial-and-error process requires time and resources, both of which are in short supply in today's operational environment. Large capital outlays for nationwide application of new technologies are rather intimidating. The upshot of all of this is that we do not see new science and technology leading to immediate and noticeable increments in QPF skill now or in the near future, regardless of the ultimate value of those new tools.

We can anticipate only modest improvements in the large-scale NWP models until such a time that the new data collection systems provide a usable and more detailed large- to medium-scale data base.

Perhaps of greater interest are the so-called mesoscale NWP models. The most likely immediate impact of mesoscale NWP is an enhanced scientific understanding of the mesoscale processes which focus and initiate heavy convective precipitation events. Without intending to denigrate the potentially valuable new guidance that may one day come from mesoscale NWP models, they have several problems which must be dealt with before operational implementation can begin. First of all, whether mesoscale NWP models can produce valuable guidance without a mesoscale *data base* has to be determined. Operational data collection is going to remain at roughly its current state for at least five years, so this is a crucial question. If it turns out that mesoscale NWP models have to have mesoscale data, it is hard to see how a truly substantial increase in NWP forecast skill is going to come from mesoscale models, except perhaps in some special situations.

Second, the computational cost of such models virtually precludes their use in our resource-limited local offices. This means that the early operational mesoscale NWP models will be run at a few centralized locations (or at *one* location). The real value of a centrally-produced mesoscale NWP model in providing help to local offices is not at all obvious to us. There are a host of issues in this regard that have never been satisfactorily addressed vis-a-vis the *large-scale* models.

Third, considerable scientific progress is required before we can be assured that the cost of such models is paid for in quantitative improvement of forecast guidance. We are only now at the threshold of insight into mesoscale processes, especially with regard to interaction with processes operating at scales above and below the mesoscale. We are not saying that progress has not been made, only that it appears that mesoscale models may not make progress as rapidly as the large-scale models, and we still seem to have a long way to go.

Since the issue of mesoscale data sets is of concern, we think we are safe in saying that *in situ* measurement systems (e.g., surface sites and rawinsondes) are not likely ever to attain mesoscale density on an operational basis, for a variety of reasons. It is probably also safe to state that remote sensing techniques require considerable developmental improvement before becoming operational. The new systems provide incredibly high "information rates" but it is not the same sort of information to which we meteorologists are accustomed (i.e., temperature, humidity, pressure, and wind at well-defined points in space and time). Instead they measure such things as returned radiation (for active sensors, which emit radiation in measured amounts), emitted radiation (for passive sensors), Doppler phase shifts, etc. To go from such measurements to more conventional data requires substantial effort and it may well be that we should contemplate reshaping our meteorological thinking to correspond more directly with what the new systems actually measure, rather than forcing the new data to look like our old data.

In any event, considerable data processing is required to assimilate the high information rate of the new observing technologies. It may turn out that while the data flow has increased, its *value to us* as meteorologists has not increased commensurately. We think it would be a tragic mistake to take it as given that new systems should replace the more traditional technology (a rawinsonde is, after all, a product of technology!) of meteorological measurement. The strategy most likely to yield success, in our opinion, is one in which new data will *supplement and enhance*, rather than replace, old data.

Moreover, if forecasting is to benefit from new scientific insights, new paths must be explored for dealing with old problems. However, computer systems which have reached the field (or are currently envisioned for the field) are not truly interactive -- decisions have been made for the field user as to what products will be available, and how they will be displayed. Human input is limited to selecting from what has been offered. Such systems are not interactive; rather, they are computerizations of what was done with teletype and facsimile. Rather than innovation, these systems are old approaches cast in a new form. If field offices are to retain a role in the "information age", they must have access to the information and the capacity to develop their own products, to manipulate data for their own ends, and to adapt the system's capability to satisfy their own requirements.

Regarding QPF, this sort of local capability would offer the chance to begin validation and documentation of local techniques for QPF, an opportunity heretofore unrealized owing to lack of local resources. Each office could experiment with different strategies, seeking what works on the local level. In fact, this would be a real boon to progress in learning how to cope with the new technological tools, because the range of experimentation would be widened automatically. We do not believe that the learning curve challenge can be overcome only by centralized research and development.

VII. Some Suggested Strategies

We have discussed the current situation with regard to QPF and indicated that in the near term, there is little reason to believe that the situation will change much. It is not our intent, however, to foster a defeatist attitude. There are some approaches which we think may offer some improvement in service to users of QPF.

Although this paper does not provide a rigorous demonstration for it, we have made the case that mesoscale processes are the key to QPF. Mesoscale research continues to remain active and the new technologies are helping to keep this a vital part of meteorological science. In lieu of having mesoscale NWP models at the forecaster's disposal, physical (or conceptual, qualitative) models are all that is available. Such models do not provide a basis for prediction of accurate observed isohyets. Rather, they give a framework within which it becomes possible to anticipate the mesoscale evolutions so crucial to QPF. It seems to us that it would be a fruitless exercise to try to employ these qualitative models for the the purpose of producing isohyets. Instead, it might be a substantial improvement in service to QPF users if physical models can be used successfully (a) to refine estimates of when and where precipitation probabilities are enhanced or diminished, or (b) to suggest the likelihood (again, probabilistically) of precipitation reaching significant thresholds. There already exists ample evidence that forecasters can use qualitative models to improve upon objective guidance, when they have the conceptual models at their disposal.

There is an urgent need for local data processing capabilities, which is independent of the new data sources. Much of this need can be addressed immediately with microcomputer techology available at low cost "off the shelf". Having local data processing resources independent of the fragile communications system can help smooth the transition to more sophisticated systems. Moreover, this offers a chance for local creativity and experimentation without the immense capital outlays for complex new technological systems. We do not say that microcomputers will solve the QPF problem, but they can help define more clearly what the new systems must be able to do and how they can be used most effectively. For the time being, at the field office level, these requirements remain mysterious and ill-defined.

It is important to emphasize what are realistic expectations. Deciding that predicted isohyets are the ultimate goal serves little purpose, and leads to an attitude of despair, since there is no valid reason to think that such a goal is attainable in the near future. If one accepts the hypothesis that human intervention is worthwhile in producing QPF (or any other forecast product, for that matter), then forecasting services of the future must develop an effective "human-machine mix" which allows forecasters to be meteorologists. More interaction with users of QPF should take place, beginning with the recognition that accurate predicted isohyets are a dream, relegated to some distant future. This interaction can lead to the design of new QPF products which fill the void between our current output and the unattainable ideal. We do not pretend to know what those products must be, but we think assuming that answers can come *only* through centralized, objective approaches is likely to lead to "answers" which are less valuable than what is possible.

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