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Front Cover: The integrated operational hydrometeorological problem. Forecasting, reservoir operation and sensor-network design are coupled by the conservation laws of the condensed water equivalent and by accrued net benefits due to the realization of the water resources potential of a region.

Credits: Designed by K. P. Georgakakos, W. F. Krajewski and M. Kundert of the Iowa Institute of Hydraulic Research, The University of Iowa. Drawn by Mike Kundert.

AMERICAN METEOROLOGICAL SOCIETY
45 Beacon Street, Boston, Massachusetts, USA 02108

ON THE USE OF NWS-RAFS (REGIONAL ANALYSIS AND FORECAST SYSTEM) OUTPUT FIELDS TO INITIALIZE MULTILAYER TRAJECTORY MODELS OF OROGRAPHIC PRECIPITATION.

Daniel F. Barrera (National Weather Service, Hydrologic Research Laboratory, Silver Spring, MD 20910, and CONICET -Argentina-)

John C. Schaake, Jr. (National Weather Service, Office of Hydrology, Silver Spring, MD 20910)

1. INTRODUCTION.

1.1 Concept and nature of orographic precipitation.

The amount of precipitation on a mountainous area depends on three factors operating on quite different scales (Sawyer, 1956). They are (1) air mass characteristics and the synoptic-scale pressure pattern; (2) local vertical motion due to the terrain; and (3) microphysical processes in the cloud and the evaporation of falling drops.

From a conceptual point of view it is possible to separate the amount of precipitation falling on a mountainous area in two parts: an amount that would occur in the absence of the mountains as a result of cyclonic convergence and mesoscale convection, and an orographic component, that we will refer as "orographic precipitation", due to the forced uplift of air by the terrain. The uplift normally produces additional condensation from available moisture, as well as the release or intensification of convective processes over the mountains.

Due to orographic action on arriving air currents, orographic precipitation is highly variable in space.

Due to both different terrain profiles that air currents reach when coming from different directions, and different thermodynamic effects on different vertical distributions of air mass properties, orographic precipitation is highly variable in time.

1.2 Analysis and forecasting of precipitation in the mountains.

The high spatial and temporal variability of orographic precipitation makes accurate forecasts and analysis very difficult. Observational systems are inadequate to explain this variability.

For hydrological purposes, statistical methods have been the most widely used techniques for NWS operations to estimate local precipitation from available data and forecast model output. These methods usually are based on long-term climate conditions and do not consider current weather patterns that have an effect on the spatial distribution of the precipitation.

One of the most fundamental problems in operational hydrology is the determination of the spatial distribution of precipitation in mountainous areas, which are the source of most of the runoff in the western United States.

Better estimates are needed for four purposes:

1) Local operational NWS forecast services need to provide more detailed and more accurate information in the mountains.

2) Hydrological models require better estimates of mountainous precipitation.

3) An accurate assessement of the climatological water balance of mountainous areas requires a method to account for the spatial variability of precipitation between observation locations.

4) Measurement networks in the mountains have been quite limited, partly due to the cost or difficulty of access to the areas over rugged, snow covered terrain. Fig.1 shows the locations of precipitation gauges at the proposed study area, the Upper Colorado River Basin. Therefore, improved objective methods of estimating precipitation distribution would be helpful as guidelines for designing higher density measurement networks.

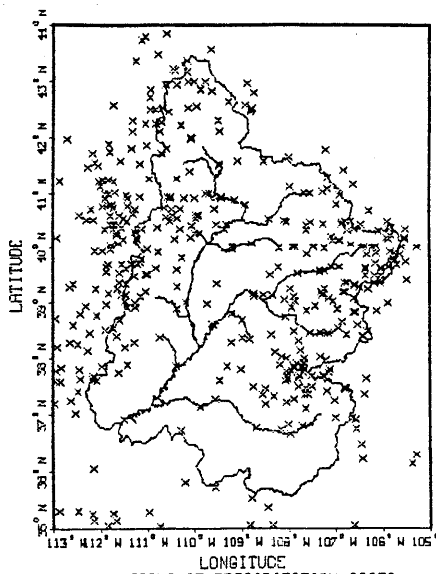


Figure 1. Upper Colorado River Basin.

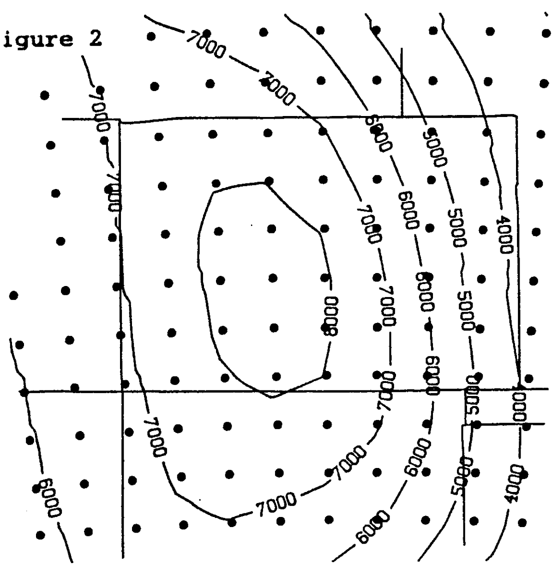
LOCATIONS OF PRECIPITATION GAGES

On the other hand, orographic precipitation is very poorly handled in current numerical weather prediction models. Principal reasons are:

1) Coarse resolution. For example, the operational Nested Grid Model (NGM) uses a grid of about 85 Km. for the continental U.S.

2) Unrealistic terrain. The smoothed terrain that the NGM uses (Fig.2) does not resolve any feature of wavelength shorter than about 5 degrees longitude.

Figure 2



ELEVATION CONTOURS OF THE RAFS TERRAIN FIELD SURROUNDING THE STATE OF COLORADO CONTOUR INTERVAL - 1000 FEET

2. OROGRAPHIC PRECIPITATION MODELS.

2.1 Background.

The essential components of an orographic precipitation model include determinations of the vertical displacement of air moving over the barrier, adiabatic ascent (descent), condensation (evaporation), and precipitation of some fraction of the condensate. It may also be important to include "blocking" of the low-level airflow by the barrier and lee-wave effects.

The amount of condensation depends on the lifting depth, the amount of air lifted, and the moisture content of the air.

The condensation rate per unit of horizontal area (c) for saturated air subject to orographic lifting can be expressed:

$$c = -\int_z \rho \, w \, (\partial r_s/\partial z)dz$$

where ρ = density of moist air, r_s = saturation mixing ratio, and w = vertical velocity. For given amounts of uplift for specific mountain cross-sections, an equation of this form can be solved by assuming appropriate profiles of w and r_s (Fulks, 1935).

There have been relatively few detailed two and three-dimensional mesoscale models developed to predict orographic precipitation. Good examples are those of Fraser et al. (1973), Young (1974), Colton (1976) and Nickerson et al. (1978). In some of them cloud microphysics is also incorporated.

Existing two-dimensional dynamic models (which require much less running time than three dimensional models) are steady state. They obtain a flow solution (and thus streamline configuration) for atmospheric stable conditions by invoking perturbation theory. They assume adiabatic (except for latent heat), frictionless flow over an ideal mountain of sinusoidal form and require that the lower boundary streamline follow the surface of the mountain. In cases of conditional instability, lifting over the higher terrain may release convection, thus invalidating the forced wave mode equations describing vertical displacement of the streamlines.

Existing models that include numerical solution of the hydrodynamic equations do not estimate spatially detailed precipitation fields, because they use unrealistically smooth topography to achieve numerical stable flow fields. Therefore, they cannot be used to produce operational precipitation forecasts, which is our final objective. Also, they require large amounts of computational time that are incompatible with operational tasks in a forecasting office.

Exceptions to this usual flow solution for two-dimensional models are found in those by Myers (1962) and Elliott (1977), who invoke the Bernoulli, mass continuity, hydrostatic, and thermodynamic energy equations for stable air to arrive at streamline configurations across a mountain of arbitrary shape (thus adding the advantages of using realistic topography). Both models assume cloudy air arriving at a mountain barrier.

We will refer this type of trajectory models of orographic precipitation as OP models.

Rhea (1978) has adapted this scheme to develop an operational model for winter precipitation in the Rocky Mountains of Colorado. He adopted a Lagrangian coordinate framework and assumed steady state two-dimensional flow (i.e., flow only along the major current direction, but with vertical displacement by underlying topography permitted). The model is multilayer and considers the interactions of air layers with the underlying topography by allowing forced vertical displacements of the air columns. It keeps track of the condensation or evaporation resulting from these vertical displacements. As the layers flow across the region, part of the condensate precipitates. In the case of sinking motion, part or all of the parcel cloud water evaporates. Precipitation falling into a layer from above partially (or totally) evaporates when encountering subsaturated conditions. Eventually, precipitation generated in the highest layers reaches the ground provided it does not totally evaporate.

This model has the advantage over the previous mentioned that it accounts for the "rain-shadow" effect in a more realistic way.

2.2 Some encouraging results from trajectory models.

After calibrating model parameters against two seasons of snow course and precipitation data, Rhea analysed 13 winter seasons using twice-daily upper-air soundings as input. Calculated seasonal totals correlate well with observed snowcourse water equivalent. For 14 out of 16 selected snowcourse locations, correlation coefficients are significant at the five percent level. A derived map of mean precipitation for the 13 winters (Fig.4) compares favourably with one

LEGEND: SAME AS FIGURE 4

Figure 3. Isohyetal map of normal October-April precipitation based on climatological data for 1931-1960 and correlation of precipitation to physiographic features by the method of Peck and Brown (1962) (From Rhea, 1978)

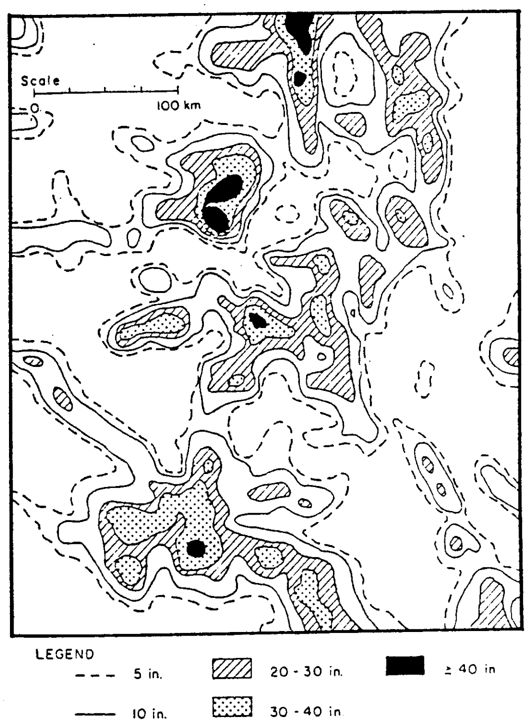


Figure 4. Isohyetal map of 13 year model average 15 October - 30 April precipitation (From Rhea, 1978)

based on point observations and altitudinal-topographic regressions by the method of Peck and Brown (1962) (Fig.3). The model gives the best results for ridges and high plateaux, but overestimates amounts in narrow mountain valleys and underestimates for broad inter-mountain basins.

These maps suggest that the scale that accounts for most of the spatial variability of orographic precipitation in climatic terms, is of the order of 1 km..

Schaake and Peck developed a simpler model. It is a one-dimensional model that accounts for mass balance of vertically integrated water vapor, condensation and precipitation. According to their results, it seems that the vertical distribution of relative humidity has secondary effects on the amount of precipitation. Their results indicate most of the spatial variability of orographic precipitation is caused by local terrain variability within a 30-40 km. radius. The optimal finite difference grid spacing was about 3 km..

3. SOME CONSIDERATIONS ABOUT RAFS.

The Regional Analysis and Forecast System (RAFS) of the National Meteorological Center (NMC) was implemented operationally in March 1985. The purpose of the system is to provide numerical guidance out through 48 hours, with principal emphasis on improved prediction of quantitative precipitation and significant weather events (DiMego, 1988). The three primary components of the RAFS are the Regional Optimum Interpolation analysis, the Baer-Tribbia nonlinear normal mode initialization, and Nested Grid Model (NGM)- a grid-point, primitive-equation model in sigma coordinates, which is in effect the forecast component (Hoke et al., 1989). The second component provides the initial fields. The NGM provides predicted fields. RAFS includes grided fields for a number of meteorological variables at 16 atmospheric levels. The terrain field that RAFS uses does not contain any terrain feature shorter than about five degrees longitude. The terrain is considered to represent the mean ground height in the area surrounding each grid point. Therefore, the maximum RAFS height in the Rocky Mountains is only about 2600 m. (Hoke et al., 1989) (Fig.2).

The NGM is run operationally in a three-level nested grid configuration. Distance between grid points on the NGM's innermost grid is about 81 km. at 39 degrees latitude (Figs.2 and 5). At each grid-points, numerous fields (temperature, relative humidity and wind components between them) are available to users at 6 hours intervals.

The initialization step will be upgraded by the replacement of the Baer-Tribbia nonlinear normal mode method with the implicit normal mode method of Temperton (1988). The new initialization has the benefit that the transform of the analysis into spherical harmonics is not needed in the new scheme. This transform has the disadvantages of filtering the analysis, especially for the specific humidity, and limiting the horizontal resolution of the terrain. Refinements of the NGM been considered may allow to greatly reduce the detrimental efects of cooling and moistening mountaintops and warming and drying valleys that such smoothing causes. Also, the use of higher resolution in the specification of snow cover is being investigated (Hoke et al., 1989). All these modifications will probably improve the quality of RAFS output fields for mountainous regions.

4. WHY USE RAFS?

We present here the main advantages and problems related to use of RAFS output fields as inputs to multilayer OP models, which were originally developed to use local soundings as inputs.

4.1 Main advantages related to the use of RAFS outputs.

RAFS initial and predicted fields are generated by applying phisically consistent system of equations to a considerably amount of observational data covering most part of the Nothern Hemisphere. Therefore, processes occurring at global and synoptic atmospheric scales are taken in account.

In addition to this, soundings are often affected by micro-scale characteristics, i.e., particular orographic characteristics of the site and sourroundings of the sounding station, and particular space and time atmospheric conditions. Both facts introduce some bias and "noise" when the observed values are transposed or interpolated to the grid point being considered. Then, these vertical distributions obtained by doing simple statistical interpolations from a few (and often away from the study area) soundings may not well represent local conditions.

Based on the above mentioned considerations, it can be assumed that vertical distributions from RAFS provide more reliable upper air estimates, and therefore they will constitute more adequate inputs to OP models.

An additional advantage the fact that the availability of tape records of RAFS outoput fields to users at frequencies of one or six hours, depending on the historical period of the required data. These frequencies provide more realistic time evolution of meteorological conditions than the twice-a-day frequency of soundings.

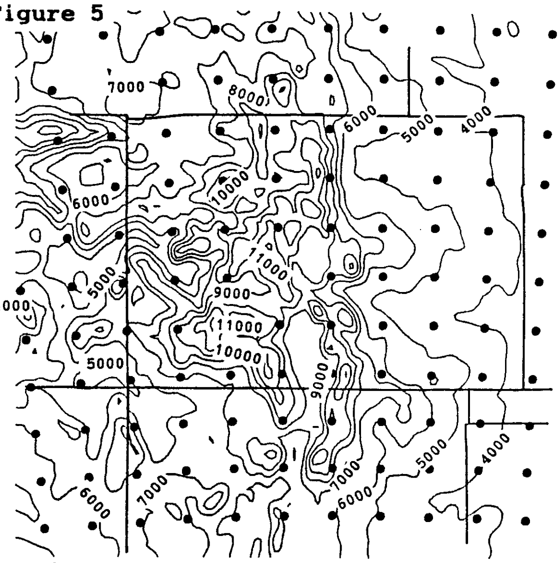
On the other hand, the use of RAFS routine outputs as inputs to an OP model could result in having an operationally oriented, high resolution, subgrid-scale model driven by the operational numerical weather prediction model to predict orographic precipitation on horizontal scales as small as 1 km. This potentially could improve considerably the precipitation forecasting in mountainous regions by the National Weather Service.

4.2 <u>Problems related to the RAFS terrain field.</u>

Meteorological fields are defined in RAFS above RAFS terrain. A problem derived from differences between the smoothed terrain field that RAFS uses and the actual one (Figs.2 and 5), is presented here. A comparison between the terrain field that RAFS supports and the more realistic one that can be used by OP models is shown in Fig.6.

The NGM model does not take in account what happens below RAFS terrain. The difference between RAFS terrain and the actual terrain raises the question: Which is the best way to estimate the vertical distributions of temperature, relative humidity and wind above the actual terrain according to the detailed OP model? This will depend on whether the RAFS terrain is lower or higher than the actual terrain.

Figure 5



ELEVATION CONTOURS OF THE ACTUAL TERRAIN FIELD
SURROUNDING THE STATE OF COLORADO
CONTOUR INTERVAL - 1000 FEET

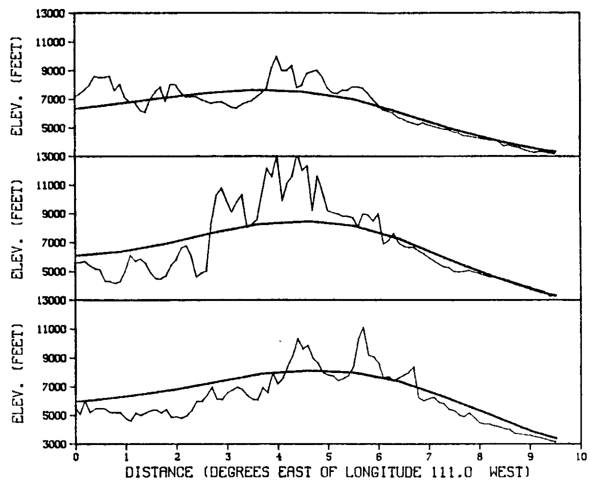


Figure 6

COMPARISON BETWEEN THE TERRAIN FIELD THAT RAFS SUPPORTS AND THE MORE REALISTIC TERRAIN FIELD THAT CAN BE USED BY OP MODELS. CROSS SECTIONS AT LATITUDES 41, 39 AND 37 DEGREES NORTH

If RAFS terrain is lower and not far from the actual one, it seems reasonable to take the part of each vertical profile that is above the actual terrain.

If the RAFS terrain is higher, it seems to be two alternatives: a) Start with the OP model simulation from an area not far upwind where RAFS terrain falls below the actual one; b) If the procedure exposed in a) is not possible, extrapolate downward the v.d. as follows: temperature from the U.S. standard atmosphere, constant relative humidity (then increasing specific humidity), and wind profile for neutral stability conditions.

As a control procedure for these extrapolations, it could be excecuted the OP model starting from a place where a sounding is available. A "link" of the RAFS vertical distribution of the property P and the respective portion of the local sounding below RAFS terrain could be performed. If z is the elevation of RAFS terrain, it will be certain vertical range H above z where both distributions have to be merged. The value of H could be proportional to the absolute diference between the values of P at level z for both profiles. In levels between z and z+H, it seems reasonable to make a linear interpolation using weighted averages, the weighting factor being proportional to the distance above level z.

4.3 A criteria for setting up the flow direction.

One of the key considerations is the criteria to set up the direction of the flow in the OP model, so the oriented elevation grid can be selected. That is, the wind direction that can be applied to air layers where condensation and precipitation processes take place over a trajectory length of about 40 km. Then the principal question is: which is the atmospheric level where most of the moisture transfer take place?

For the mountainous region of Colorado, Rhea (1978) used the wind direction at the 700 mb. level at the center of the study area (interpolated vertical distributions from nearest available soundings). By taking this quite high level (about 9800 feet) Rhea avoided local influences at the site of sounding stations on lower level winds.

But the wind vertical profiles from RAFS are determinated for the very smoothed terrain that RAFS uses, so no local orogaphic influences are present in them. But the best level may vary from storm to storm and from place to place. Because the Rhea model sets-up the streamline configuration in the first step of calculations, it is possible to know which are the layers that will account for most of the condensation over the selected area. We plan to investigate the importance of how the flow direction is selected.

5. PROPOSED RESEARCH.

This will be a pilot study to investigate the operational feasibility of such a model.

We will try to determine if such a model can be driven by an operational Numerical Weather Prediction model and produce realistic orographic precipitation on a daily basis, to be used operationally in the national weather forecast system as a post-process product.

This project will represent the first collaborative research effort between the Development Division of the National Meteorological Center and the Hydrologic Research Laboratory of the Office of Hydrology.

Data sets and software to operate the model exist on the Office of Hydrology PRIME computer ; additional data are readily available from NMC data files.

This study will involve:

1) For the study area, selecting sites where precipitation is observed at precipitation gauges or can be inferred from the snowcourses.
2) Developing and calibrating the model (described in the next section) using upper air data from NGM output fields and local soundings for setting upstream boundary conditions, and using observed precipitation for comparison with model predictors. The model will be calibrated to produce long-term observed precipitation (i.e., a whole winter).
3) Investigating how much spatial variability seems to occur in model parameters.
4) Evaluating model accuracy and developing a statistical representation of the model errors. The statistics of model errors are needed to use the model to interpolate observed precipitation amounts to ungauged locations and to make areal averages.
5) Illustrating how the trajectory model could be used in NWS operations for local precipitation forecasting and for hydrologic analysis. The trajectory model outputs will suggest that precipitation and snow course observations should be weighted differently from, say, month to month because of the predominant storm direction or type during different months.
6) Analyzing the relationship between spatial average precipitation at the

scale of NMC's regional model and the variability of the process at the trajectory model scale. Suggest how to parametrize the orographic precipitation process in the NMC regional model using the results of the trajectory model in further steps of the research.

We propose in this research to develop an operationally-oriented model of orographic precipitation starting from the basic scheme of Rhea, with the characteristics of simplicity, fast-running time, and usage of routinely available data from the NGM model as model input. Also, since marked variations of average precipitation occur over distances of just a few kilometers in regions of complex terrain, we will use a high degree of realism in the topography.

6. TASKS ALREADY ACCOMPLISHED.

Large amounts of data must be processed to study orographic precipitation. Therefore, some of the computational aspects of the study are presented. Efficient software to set up wind-oriented orographic profiles from the elevation data base was written. A RAFS outputs data base on the LFM grid was created, as well as software to rapidly retrieve the data.

The following software was developed in order to implement the orographic precipitation model on the OH PRIME:

1) Reprogramming the model of Rhea, written in Fortran 77 language, taking in account:
a) Structured programming.
b) Memory capacity, in order to reduce input- output operations. This will permit greater facilities to use statistical analysis techniques with model outputs.
c) Need to operate the model over a large area and to monitor model results at many point locations for comparison with surface observations.
2) Generating a realistic orographic profile, by means of a wind-oriented horizontal grid with terrain elevation data. The software developed taking in account the above-mentioned requirements permits: a) Setting up the area coordinates where needed elevation data, as well as the resolution of the elevation base map, given the grid size and the number of side points of inscribed work grids; b) Generating an array containing elevations for the setted area, and keeping it in memory. Values are read from the HRL terrain elevations data base system; c) Generating an oriented rectangular work grid for any given direction, with a sensibility of one degree in fixing the orientation of the grid, instead of ten degrees in the original version; d) Taking for further calculations any desired portion of the work grid; e) Finding the terrain elvation values for choiced grid points.
3) Retrieving, controlling and compressing RAFS output information needed to initialize the orographic precipitation model.
4) Setting-up locations of grid points with RAFS output information, raingauges and snowcourses, and referring them to rotated coordinates of an arbitrarily-oriented grid.

7. ACKNOWLEDGEMENTS

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