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Estimating Precipitation Areas from Satellite Image Data

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I. The Challenge

Knowledge concerning areas of precipitation at analysis time is a necessary requirement for the preparation of accurate forecasts. Delineating precipitation areas over the data sparse Pacific Ocean continues to be a difficult challenge to operational meteorologists at the Pacific Weather Centre. In many instances, ship reports are very scarce and the forecaster must rely almost entirely upon satellite imagery. Unfortunately, discriminating between precipitating cloud areas and non-precipitating cloud areas based on the satellite data has proven to be difficult.

This technical note will present a procedure for determining areas of precipitation using satellite imagery alone. The procedure will be based on elementary atmospheric dynamics theory. It is hoped that in the future this procedure might be partially automated using the PWC satellite facility, and utilized on an operational basis in the Weather Centre.

II. The Concept

Within a developing cloud system, the mean vertical motion is upward. This is true notwithstanding the mesoscale downward motions which take place. In order to be able to estimate precipitation amounts falling under the cloud (or for that matter to determine whether or not a cloud area is precipitating at all) some knowledge about the mean vertical velocity of air within the cloud is required. From the continuity equation it follows that for upward vertical velocity to occur, convergence must occur at low levels and divergence at high levels (See Figures 1 & 2). Low level convergence is a very difficult quantity to measure, as is vertical velocity at the level of non-divergence. In many cases, however, divergence at high levels can be estimated by examining the amount of expansion in the cloud tops, over some time interval (Stout, et al., 1979).

III. Theory

The amount of precipitation falling in some time Δt can be approximated by the polynomial:

$$P_2 - P_1 = f(m, \Delta \ln A) \approx \sum_{i=o}^{n} a_i [m \Delta \ln(r^2 N)]^i \qquad \ldots(1)$$

where m is the precipitable water through a column of the atmosphere, N is the number of pixels on GOES imagery that are colder than an arbitrary threshold value (for a given cloud system), r is a resolution factor to transform number of pixels into a measure of cloud area, and a_i are empirical constants in the n^{th} degree polynominal. See the appendix for derivation of this equation.

IV. Experimental Approach

A number of test cases, constituting a dependent sample, must be collected and analyzed. The degree of the polynominal which would best represent the relationship between precipitation amount and change in cloud areas must then be determined. The constants a_i can be obtained by application of the least-squares principle.

Precipitation amounts are available for a number of ground stations along the coast. Precipitable water content is available from TOVS data. The resolution factor r is easily calculated, and the number of pixels contained in a cloud area can be measured using the PWC satellite METDAS (Meteorological Data Analysis System) statistics report program. Typically two images, taken one hour apart, would be used to measure the change in r^2N. Hence all of the required information is available for the compilation of a dependent sample.

Once the constants are determined, precipitation amounts can be calculated for any cloud area where GOES imagery and TOVS data are available. However as a first step, and for the purposes of this study, we only wish to determine whether a distinction can be made between precipitating clouds and non-precipitating clouds. Later the results of this technique can be used in a procedure for resolving more specifically the location of precipitation within a cloud system.

V. Complications

This approach can only work for cloud areas for which the term $\Delta \ln(r^2N)$ in the governing equation is positive or zero. A discontinuity exists where this term becomes negative, and the relationship is no longer valid. However spotty precipitation may still exist in weakening systems where the cloud area is decreasing, due mainly to airmass instability. The question of whether or not a direct measure of stability should be included in this rain estimation technique is something which will have to be determined on the basis of observation and experimentation. It is likely that a subjective determination of stability by the meteorologist will be the best method of approaching this problem.

Orographic effects have a strong influence on cloud systems. The necessity of collecting data for the dependent sample over an area for which precipitation values are available means that the coastal mountains will influence the results. In general, precipitation values along the coast are assumed to be higher than they would have been over the ocean. The fact that many of the coastal stations are located in "rainshadows" compensates for the topographical enhancement of precipitation.

A third complication arises when one considers that a cloud element which produces precipitation will usually not be found directly above the point where it falls to the ground. Only when the magnitude of the thermal wind is zero would the two positions be collocated. In general, a precipitation event at the surface at point "P" will be "seen" at the point "C" at the cloud top level where $C = P + \vec{V}_{THERMAL} \cdot \Delta t$, Δt being the time it takes for the precipitation to reach the surface. In many cases this may explain the heavy precipitation often seen under apparently low level clouds during the process of decoupling. Much of the precipitation is likely being produced by the higher, thicker clouds downwind, and has fallen into the area covered by the thinner cloud layer.

A fourth problem arises due to the fact that the particular threshold temperature that is selected to delineate a meaningful cloud top on the IR imagery may influence the results when using this technique. It will be necessary to select a threshold temperature for use in this procedure or at least to determine a consistent method for selecting such a threshold value under all circumstances.

Suggestions and Conclusions

Experimentation should be conducted to determine whether the technique described in this note could prove to be useful operationally in a Weather Centre. In particular, answers should be found to the following questions:

(1) Will this procedure only work under certain circumstances? If so, what circumstances?
(2) Do the values of the empirical constants vary significantly in different synoptic situations, or from season to season?
(3) Would cloud top areas derived from normalized visible imagery give better results than using IR imagery. Or would some combination of visible and infrared values be best?
(4) Will it be necessary to incorporate an index of stability into the calculations?

Due to the unique capabilities of the PWC satellite system to work with unprocessed digital data, it should be possible to explore in considerable detail this avenue for determining precipitation areas from satellite imagery.

A subsequent technical note will describe more specifically the procedures to be followed in the collection and analysis of a developmental sample. From this sample, the empirical constants will be determined, and the utility of this procedure evaluated.

REFERENCE

Stout, John E., Martin, David W., and Sikdar, D.N., "Estimating GATE Rainfall with GOES Images", Monthly Weather Review, (1979), page 107.

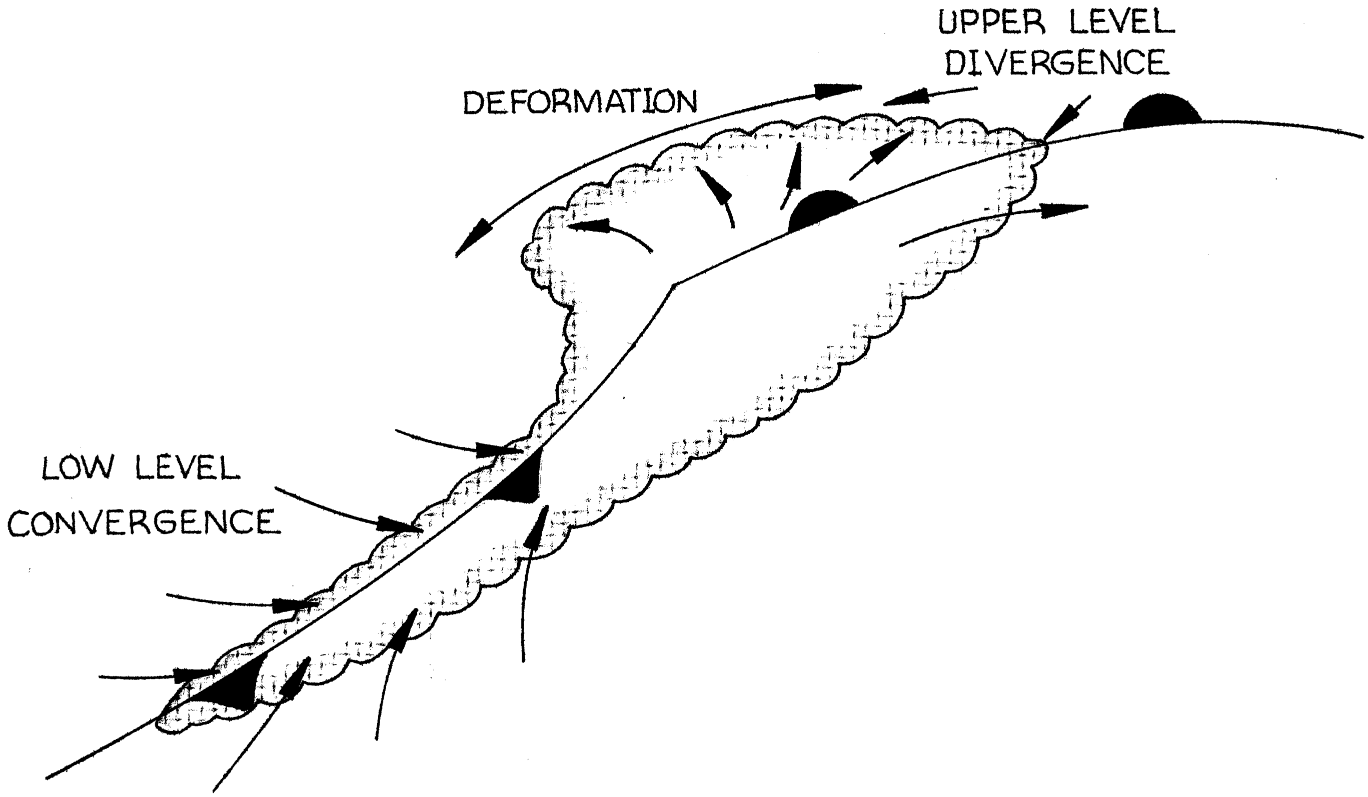

Figure 1

A developing baroclinic wave: Figure shows areas of maximum low level convergence and upper level divergence.

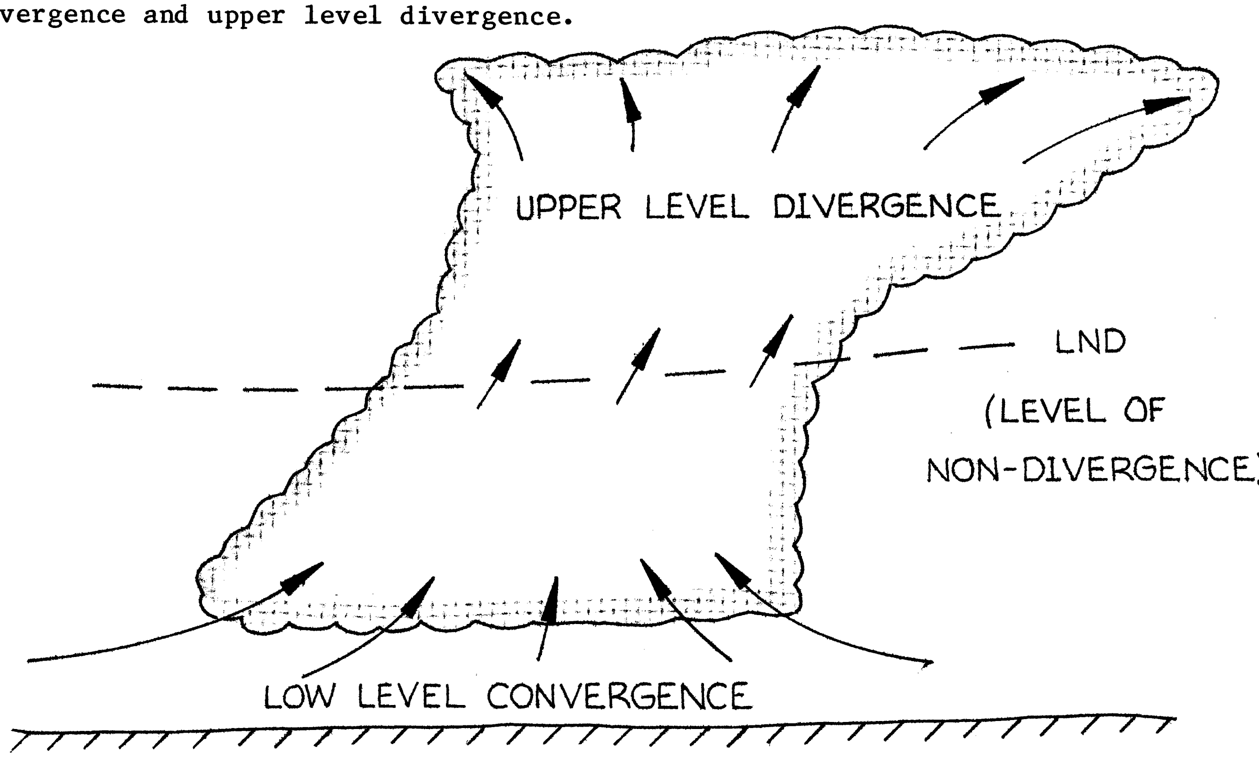

Figure 2

Cross section through a cloud band showing relative motions of air within it. Figure is valid for mean synoptic scale motion as well as for mesoscale situations.

Appendix

Derivation of Equation 1 for Determining Precipitation Amounts

Assuming that all condensate is immediately precipitated, the maximum possible rate of precipitation at the bottom of the atmospheric column is given by the vapour flux through the column.

Therefore, $R_{max} = \rho_w W$ where ρ_w is the density of water vapour and $W = \frac{dz}{dt}$ is the vertical velocity.

Furthermore, since $\rho_w = \frac{dm}{dz}$ where m is the precipitable water, we have:

$$R_{max} = \frac{dm}{dz} W \qquad \ldots(1)$$

Also from the continuity equation...

$$\frac{dW}{dz} = -\frac{1}{A}\frac{(dA)}{(dt)} = \frac{-d(\ln A)}{dt} \qquad \ldots(2)$$

Assume that the real rate of precipitation at the surface is directly proportional to the maximum rate of precipitation through the bottom of the cloud layer, i.e.,

$$R_{max} \propto R_{real} = R \qquad \ldots(3)$$

Let the area enclosed by a certain contour of cloud top temperature on the IR imagery, at some time t, be represented by "A". Then from the continuity equation, the rate of change in the cloud top area "A" is related to the vertical velocity at the level of non-divergence, i.e.,

$$W \mathrel{\tilde{\propto}} -\frac{d(\ln A_{top})\Delta Z}{dt} \qquad \ldots(4)$$

(where $\tilde{\propto}$ denotes approximately proportional)

To further simplify the equations, assume that the distribution of precipitable water through a cloud varies linearly through its cross section, i.e.,

$$\frac{dm}{dz} \propto \frac{m_{top} - m_{bot}}{z_{top} - z_{bot}} = \frac{\Delta m}{\Delta z} \qquad \ldots(5)$$

Combining equations 1 to 5...

$$R \approx \frac{\Delta m}{\Delta z} \cdot \frac{-d(\ln A_{top})\Delta Z}{dt} \qquad \text{...(6)}$$

Rearranging (6) we have (Spagnol, 1980):

$$\frac{dP}{dt} = R \approx (m_{bot} - m_{top}) \cdot \frac{d\ln A_{top}}{dt} \qquad \text{...(7)}$$

If the moisture content is assumed to decrease to near zero at the top of the column, then (Siermacheski, 1983):

$$P_2 - P_1 \approx m\Delta \ln A_{top} \qquad \text{...(8)}$$

where m is the precipitable water content through a vertical cross section of the cloud, and $P_2 - P_1$ is the precipitation amount that falls during some time Δt. Then $P_2 - P_1 = \Delta P$ can be written as a function of precipitable water content and change in cloud area...

$$\Delta P = f[m, \Delta \ln A]$$

Now if a function f(x) is differentiable and continuous over an interval in question, an approximating polynominal function g(x) of degree n can be found where

$$f(x) \approx g(x) = \sum_{i=o}^{n} a_i x^i \qquad \text{(Carnahan, et al., 1969)}$$

Then the function ΔP can be approximated by a polynominal of degree n...

$$\Delta P \approx \sum_{i=o}^{n} a_i [m\Delta \ln A]^i \qquad \text{...(9)}$$

In other words,

$$\Delta P \approx a_0 + a_1 m\Delta \ln A + a_2(m\Delta \ln A)^2 + \ldots + a_n(m\Delta \ln A)^n$$

Now the true area of a pixel on a satellite image is given by $A = r^2 A_s$ where A_s is the area of the pixel at the satellite's sub-point and r is a resolution factor defined by the geographic position of the pixel, and by the satellite's position. Also, $A \propto N$, the number of pixels on the imagery contained in the cloud top.

So equation (9) becomes:

$$\Delta P = P_2 - P_1 \approx \sum_{i=o}^{n} a_i [m \Delta \ln(r^2 N)]^i \qquad \ldots(10)$$

where a_i are empirical constants.

<u>REFERENCES</u>

Carnahan, B., Luther, H.A., and Wilkes, James O., "Applied Numerical Methods", John Wiley and Sons, publishers, 1969.

Siermacheski, P., "Rain Estimates from Satellite Imagery for the Northeast Pacific Region", PWC ODIT Internal Report 83-039, (1983).

Spagnol, J., "Combining Radar and Satellite Data to Estimate Precipitation Rates over the Pacific", Pacific Region Technical Note 80-002, (1980).