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A 10-level atmospheric model and frontal rain

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SUMMARY

A 10-level primitive equation model suitable for studying the dynamics of fronts and frontal rainfall is described. The atmosphere is assumed to be hydrostatic and inviscid and the effects of friction and topography are ignored. Latent heat due to evaporation and condensation is incorporated in the thermodynamic equation. No distinction is made between the ice and water stage and the atmosphere is assumed to be dry above 300 mb. The horizontal grid length is 40 km. The results of one 24-hr integration are described in detail.

1. INTRODUCTION

Numerical weather prediction has now reached the stage where forecasts of pressure patterns on the scale of anticyclones and depressions can be computed for up to three days ahead. Many National Meteorological Offices produce numerical forecasts which range in period from 24 to 72 hours and which vary from simple barotropic forecasts to those based on multi-level baroclinic models. Although some problems remain to be solved, the standard of these forecasts is as good as, if not better than, those produced by conventional methods. It is clear that numerical weather prediction can be advanced in two main ways; by extending the useful period of the forecast and by increasing the amount of detail in the forecast. This paper describes a numerical experiment designed to investigate atmospheric disturbances on the scale of fronts. This model has been developed for two main purposes; the study of the dynamics of fronts and the prediction of frontal rainfall.

Observations from the free atmosphere are available only from aerological sounding stations. These are separated by distances of at least several hundred kilometres and by very much greater distances over the oceans. Thus it is not possible to specify the detailed structure of fronts in the data which are used as the initial conditions for a forecast. It has been necessary to start the integrations from smooth but realistic fields of motion, temperature and humidity in the expectation that the characteristic concentration of gradients will develop gradually at the frontal surface if the problem has been properly formulated.

It is recognized that the quasi-geostrophic formulations of the dynamical equations become increasingly inaccurate as they are applied to systems with a scale less than 1,000 km. Ageostrophic motions are clearly very important in the vicinity of fronts and it is desirable to use the basic first order hydrodynamic and thermodynamic equations applicable to an inviscid hydrostatic atmosphere. These equations are frequently referred to in the literature as the primitive equations of motion. Charney (1955), Hinkelmann (1957, 1959) and Smagorinsky (1958, 1963) are among the early workers who demonstrated that it is possible to use the primitive equations in dynamical meteorology on the synoptic scale, whereas it had previously been thought that it was necessary to use the quasi-geostrophic approach in order to filter out unwanted noise from the equations.

The emphasis of the work reported in this paper is on the development of a model which is sufficiently realistic to give a reasonable estimate of frontal rainfall. The model should also be simple enough to enable the computation of 24 hr forecasts to be completed on computers which are likely to be available in the near future in time to be of use to a practising forecaster. Previous work on the computation of rainfall by the use of primitive equations, e.g. Manabe, Smagorinsky and Strickler (1965), and Smagorinsky and Staff Members (1965), has used finite difference schemes with a much longer grid length than that used in this work, and therefore has not been able to represent realistically the motion near fronts.

2. THE MODEL

(a) *General*

The atmosphere is represented by the model at 10 levels in the vertical at 100 mb intervals from 100 mb to 1,000 mb. Pressure is used as a vertical coordinate, and the horizontal coordinates are taken on a stereographic map projection. The state of the atmosphere at a given time is specified in the model by the height h of the pressure surfaces, the two components of wind u and v at each level and the humidity mixing ratio r of each of the seven 100 mb layers below 300 mb. The atmosphere is assumed to be dry above 300 mb and no distinction is made between the ice and water stage below 300 mb. The atmosphere is assumed to be hydrostatic and inviscid and the effects of friction and topography are ignored.

Humidity mixing ratio was chosen as the most suitable parameter for the representation of moisture. Smagorinsky and Collins (1955), Miyakoda (1956) and Manabe *et al.* (1965) also worked with this parameter, though their treatment of the precipitation process was quite different from that used in this model. In contrast, specific humidity was used for the representation of moisture by Komabayasi, Miyakoda, Aihara, Manabe and Katow (1955) and Aubert (1957).

The thermodynamic equation is expressed in terms of the thickness h' of 100 mb layers. In order to deal with condensation and evaporation effects it is necessary to know whether or not the air is saturated. The saturated humidity mixing ratio, r_s, of any 100 mb column is computed by evaluating a quartic polynomial of the thickness of the column. The coefficients of the polynomials, different for each layer, have been computed by fitting values of r_s and h' obtained from a tephigram to a quartic curve by the method of least squares. Quartic polynomials were found to give a very good representation of the actual relationship between r_s and h' which is much more complicated arithmetically, and this good representation extends over a much wider range of thickness than would be observed in the atmosphere.

If a column in a layer is not saturated then the humidity mixing ratio is changed by horizontal and vertical advection and by the evaporation of any water which is falling into that column from the column above. If the air is saturated and the rate at which moisture is arriving, both by advection and as liquid water from above, is greater than that required to keep the air saturated, allowing for changes in the temperature of the column, then any excess moisture is passed as liquid water into the column in the next layer below. The latent heat due to evaporation and condensation is included in the thermodynamic equation. Should, due to truncation or round-off errors, r become negative at a time t, then r is made zero. The humidity mixing ratio is also made equal to zero if the thickness of the layer is computed to be so low as to be outside the range for which the empirical formulae relating r_s to h' were derived.

(b) *The basic equations*

The motion is assumed to be frictionless and inviscid and the horizontal equations of motion are used in the form