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THE BULK WATER BUDGET OF HURRICANE NORBERT (1984) AS DETERMINED FROM THERMODYNAMIC AND MICROPHYSICAL ANALYSES RETRIEVED FROM AIRBORNE DOPPLER RADAR

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1. Introduction

The main source of energy in a tropical cyclone which maintains the warm core is the release of latent heat of condensation. Shapiro and Willoughby (1982) have shown that the location of this latent heat source relative to the radius of maximum wind is one important factor in storm intensification. It is our goal, therefore, to determine not only the magnitude of the bulk condensation, evaporation, rainfall and water transport, but the intensity distributions of each of these processes as well.

On 24 September 1984, two US NOAA WP-3D research aircraft probed eastern Pacific Hurricane Norbert in a mission to determine the inner core water budget. One aircraft, carrying the airborne Doppler radar flew at 3 km in altitude, while the second flew at 6 km. Reflectivity and wind were determined within a 38 km radius of the storm center.

Two methods are used to determine the water budget. In both methods, the thermodynamic structure and water distributions are assumed to be steady state following the storm motion. In the first the cloud water and ice contents are determined by manipulating formulations for autoconversion and collection, where precipitation contents and formation rates have been determined from radar and Doppler analyses. The method is similar to that of Churchill and Houze (1984). In the second method, the specific humidity and cloud content are determined using the techniques of Hauser and Amayenc (1986). In this method the cloud virtual temperature field has been retrieved from a Doppler thermodynamic retrieval method developed by Roux et al. (1984) and Roux (1985). The total water content (the sum of vapor, water and ice) is computed by solving the water continuity equation with boundary conditions. The cloud water and specific humidity are then computed so they are thermodynamically consistent with the retrieved cloud virtual temperature.

2. The microphysical retrieval

To compute the water budget using the first method, referred to hereafter as the microphysical method, the precipitation formation rates are determined by examining the change in the precipitation content following a parcel of air. In a steady state storm,

$$\frac{dM_p}{dt} = \vec{V}_r \cdot \nabla M_p, \qquad (1)$$

where M_p is the precipitation mass concentration and V_r is the three-dimensional wind velocity relative to the moving storm center. The wind velocity is the Doppler-analysis wind, and M_p is determined from radar reflectivity. Two mechanisms cause a change in precipitation content: the actual production of precipitation by collection or autoconversion of cloud, and the flux convergence of precipitation falling with respect to the parcel of air. The precipitation formation rate is therefore the difference between the rate of change of precipitation content and the precipitation flux convergence. Thus,

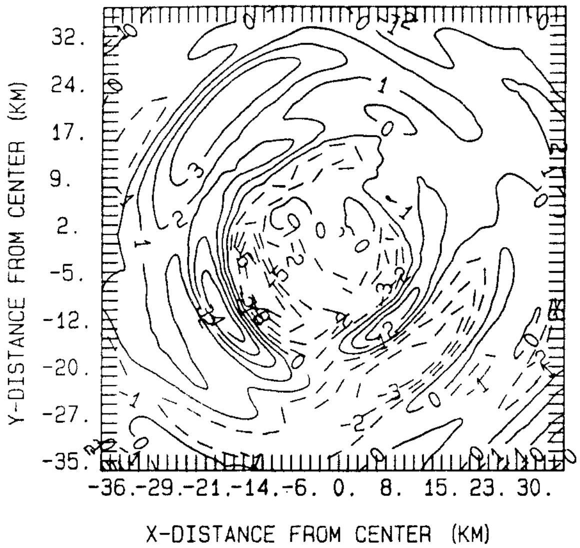

Fig. 1. Vertical wind in m/s. Dashed contours indicate negative (downward) vertical wind.

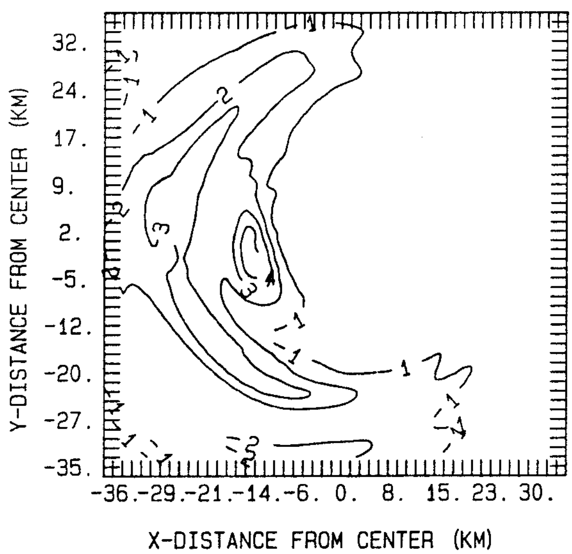

Fig. 2. Precipitation content in .1 g m^{-3}.

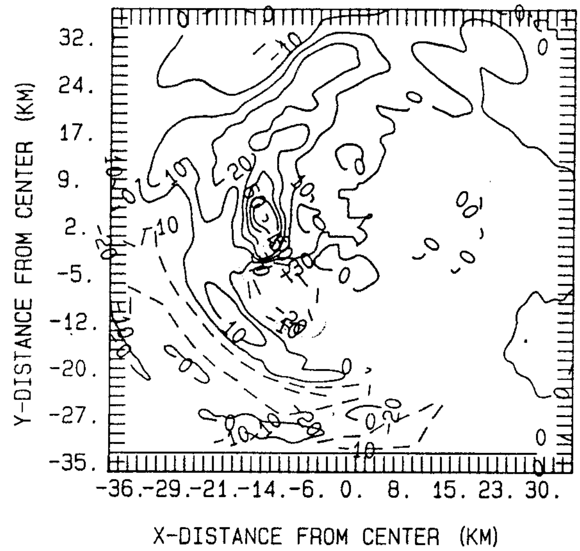

Fig. 3. Precipitation formation rate in .1 g m^{-3} h^{-1}.

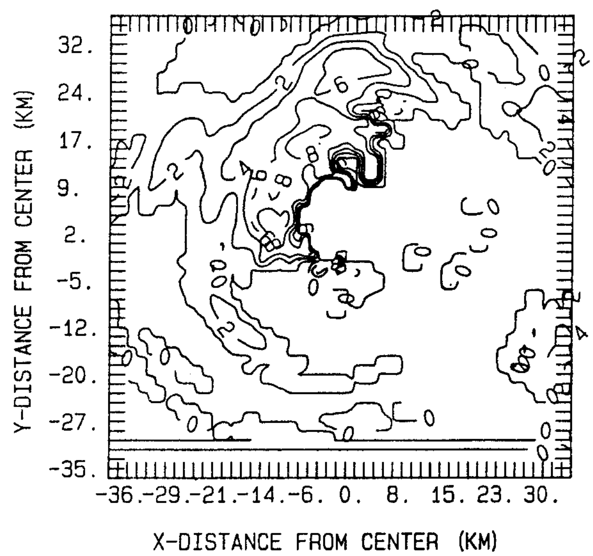

Fig. 4. Cloud water content in .1 g m^{-3}.

$$\left(\frac{dM_p}{dt}\right)_F = \vec{V}_r \cdot \nabla M_p + \frac{\partial}{\partial z}(M_p V_T) - \frac{M_p}{\rho}\frac{d\rho}{dt}, \quad (2)$$

where the left hand side is precipitation formation, the second term on the right side is the precipitation flux divergence, and the third term accounts for changes in air density as the parcel ascends and descends in vigorous drafts. V_T is the terminal fallspeed of the precipitation and ρ is air density. Precipitation formation is also expressed by:

$$\left(\frac{dM_p}{dt}\right)_F = \alpha(M_c - M_{c0}) + M_c f(M_p), \quad (3)$$

where α and β are constants, M_c is the cloud mass concentration, and M_{c0} is an autoconversion threshold value. The first and second terms on the right hand side are autoconversion and collection, respectively. If $M_c < M_{c0}$, then the first term (autoconversion) on the right hand side is set to zero. Equation (3) may then be solved for M_c. The condensation and evaporation are determined from water continuity using a specific humidity field derived from the cloud virtual temperature. This temperature is retrieved from the Doppler winds. In regions of updraft, saturation is assumed. In regions of downdraft a saturation deficit is determined from the precipitation evaporation rate.

The vertical velocity field at 3 km is shown in Fig. 1, while the precipitation concentration is shown in Fig. 2. The precipitation formation rate determined from the velocity and precipitation fields is shown in Fig. 3. The cloud water concentration determined from (3) is shown in Fig. 4.

3. Thermodynamic retrieval

In the second method, following Hauser and Amayenc (1986), the condensation and evaporation are determined directly from the thermodynamic retrieval of temperature and specific humidity. The specific humidity and cloud water are determined by solving the water continuity equation. The equation is

$$\vec{V}_r \cdot \nabla q_T - \nabla\cdot(K\nabla q_T) = -\frac{1}{\rho}\frac{\partial}{\partial z}(\rho q_p V_T), \quad (4)$$

where the first term on the left hand side is the rate of change of total water mixing ratio q_T following the parcel in the absence of diffusion, the second term on the left hand size is the diffusion of total water, the right hand side is the precipitation flux convergence, and q_p is the precipitation mixing ratio. The flux convergence is again inferred directly from radar reflectivity. Through an iterative process, the temperature, specific humidity, precipitation, cloud and total water fields are made consistent with the retrieved cloud virtual temperature while conforming to the water continuity equation (4). Once q_v is known everywhere, condensation (c) and evaporation (e) may be computed. Following an air parcel,

$$c-e = \vec{V}_r \cdot \nabla q_v. \quad (5)$$

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