The Hampstead storm:
A numerical simulation of a quasi-stationary cumulonimbus system

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SUMMARY

A numerical simulation of the storm which occurred over north London on 14 August 1975 is presented. This storm was notable in giving record rainfall totals for the London area while confining the rainfall to an area of about 100 km² despite lasting three hours. The results of the simulation define a distinctive model of the storm dynamics, featuring an impulsive yet quasi-stationary system of cumulonimbus which contributed successively to the rainfall over a limited area. Furthermore the simulation emphasizes the dominant role of the downdraught outflow which establishes and sustains the storm through its interaction with the low-level flow. A mechanism by which the prevailing vector shear maintains the storm is presented. Trajectories computed for the simulated storm show an interlocking updraught/downdraught structure similar to that proposed by Browning (1964).

In order to simulate the observed high surface rainfall it was found necessary to model the high fallspeeds associated with hail by a simple modification to the 'warm' rain parameterization. The simulated and observed rainfall patterns compare remarkably well.

The localization of the storm is considered but the local orography is thought to have no significant influence. Dynamical points arising from the model identify aspects of storm modelling that require further investigation.

1. INTRODUCTION

On 14 August 1975 a severe thunderstorm occurred over north London - the 'Hampstead storm'. Three hours of heavy rain and hail resulted in serious flooding of homes and disruption of transport. Despite lasting three hours the storm affected a very small area of approximately 100 km² and hence must be considered a 'stationary storm'.

The persistence of the storm for such a period suggested that the storm was organized in such a manner as to allow an essentially 'steady' updraught/downdraught circulation to exist, which furthermore had little motion relative to the ground. The steadiness of a storm is often interpreted in the sense of a 'supercell', where one identifiable updraught/downdraught system persists for hours (Browning 1962); however, when evolving (relatively short lived) cumulonimbus cells form components of a much longer lasting storm (e.g. Browning et al. 1976), the storm can also be considered steady in a broad sense, and this is discussed in section 6. These quasi-steady storms have been extensively studied observationally (e.g. Newton and Newton 1959; Browning and Ludlam 1962; Ludlam 1963; Chisholm 1973), and more recently numerical and analytic techniques have been applied (e.g. Takeda 1971; Moncrieff and Green 1972; Pastushkov 1975; Moncrieff and Miller 1976, hereinafter referred to as MM).

All these studies emphasize the importance of vertical wind shear in organizing the storm circulation and allowing coexistence of updraught and downdraught branches. For such storms to be nearly stationary, as observed in this instance, the mean wind in the troposphere must in general be weak, although some examples of stationary storms have been linked to prominent orographic features.

Inspection of the environmental wind structure for the Hampstead storm showed a wind field veering with height and a southerly component at all levels increasing from a few
metres per second at the surface to twenty metres per second at upper levels, giving a substantial mean southerly component of approximately ten metres per second. With such a wind field the stationarity of the storm and the observational evidence referred to in the next section posed many questions which stimulated the simulations described in this paper.

2. OBSERVATIONAL STUDIES

The Hampstead storm has been the subject of three papers: a preliminary discussion by Keers and Westcott (1976), and two more detailed analyses by Atkinson (1977) and by Grove (1978). They describe the overall storm characteristics and aspects of the storm's synoptic and mesoscale environment. The relevance of London's urban 'heat island' and the possible role of the local topography in the rain area are also discussed.

In order to facilitate comparison with the simulations a brief summary of these observations follows:

The storm occurred between about 1600 and 1900 GMT, and produced a maximum rainfall of 177mm. (Fig. 1.)

From both visual observations and autographic rainfall records the storm appeared to exhibit a multicellular character with several cumulonimbus contributing to the total rainfall.

Grove describes observations of a cold downdraught which spread out strongly to the north and west. He also comments on the apparent lack of downdraught observations to the south and east.

The maximum rainfall coincides with a local hill (height ~ 400ft) and so the possible influence of such a hill in localizing the rainfall was considered. The simulations do not model the presence of a hill and hence conclusions based on the numerical results necessarily preclude orographic influence.

Figure 1. Isopleths of rainfall (at intervals of 25mm) for the period 09 GMT 14th to 09 GMT 15 August 1975 over north London. The map includes the 100 and 300ft height contours.
3. THE SIMULATION OF SEVERE STORMS

The numerical simulation of cumulonimbus has progressed steadily during the last decade with increasingly sophisticated two-dimensional models such as those of Orville and Sloan (1970), Takeda (1971), Schlesinger (1973), Orville and Kopp (1977). Three-dimensional modelling has also been attempted, e.g. Wilhelmson (1974), Miller and Pearce (1974), Pastushkov (1975) and MM. Models have also been developed, somewhat larger in space domain, some hydrostatic, others non-hydrostatic, which are designed for modelling mesoscale phenomena including groups of cumulonimbus organized by topographic or orographic features (e.g. Pielke 1974; Tapp and White 1976).

Several of these cloud or mesoscale models endeavour to model almost every physical process or effect that might play a role in determining the precise details of a particular convective situation or event.

While appreciating this ideology and the advantages to be gained, certain disadvantages also seem apparent. The inclusion of a large number of parameterizations into a fully three-dimensional model results in a cumbersome, expensive research tool which does not readily allow the modeller to gain insight into the sensitivity of the results to various parameters by rerunning the simulations many times.

Alternatively, therefore, many models are run in a two-dimensional mode, allowing much more flexibility. This limitation to two dimensions, however, imposes restrictions on the representativeness of the results of such cloud simulations, effectively precludes simulations using observed atmospheric wind soundings, and hence cannot properly tackle the problem of severe storm simulation. The dynamical restrictions imposed by two dimensions are discussed further in Moncrieff (1978).

The modelling approach used in the following study is also a compromise, retaining fully-three-dimensional flows but restricting the parameterization of sub-grid-scale processes, and hence retaining flexibility of use.

This compromise is based on certain fundamental assumptions. The types of organized storms under study are viewed as dynamical systems dominated by advective rather than by turbulent processes; also only sufficient microphysics need be parameterized to model a gross configuration of heat sources and sinks within the system. Such assumptions support the use of relatively coarse finite-difference grids (of order 1 km) and relatively simple microphysical parameterizations whose basic aim is to allow liquid water trajectories to deviate from those of the air enabling water condensed in the updraughts to escape and evaporate in downdraughts.

These various modelling approaches all have advantages and disadvantages and a hierarchy of models of varying complexity and sophistication emphasizing different aspects of behaviour would seem essential.

4. THE NUMERICAL MODEL

The numerical model used in this simulation is a three-dimensional primitive equation model using pressure as vertical coordinate and a grid of $30 \times 30 \times 10$ points (giving a domain $29 \text{ km} \times 29 \text{ km} \times 900 \text{ mb}$). The model is essentially that described in Miller and Pearce (1974) with the modifications discussed in MM. This model, improved and refined over several years, has diagnostic programs allowing budgets of total energy, water substance, etc., which also provide tests of the model's accuracy and veracity.

For this simulation, certain adjustments to the microphysical parameterization were made, demonstrating an interesting sensitivity result which is discussed later.
Figure 2. (a) Temperature sounding from Crawley for midday, 14 August 1975. (b) Tephigram and hodograph showing the representative temperature and wind data used as input for the numerical simulation.

(a) Methodology

Previous simulations (such as the one described in MM) utilized the thermodynamic and wind sounding from a radiosonde ascent just prior to the storm event. The sounding was used as an initial horizontally stratified model atmosphere and perturbed by a low-level heat source to initiate convection.

The adoption of a similar approach in the case of the Hampstead storm was complicated by several factors, a discussion of which follows.

The nearest radiosonde station to the storm region is at Crawley (about 50km south of London). This station provides a radiosonde ascent at 12 GMT and pilot balloon winds at 06 and 18 GMT. Grove (1978) has discussed the inadequacies of this midday sounding as a description of the storm’s environment some four hours later, and in particular, emphasizes the inappropriateness of the Crawley boundary layer at noon as a description of the late afternoon boundary layer over London. The Crawley sounding and a modified sounding, taking into account surface observations in London, are reproduced in Figs. 2(a) and (b).

The first simulation with the modified sounding used a heat source of 0·3 K min\(^{-1}\) (for the first three minutes) at four grid points with two thirds of this value at the surrounding twelve points, all at the 850mb model level, resulting in a maximum perturbation of \(\pm 0·6\) K. This perturbation developed rapidly, and by 25 minutes a cloud had deepened sufficiently to produce the first precipitation at the ground. Despite an apparent abundance of liquid water aloft, however, only a few millimetres of rain reached the surface, and by 50min the cumulonimbus cell had almost dissipated with only a little medium and high
cloud remaining. A weak, short-lived downdraught outflow at the surface spread out and rapidly lost any coherent identity.

The inability of this model to produce significant rainfall could be due either to the convection not being vigorous and deep enough to develop substantial liquid water content or to the microphysical parameterization being inadequate in some way. However, the convection was deep (up to 250mb) with substantial updraughts of \( \approx 25 \text{ ms}^{-1} \) and liquid water concentrations of up to 10 g kg\(^{-1}\). These values are normally adequate for rainfall, hence attention was focused on possible inadequacies in the parameterization of the model’s microphysics.

(b) The model microphysics

The parameterization follows the methods developed by Srivastava (1967) and Kessler (1969) with certain modifications as in Liu and Orville (1969). Four main processes are parameterized:

(i) the ‘auto-conversion’ of cloud droplets to raindrops;
(ii) the coalescence process of raindrop growth;
(iii) the evaporation of raindrops;
(iv) the fallspeeds of raindrops.

The distinction between rainwater and cloudwater is that cloudwater is assumed to move only with the local air velocity while rainwater has an additional (terminal) fallspeed.

The lack of rainwater reaching the surface suggested either that too much liquid water existed as cloudwater and hence never dropped out but reevaporated at higher levels, or that the rainwater was not ‘escaping’ from the updraught (or only at high levels). The numerical factors describing the rates of processes (i)–(iii) and fallspeed (iv) were all unchanged from the tropical simulations to which the model had previously been applied. An experiment in which the conversion and coalescence rates were both increased by a factor of five resulted in large concentrations of rainwater in the cloud, particularly in middle levels, but only a doubling of rainfall at the surface.

The most significant microphysical difference between tropical and midlatitude convection is in the relative importance of the icephase, of which the parameterization takes no explicit account. The fact that the rainwater was not escaping from the updraught sufficiently rapidly suggested that the parameterization might be modified to include hail fallspeeds. A crude modification was effected by increasing the factor \( \alpha \) in the terminal fallspeed expression \( V_t = \alpha \times \text{RAIN} \) (in g kg\(^{-1}\)) from 5·32 to 10·0. This almost doubles the parameterized rainwater fallspeed and had fundamental consequences on the rainfall and ultimate structure and behaviour of the storm, contrasting with the lack of sensitivity shown in other microphysical parameters.

The increased value of the parameter \( \alpha \) was the only value used and was a simple estimate of a weighted average of raindrop and hailstone fallspeeds. In view of the nature of this parameterization, any attempt to ‘tune’ this parameter for optimum results seemed unjustified.

With the increased fallspeeds the initial or ‘primary’ cell now produced \( \approx 20 \) mm of rain – almost a tenfold increase. This rainfall generated and maintained a strong downdraught which will be seen to play a crucial role in the storm’s history. The relative importance of evaporation (of rainwater and cloudwater) and of water loading in initiating and maintaining this downdraught is being studied further.

The spreading downdraught, propagating as a density current, produced boundary layer convergence and hence the potential for new convective growth similar to that described in the tropical simulation of MM. In this present simulation, however, the con-
vergence failed to initiate new growth and the simulation was terminated. Examination of the moisture and temperature fields showed that the convergence had produced regions very close to saturation, and in view of the modifications already made to the original sounding a further small increase was made to the mixing ratio at 750 mb so that at least parts of these regions would attain saturation when the simulation was repeated. The resultant sounding is shown in Fig. 2(b).

5. THE SIMULATION

Following these preliminary experiments a simulation using this modified sounding and microphysics (but unchanged initiating heat source) was generated and is now described. The initial perturbation, located south-southeast of the centre of the grid region, moved slowly (≈4 ms⁻¹) towards the NW, then grew rapidly into a precipitating cumulonimbus cell (Fig. 3) while moving towards the north-northeast. By 30 min a downdraught had begun to spread out at the surface and the rainwater fields in middle and lower levels were beginning to elongate in the NE–SW direction, as were the height and potential temperature fields, as shown in Figs. 4(a), (b), (c). This elongation of the fields and the downdraught outflow was maintained through the whole simulation (e.g. Figs. 4(d) and 5(e)) and will be referred to again later.

![Figure 3. Section through model showing flow in the vertical plane aligned along 210°-030° (left–right) with vector arrows (spaced every 100 mb in the vertical) formed from the wind components in that plane only; 0.1 g kg⁻¹ cloudwater contour and hatching of rainwater (light > 0.1 g kg⁻¹; dark > 2.0 g kg⁻¹). Flowfield is relative to the ground. Horizontal scale in km.](image)

(a) Secondary cell and downdraught development

The spreading outflow produced a short-lived shallow cloud 'ring' (Fig. 5(b)), however, the strongest boundary layer convergence or 'forcing' was on the southeast side of the downdraught outflow where it opposed the low-level winds. New convective cells were generated which exhibited a similar lifecycle to the primary cell, moving from the south while growing and merging with a larger region of raining and decaying cells moving to the northeast in the elongated anvil and rain area. Examples of this multicelled structure are shown in Figs. 5(a) and 7.

By 80 min further cells began to develop along the downdraught front including one at the northeast end, which by 96 min was close to the northern boundary and the simulation was terminated due to the model's inability to handle strong updraughts near boundary gridpoints.

The development of the surface outflow and its interaction with the ambient flow has
interesting features. The downdraught from the primary cell spread out relatively rapidly to the northwest, less so to the northeast and southwest, and only very slowly to the southeast. Thus the shape evolves as shown in Figs. 5(c), (d) and (e). The southeast edge is located about 6 km southeast of the rainfall maximum and moves only a kilometre or two during an hour of simulation (equivalent to \( \approx 0.5 \text{ m s}^{-1} \)), while the northwest edge moved away at between 7 and 10 m s\(^{-1} \).

![Diagram](attachment:diagram.png)

**Figure 4.** (a) Flowfield on a pressure surface. Horizontal winds in vector form. (b) Rainwater concentrations on a pressure surface, contours at 0.1, 2.0 and 4.0 g kg\(^{-1} \). (c) and (d) Potential temperature deviation field contoured every 1 deg C. Height deviation contoured every 3 m. Zero contour dot-dash, positive contours continuous, negative contours dashed. Horizontal scales in km.
FLOW FIELD ON A PRESSURE SURFACE (except (b))

\[ \rightarrow = 15 \text{ m s}^{-1} \]

Figure 5. (a) As Fig. 4(a) with vertical velocities contoured every 3 ms\(^{-1}\); zero contour dot-dash, positive contours continuous, negative contours dashed. (b) As Fig. 4(b) for cloudwater. (c), (d), (e) As Fig. 5(a) but allowing vectors to move with their local velocity.

(b) *Rainfall*

The simulated surface rainfall rates and total are shown in Figs. 6(a) and (b). The basic pattern of the primary cell's rainfall is maintained with a pronounced local maximum of 45 mm and elongation to the northeast. The maximum is formed mainly during the two periods 24–44 min and 60–84 min. Typical rainfall rates were \(\sim 25-50 \text{mm h}^{-1}\), but grid-
point maxima of 200 mm h\(^{-1}\) for a minute occurred. Despite the unsophisticated rainfall parameterization and appreciating that the simulation only describes approximately one-third of the actual storm’s rain duration, the observed and simulated rainfall patterns compare remarkably well (Figs. 1 and 6(b)). It would therefore suggest that the parameterization used is adequate in many respects.

(c) **Multicell structure**

A vertical section through the storm along the line marked on Fig. 9 is shown in Fig. 7(a). The coexistence of these cells in different stages of their lifecycles is clear. The cell on the downwind side (r.h.s.) of the figure is in an advanced state of decay with downdraughts only and moderate rain, the centre cell is fully developed with strong updraughts and downdraughts and heavy rain, while the upwind cell is growing strongly with no rain-driven downdraught. Part of the mature cell and the decaying cell are merged to form an elongated raining anvil. The repetition of this process of growth and decay can be seen in Figs. 7(a), (b) and (c) where the respective cells are identified.

Since the cells move in curved paths it is difficult to show vertical cross-sections; however, for the mature and decaying stages the cells do move approximately along 210°–030° and the vertical cross-sections of Figs. 3 and 7 are taken correspondingly. (Because the line 210°–030° is not parallel to a line of gridpoints it was necessary to rotate the simulated fields about a vertical axis until the desired line coincides with a line of points. Such rotation involves some simple interpolation and loss of data close to the grid boundaries but this is not serious. An equivalent calculation can be done avoiding rotation of the entire field but complicating the computer graphics.)
6. DISCUSSION

(a) Storm model

The numerical simulation describes a storm with a localized rainfall distribution and distinctive downdraught behaviour. Comparison with the observational studies referred to above confirms the multicellular character and successive cell movement from the south into the storm area. The simulation shows that these cells are forced by the downdraught outflow and that the very slow movement of the downdraught front results in each cell maturing and decaying in a similar position relative to the ground. Despite the obvious cellular character of the storm, it appeared that during the simulation, the basic low-level inflow, anvil outflow and the downdraught outflow were relatively steady in the sense that the airflow configuration persisted much longer than the time taken for air to move through it. To support this, and to describe the storm macrostructure, trajectories were computed from the 4-D model fields as described in Miller and Betts (1977).
A selection of these trajectories is shown in Fig. 8. The trajectories approximate to streamlines relative to the ground since, on the storm scale, trajectories generated from different starting times have similar configurations. These, together with many more, identify a relatively deep ($\simeq 200 \text{ mb}$) updraught inflow approaching from between $140^\circ$ and $115^\circ$ with outflow towards $030^\circ$ predominantly in the layer between 400 and 250 mb.

The downdraught is fed from below 600 mb, mostly the layer 600–800 mb, flowing in from between $160^\circ$ and $210^\circ$, and out below 900 mb with the major part towards the northwest between $300^\circ$ and $340^\circ$.

Middle- and high-level trajectories are omitted from Fig. 8 for clarity. These deviate round the updraught which thus acts as a form of obstacle to the higher-level flow.

Fig. 9 shows a simplified storm structure based on these trajectories and previously
discussed figures. The storm circulation is simplified into major updraught and downdraught branches and the 'interlocking' nature of these is similar to that proposed by Browning (1964).

Both the updraught and downdraught enter and leave the storm with a southerly component, and a N–S vertical projection, Fig. 8(b), shows this clearly. The flow thus resembles the tropical model of MM. Similarly the E–W vertical projection, Fig. 8(c), shows a configuration resembling that usually identified with large vertical wind shear. It should be noted that both N–S and E–W projections show *downshear* updraught trajectory slopes.

The nature of the storm's 'periodicity' or impulsiveness is an interesting feature of these results. The periodicity can be related to the convective growth time and the microphysical timescales; however, it was suggested in MM that provided the cloud propagation velocity was comparable with the velocity of the density current formed by the downdraught outflow, then the convection would be steady with the boundary layer forcing coupled to the cloud. Clearly this is not the case for the *individual* cells of the Hampstead storm which move away from the downdraught front. It is possible that the inequality of cloud and current velocities is related to the periodicity. Analysis of this, and of the relation of the storm structure to its propagation and longevity, is in progress.

(b) *Vector shear*

A principal feature of the storm's ambient wind field was the veering of the wind with height (see Fig. 2(b)). Inspection of the simulated development of the storm suggested a mechanism through which the vector shear establishes a regenerating storm.

The shear in middle and upper levels elongates the rain region of the first cumulonimbus cell towards the northeast (Fig. 4(b)). The cooling of lower levels by evaporation of this rain, with an associated hydrostatic pressure increase, results in a similarly elongated surface height field (Fig. 4(c)) whose orientation is therefore determined by the middle- and upper-level winds. Since the winds turn through approximately 90° between the surface and 400 mb, this surface 'meso-high' is elongated *across* the low-level flow and is ideally oriented to maximize the convergence of air approaching the storm. Cells thus generated maintain this 'meso-high', as can be seen in Fig. 4(d).

![Figure 9](image_url)  
Figure 9. A schema of the primary features of the storm model deduced from the simulation. Dashed line XY shows orientation of the vertical sections of Figs. 3 and 7.
Support for this mechanism was obtained by rerunning the simulation with the middle- and upper-level winds now from a southeasterly direction but with no speed change. The rain area and low-level temperature and pressure patterns again elongate along these (modified) winds towards the NW and hence along the low-level winds. No significant new growth occurred on the SE flank and the basic stationary character was lost. Fig. 10 summarizes schematically this proposed mechanism for coupling the upper and lower wind directions. Vector shear also determines the 3-D storm flow configuration (Fig. 9) and some such form of 3-D circulation seems necessary for steady deep convection (Moncrieff 1978). Relating the character of the storm to a basic mean flow parameter such as a Richardson number is complicated by vector shear, and a 3-D generalization of the work of Moncrieff and Green (1972) and MM is necessary.

(c) Microphysical implications

Some of the microphysical implications of these experiments seem complex, even though based on highly simplified parameterization. It appears that the transition from tropical to colder clouds requires an increase in mean fall speeds. The presence of hail in these colder clouds (not explicitly parameterized in the model) would contribute to such an increase; this is supported by the recent results of List and Gillespie (1976) who discuss and quantify this difference between ‘warm’ and ‘cold’ rain which has been crudely parameterized in the numerical model.

From a cloud dynamics viewpoint the major role of the ice phase and the precise form of drop size spectrum is in releasing water from the storm fast enough. Analysis of the results shows that in the main downdraught, rainwater evaporation dominates that of cloud water; however, entrainment of cloud droplets into the downdraught is not explicitly represented (Ham 1973). The model parameterization of rain evaporation assumes no drop size dependence other than that implied by the evaporation rate, and questions concerning the evaporation and its relation to drop size, number and availability remain unanswered. The modelled cooling of downdraught air does however compare well with observed surface temperature changes.

(d) Localization

The limitation of the rain area and its precise locality are important features of the storm.

This study has identified the mechanism for giving localized heavy rainfall, but has not determined precisely why this occurred over the area of Hampstead. The model has no initial horizontal inhomogeneity (other than the perturbing heat source) and no orography.
The location of the initial heat source was about 5–8 km south-southeast of the modelled rain area (see section 4(a)), this location is the only specified parameter at initial time. Geographically this location would correspond to the centre of the city.

As discussed by Grove (1978), no other severe cumulonimbus activity occurred within 100 km of the area. The sounding used in the simulation (section 4(a)) together with the perturbing heat source are therefore fundamental to the occurrence of cumulonimbus convection over the London area. Both Grove (1978) and Atkinson (1977) discuss the enhancement of typical boundary layer evolution by a mesoscale convergence field and the urban 'heat island' and it would seem that these processes were sufficient to isolate the convection over London, although the relative importance of these is unclear. The city centre also acted as the initiating heat source upwind of the Hampstead area.

The simulation prior to the one described in section 5 suggested that new cell generation from the downdraught outflow was rather sensitive to the boundary layer properties of the sounding. Consequently the sounding used in the main simulation probably represented marginally too great an ability to initiate new cell growth and it was this feature that terminated this simulation prematurely. A model of much better resolution would be required to examine this sensitivity further.

7. Concluding Remarks

The numerical simulation of a particular storm occasion has provided a graphic yet dynamically consistent model of a quasi-stationary severe storm. The simulation enabled several important factors to be identified. The storm consisted of several cumulonimbus exhibiting similar, consecutive lifecycles; the downdraught outflow played a major role in establishing and maintaining the storm system, forming on its southeast flank a slow-moving gust front which acted as a cell-initiation mechanism over central London resulting in prolonged heavy rain downwind.

This study was directed towards the understanding of the storm dynamics. As such it has not investigated many of the more detailed aspects of the storm's behaviour, making certain generalizations impossible. However, further progress can be made by using the type of model discussed here as interfacing between theory and observation, particularly in the study of storm macrostructure and propagation.

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