

Modelling of composition changes during *F*-region storms: a reassessment

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(Received in final form 12 November 1990)

Abstract—A recalculation of the global changes of thermospheric gas composition, resulting from strong heat inputs in the auroral ovals, shows that (contrary to some previous suggestions) widespread increases of mean molecular mass are produced at mid-latitudes, in summer and at equinox. Decreases of mean molecular mass occur at mid-latitudes in winter. Similar results are given by both the ‘UCL’ and ‘NCAR TIGCM’ three-dimensional models. The computed composition changes now seem consistent with the local time and seasonal response observed by satellites, and can broadly account for ‘negative storm effects’ in the ionospheric *F*₂-layer at mid-latitudes.

1. INTRODUCTION

Some decades ago, it was suggested that the depletions of electron density in the ionospheric *F*₂ layer during magnetic storms might be due to increased concentrations of the molecular gases O₂ and N₂ (SEATON, 1956; RISHBETH, 1962). No mechanism for such composition changes was advanced at the time, but the idea evolved gradually that they might result from a global scale ‘storm circulation’ in the thermosphere. This idea was discussed qualitatively by DUNCAN (1969) and subsequently developed by MAYR and VOLLAND (1972), OBAYASHI and MATUURA (1972), HAYS *et al.* (1973) and RISHBETH (1974).

A review of satellite observations by PRÖLSS (1980) showed that the latitude penetration of the composition changes depends on local time and season. In the night and morning sectors the storm response (i.e. the increase in mean molecular mass) extends to lower latitudes than in the afternoon sector. In summer, the response has a rather flat latitude variation, which extends to quite low latitudes, whereas in winter the response is larger, but confined to higher latitudes. Ionospheric changes correlate with the composition changes, both in latitude and in local time. The study of *F*₂-layer storm effects by WRENN *et al.* (1987) essentially confirmed PRÖLSS’ (1980) analysis.

Detailed numerical simulations of the ‘storm circulation’ had to await the development of global thermospheric circulation models to the point at which they included composition changes, as at University College, London (UCL) (FULLER-ROWELL

and REES, 1983) and at the National Center for Atmospheric Research, Boulder, Colorado (NCAR) (DICKINSON *et al.*, 1984). A crucial question was whether global-scale composition changes (specifically, increases of molecular gas concentration) could be produced by localized heat inputs in the auroral ovals. The NCAR thermospheric global circulation model (TIGCM) has been used to describe composition changes (ROBLE *et al.*, 1987; CROWLEY *et al.*, 1989; BURNS *et al.*, 1989), though it has not been used to compute *F*₂-layer storm effects. Computations with the UCL model, both in its ‘3DTD’ (three-dimensional, time-dependent) and ‘2DTD’ (two-dimensional) versions (RISHBETH *et al.*, 1985, 1987a), cast doubt on the composition change theory, as they implied that the molecular enhancements are confined in latitude to within a few degrees of the auroral ovals.

We have recently found that both versions of the UCL model seriously underestimated the horizontal transport of molecular gas. In this paper we present corrected results showing that the horizontal transport of molecular gas is indeed important in producing composition changes. We compare the ‘new’ (corrected) results with those of the ‘old’ model, and show that the ‘new’ results agree with those of the NCAR model.

2. RESULTS FROM THE THREE-DIMENSIONAL MODEL AT SOLSTICE

Figure 1a–c is a global map of mean molecular mass *M*, computed with the UCL model at the fixed

pressure level $Z = 12$, defined as in RISHBETH *et al.* (1985); it lies 11 scale heights above the base level ($Z = 1$) which is taken to lie at 80 km. The pressure level $Z = 12$ lies at a real height $h \simeq 260$ km, and roughly corresponds to the level of the daytime $F2$ peak. In the model, the air and plasma motions are computed self-consistently using the UCL/Sheffield coupled thermosphere-ionosphere model (FULLER-ROWELL *et al.*, 1987); the ion density is computed self-consistently at latitudes above 45° , but for lower latitudes it is taken from the empirical model of CHIU (1975).

The maps show the situation at 18 UT at December solstice, sunspot maximum (10.7 cm solar flux = 185). The imposed storm lasts 6 h, during which the high-latitude power input from auroral precipitation is 125 GW in each hemisphere, roughly corresponding to $K_p = 6$ – (FOSTER *et al.*, 1986); about half of this input goes into direct heating of the neutral air. The main heat input comes from Joule heating through a combination of the increased convection electric field and enhanced conductivity. Joule heating is typically four times the particle heating rate, giving a total heat input of about 300 GW per hemisphere.

Figure 1a shows the distribution of mean molecular mass, with superimposed wind vectors, at the end of the 6-h storm. Figure 1b maps the difference ΔM in molecular mass between the 'storm' case of Fig. 1a and the corresponding 'quiet-day' case at the same UT (which is not shown here, but appears as fig. 1 of FULLER-ROWELL *et al.*, 1990). For comparison with Fig. 1b, the corresponding plot from the 'old' (uncorrected) program is shown as Fig. 1c (taken from fig. 3 of FULLER-ROWELL *et al.*, 1990).

In Fig. 1c the contour that separates the regions of $\Delta M > 0$ and $\Delta M < 0$ lies within a few degrees of the auroral oval, apart from an extended region of very slight molecular enhancement ($\Delta M < 0.227$) at 45 – 75° latitude in the noon sector. Over the whole mid-latitude and low-latitude region, ΔM is slightly negative, corresponding to a slight enhancement of the proportion of atomic oxygen. In Fig. 1b, as compared to Fig. 1c, the boundary of the region of molecular enhancement ($\Delta M > 0$) lies about 40° nearer the equator in the morning sector in the summer (southern) hemisphere, though in the afternoon/evening sector the shift is only 10 – 20° . In the winter (northern) hemisphere the differences are very much smaller.

Figure 1d is the corresponding map computed for similar geophysical conditions from the NCAR TIGCM (ROBLE *et al.*, 1988). The assumed solar activity is slightly higher and the storm input slightly larger than in the UCL simulation. In spite of these

differences, the overall results are very similar to those shown in Fig. 1c, so the results of the UCL and NCAR models are basically in agreement.

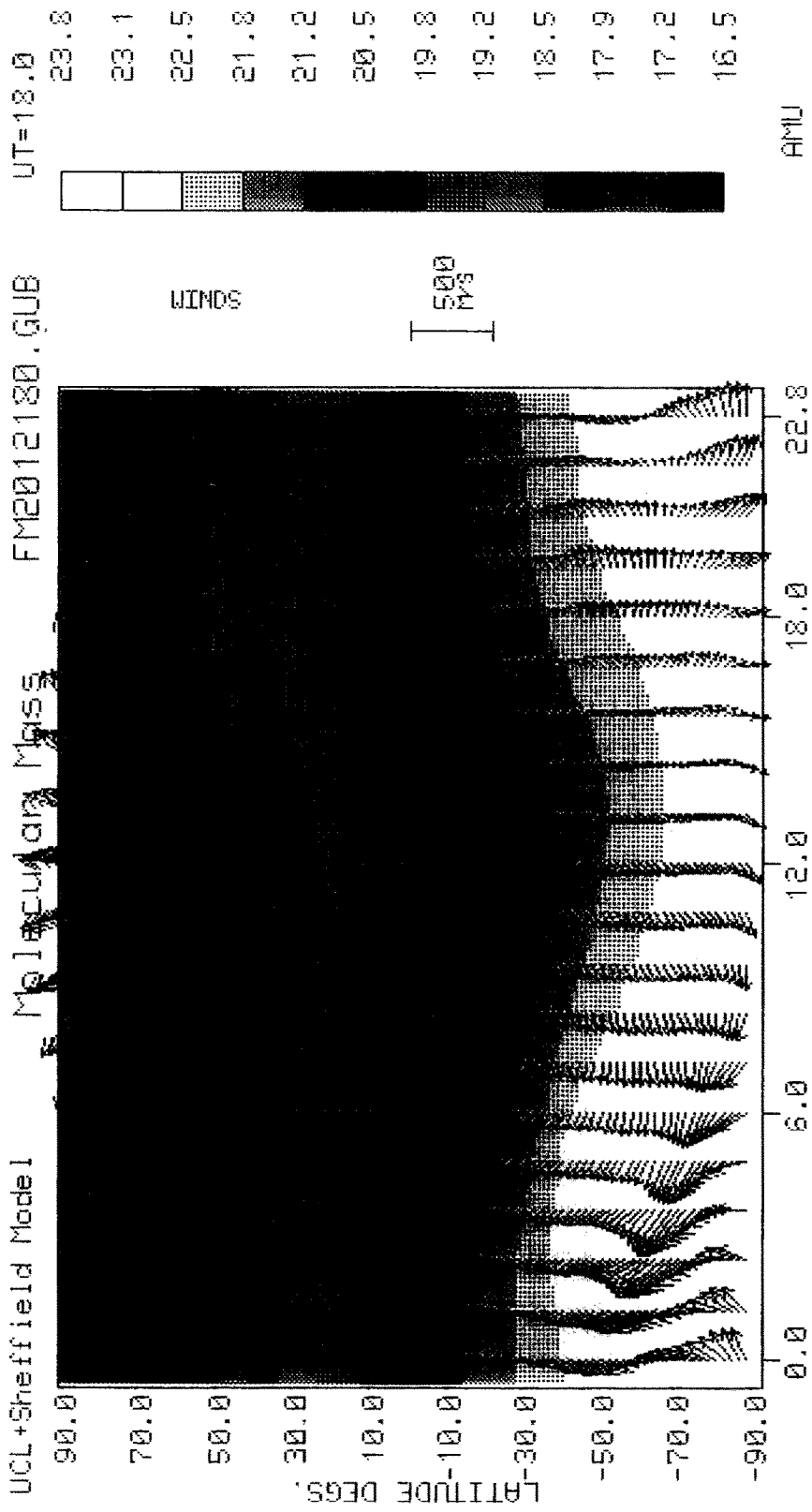
Figure 2 shows the latitude dependence of M at four local times (LT) for quiet-day conditions (Q), and at the end of the 6-h storm (S), the 'S' curves being cross-sections of Fig. 1b. In the southern (summer) hemisphere, the storm increases of M (i.e. $\Delta M > 0$) extend to quite low latitudes (about 25°) in the 00–06 LT sector, but only to about 40° at 12 LT and 50° at 18 LT. In the northern (winter) hemisphere, $\Delta M < 0$ at latitudes up to 50 – 60° at all local times.

3. RESULTS FROM THE TWO-DIMENSIONAL MODEL AT EQUINOX

We now present results for a storm simulation at equinox, using the UCL zonally averaged model at a lower level of solar activity (10.7 cm solar flux = 160). In this model, cooling by nitric oxide (KOCKARTS, 1980) is included self-consistently in the temperature computations. The storm input is characterized by increases in auroral precipitation and Joule heating, from quiet conditions at activity level 5 (corresponding to $K_p = 2$), as defined by FOSTER *et al.* (1986), FULLER-ROWELL and EVANS (1987) and EVANS *et al.* (1988). During the first 6 h of the storm, the energy input is raised to level 10 ($K_p = 6$), and is reduced to level 9 ($K_p = 5$) for 6 h, before returning to the quiet-time level 5 for the recovery phase, which continues for a further 4 days.

Figure 3 shows the latitude variation of mean molecular mass for equinox at pressure level $Z = 13$ in the two-dimensional model, for which the base level $Z = 1$ lies at 70 km. Under quiet conditions the pressure level $Z = 13$ lies at a real height $h \simeq 270$ km, but during the storm its height rises to about 330 km in the auroral oval and 300 km at the equator. The dashed curves show results for the 'old' program at stormtimes 0, 3 and 6 ST (hours). There is little further effect in this model if the storm input continues beyond 6 h. Full curves show the results from the 'new' (corrected) model for stormtimes 0, 3, 6 and 12 ST. The substantial increases of molecular mass extend about 15° nearer the equator in the 'new' model than in the 'old'.

Figure 4 shows the latitude variation of temperature T , mean molecular mass M and the vertical divergence velocity W_v for quiet conditions (0 ST), three stages of the storm (3, 6, 12 ST), and two stages of the recovery (18, 24 ST). [W_v is the contribution to the vertical air motion that balances the divergence of the horizontal wind field; it is the component responsible



Elec. Fld: MH-5
 Elec. Dens: SHEFF/CPLD
 DEC 21 F10.7cm 185
 6 HR STORM, GW 8
 NO RING CURRENT

Fig. 1a. UCL 3DTD model at December solstice: map of mean molecular mass in geographic latitude and local time, with superimposed wind vectors, at pressure level $Z = 12$ ($h = 260-320$ km) at 18 UT, at the end of a 6-h storm (high-latitude energy input about 300 GW per hemisphere). Solar 10.7 cm flux = 185; electron density derived from the UCL/Sheffield "coupled model".

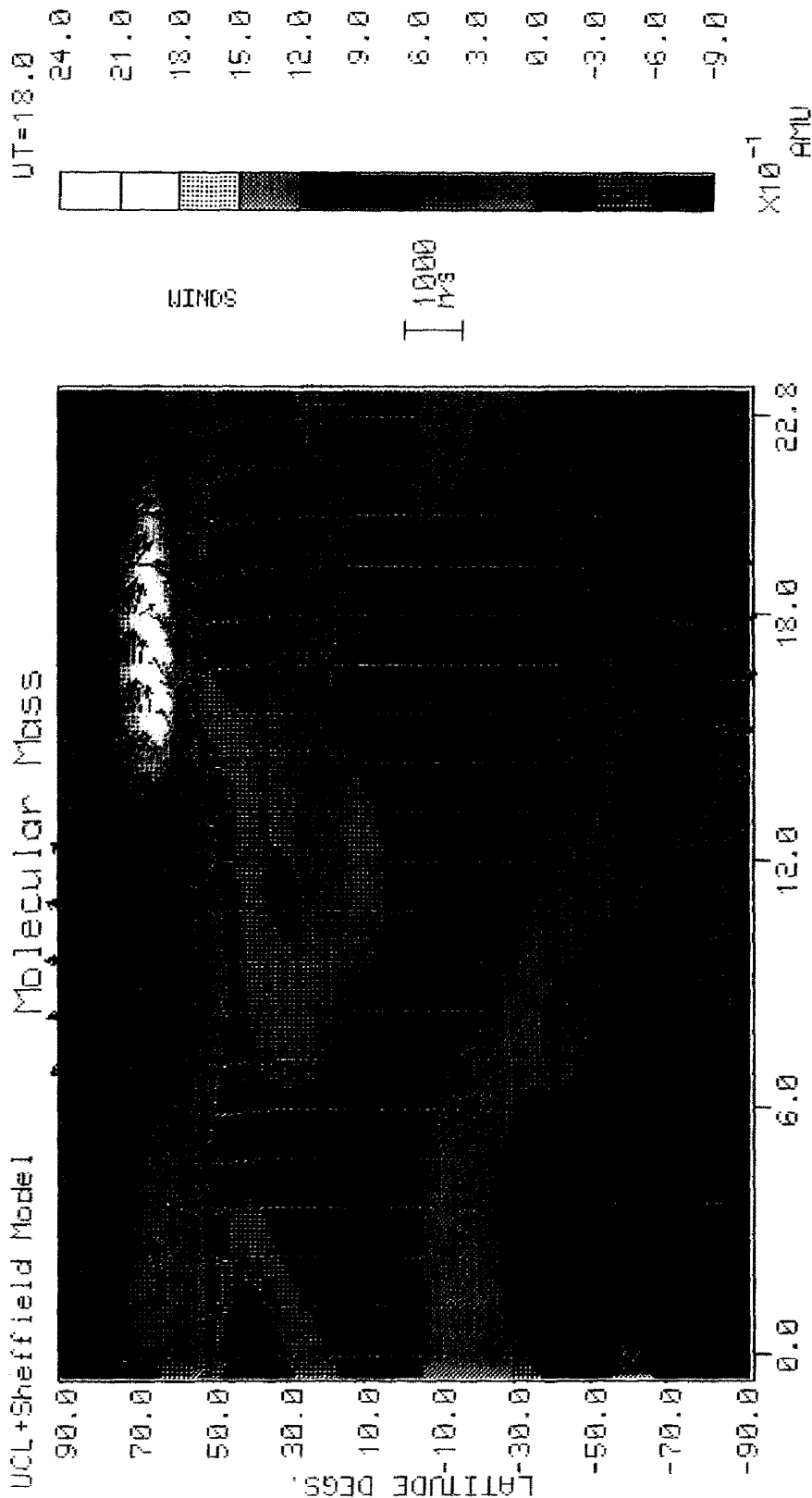


Fig. 1b. UCL 3DTD model at December solstice: map of the difference in mean molecular mass between the end of the 6-h storm (as shown in Fig. 1a) and on a quiet day. The vectors show the (storm-quiet) difference in wind velocity. Other parameters as Fig. 1a.

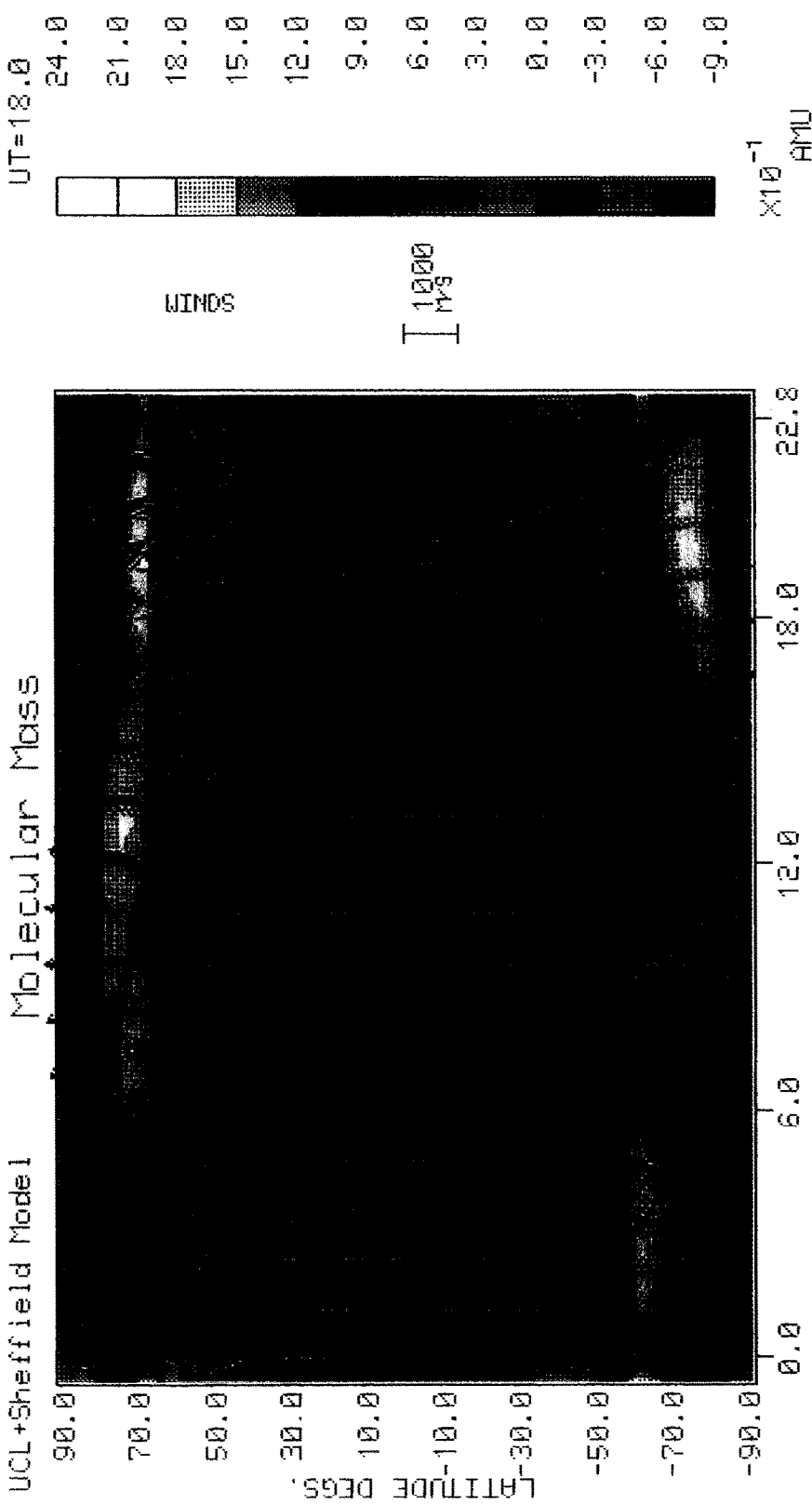


Fig. 1c. As Fig. 1b, but for 'old' version of the UCL 3DTD model, which underestimated the effects of horizontal winds on molecular mass.

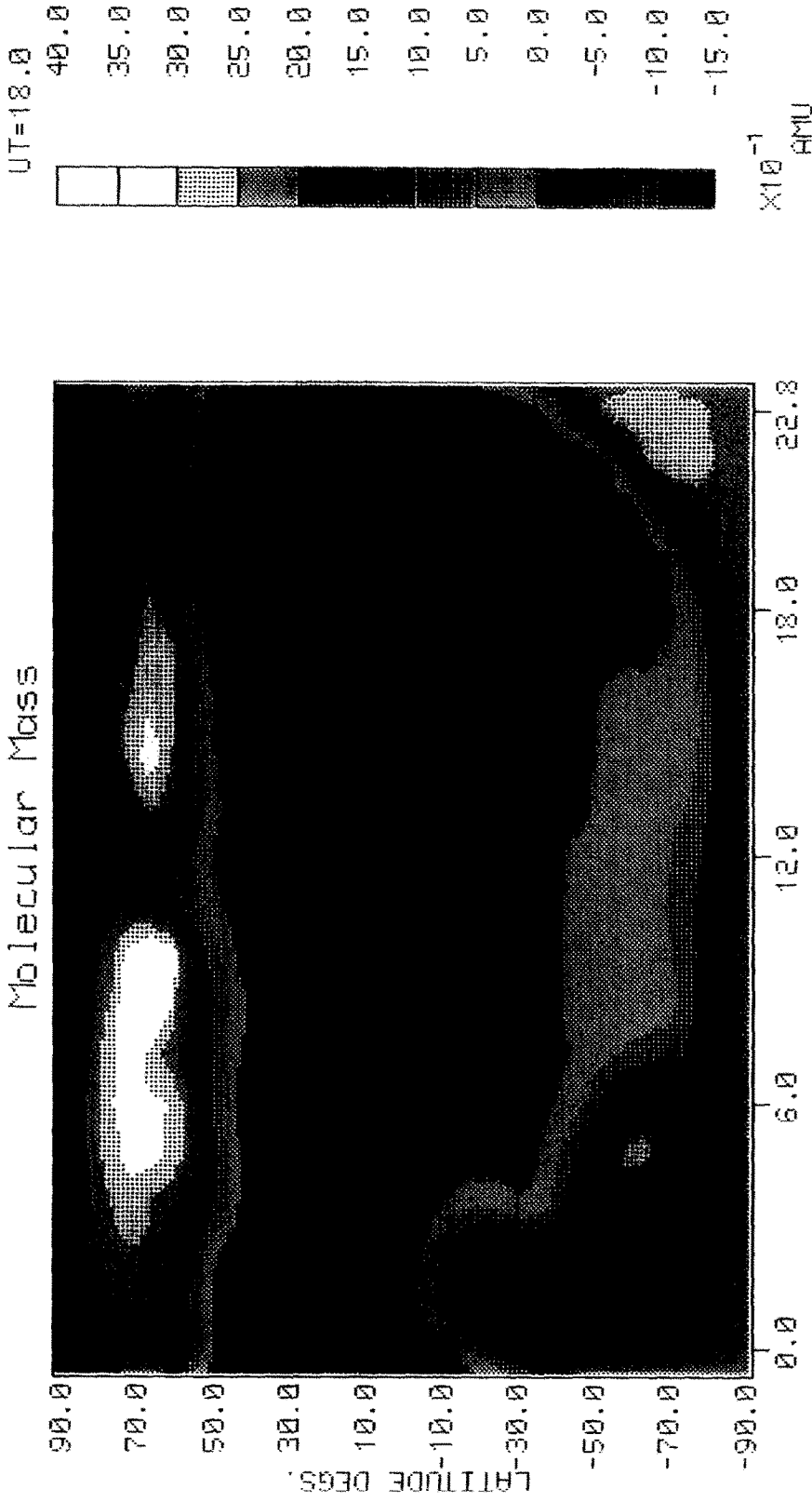


Fig. 1d. As Fig. 1b, but for the NCAR TIGCM.

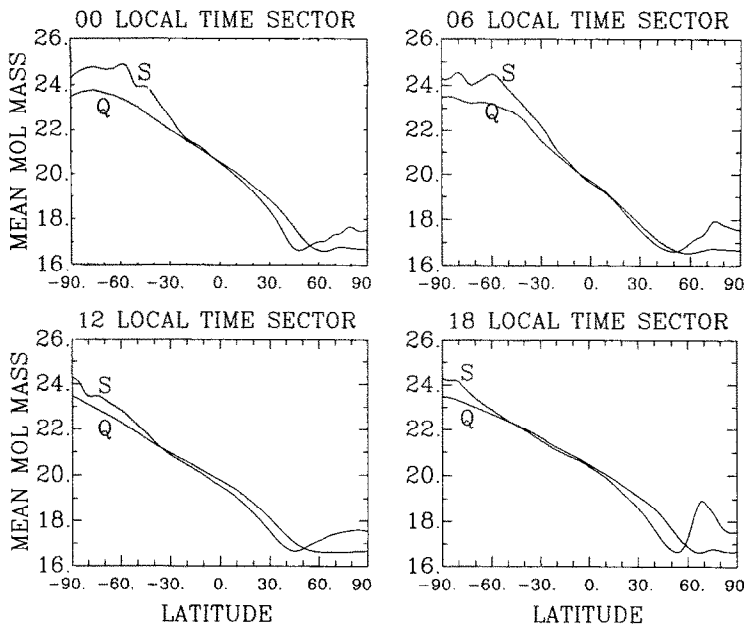


Fig. 2. UCL 3DTD model at December solstice: mean molecular mass vs geographic latitude at pressure level $Z = 12$ for 'storm' (S) and 'quiet' (Q) conditions (defined as for Fig. 1) at four local times.

for composition changes at fixed pressure levels (RISHBETH *et al.*, 1987b.) The small latitude variation at 0 ST is due to the quiet-time level of auroral activity. The effect of the storm energy input is shown by the localized upwelling (positive W_D) and by the temperature response, which is rather more spread in latitude. The accompanying increase of molecular mass lies equatorward of the upwelling; the dis-

placement between the peaks of M and of W_D is only about 3° at 3 ST, but increases to about 10° at the end of the storm at 12 ST. Thereafter, the localized effects in both temperature and W_D rapidly decrease, and have greatly declined by 18 ST. The composition effect persists, and is still marked at 24 ST. In a further computation (not plotted), in which the storm energy input continued at level 8 ($K_p = 4$) to 18 ST, the molecular mass vs latitude profile does not change much between 12 and 18 ST, which suggests that the composition effect is more-or-less saturated by 12 ST.

At low latitudes the mean molecular mass decreases during the storm, typically by 0.5 unit. By 6 ST the boundary between positive ΔM and negative ΔM (shown by the arrows) has reached latitude 40° , where it remains for the rest of the storm. The decrease of M is attributed to the downwelling (negative W_D) that balances the upwelling at higher latitudes, but the boundary between positive and negative W_D lies near latitude 50° during the storm, some distance poleward of the corresponding boundary in ΔM . The penetration of the region of negative ΔM into the region of downwelling is due to horizontal advection by the storm circulation, the degree of penetration being determined by a balance between downwelling and horizontal advection. This balance depends on the strength of the storm and also on season. Poleward of the auroral oval, ΔM and W_D are positive throughout the storm to 12 ST, but collapse thereafter. During

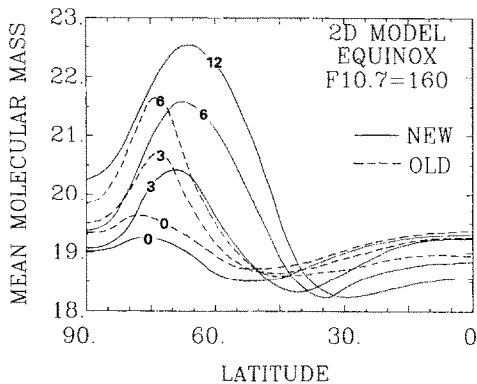


Fig. 3. UCL 2DTD (zonally averaged) model at equinox, solar $10.7 \text{ cm flux} = 160$. Mean molecular mass vs latitude at pressure level $Z = 13$ ($h = 270\text{--}330 \text{ km}$). Full curves for 'new' (corrected) model, dashed curves for 'old' model, for storm times 0 ST (initial condition, activity level 4), 3 ST (activity level 10), 6 ST (activity level decreasing from 10 to 9), 12 ST (end of storm—'new' model only).

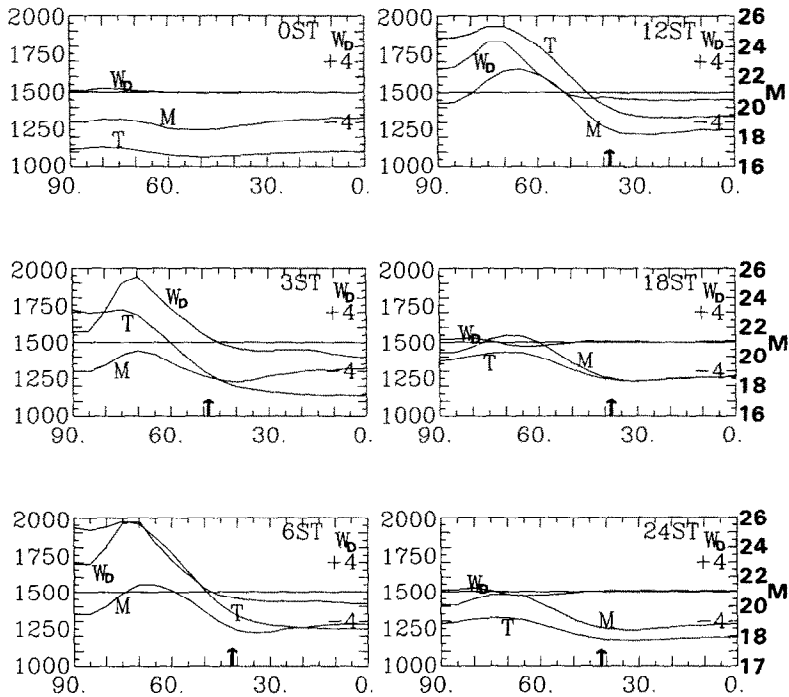


Fig. 4. UCL 2DTD (zonally averaged) model at equinox, solar 10.7 cm flux = 160. Mean molecular mass M , temperature T and vertical divergence velocity W_d vs latitude (in one hemisphere only) at pressure level $Z = 13$, for storm times 0, 3, 6, 12 ST (end of storm), 18, 24 ST (recovery phase). The arrows denote the boundary between increases and decreases of M , as compared to its values at 0 ST.

the recovery (18 ST and later), the thermosphere settles back to normal, with W_d small and negative at high latitudes as the global storm circulation reverses and establishes a weak poleward wind.

Figure 5 shows the evolution of temperature, mean molecular mass and divergence velocity with storm-time, at latitudes 70, 50 and 30°. At all three latitudes the temperature has peaked by the end of the storm (12 ST), and by 30 ST has recovered to within 100 K or so of its pre-storm value. The molecular mass responds rather more sluggishly, both to the storm heating and to its cessation, particularly at 30°. Recovery is incomplete at 30 ST, and approaches completion only at 100–150 ST (not shown in Fig. 5). The strong upwelling at 70° is closely confined to the period of the heat input, which is not surprising in view of the energy needed to drive the upwelling. The downwelling at lower latitudes also stops within about 3 h of the end of the storm. The dip in T and M at 9 ST is associated with the reduction of activity from $K_p = 6$ to $K_p = 5$ at 6 ST.

4. DISCUSSION

The results presented in this paper show that energy inputs in the auroral latitudes can lead to increases of molecular gas concentration in the mid-latitude thermosphere, contrary to the conclusions of earlier papers (RISHBETH *et al.*, 1985, 1987a). This strongly supports the 'composition change' theory of F_2 -layer storms, and may dispose of any need to invoke a significant energy input from the Dst ring current as a mechanism for composition changes (FULLER-ROWELL *et al.*, 1990). It therefore seems likely that the composition changes during storms detected by satellite-borne instruments (e.g. PRÖLSS, 1987) can be explained in terms of the auroral-oval energy inputs. In particular, the penetration of the composition disturbance to low latitudes in the early morning sector, especially in summer, agrees with the satellite observations. There now seems to be no major difference between the results of the Boulder NCAR TIGCM and the UCL 2DTD and 3DTD models.

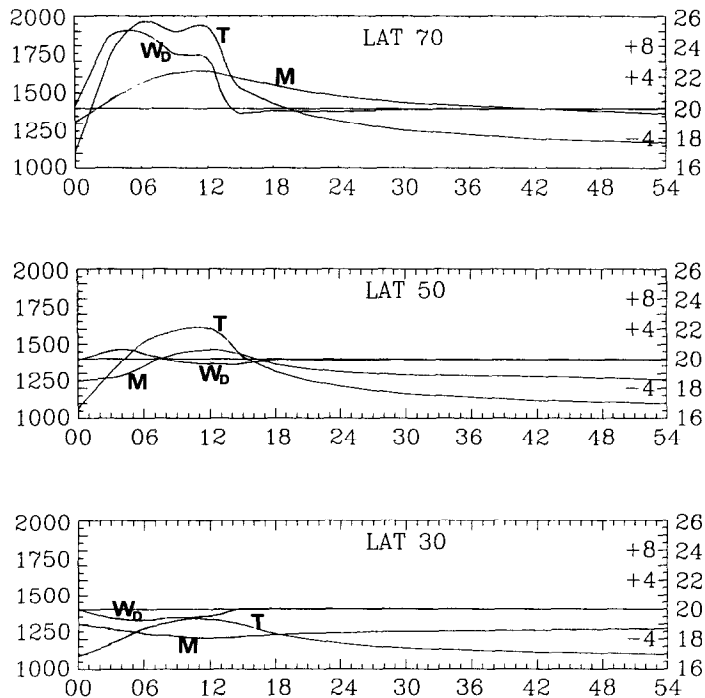


Fig. 5. UCL 2DTD (zonally averaged) model at equinox, solar 10.7 cm flux = 160. Mean molecular mass M , temperature T and vertical divergence velocity W_b vs storm time at pressure level $Z = 13$, at latitudes 70, 50, 30.

Concerning storm effects in the F_2 -layer: as a very rough guide, simple F_2 -layer theory gives a relationship between changes of molecular mass and changes of peak electron density, namely $\Delta(\ln NmF_2) \simeq -0.35\Delta M$ (RISHBETH, 1989). On this basis, the storm-induced composition changes shown in our figures (which roughly correspond to the height of the F_2 peak) should be sufficient to cause the decreases of NmF_2 at summer mid-latitudes, though much more work is needed to unravel the complicated local-time and storm-time variations. As well as explaining the 'negative storm effects', the three-dimensional results (Figs 1b, d and 2) and the two-dimensional results (Figs 3–5) give some

support to the suggestion of RISHBETH *et al.* (1985) that the 'positive storm effects' (increases of NmF_2) often seen in the low-latitude and winter mid-latitude F_2 -layer are due to decreases of mean molecular mass produced by downwelling, that is, the downward flow of air remote from the high-latitude energy inputs.

Acknowledgements—We acknowledge with thanks the use of the SERC Cray XMP at the Rutherford Appleton Laboratory. The work at UCL and Southampton is supported by the U.K. Science and Engineering Research Council (grants GR/E 58007 and GR/E 73956, respectively). The National Center for Atmospheric Research is sponsored by the U.S. National Science Foundation.

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