THE IMPACT OF SOME PHYSICAL PARAMETRIZATIONS ON THE UK METEOROLOGICAL OFFICE'S FORECAST MODELS

A. Dickinson
Meteorological Office
Bracknell, U.K.

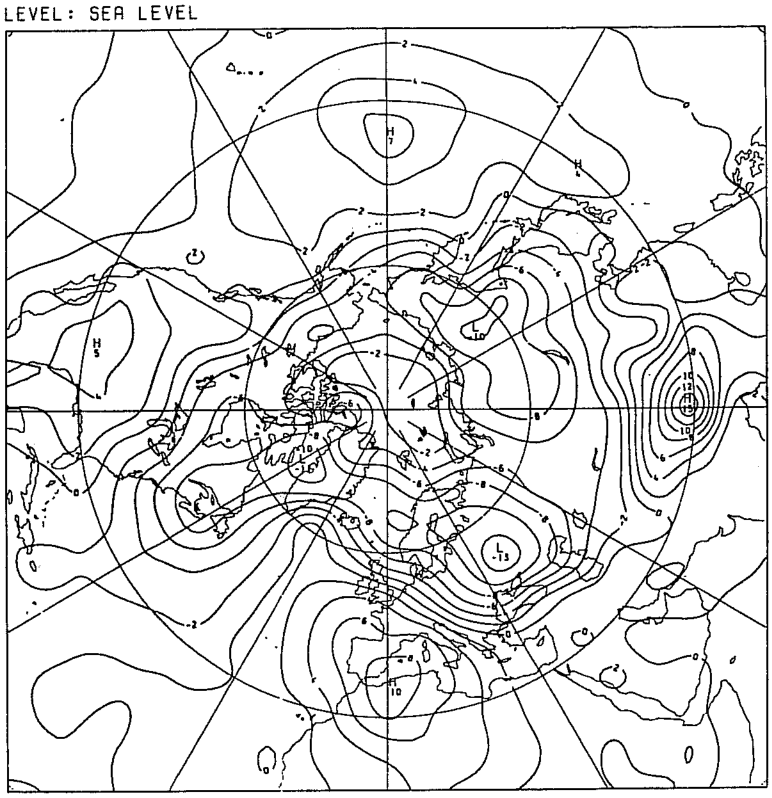
1. Introduction

The UK Meteorological Office uses two versions of a 15-level latitude-longitude sigma co-ordinate grid point model to carry out its operational forecasting commitments. A global version using a $1^1/_2°$ x $1^7/_8°$ grid is run twice a day and provides guidance for up to 6 days ahead, whilst a regional higher resolution model, using a $^3/_4°$ x $^{15}/_{16}°$ grid covering the North Atlantic and Europe, is used to provide more detailed forecasts of the weather affecting the UK and Western Europe for up to 36 hours ahead. A general overview of these models is given by Gadd (1985) and Atkins and Woodage (1985), and a description of their applications by Hunt (1985) and Hardman (1985). The finite difference formulation is described in Cullen (1983) and the physical parametrizations in Foreman (1983). A fuller description of the forecast models is given in Dickinson and Temperton (1984).

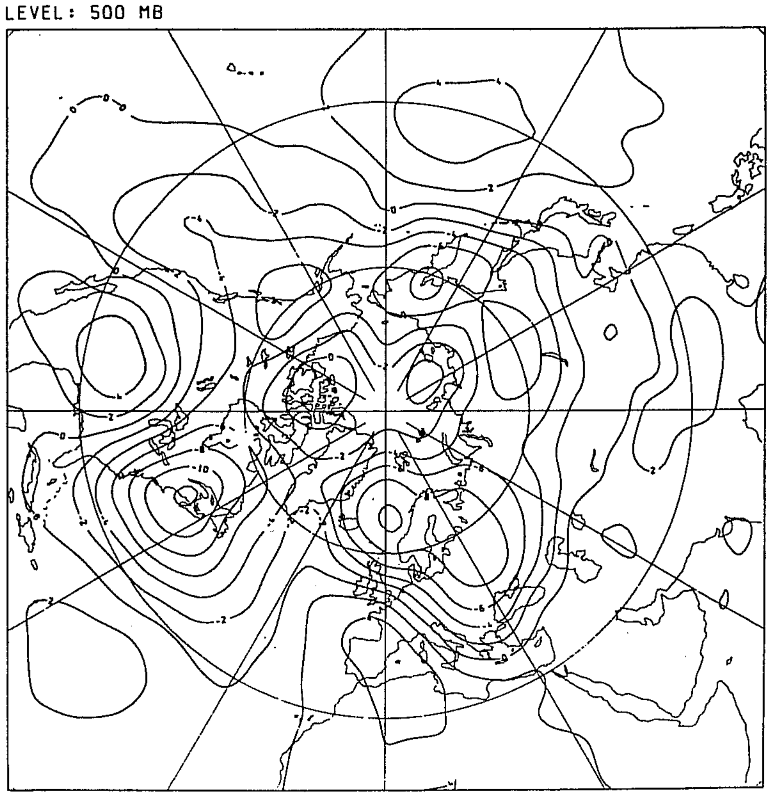
In order to illustrate the impact of a particular physical parametrization on our models, we consider a problem that has affected both climate integrations and operational forecasts alike - that of predicting excessive westerly flow during the northern hemisphere winter. This problem was most acute in the operational global model as can be seen from mean error maps for winter 1983-84 (Figure 1). By day 5, the flow is

Figure 1. UK operational global model. 5-day forecast mean error maps for period December 1983 - February 1984.

LEVEL: SEA LEVEL



LEVEL: 500 MB



unrealistically strong in high latitudes with large negative pressure anomalies over the major land masses. This sytematic error was also detectable in individual medium range forecasts where depressions pushed too quickly into the European Continent from the Atlantic and often retained their identity throughout a forecast.

This error pattern appears to be a common feature, in varying degrees, of the forecasts issued by many of the major forecasting centres. A comparison by Lange and Hellsten (1984) of the 3 day predictions produced by a number of operational models during 1983 illustrates this quite well. The mean 1000 mb geopotential height error maps for the months January to March inclusive all exhibit error patterns broadly similar to those described above, with negative anomalies over Europe, the USSR and Canada and positive anomalies over the North Pacific and in lower latitudes. The pattern of these errors seems to indicate an underestimation of the momentum exchange between land surfaces and the atmosphere. This has been confirmed by the experience at ECMWF (Wallace et al, 1983) which has shown the benefits of using envelope orography in reducing this type of systematic error. In this approach the model's orography is increased by an increment proportional to the standard deviation of it's sub-grid scale variance, leading to extra drag on the model atmosphere as a consequence of the larger barrier presented to the flow.

The technique currently used to moderate this bias in the UK operational models is based on a simple parametrization of the momentum transfer between the earth's surface and the free atmosphere occurring as a result of remote forcing by sub-grid scale orographically induced gravity waves. These waves propagate vertically extracting momentum from the troposphere and stratosphere as they dissipate. The operational scheme is simpler than that derived by Palmer et al (1986) and discussed in this publication by Shutts (1985) in several respects. The two schemes are described more fully in Section 2, but the important difference lies in the specification of the vertical distribution of drag. The operational scheme assumes that the gravity waves break at all levels below a critical line by applying the same deceleration to the wind field at each model level below the critical line. It is therefore independent of the model's vertical structure. On the other hand, the Richardson number scheme of Shutts which was developed at a later stage, takes more account of observational evidence and theory, and relates the wave breaking to a measure of the local stability. As will be seen later, this leads to a vertical drag profile in mid-latitudes in which most of the drag is applied at stratospheric levels.

The remaining sections of this paper examine the model's systematic error pattern in relation to the performance of these two parametrizations. This evidence suggests that while use of either scheme can lead to a significant improvement in model forecast skill at the medium range, the operational scheme produces changes with a structure more similar to the model's error structure than the Richardson number scheme. Details of the two parametrizations are given in Section 2. Section 3 records our operational experience with gravity wave drag and Section 4 describes the results of the experiments comparing the two schemes. Finally Section 5 discusses these results and their implications.

2. Gravity wave drag parametrizations

The two formulations of gravity wave drag are expressed in terms of the surface pressure drag exerted on the sub-gridscale orography and a separate estimate of the vertical distribution of wave stress accompanying the surface value. The derivation of the formulas used for the surface stress and the wave Richardson number is given in Shutts (1985). In the following we concentrate on the details of the implementation of these schemes in the model.

2.1 Richardson number scheme

The surface stress τ_s is expressed in terms of near-surface model variables and the variance of the orography about its grid-box mean value, $\overline{h^2}_s$. In practice this is limited to a maximum value of 400 m^2 to prevent the larger mountain ranges from having an unrealistically dominant effect. If L is the lowest sigma level at which drag is calculated, then the surface stress is calculated from

$$\tau_s = \tau_{L-1/2} = K \rho_L |\underline{V}_L| N_{L+1/2} \overline{h^2}_s \qquad (1)$$

where N is the Brunt-Vaisala frequency, ρ is the density of air, $\underline{V}$ is the wind and K is a constant. Values of $K = 2.5 \times 10^{-5} m^{-1}$ and $L = 2$ are normally used in the scheme.

The stress at level $n+1/2 > L$, is similarly related to the displacement amplitude $|\delta h|$ of the gravity waves by

$$\tau_{n+1/2} = K\rho_{n+1/2} |\underline{V}^*_{n+1/2}| N_{n+1/2} |\delta h_{n+1/2}|^2 \qquad (2)$$

where $\underline{V}^*$ is the vector component of the wind in the direction of $\underline{V}_L$. This means that the stress at all heights is assumed to be in the direction of the surface stress and that the vertical profile of wind in this direction is the one relevant to the gravity wave model.

The algorithm for calculating the stress at level n+1/2 now proceeds as follows:

(i) Estimate $\tau_{n+1/2}$ by setting $\tau_{n+1/2} = \tau_{n-1/2}$ and calculate $|\delta h_{n+1/2}|^2$ from equation (2).

(ii) Using this value the wave Richardson Number is calculated from

$$\tilde{Ri} = \left(N^2 \left[1 - N \frac{|\delta h|}{|\underline{V}^*|} \right] \left[\left| \frac{\Delta \underline{V}^*}{\Delta Z} \right| + N^2 \frac{|\delta h|}{|\underline{V}^*|} \right]^{-2} \right)_{n+1/2} \quad (3)$$

where Z is height.

If $\tilde{Ri} > .25$ then the stress at level n-1/2 is carried over to level n+1/2, otherwise equation (3) is solved for $|\delta h_{n+1/2}|$ with $\tilde{Ri} = .25$ and $\tau_{n+1/2}$ is found by again solving equation (2).

(iii) If either $N_{n+1/2} < 0$ or $|\underline{V}^*_{n+1/2}| < 0$ or $|\delta h_{n+1/2}| < 0$ then we set $\tau_{n+1/2} = 0$ so that all the stress is absorbed at this level. If some stress remains at the uppermost level then it is absorbed into the top layer by requiring $\tau = 0$ at $\sigma = 0$.

(iv) The increments to the horizontal wind field are then computed from

$$u_n = \sin\beta \frac{\Delta t\, g}{\Delta p_n} (\tau_{n-1/2} - \tau_{n+1/2})$$

$$v_n = \cos\beta \frac{\Delta t\, g}{\Delta p_n} (\tau_{n-1/2} - \tau_{n+1/2})$$

where β is the direction of the wind at level L.

A critical line beyond which the waves are not allowed to propagate occurs if the wind direction is more than 90° to the wind at level L. All of the remaining flux is then absorbed.

2.2 The operational scheme

This scheme was developed as a preliminary step towards that described above. In many ways it is much simpler and hence more rudimentary.

The scheme treats the u and v components of stress independently. The surface stress is given by

$$\tau_s = A\, p_s\, u_2\, (\theta_3 - \theta_1)^{1/2}\, \overline{h_s^2} \qquad (4)$$

with a similar expression for the v-component of stress. Here p_s is surface pressure and θ is potential temperature. Subscripts 1, 2 and 3 refer to model levels. The constant A is derived by substituing typical values for p_s, u and θ into (4), so that in terms of a reference value of the surface stress τ_o

$$A = 1/\,(5\sqrt{10}\; 10^5\; H^2{}_s)\; \tau_o,$$

where $H_s{}^2$ is the global mean variance of the sub-gridscale orogrpahy. τ_o is a constant which is currently taken to be .15 Nm^{-2}.

The vertical distribution of drag is imposed independently of the stability properties of the model atmosphere. An arbitrary vertical profile of stress such that

$$\frac{\partial \tau}{\partial p} = \text{constant}$$

is assumed. This means that in the absence of critical line effects the deceleration is constant with height. In the current implementation of the scheme, the drag is applied between the top of the boundary layer and the critical line. This leads to increments to the horizontal wind field of the form

$$\Delta u_n = - \frac{\Delta t}{p_{b+1/2}}\; g\; \tau_s$$

where b is the number of levels in the model's boundary layer (b = 4 operationally).

The critical line is assumed to occur at a reversal in direction of a wind component. The wave momentum flux carried by a particular component is considered unable to propagate beyond this level and 50% is absorbed. The remainder is assumed to be reflected and is ignored.

3. Operational experience

The simple parametrization of gravity wave drag described in section 2.2 was introduced into the operational global forecast model in December 1984 and has continued to be used since that time. The impact of the scheme on this model may be seen from the operational verification statistics from the past two years (Figure 2) and the results of a rerun of 10 cases from Winter 1984-85 (charts a and b of Figures 3-4). There is a clear and significant reduction in both the westerly bias and the negative errors over land areas in both the surface and 500 mb fields at 5 days. The operational verification figures for MSLP and 500 mb show a marked improvement from the beginning of December 1984. Indeed the results for this winter were the best ever recorded during the history of numerical weather prediction in the UK. However, not all the verification figures show an improvement. The additional drag has led to a negative bias in the 250 mb mean wind field, an indication that jet strengths have been slightly reduced.

The data assimilation scheme used at Bracknell (Bell, 1983) also requires the use of the forecast model, not only through the provision of a background field, but more importantly as an integral part of the assimilation process itself. An initial state is achieved by repeated insertion of observations into a 6-hour forecast from the previous analysis time, using optimum interpolation to provide corrections at model grid points and divergence damping to control unwanted high frequency oscillations. Inclusion of gravity wave drag into this part of the operational suite was delayed until February 1985 since its impact on the climatology of the analysis was unknown, and it was felt that some adjustment of the amount of drag being applied during a forecast might be necessary. In the event after running a 2-week parallel suite of analyses and test forecasts, the impact of the drag on the analysis was found to be negligible and the change was included mostly for reasons of compatibility. Part of the reason for this result may be that the errors themselves occur mostly in data dense regions (ie over the major land masses of the Northern Hemisphere) and are therefore compensated for by the corrective action of observations during the assimilation.

The regional, finer mesh version of the operational model which is run twice daily to 36 hours also includes a treatment of gravity wave drag. Initially it was felt to be unnecessary, partly because of the short forecast period and also since this model uses a more detailed description of orography. Experience has, however, proved somewhat different, with this model often maintaining the central pressure of mature continental depressions far too low. Experiments showed that this bias could again be removed by including gravity wave drag. Interestingly, they also showed that there was little additional advantage in including the scheme in the coarser mesh forecast used to provide the lateral boundary conditions.

4. Some experiments

In this section we examine the performance of the two parametrizations of gravity wave drag in terms of their effect on an ensemble of 10 5-day global forecasts using cases from Winter 1984-85. These experiments are part of an ongoing series aimed at examining the impact of both envelope orography and the Richardson number scheme on the model. Results from using two versions of the Richardson number scheme are shown. The first is as descirbed in section 2.1 and the second is a version designed to allow more stress to be absorbed outside the boundary layer by setting $L = 3$ and $K = 3.7 \times 10^{-5} m^{-1}$ in equation (1). These are denoted as experiments R and

Figure 2. Operational global model. Verification against observations. Northern hemisphere.

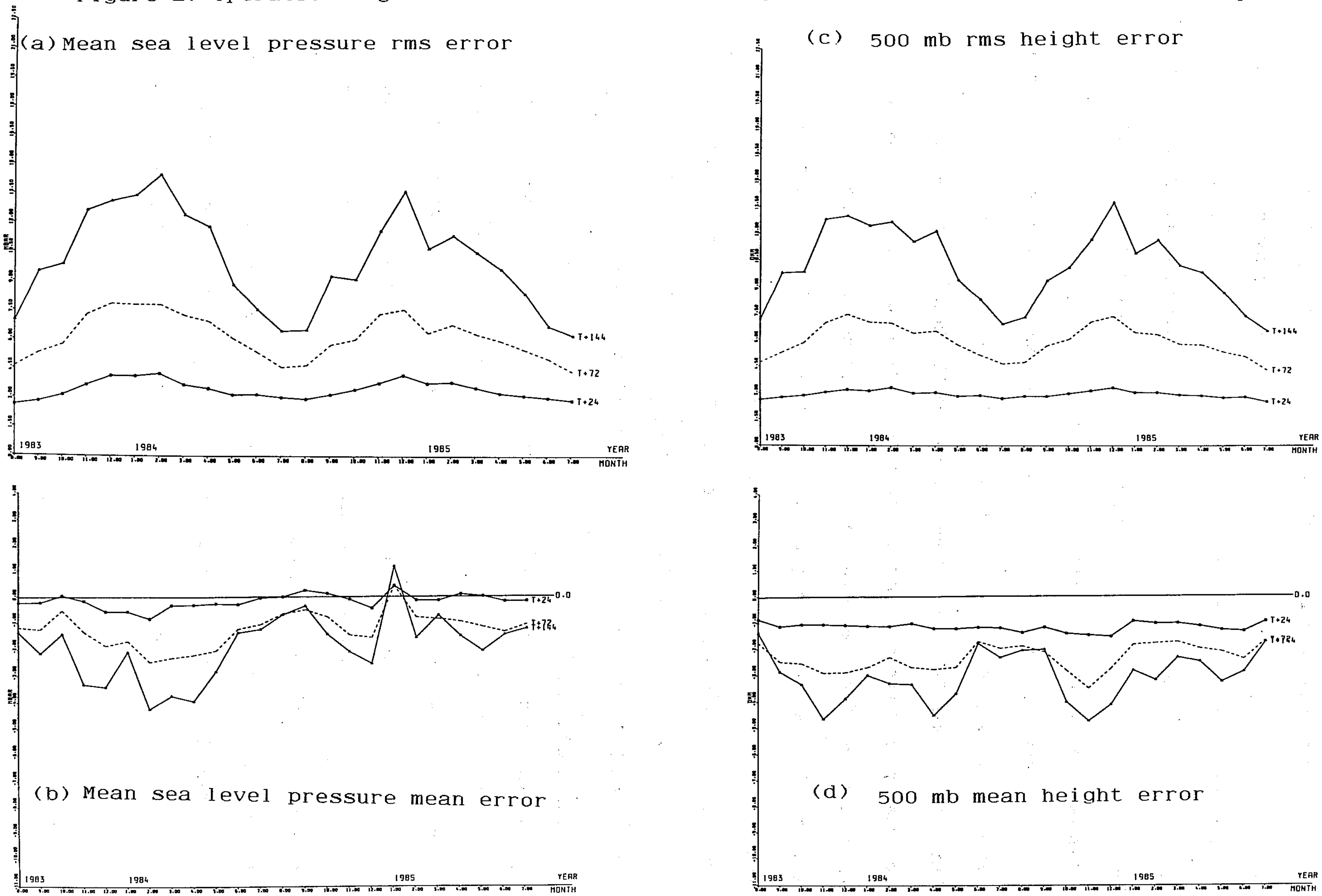
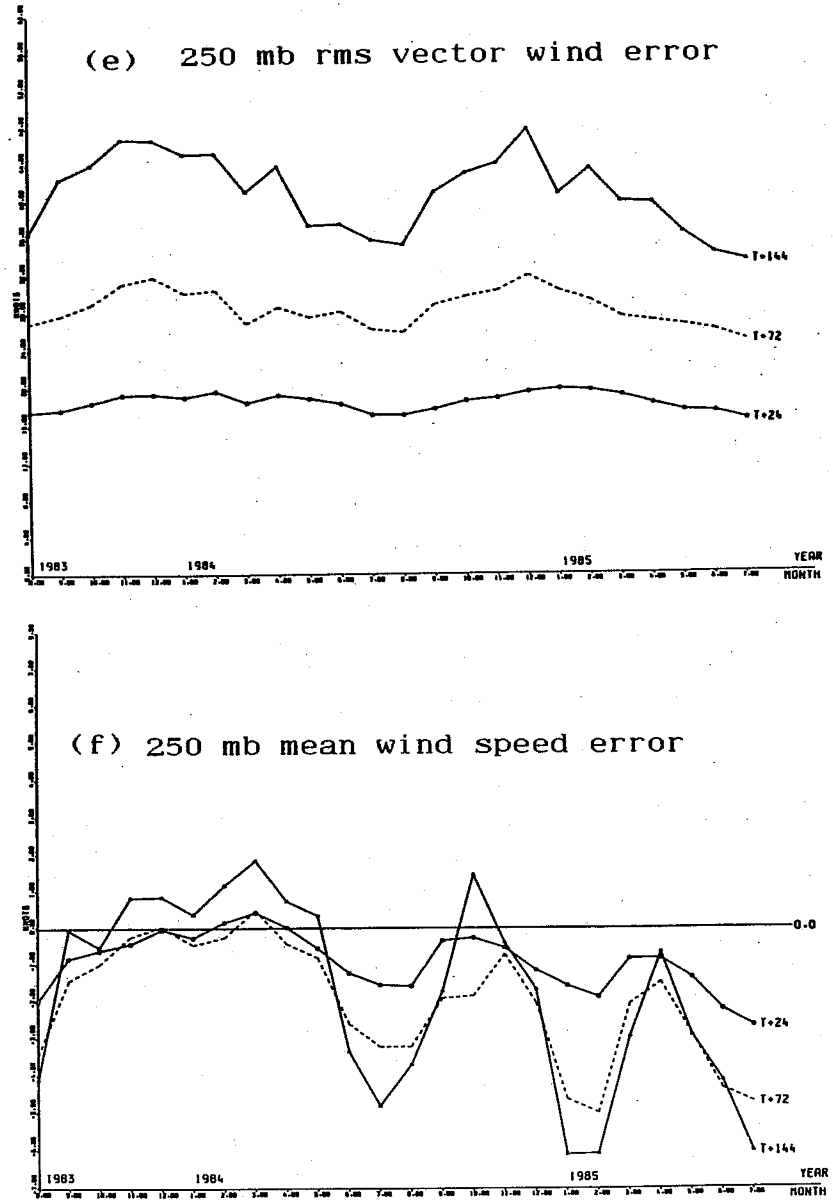


Figure 2. Continued.



S respectively. The control run with no drag is denoted as experiment C and the run using the operational scheme as experiment O. Charts from these tests are shown in Figures 3-7.

Before discussing the results of these experiments, it is useful to understand the differing ways in which the two parametrizations act. This is illustrated by Figure 8, the zonally averaged cross section of the deceleration being applied to the zonal wind field. This example is at T+72 for one case from experiments R and O, but is typical of other times and cases. The operational scheme leads to a deceleration at 50°N which is almost constant with height. There is no drag below $\sigma = .8$ since this level corresponds to the top of the model's boundary layer. In comparison, the Richardson number scheme leads to stress absorption in the boundary layer at those latitudes where the surface wind is predominantly easterly. There is little or no absorption in mid-troposphere levels so that most of the flux of gravity wave momentum is carried up into the stratosphere and absorbed there. Values at these levels are up to 4 times larger than with the operational scheme, with the maxima occurring at the top most level at 50°N. This diagnostic has also been calculated by Palmer et al. Their map of the deceleration due to gravity wave drag is almost identical to Figure 8b.

A further difference between the schemes is highlighted by Figure 9, which shows the global mean surface stress calculated for just one case from each of experiments O and R. Note the larger value computed by the operational scheme which is nearly twice that inferred from observational evidence. The diurnal variation is a consequence of using a value of θ from the lowest model level when calculating the stability term and reflects the global distribution of orography. Experiment S is therefore

Figure 3. 1000mb mean error (Dm) of 10 5-day forecasts from winter 1984-85. C = no drag, O = operational gravity wave scheme, R = Richardson number scheme and S = Richardson number scheme with enhanced surface flux.

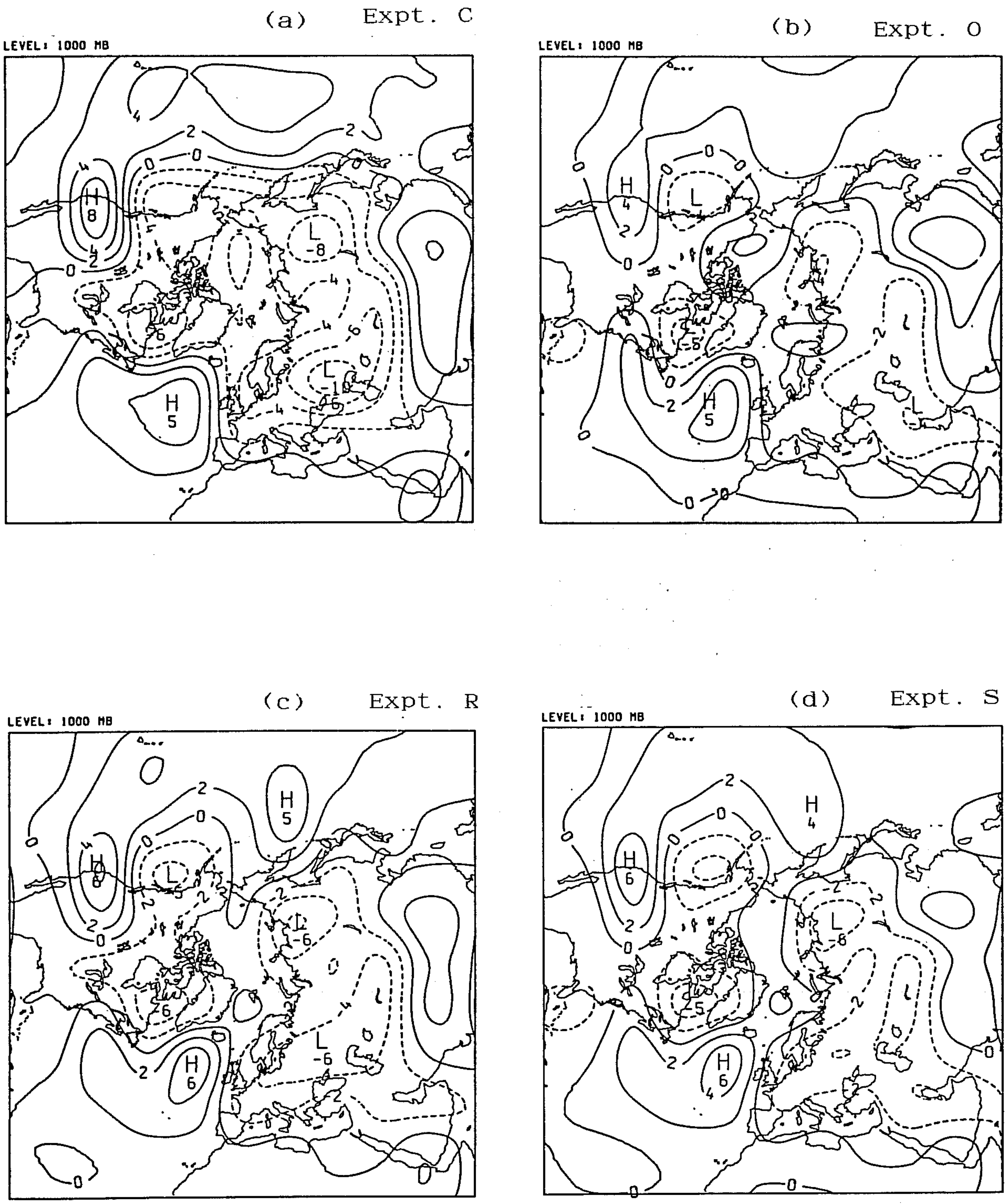


Figure 4. 500mb mean error (Dm) of 10 5-day forecasts from winter 1984-85. C = no drag, O = operational gravity wave scheme, R = Richardson number scheme and S = Richardson number scheme with enhanced surface flux.

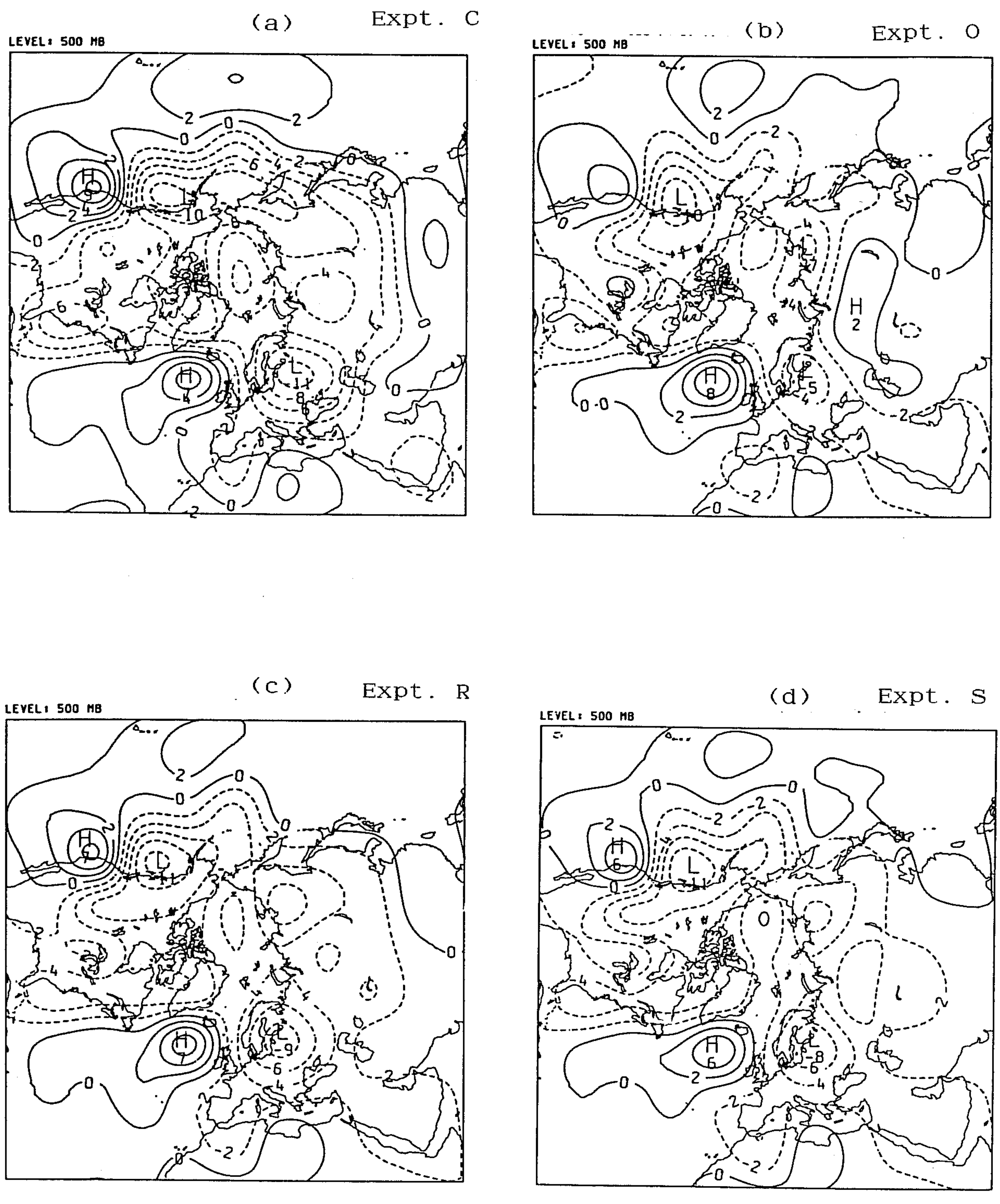


Figure 5. 50mb mean error (Dm) of 10 5-day forecasts from winter 1984-85. C = no drag, O = operational gravity wave scheme, R = Richardson number scheme and S = Richardson number scheme with enhanced surface flux.

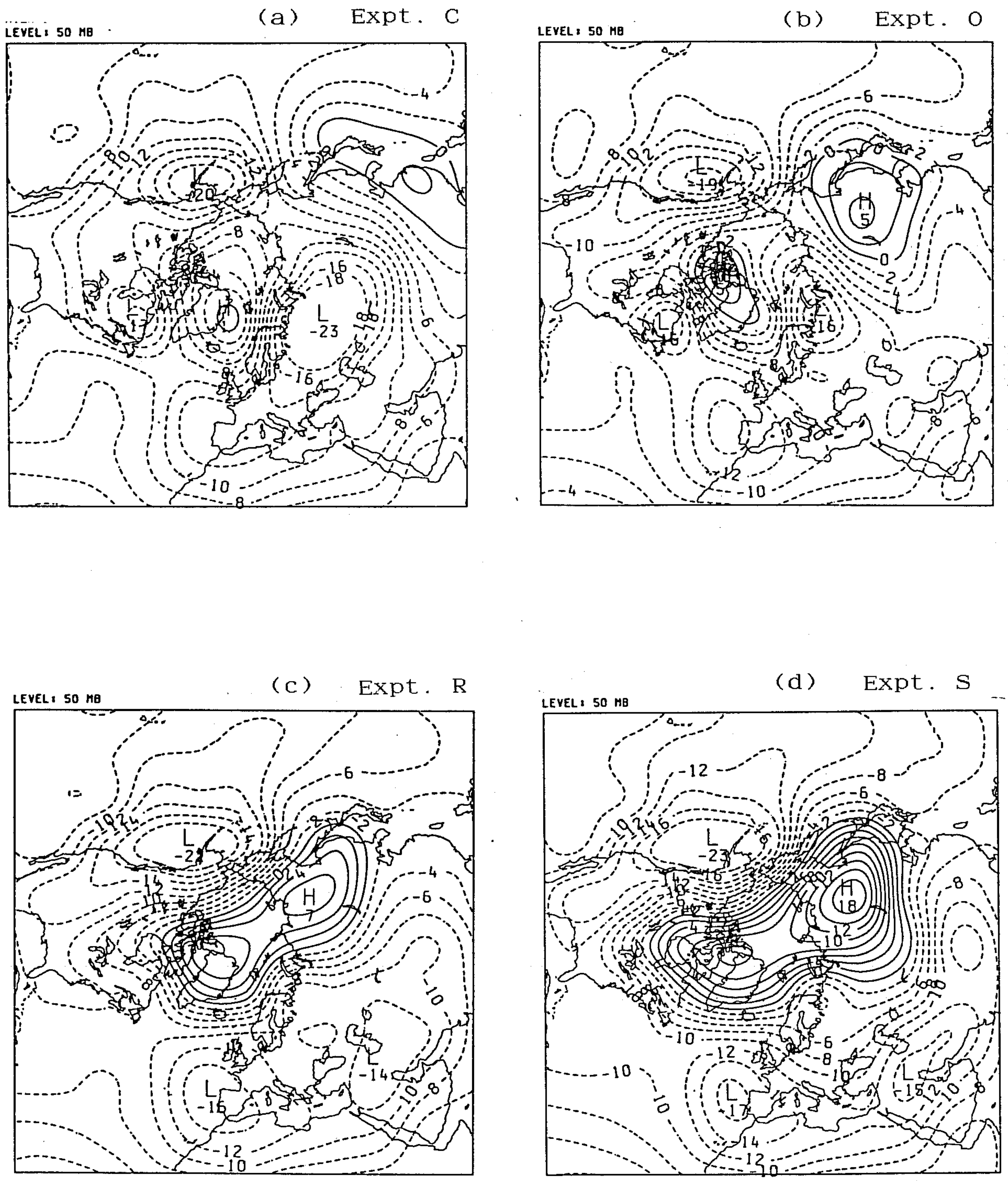


Figure 6. Zonally meaned height error (Dm) from 10 5-day forecasts taken from winter 1984-85. C = no drag, O = operational gravity wave scheme, R = Richardson number scheme and S = Richardson number scheme with enhanced surface flux.

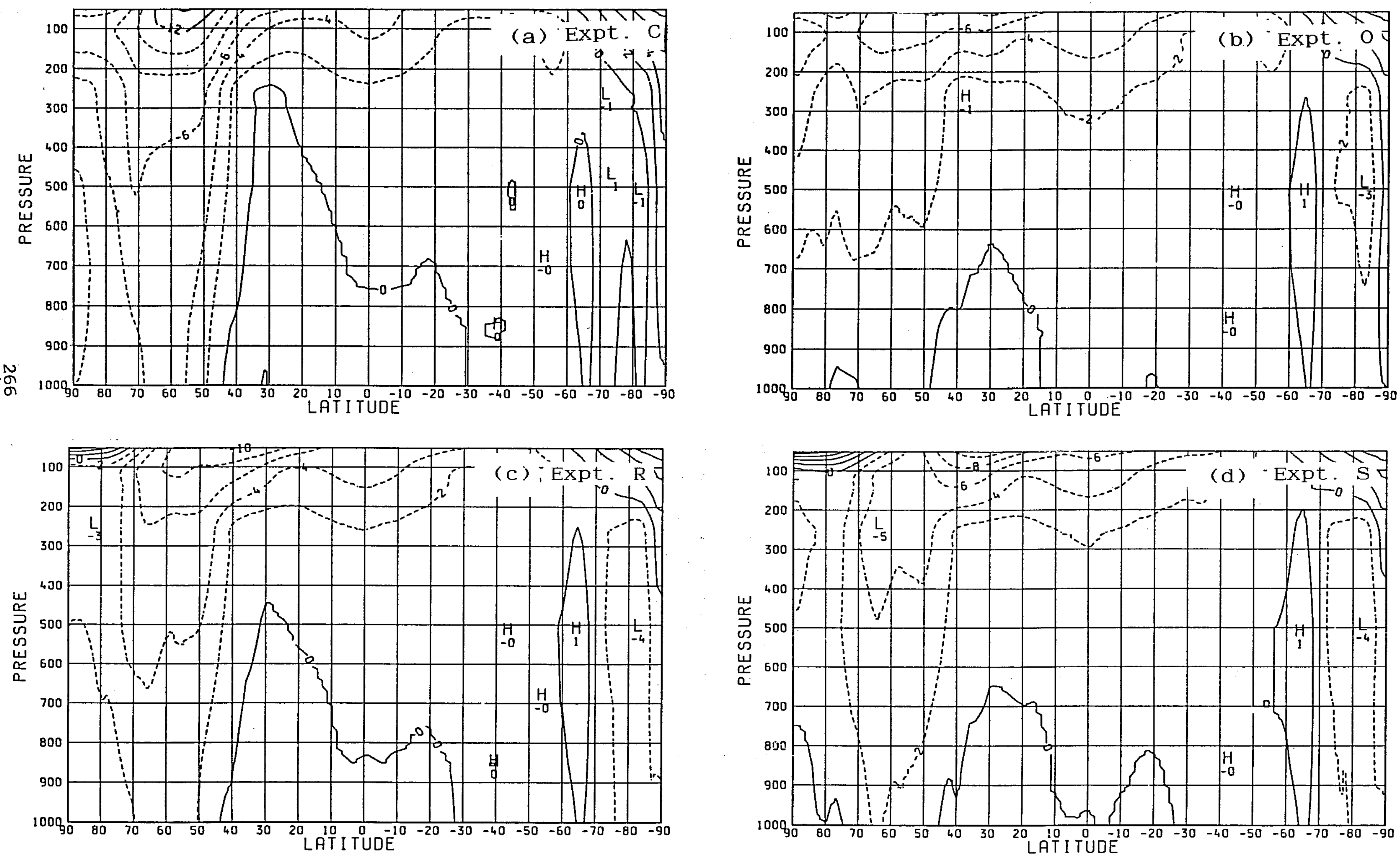


Figure 7. Zonally meaned zonal wind error (m/s) from 10 5-day forecasts taken from winter 1984-85. C = no drag, O = operational gravity wave scheme, R = Richardson number scheme and S = Richardson number scheme with enhanced surface flux.

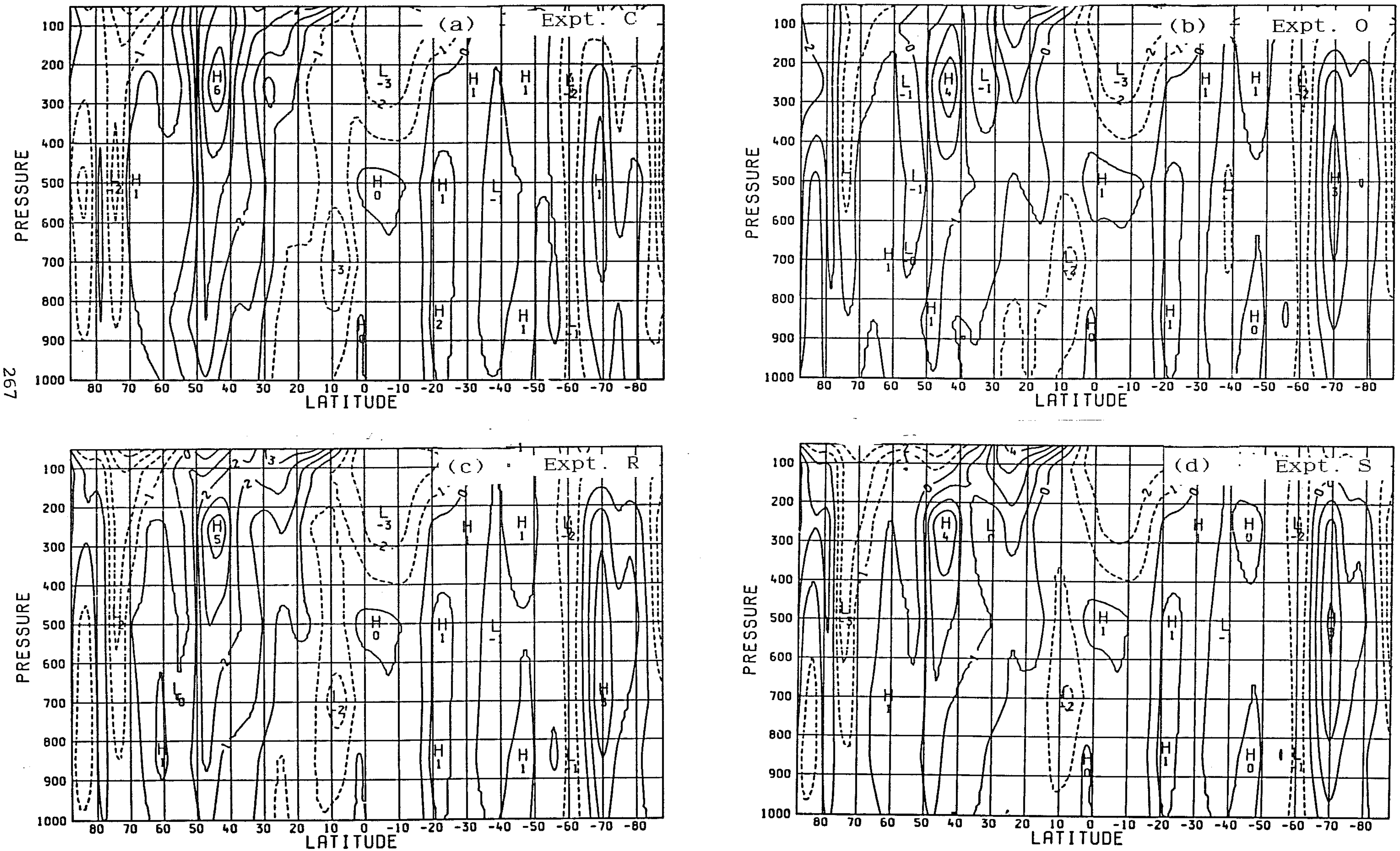
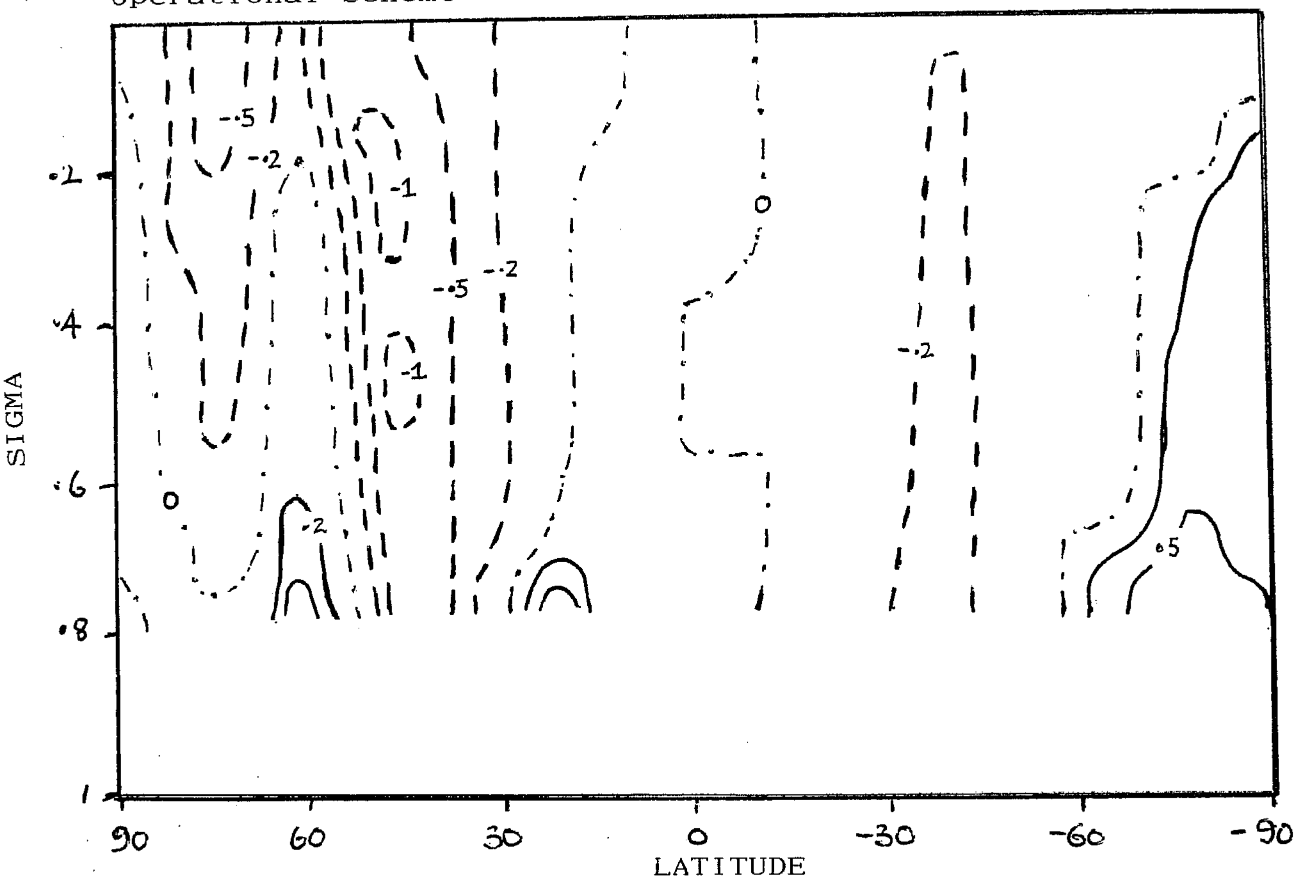


Figure 8. Zonal mean acceleration due to gravity wave drag ($ms^{-1}day^{-1}$). Values calculated at T+72 of forecast from 12z 16-11-84.

(a) Operational scheme



(b) Richardson number scheme

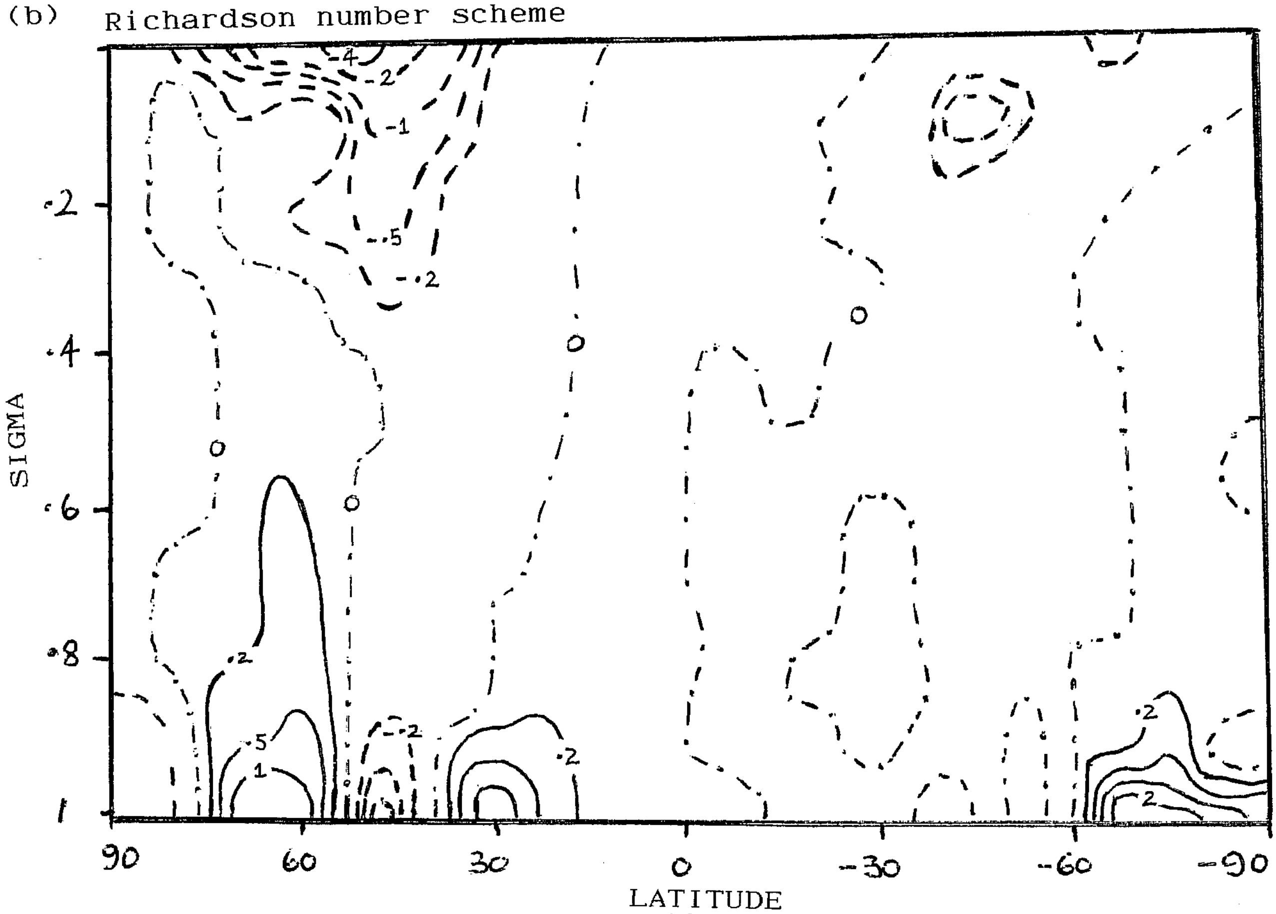
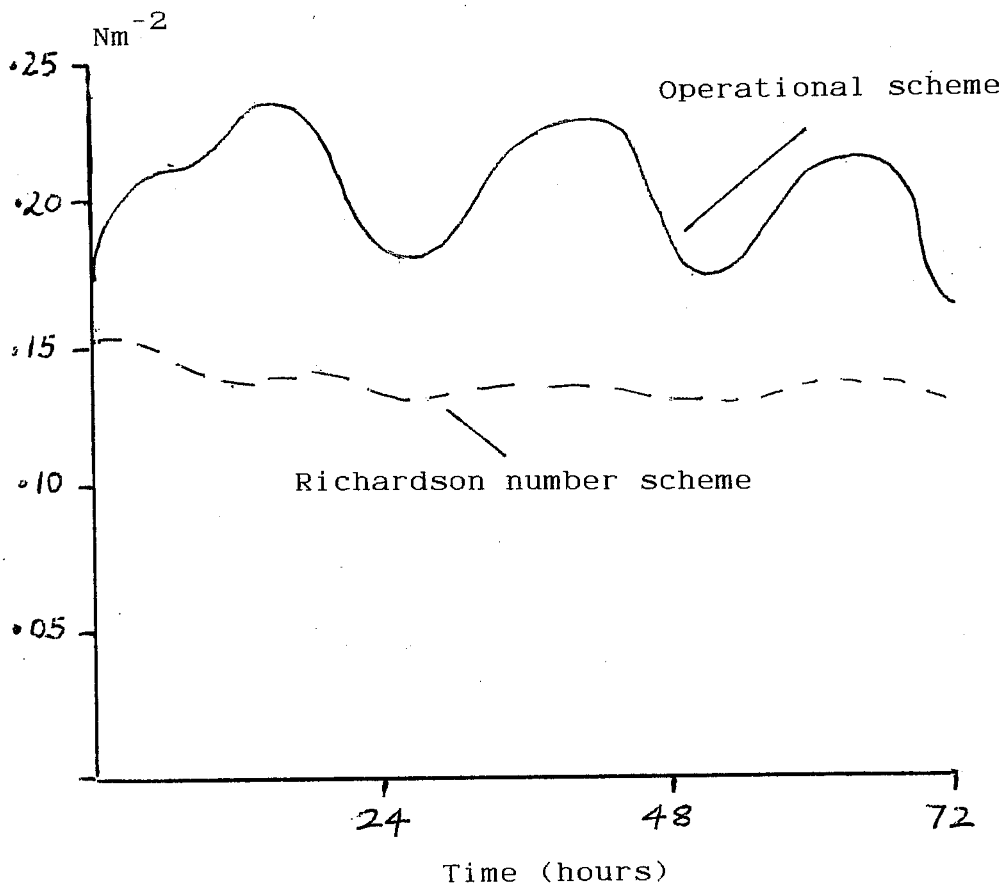


Figure 9. Global mean surface stress calculated from forecasts run from 12z 16-11-84.



designed to make the time averaged surface stress calculated by the Richardson number scheme approximately the same as in the operational scheme by increasing its value by 50%. However, it is still not possible to guarantee that the amount of stress absorbed by the model atmosphere is the same for each scheme. This is because the operational scheme ignores 50% of the remaining flux at the critical line and so less stress is actually absorbed than implied by Figure 9.

Let us now consider the results of the experiments. A comparison of the 1000 mb error patterns (Figure 3) shows that experiments, O, R and S have all led to a significant reduction in the systematic bias, the geographic distribution of the reduction being similar in each case. The amount of reduction in experiment O is greater than that in experiment S which in turn is greater than that in experiment R. Note, for example, the effect on the negative European anomaly. The relative impact of these experiments on the 500 mb error pattern is somewhat similar (Figure 4), but the reduction in the negative height error in northern regions is not as large. At 50 mb (Figure 5) the difference between the impact of experiment O and that of experiments R and S is much larger. The extra drag at stratospheric levels resulting from the Richardson number scheme has led to a warming of the pole with the negative anomaly of the control experiment being replaced by a larger positive one. The effects of experiment O at this level appear small but beneficial.

The cross-sections of zonally meaned height error (Figure 6) also highlight similar differences in the behaviour of the two parametrizations. The barotropic nature of the model's westerly error is clearly shown by the results of the control experiment, where underestimation of the height field at all levels between 50°N and 70°N has led to a chracteristic trough in the error pattern. Experiment O removes much of the tropospheric error as well as some of the stratospheric bias. Experiments R and S have smaller effects on the mid-tropospheric error and lead to an additional positive error above 100 mb near the North Pole. The zonal wind error charts (Figure 7) show a reduction in the tropospheric westerlies consistent with the height errors. Although the experiment O results are again the most satisfactory, there is evidence of a dipole at 250 mb and 40°N suggesting that the subtropical jet has now moved too far northwards. A worrying aspect of experiments R and S is the large easterly error that occurs at 75°N, intensifying a bias which was already present in the control experiments.

5. Discussion

The results of these experiments clearly show that a parametrization of atmospheric drag caused by the breaking of gravity waves whose source is the unresolved sub-gridscale variation in orography can lead to a large reduction in the tropospheric westerly bias that is a feature of many high resolution forecast and climate models. It appears that the best response in the UK operational forecast model is obtained by using a parametrization of the vertical distribution of drag which leads to a constant deceleration of the wind field with height. Such a distribution does not conform to current ideas on gravity wave propagation and breaking. The Richardson number scheme developed by Palmer et al (1986) relates the breaking mechanism to a measure of the local stability, such that most of the flux of gravity wave momentum is absorbed in the stratosphere. Tests with this scheme show a smaller but still positive impact on tropospheric errors, but suggest that stratospheric errors may be increased.

It is tempting to try to explain the apparent benefits of the operational scheme in purely physical terms. It may be argued, for example, that gravity waves do indeed break at all levels of the atmosphere in some manner consistent with this parametrization. Radiosonde ascents often show a great deal of fine structure in their vertical profiles. Danielsen (1959), for example, plots vertical sections of potential temperature using raw radiosonde data, which show highly stable layers sandwiched between layers of virtually neutral stability. The vertical extent of these stable layers is only of the order of a few hundred metres. Such detail cannot possibly be represented by the smooth vertical profile of a numerical model, but the presence of these thin layers would undoubtedly lead to gravity wave breaking in the atmosphere. The Richardson number parametrization can only respond to the smooth model profile and may imply no breaking at all. Further tuning of the Richardson number scheme in which a larger threshold values of $\widetilde{Ri}$ is used to determine whether wave breaking takes place may be necessary. This would allow wave breaking to occur more readily and the vertical distribution of drag would then become more like that of the operational scheme.

Further help in understanding the results of these experiments may be provided by a recent comparison by Slingo and Pearson (1986) of the effects of envelope orography and the Richardson number formulation of gravity wave drag on the UK's general circulation model. Using results from parallel 4-year integrations, they conclude that both envelope orography and gravity wave drag can substantially reduce the westerly bias during the northern hemisphere winter, though the gravity wave integration generally gave a better representation of the details of the winter climate. However, they found no evidence of the stratospheric errors shown by experiments R and S.

Indeed one of the major faults in their control experiments was an intensification of the polar night jet, which was successfully removed in their gravity wave experiment. This evidence suggests that we should perhaps look to deficiencies in the treatment of the stratosphere in the operational model. Although the operational model verifies well in these regions, there may be compensating errors which are exacerbated by the Richardson number scheme. Two differences between these models are currently being investigated. The first is the horizontal diffusion of thermodynamic variables and how this interacts with the model's stability filtering at high latitudes. Recent tests with a revised formulation of horizontal diffusion have led to a small reduction in the easterly bias in polar regions shown in Figure 7. The second difference is the treatment of radiation. The operational model uses a simple climatological scheme which uses zonally averaged observed heating and cooling rates, whilst the climate model uses a fully interactive scheme in which the effects of absorption and emission by ozone and carbon dioxide in the stratosphere are explicitly calculated.

In conclusion, it can be seen that much work is still required to fully understand the impact of gravity wave drag on our operational model. We have chosen a scheme that best fits our model's error structure. This is at variance with the ideas embodied by the Richardson numbers scheme. Caution needs to be exercised in its use and we should reinterpret our results as and when further deficiencies in the model's formulation come to light. Further understanding of the role played by orography in the momentum exchange between the earth's surface and the upper atmosphere is clearly needed. Orographically induced gravity waves may be just one of many mechanisms that contribute to this exchange and these are still poorly understood. Nevertheless, from a pragmatic point of view the scheme has many advantages; much of the model's systematic error is removed; it is simple in concept and economical in computer resources; and unlike envelope orography its effects are reduced in summer because of its dependence on the low level wind speed and static stability.

References

Atkins, M.J. and Woodage, M.J.	1985	Observations and data assimilation. Meteorol Mag, 114, 227-233.
Bell, R.S.	1983	The Meteorological Office operational global data assimilation and forecast system. Amer. Meteor. Soc, 6th Conf. on Num. Weather Prediction, Omaha, Nebaska.
Cullen, M.J.P	1983	Current progress and prospects in numerical techniques for weather prediction models. J. Comp. Physics., 50, 1-37.
Danielson, E.F.	1959	The laminar structure of the atmosphere and its relation to the concept of a tropopause. Arch. Met. Bioklim., 11, 293-332.
Dickinson, A. and Temperton, C.	1984	The operational numerical weather prediction model. UK Met. Office, Met O 11 Tech. Note No. 183.

Foreman, S.J. 1983 The numerical weather prediction model of the Meteorological Office. Amer. Meteor. Soc., 6th Conf. on Num. Weather Prediction, Omaha, Nebraska, 96-101.

Gadd, A.J. 1985 The 15-level weather prediction model. Meteorol Mag, 114, 222, 226.

Hardman, M.E. 1985 The use of the 15-level model products in the Central Forecasting Office for forecasts for civil aviation. Meteorol Mag, 114, 273-281.

Hunt, R.D. 1985 The models in action. Meteorol Mag, 114, 261-272.

Lange A. and Hellsten, E. 1984 Results of the WMO/CAS NWP data study and intercomparison project for the Northern Hemisphere in 1983. WMO Programme on Short and Medium Range Weather Prediction Research.

Palmer, T.N., Shutts, G.J. and Swinbank, R. 1986 Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parametrization. (To be submitted to the Quart. J. Roy. Met. Soc).

Shutts, G.J. 1985 Parametrization of sub-grid scale gravity wve momentum transfer and its influence on forecast/climate models. 1985 ECMWF Seminar.

Slingo, A. and Pearson, D.W. 1986 A comparison of the impact of an envelope orography and of a parametrization of gravity wave drag on simulations with an atmospheric general circulation model. (To be submitted).

Wallace, J.M., Tibaldi, S. and Simmons, A.J. 1983 Reduction of systematic errors in the ECMWF model through the introduction of an envelope orography. Quart. J. Roy. Met. Soc., 109, 683-718.