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SENSITIVITY OF DYNAMICAL QUANTITIES TO HORIZONTAL RESOLUTION IN A CLIMATE SIMULATION WITH THE ECMWF ATMOSPHERIC GENERAL CIRCULATION MODEL (CYCLE 33)

by

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ABSTRACT

The ECMWF model (cycle 33) was integrated for a full seasonal cycle at the four horizontal resolutions T21, T42, T63 and T106. Within the limits imposed by the varying horizontal resolution, all other aspects of the model were identical for each integration. In this paper a comparison is made of the dynamical aspects of the simulations. Fields of zonally averaged zonal wind, eddy heat and momentum fluxes, global divergent wind and vorticity, and stationary wave patterns are presented and compared for each resolution.

The conclusions reached by this study are: (1) T21 is qualitatively different from the higher resolutions; (2) the highest resolution does not provide a simulation which is egregiously superior to T42 and there are aspects of the T21 simulation, especially in tropical convection, which are clearly better than those of the higher resolutions; (3) aside from differences in smaller scale boundary forcing at the higher resolutions, the T42, T63, and T106 simulations are nearly identical in the dynamical aspects of the circulation considered here; (5) increasing horizontal resolution alone will evidently not result in an overall superior simulation unless other aspects of the model are modified *pari passu*.

1. Introduction

Recently there have been a number of studies concerned with effects of varying horizontal and vertical resolution on GCM simulations, such as Mahlman and Umscheid (1987), Boer and Lazare (1988), Rind (1988), Tibaldi et al. (1990), Boville (1991), Kiehl and Williamson (1991). There are several motivations for conducting such studies. From the perspective of climate research, one would be interested in the coarsest (and presumably fastest running) resolution that adequately simulates the features of interest. Since climate simulation is non-deterministic, convergence of a model simulations with increasing resolution would enhance the confidence that could be placed in the various climate change scenarios to which the model is applied. A practical consideration is to determine how much improvement can be had simply by increasing the horizontal resolution of the current model.

Given the history of increases in computer power, it might well be more efficient just to increase the computational resources rather than reformulate the model in any significant fashion. The resolution studies may provide some insight on the scale dependencies of the various parameterization that comprise the physical representations in a GCM. There is no guarantee that relationships that behave quite satisfactorily at T21 will continue to provide realistic simulations at T106. In addition, new physical parameterizations might be needed as resolution increases. Palmer et al. (1988) point out that at higher resolutions gravity wave drag is needed to improve the simulations. Boundary conditions and other parameters that were adequate at lower resolutions might have to be revised as new phenomena are now resolved.

It is important to realize as Boer et al. (1984) and Stone and Risby (1990) point out, that the GCMs do not compute the physics of the atmosphere from first principles but rely on a set of assumptions relating variables on the scales that the models resolve to the underlying physical processes that they are attempting to simulate. The model equations thus embody approximations that may change as the resolution changes. Kiehl and Williamson (1991), for example, find that the simulated total cloud amount decreases monotonically with increased resolution in the NCAR CCM1 due to increased advective drying in the lower atmosphere by subsidence, which raises the question of the scale dependence of the cloud and precipitation parameterization in the NCAR CCM1.

With the exception of Boer and Lazare (1988), the studies cited above all report improvement in some sense as the resolution of the models is increased. Boer and Lazare (1988) noted differences in the simulations but did not find a consistent improvement of the fields they examined with increased resolution. It may, however, be significant that their study considered resolutions only from T20 to T40, while other studies went to appreciably higher resolution (from T63 to T106). On the other hand, all studies observe that the improvement with resolution is not uniform for all aspects of the simulation. For some variables and processes in some regions, the simulation seriously degrades as the resolution becomes higher.

In general, the mean state variables improve most consistently with resolution and, as might well be expected, the eddy properties often change more dramatically. Boville (1991) noted that the T63 simulation in his study with the CCM1 produced eddy fluxes somewhat greater than the climatological values. He attributed this to the fact that the model at T63 produced a sudden stratospheric warming, which has a dramatic impact on the eddy structure. Mahlman and Umscheid (1987) also observed that their model was able to produce such a warming as the resolution was increased to 1 x 1 degree. From these two simulations, there is a hint that stratospheric warmings might be more common at higher resolutions. Care must be taken when comparing different resolution simulations to account for such newly resolved phenomena. Interestingly, the greatest impact of higher horizontal resolution is often seen in the stratospheric simulation, especially when there is sufficient vertical resolution to adequately model the stratosphere. This indicates that models that do not make a serious attempt to model stratospheric processes may encounter problems as such phenomena are initiated but are subsequently poorly simulated.

The present study focuses on the large-scale dynamical aspects of the simulations, and is intended to shed some light on the resolution issue in two ways. First, the resolution is extended to T106 which is higher than all the previous climatological studies with the exception of Kiehl and Williamson (1991), who comment that it would be important to consider resolutions as high as T106 with a model containing significantly different parameterization. Second, this work extends the duration of the resolution study of Tibaldi et al. (1990) using the ECMWF model whose runs only went to 30 days. Tibaldi et al. (1990) indicated that T42 might be an adequate resolution for extended time integrations, and the present work tests this conjecture on a complete seasonal cycle. Kiehl and Williamson (1991) concluded that T63 was probably needed for climate work, although the substantial increase in computing resources required to go from T42 to T63 also needs to be considered.

This work only addresses the effects of changing the horizontal resolution. Lindzen and Fox-Rabinovitz (1989) have argued that the horizontal and vertical resolutions should be consistent, and that in general the present generation of models have horizontal resolutions which require finer vertical resolution than they now possess. From a practical standpoint, it is rather more difficult to change the vertical resolution of a model than the horizontal resolution. The vertical structure in the model tends to be more closely tied to the details of the physical parameterizations. Boville(1991) did undertake a limited experiment in varying the vertical resolution but found little impact. Lindzen and Fox-Rabinovitz (1989) advance a number of speculations on why the models are relatively insensitive to their apparent horizontal and vertical resolution mismatches.

2. Model description and experiment design

The model used is the ECMWF operational forecast model (cycle 33) with no major modifications. The model code used for the experiments was that used operationally in July 1989. The sea surface temperature and sea ice distributions were specified from Alexander and Mobley (1976) and were interpolated to each day. The model uses a hybrid sigma vertical coordinate system in which the topmost level carries dynamically useful information to 10 hPa. There are 19 levels in the vertical,with extra resolution in the boundary layer. Although there is little attempt to model the stratosphere adequately, the simulation will be described to 10 hPa in order to ascertain the impact of the upper boundary on the tropospheric simulation.

The ECMWF model is cast in the spectral transform method in the horizontal, with the spherical harmonic expansions being truncated in the triangular mode in this experiment. Table 1 lists the four resolutions used, and the latitude longitude characteristics of the transform grids associated with each spectral truncation. All model runs were made with the same 19 level vertical resolution. The top boundary of the model is formally at zero pressure. The surface terrain was derived from the operational T106 values used at the ECMWF.

All the simulations except the T21 truncation were run using the gravity wave drag (GWD) parameterization described by Palmer et al.(1986). An attempt was made to run the T21 model with GWD but the integration proved to be unstable. A plot (not shown) was made of the zonally and vertically integrated GWD stress for each of the resolutions for which it was included(T42, T63, T106). The plot was found to be uncannily to that of Fig. 9 of Boville(1991) which is the plot of the same quantity for the T63, T42, T31 and T21 simulations of the CCM1. Boville's plot shows that above T21 all the curves are quite similar. The present work indicates that this correspondence extends to T106 for the ECMWF GWD parameterization as all the curves are very close.

A bi-harmonic horizontal diffusion operator (K_H) (Table 2) was used at all levels with the coefficients following the practice of the ECMWF, Tibaldi et al. (1990). A modified diffusion is used for temperature to avoid unrealistic warming over mountain tops and excessive summer precipitation on steep slopes. The diffusion coefficients used are listed in Table 1. For the T21 and T42 simulations, the coefficients are substantially larger than those presented by Boville(1991). The choice of diffusion coefficient should probably be more closely tied to the truncation of the model. The abrupt halving of the coefficient at T106 would seem to put the T63 simulation at the greatest disadvantage with respect to this parameter.

The integrations were performed for fifteen months with climatological monthly SST and sea-ice distributions. The initial conditions were set to 1 Jan 1987. The initial January means would be contaminated by the initial conditions, so the integration was extended to simulate a full winter (DJF) of data.

3. Description of results

a. *Introduction*

In assessing the results of a resolution study such as this there are two overlapping criteria to be considered. The first is that of the absolute evaluation of the simulations in terms of their comparison with published climatologies. The second is the relative evaluation of the different resolutions to each other. It should be noted that the simulations need not be perfect to yield useful information on the relative merits of the resolutions.

In undertaking the simulations' validation, one quickly realizes that this procedure is somewhat less objective than it appears. The various climatologies often do

Table 1. Spectral and transform grid resolution

Spectral truncation	Number longitudes	Number latitudes	Transform grid spacing (approximate deg lat)
T21	64	32	5.6
T42	128	64	2.8
T63	192	96	1.875
T106	320	160	1.125

Table 2. Horizontal diffusion coefficients

Spectral truncation	K_H ($10^{15} m^4 s^{-1}$) divergence	K_H ($10^{15} m^4 s^{-1}$) other fields
T21	5.0	2.0
T42	5.0	2.0
T63	5.0	2.0
T106	2.5	1.0

not cover the same period of time, and use different interpolation, analysis and data processing techniques. The result is that the climatologies differ and it is difficult to judge which is the most appropriate to use for comparison. Since we have only a single year of simulation the evaluation problem is greatly exacerbated. Unless a model discrepancy significantly exceeds the observed interannual variation, one can say little about its validity from such a short term integration.

Here a total of five different data collections will be used for comparison and evaluation. The data of Oort (1983), hereafter OORT, covers a span of 15 years from 1958 to 1973. The data of Newell et al. (1973), hereafter NKVB, covers 7 years from 1957 to 1964 with special emphasis on the Tropics. The Joint Diagnostics Project, hereafter JDP, described by Hoskins et al. (1990) uses ECMWF operational analyses for the 10 years from 1979 to 1989. They divide the analyses into the full 10 year period and the subset from 1983 to 1989 when the ECMWF used the diabatic initialization technique. This initialization procedure has a significant impact on the tropical circulation statistics. Another data set is available from the operational NMC analyses from 1979 to 1988. These data provide an important independent check on the ECMWF data. Since the ECMWF model is being evaluated it is important to have this data for comparison.

The evaluations will be made using time mean seasonal averages for the solstitial seasons of June, July and August (JJA) and December, January and February (DJF). The next section considers the zonally averaged fields, while the following section examines the geographically distributed fields for both the time mean and stationary waves.

b. *Zonal means*

Figure 1 presents the zonally averaged zonal wind for the northern winter from the OORT, NKVB, NMC observed data and from the T106 model simulation. The northern hemisphere simulation of this quantity by the T106 model appears to be adequate. The strong upper level tropical easterlies in the T106 data are large enough to definitely be in error. Likewise, the vertical extent of the jet and its magnitude in the Southern Hemisphere is not correct. The T106 simulation of the JJA season (not shown) has similar problems, with the tropical easterlies being too strong and the southern jet poorly simulated. Obviously, the very high resolution has not resulted in an outstanding simulation of the zonal wind.

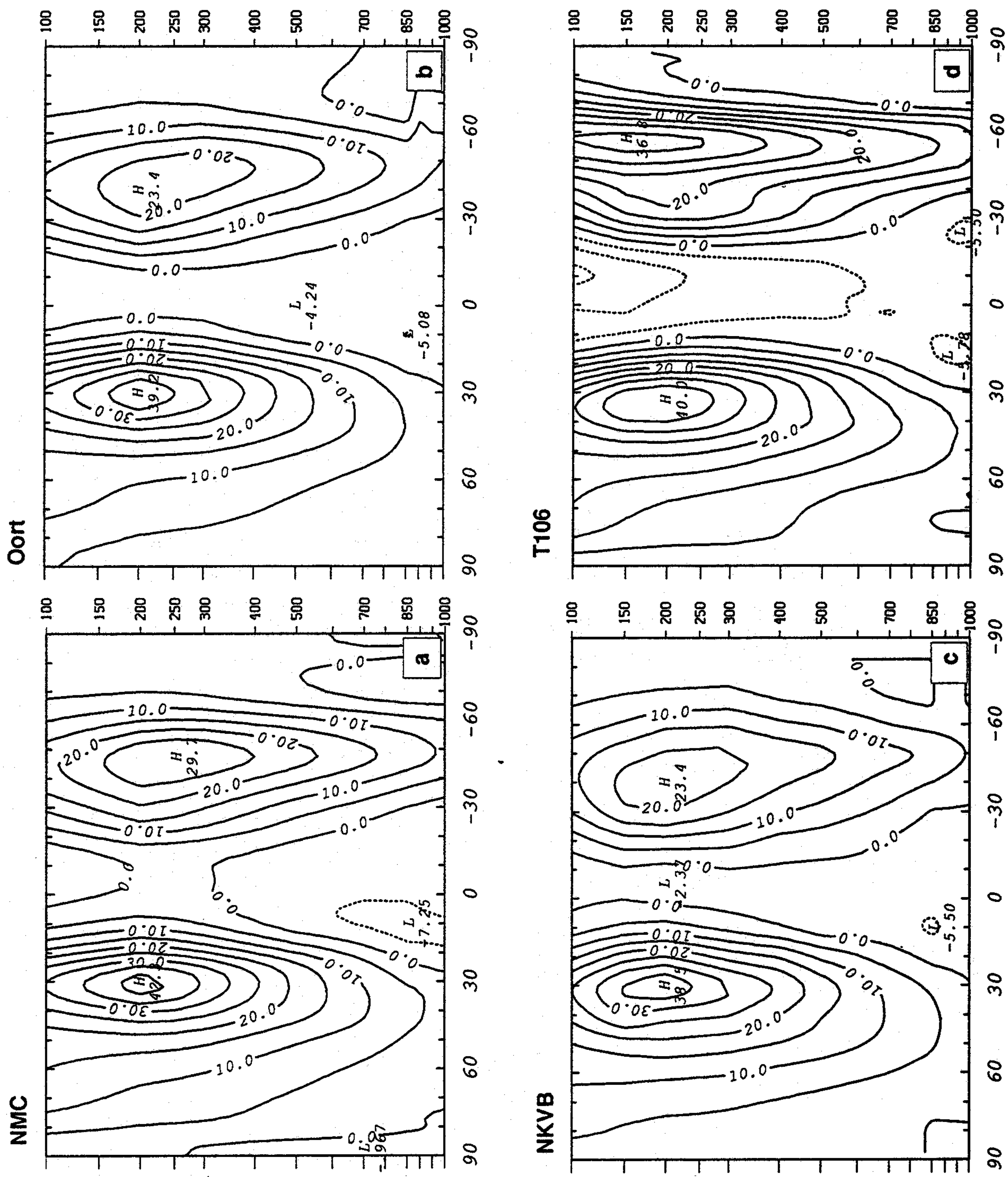


Fig. 1. Zonally averaged zonal wind for DJF from (a) NMC data, (b) OORT, (c) NKVB, and (d) T106 simulation. Contour interval is 5 m s^{-1}. Dashed contours indicate negative values (easterlies). (See text for data references.)

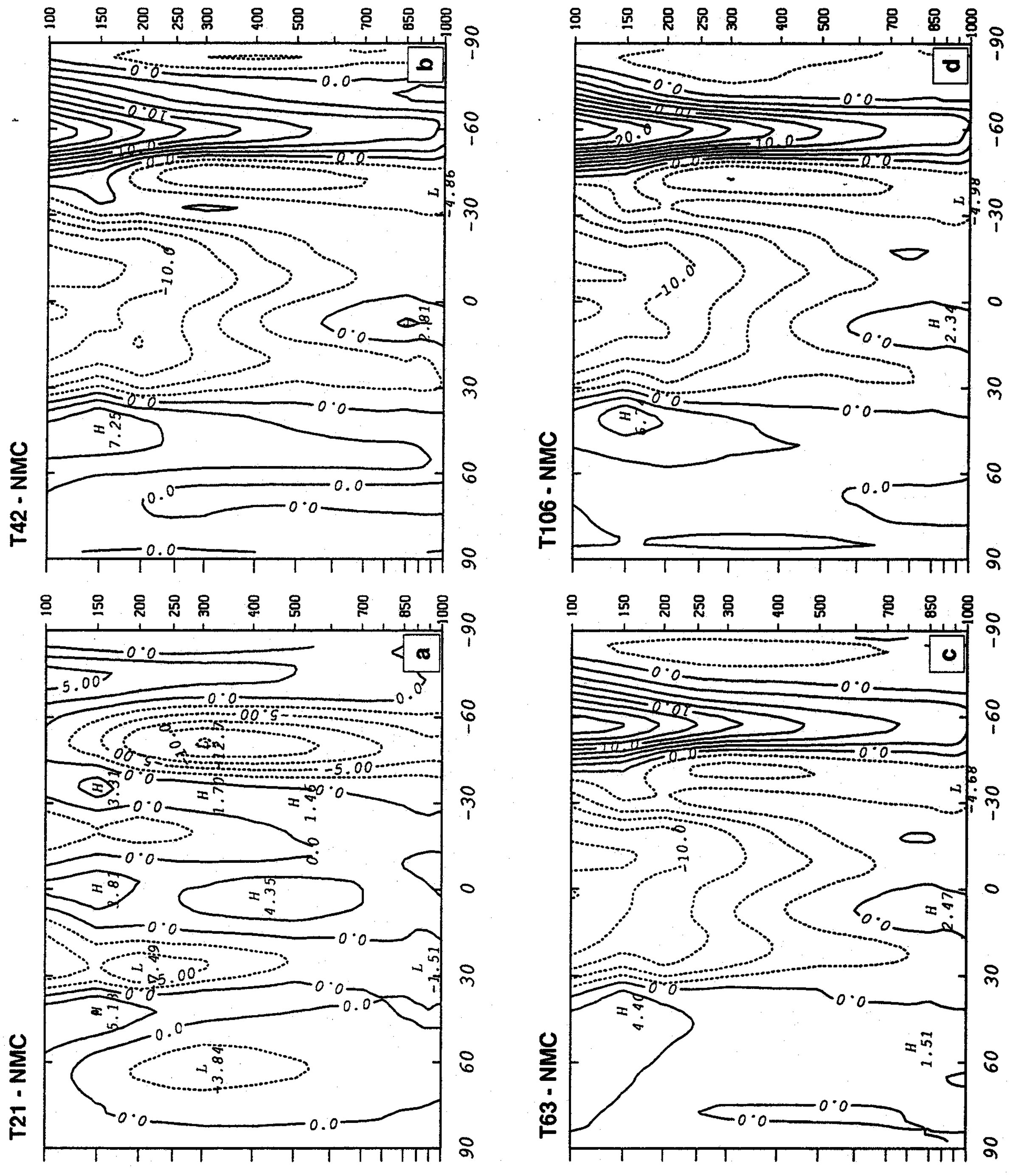


Fig. 2. Difference fields for zonally averaged zonal wind between the various resolutions of the model and the NMC data for DJF. (a) T21 - NMC, (b) T42 - NMC, (c) T63 - NMC, (d) T106 - NMC. Contour interval is 5 m s^{-1}. Dashed contours indicate negative values.

These types of errors are typical of the current generation of GCMs (WMO, 1991). To provide information on how the various resolutions performed relative to each other the differences of each simulation with respect to the NMC data (e.g. T106 - NMC) are shown in Fig. 2. The NMC data are chosen since it is felt that these data probably provide the best estimates in the Southern Hemisphere that are formally independent of the ECMWF data assimilation. The patterns of the difference in the resolutions above T21 are strikingly similar. As shown by Tibaldi et al. (1990), the T21 simulation possesses a unique character with respect to the higher resolutions. On the basis of Fig. 2 alone, it would be hard to argue whether T106 is greatly superior to T21. Below 200 hPa the magnitude of the differences are of the same order with the T106 errors appearing to be more systematic than T21. All the wind features in the T42 to T106 simulations appear too strong with respect to the NMC climatology. This is not too surprising in light of the fact that here only a single year simulation is represented. However, the magnitude of the difference in the tropical easterlies and in the southern jet indicate that the model is in error. The differences taken with respect to the OORT data (not shown) exhibit similar error patterns, although the magnitudes vary. The patterns of error in Fig. 2 are similar to those shown by Tibaldi et al. (1990) for 30 day integrations of the ECMWF model during the northern winter. Thus, the characteristic (systematic) errors that appear at 30 days in the integration of the model generally persist for at least a year, although they do not grow catastrophically. Tibaldi et al. (1990) displayed time series which indicated that the systematic error in the temperature field grew quickly and then started to level off after about 7 days.

It is not the purpose of this paper to focus on the shortcomings of a state of the art forecasting model used as a climate model; rather we wish to emphasize differences brought about by changing the horizontal resolution. To this end we present the differences in zonally averaged zonal wind between the various resolutions in Fig 3, where the difference field is obtained by subtracting the immediately higher resolution from the lower, *e. g.* (T21-T42). As before the T21 data stand apart. The (T21 - T42) fields are large, and below 100 hPa they resemble the T42 differences from the NMC data in Fig. 2. Note that due to data availability, Fig. 2 only goes to 100mb while Fig. 3 extends to the top of the model domain. The (T42 - T63) and (T63 - T106) fields have much smaller magnitudes than the (T21 -T42) data. The differences in the three higher resolutions do not indicate a smooth progression to a converged simulation.

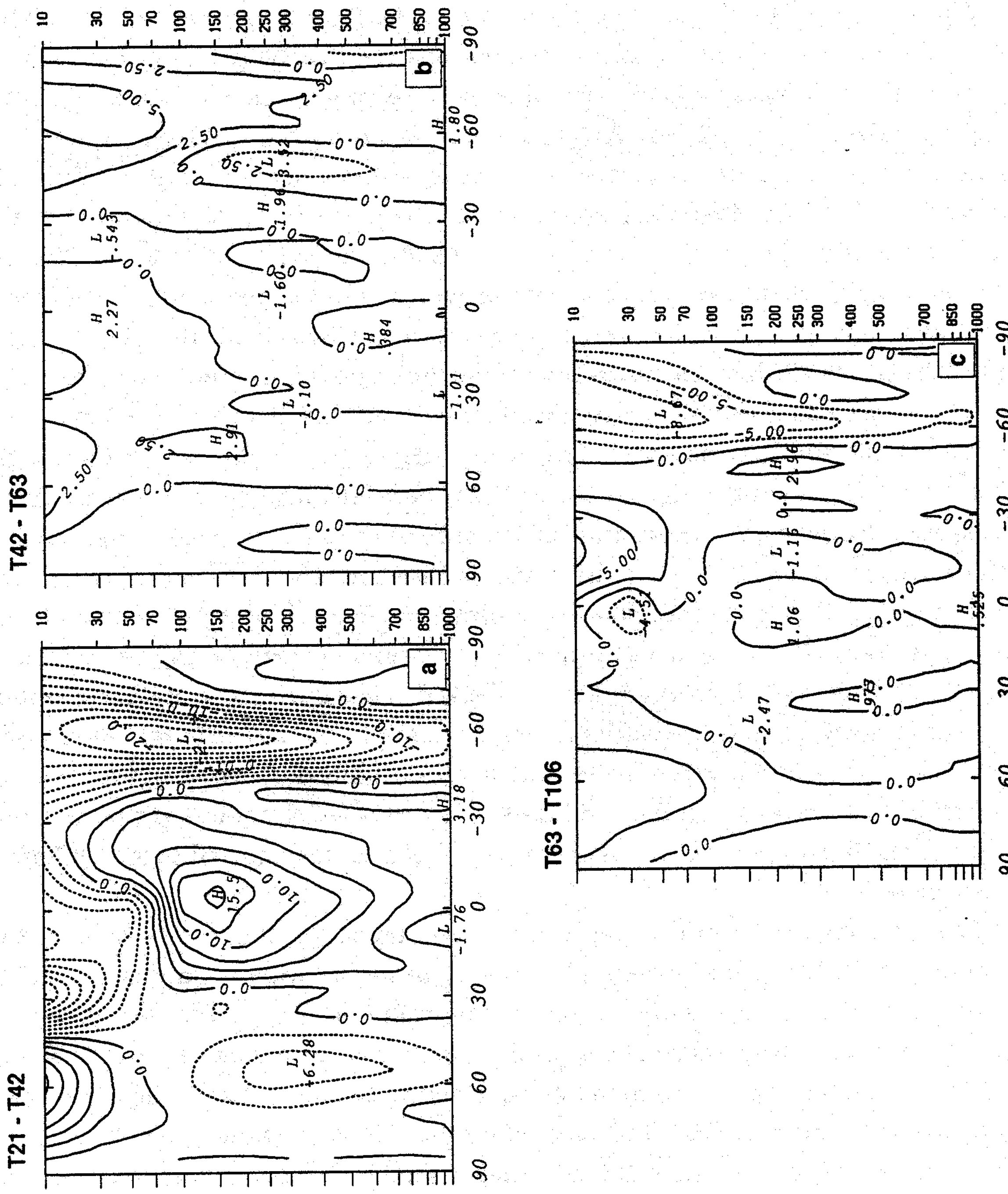


Fig. 3. Difference fields for zonally averaged zonal wind between successively higher resolutions for DJF. (a) T21 - T42, (b) T42 - T63, (c) T63 - T106. Contour interval is 5 m s^{-1}. Dashed contours indicate negative values.

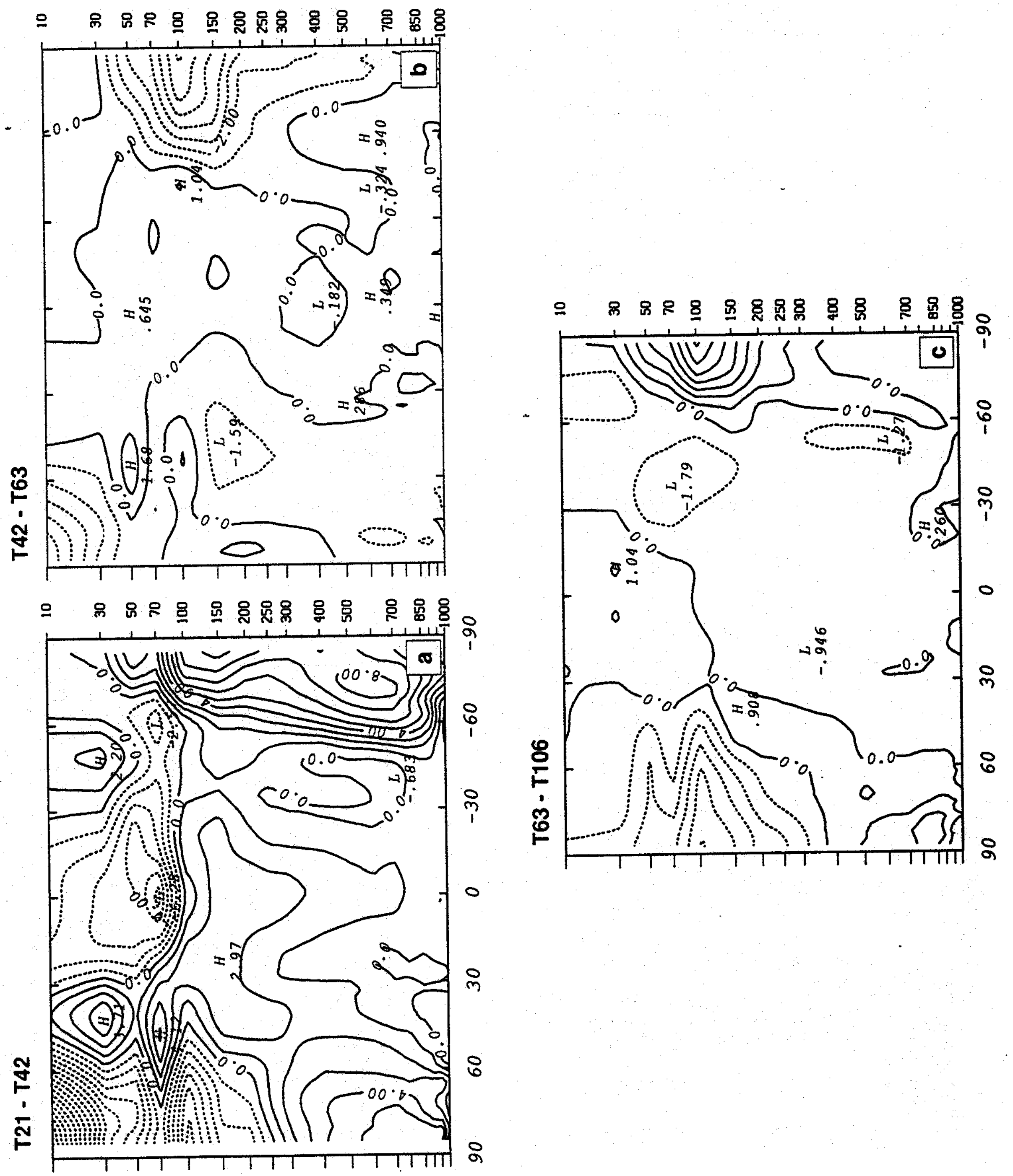


Fig. 4. As in Fig. 3 except for the zonally averaged temperature. Contour interval for (a) is 1 K, contour interval for (b) and (c) is 0.5 K. Dashed contours indicate negative values.

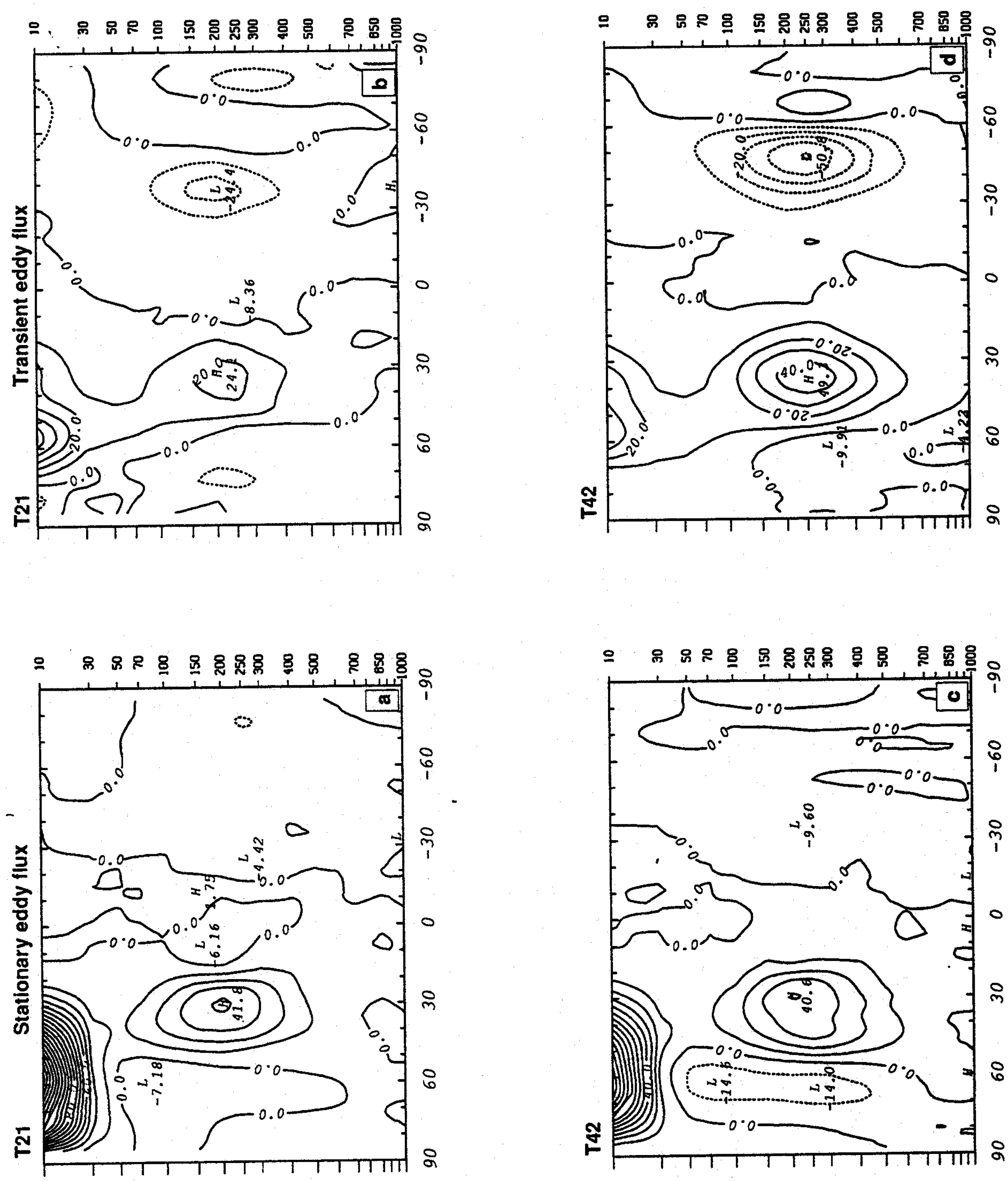


Fig. 5. Zonally averaged eddy momentum fluxes for the transient and stationary eddies for all resolutions for DJF. The contour interval is 10 $m^2 s^{-2}$. Dashed contours indicate negative values. (a) T21 stationary eddy flux, (b) T21 transient eddy flux, (c) T42 stationary eddy flux, (d) T42 transient eddy flux, (e) T63 stationary eddy flux, (f) T63 transient eddy flux, (g) T106 stationary eddy flux, (h) T106 transient eddy flux.

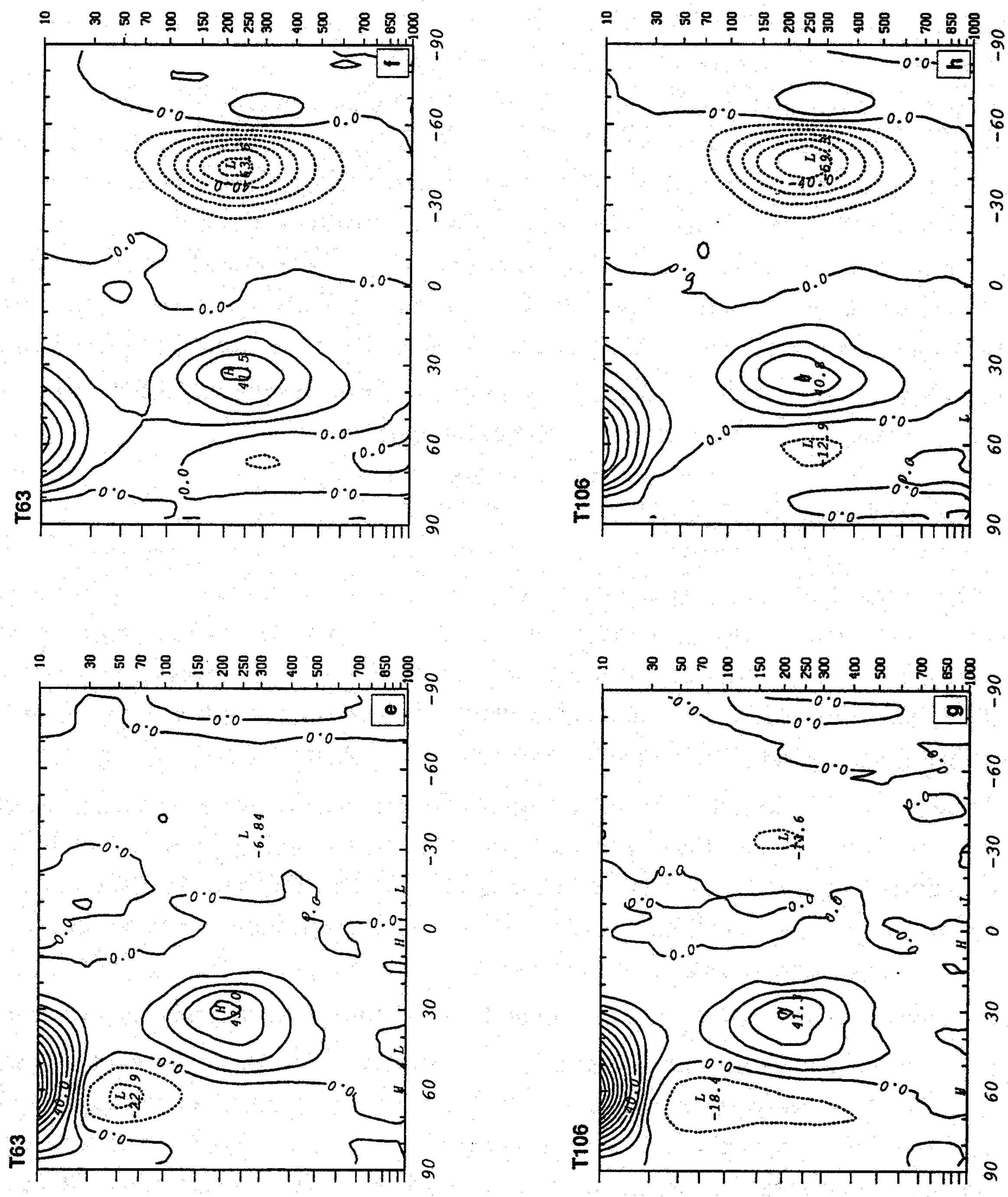

T63
T106
e
f
g
h
10 30 50 70 100 150 200 250 300 400 500 700 850 1000
90 60 30 0 -30 -60 -90
0.0
L
-6.84
-22.9
-18.4
-40.0

Fig. 5 (part 2)

The (T63-T106) and (T42-T63) fields often have opposite sign. The data for the southern winter, JJA (not shown) have the same features.

Figure 4 presents the difference fields for the zonally averaged temperature. The same comments can be made concerning this figure as with the zonal wind. Note that in Fig. 4 the contour interval for (T21 - T42) is double that of the others. The reversal in sign of the difference from (T42 - T63) to (T63 - T106) is even more evident in Fig. 4. This indicates that there is no consistent correction of the model's known cold bias with increasing resolution. Below 200 hPa at least, the differences between the higher resolutions are less than those associated with CO_2 doubling experiments (Schlesinger and Mitchell, 1985). This indicates that resolution differences alone might not obscure the effects of such climate experiments.

4. Eddy fluxes of momentum

Quantities often considered in detail in resolution studies are the eddy fluxes. It seems reasonable that as the smaller scale eddies are resolved these quantities would be better simulated, if the model embodies the proper descriptions of the various scale interactions. One could as easily incur deterioration of the eddy simulation with increasing resolution if the model is erroneously modelling the flow of energy between the scales. As seen in Fig. 5, in the Northern Hemisphere there is a jump of 25 m^2s^{-2} in the maximum value of the transient poleward flux in going from T21 to T42, and then a small but steady decrease in going to T106. In the Southern Hemisphere, there is again a sharp rise from T21 to T42 but there is a more pronounced increase in going from T42 to T63 and then a slight decrease in proceeding to T106. The JDP data indicate a northern hemisphere maximum of 40 m^2s^{-2} and a southern hemisphere maximum of -50 m^2s^{-2}. From just a single year simulation all that can be said is that the T21 data are clearly too small and that the higher resolutions produce credible magnitudes of transient flux. The positions of the maximum flux convergence appear to be slightly poleward of the climatological positions, which is a typical GCM error WMO(1991). The decrease in the northern hemisphere maxima of transient eddy flux in going from T42 to T106 does indicate that the model is not relentlessly cascading energy to smaller scale eddies as the resolution increases. The stationary eddy fluxes display little variation in the northern hemisphere poleward maximum for the four

Table 3. Momentum fluxes for DJF (m^2s^{-2})

	Transient			Stationary		
Resolution	NH	Tropics*	SH	NH	Tropics*	SH
T21	24	-8	-24	42	-6	-4
T42	49	0	-51	41	0	-10
T63	42	0	-64	43	0	-7
T106	41	0	-59	41	0	-12
Observed (JDP)	40	-5	-50	35	-10	-5

* Tropics defined as extremem nearest equator within 15N to 15S.

Table 4. Momentum fluxes for JJA (m^2s^{-2})

	Transient			Stationary		
Resolution	NH	Tropics*	SH	NH	Tropics*	SH
T21	10	14	-43	9	28	-5
T42	33	6	-70	13	12	-9
T63	37	6	-69	21	12	-6
T106	29	7	-64	13	10	-7
Observed (JDP)	30	5	-55	10	5	<5

* Tropics defined as extremum nearest equator within 15N to 15S.

Table 5. Eddy kinetic energy for DJF (m^2s^{-2})

	Transient		Stationary		
Resolution	NH	SH	NH	Tropics*	SH
T21	199	187	136	50	35
T42	181	202	178	lt 25	41
T63	212	284	202	lt 25	36
T106	221	279	177	lt 25	31
Observed (OORT)	260	260	80	10	< 10

*Tropics defined as extremum nearest to Equator within 15N to 15S.

Table 6. Eddy kinetic energy for JJA (m^2s^{-2})

	Transient		Stationary		
Resolution	NH	SH	NH	Tropics*	SH
T21	156	212	42	86	50
T42	173	219	42	55	32
T63	187	271	62	63	37
T106	184	251	54	61	48
Observed (OORT)	200	250	20	15	20

*Tropics defined as extremum nearest to Equator within 15N to 15S.

resolutions. The variation that does exist is mostly in the equatorward flux, poleward of 55 N. All the maxima exceed the JDP value of 35 m^2s^{-2}. The stationary wave fluxes in the Southern Hemisphere at least double in magnitude in going from T21 to T42, but remain relatively small compared to their northern counterparts consistent with the observations.

Tables 3 and 4 provide a summary of the character of the zonally averaged transient and stationary eddy momentum fluxes, along with the values of the principal maxima and minima in these fields. In general the model has maxima at the climatological levels, but the position is usually slightly poleward of the climatological position. This poleward bias is a common feature of many GCM simulations. For comparison the climatological data from the JDP are also shown in Tables 3 and 4, and represent 10 year means. It can be seen that the T21 simulation is especially poor with regard to the transient flux. The T106 fluxes exhibit a slight decrease in transient flux relative to T63, after an increase in going from T21 to T63. Since multiple season flux means are often less than individual years, the agreement seen in Tables 4 and 5 between the JDP and model data is probably not as good as it might seem. For an ensemble of seasons the model means might be significantly reduced.

a. Eddy kinetic energy

Tables 5 and 6 present the maximum values of the prominent maxima and minima of the transient and stationary eddy kinetic energy. In the higher latitudes the maxima are between 200 and 300 hPa, while in the Tropics they are generally higher. In JJA the tropical maxima are in the location of the tropical easterly jet at 150 hPa at 10N. In general, the model underestimates the energy of the transients, although the increase in resolution increases the total energy. As noted in other studies, the fact that the kinetic energy of the eddies is underestimated while the fluxes are about correct indicates that the structure (i. e. tilt) of the eddies is probably not correct on average. Boville(1990) demonstrated a rather marked increase of about 20 percent in the transient kinetic energy in going from T21 to T63. However, his T21 energy levels were substantially lower(125 m^2s^{-2})than obtained here and his T63 energy was somewhat less than observations and our results. It should be noted, however, that Boville(1990) used an average of 4 seasons for the T21 data, 2 seasons for T42 and just one season (as here) for T63. This tends to make the interpretation slightly less

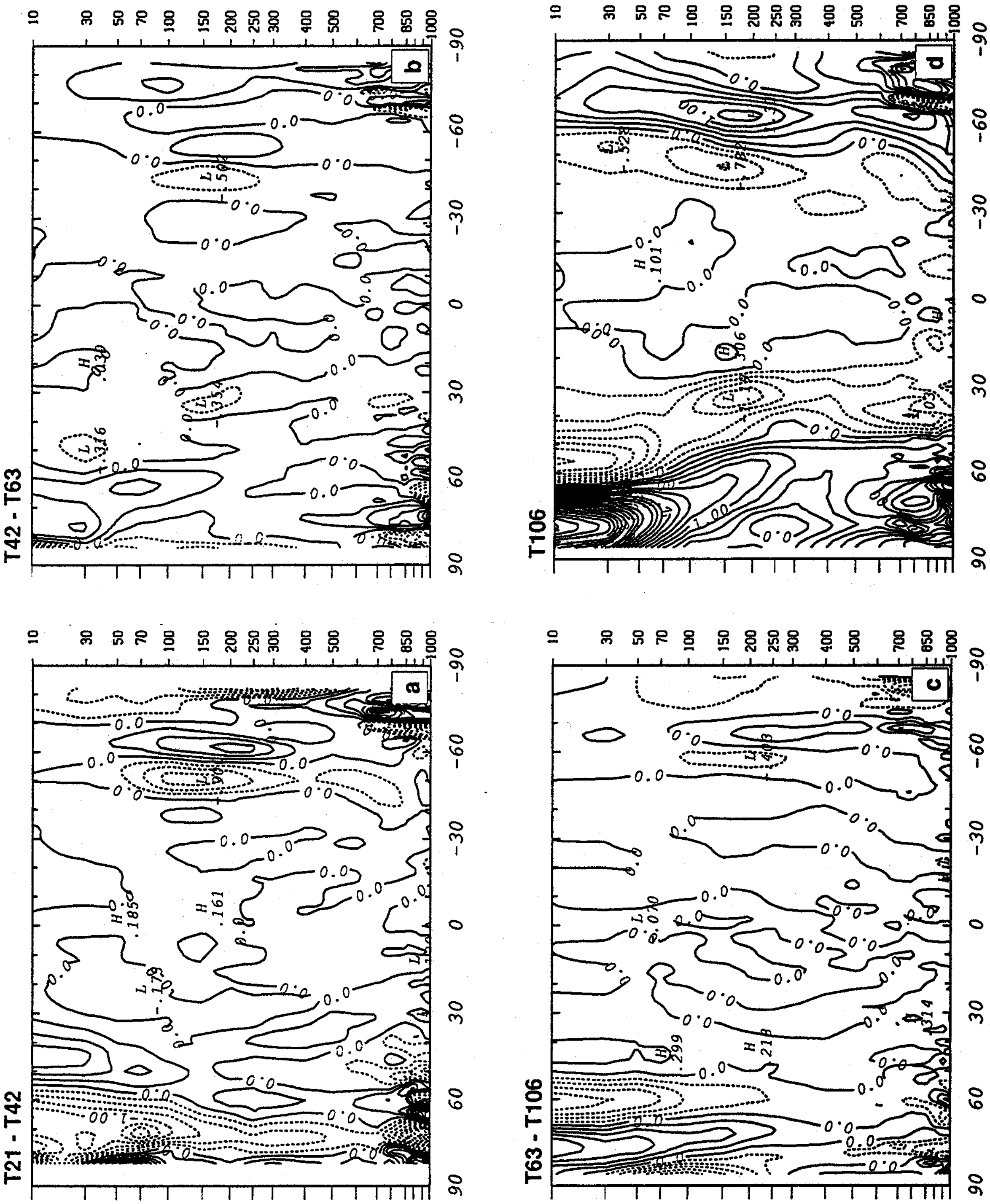


Fig. 6. (a) The difference in the zonally averaged eddy (transient and stationary) heat flux convergence between T21 - T42 for DJF. Contour interval is 0.25 deg C day^{-1}. Dashed contours indicate negative values(cooling). (b) As in (a) except for T42 - T63. (c) As in (a) except for T63 - T106. (d) Zonally averaged eddy (transient and stationary) heat flux convergence for T106 for DJF.Contour interval is 0.25 deg C day^{-1}. Dashed contours indicate negative values(cooling).

straightforward since the ensemble average will have smoothed values from a single realization even if the model were perfect in its simulation. Interestingly, the stationary energy shown in Tables 5 and 6 is somewhat greater than the climatological values, with the increase in resolution not ameliorating the condition in any consistent fashion.

b. Heat transport and budget

Computations of the eddy fluxes of heat were also carried out with results analogous to those cited above for the momentum fluxes. However, the quantity that actually determines the tendency of the temperature or momentum is the divergence of the fluxes. Since this depends on the derivatives of the fluxes, the flux divergence should be a more sensitive indicator of the effects of resolution than the fluxes themselves. Figure 6 presents the differences in the zonally averaged eddy (transient and stationary) heat flux divergence between the four resolutions and the flux divergence for T106 for the DJF season. Figure 7.20 of NKVB is appropriate for comparison with the T106 data. The pattern of T106 is quite similar to the NKVB data with the extrema being larger in the T106 data, in many cases a factor of two. The differences in the resolutions follow the pattern established by other fields in that the T21-T42 data generally exhibit the largest values. The basic conclusion is that none of the differences among the resolutions above T21 are substantial enough to alter the basic heating pattern due to this field. The large differences in the region of the south pole are due to extrapolation of values below the terrain height.

The zonally averaged heat budget was computed for the four resolutions. The diabatic heating was calculated from a residual of the thermodynamic equation since the actual model heating rates were not archived. The most prominent differences in the various budget terms between the resolutions occurred in the adiabatic/diabatic heating terms. As should be expected, the higher resolutions develop a more robust and detailed vertical motion field. On the seasonal time scale, the diabatic heating and adiabatic response terms are closely compensating, with the heat flux divergences playing a secondary role in balancing the budget. Figure 7 displays the zonally averaged vertical motion and diabatic heating for T21 and T106 for the JJA season. The T42 and T63 diabatic heating rates shared similar patterns with T106 and are not shown. The T106 vertical motion displays a double Hadley cell with descent along the equator, corresponding to a region of diabatic cooling. The same double cell struc-

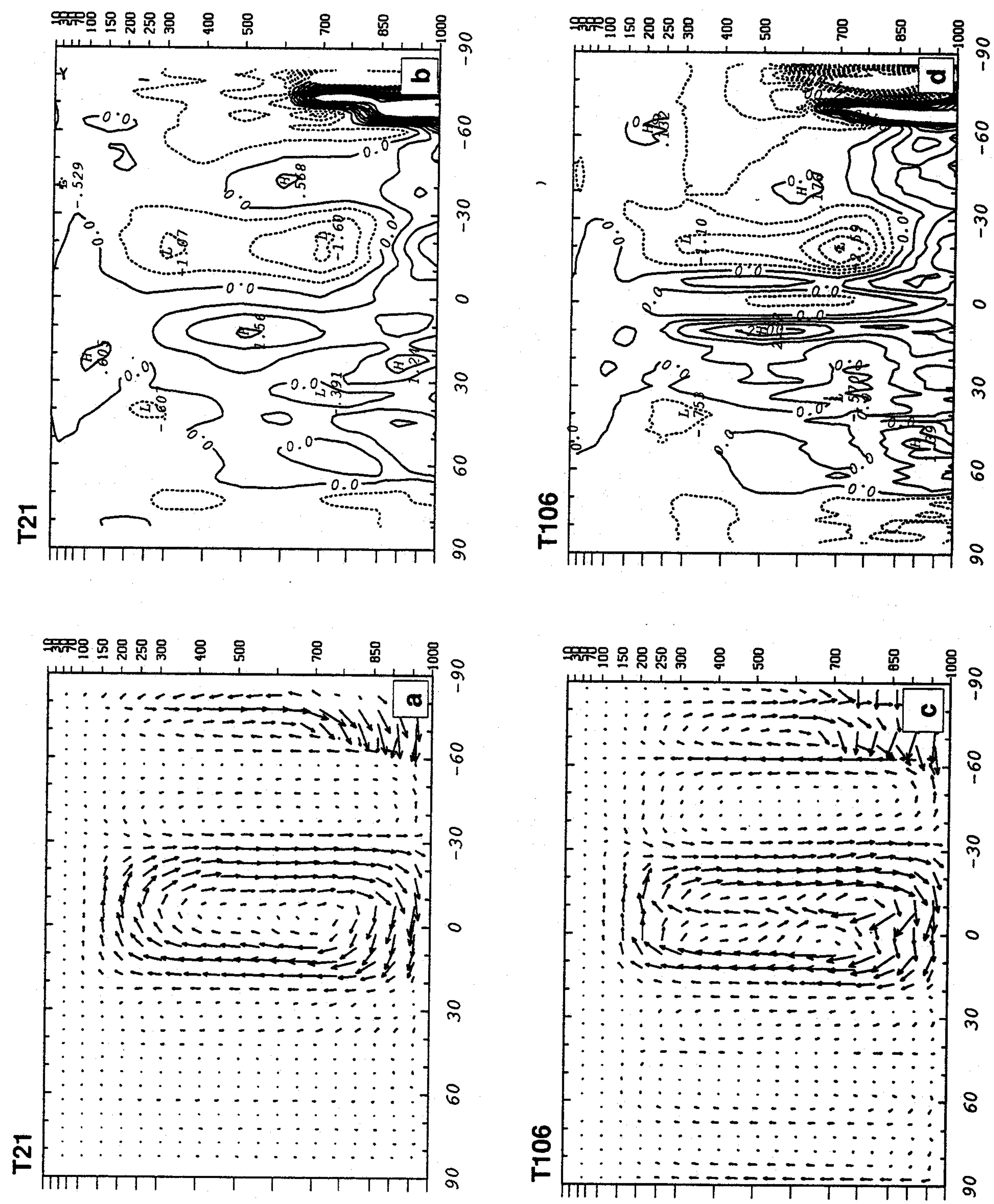


Fig. 7. (a)The zonally averaged mean meridional circulation for T21 for JJA. (b) The zonally averaged diabatic heating rate computed as a residual from the thermodynamic equation for T21 for JJA. Contour interval is 0.5 K day^{-1}.(c) As in (a) except for T106. (d) As in (b) except for T106. (e) As in (b) except for the difference (d) - (c).

ture is apparent in all the simulations with resolutions higher than T21. Outside of this narrow equatorial region the simulation at T106 is realistic. Sumi (1990) also reports a split in the Hadley cell when he increased the resolution of the model he used from T21 to T42. Some reasons for the failure of the higher resolutions to sustain tropical convection will be advanced in the next section.

5. Geographically distributed fields

a. *Mean sea level pressure*

The mean sea level pressure fields for the four resolutions can be described adequately without presenting the plots. As with the zonally averaged quantities discussed above, the T21 simulation is markedly different from the other resolutions. In comparison to T21, the T42 has a much better simulation of the belt of low pressure surrounding Antarctica, the sub-tropical highs in the Southern Hemisphere have better amplitude, and the Icelandic low is brought nearer to its position just east of the tip of Greenland. Most of the improvement would appear to be directly attributable to the better resolved topography in the T42 simulation. The results with resolutions higher than T42 are slightly different but it is difficult to argue that they are better. For this variable and this simulation, T42 certainly appears to be comparable with T106. The JJA results are similar.

b. *Divergent wind and vertical motion*

Figure 8 displays the 200 hPa divergent wind for the four resolutions for DJF. The T21 field resembles those of the JDP climatology (for the winters using diabatic initialization). The quality of the simulation of this field appears to deteriorate somewhat at higher resolutions. The divergent center over Amazonia is somewhat overdone in the higher resolutions, and over Indonesia there is weak convergence over the equator. Plots of vertical motion (not shown) show this to be a zone of descent. These findings are in accord with those of Tibaldi et al. (1990) who found that the T21 simulation provided the best representation of tropical convection. It is important to realize that Tibaldi et al. (1990) used a version of the model with a modified Kuo scheme (Tiedtke et al., 1989), while the model version used here implemented the Tiedtke (1990) mass flux scheme. The point here is not to focus on the shortcomings of any convective parameterization, but to emphasize that these schemes can be resolution

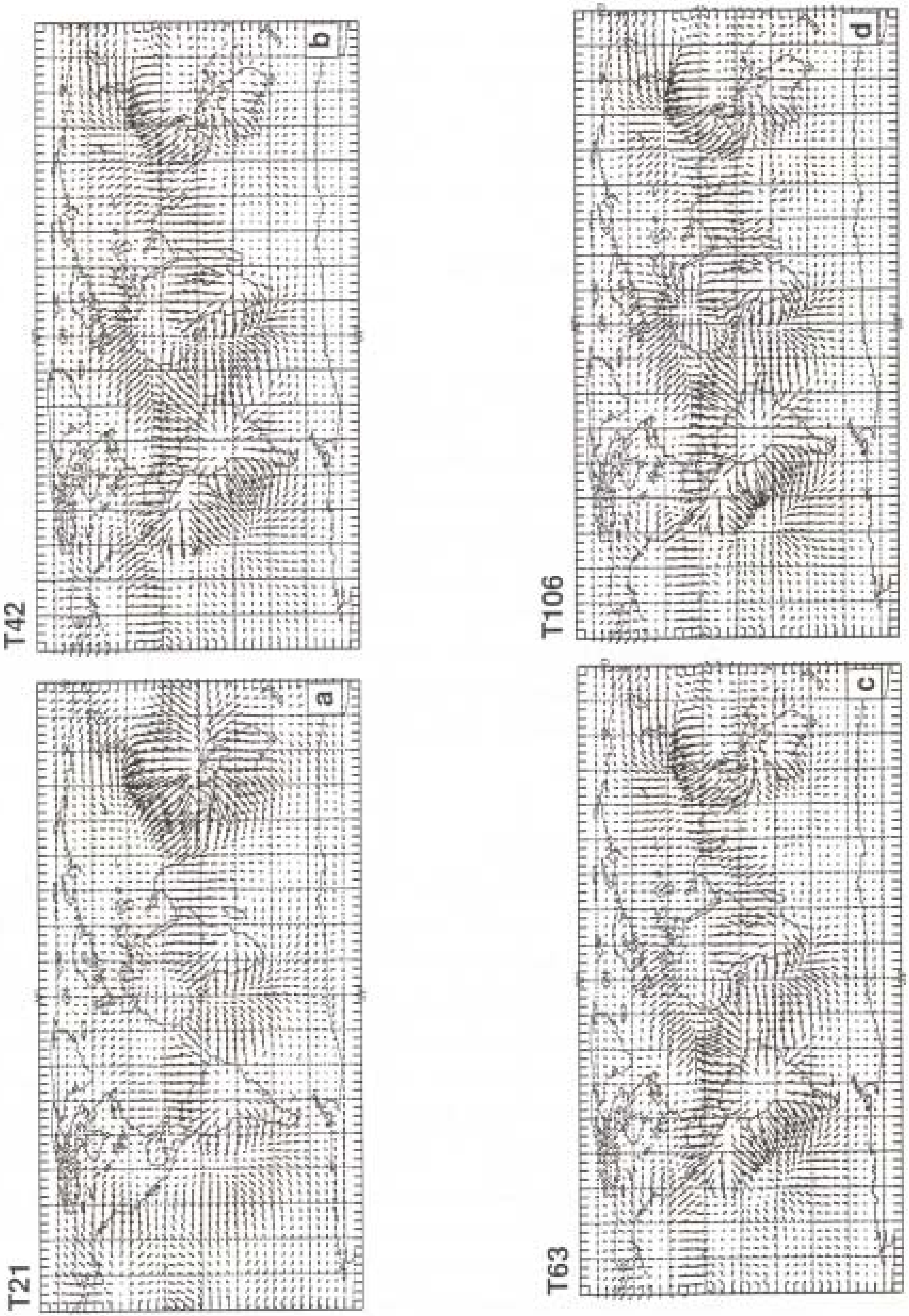


Fig. 8. Divergent wind at 200 hPa for DJF for all model resolutions. The wind vector scale is such that a length of 5 degrees of latitude is 8 ms^{-1}. (a) T21, (b) T42, (c) T63, (d) T106.

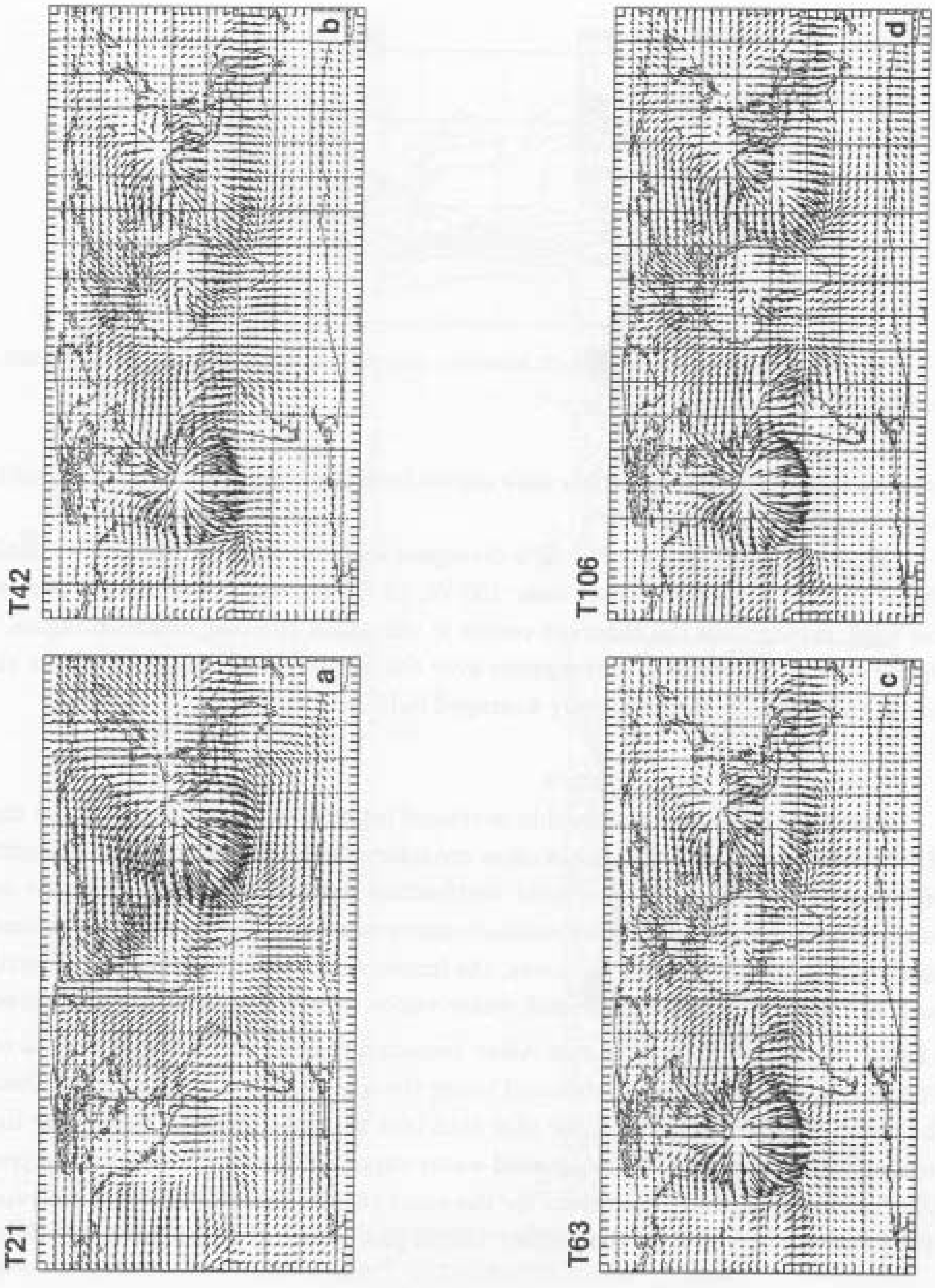


Fig. 9. As in Fig. 7 except for JJA.

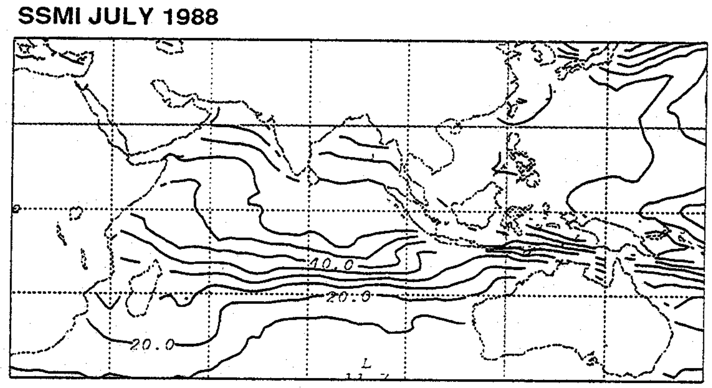


Fig. 10. Vertically integrated specific humidity over the oceans derived from DMSP SSM/I data for July 1988. Contour interval is 5 kg m^{-2}.

dependent and that for the single case shown here the impact of increased resolution is apparently deleterious.

Figure 9 is a plot of the 200 hPa divergent wind for JJA for the four resolutions. Above T21 the divergent center near 100 W, 10 N becomes the dominant feature in this field, rather than the observed center in the Asian summer monsoon region. The higher resolutions exhibit convergence over the equator near Indonesia. This structure is consistent with the zonally averaged fields shown in Fig. 7.

c. Vertically integrated moisture

Figure 10 presents the monthly averaged integrated water vapor for the month of July 1988. A variable that is not often considered in GCM assessments is moisture, probably due to the lack of reliable verification data. The integrated water vapor values from microwave satellite measurements can now provide accurate estimates, especially for climatological purposes; the instrument and the processing algorithms permit measurement of integrated water vapor over the oceans to an accuracy of 4 kgm^{-2}. Figure 10 shows the east Asian monsoon region, estimated from data taken from the DMSP SSM/I and processed using the algorithms of Wentz(1988). Data for the other four Julys available for this data (not shown) appear to be similar in this region. Figure 11 shows the integrated water vapor simulated for July for the present ECMWF model at four resolutions for the same region. The most glaring discrepancy is a relative minimum in the Indian Ocean just north of the equator for T42 and

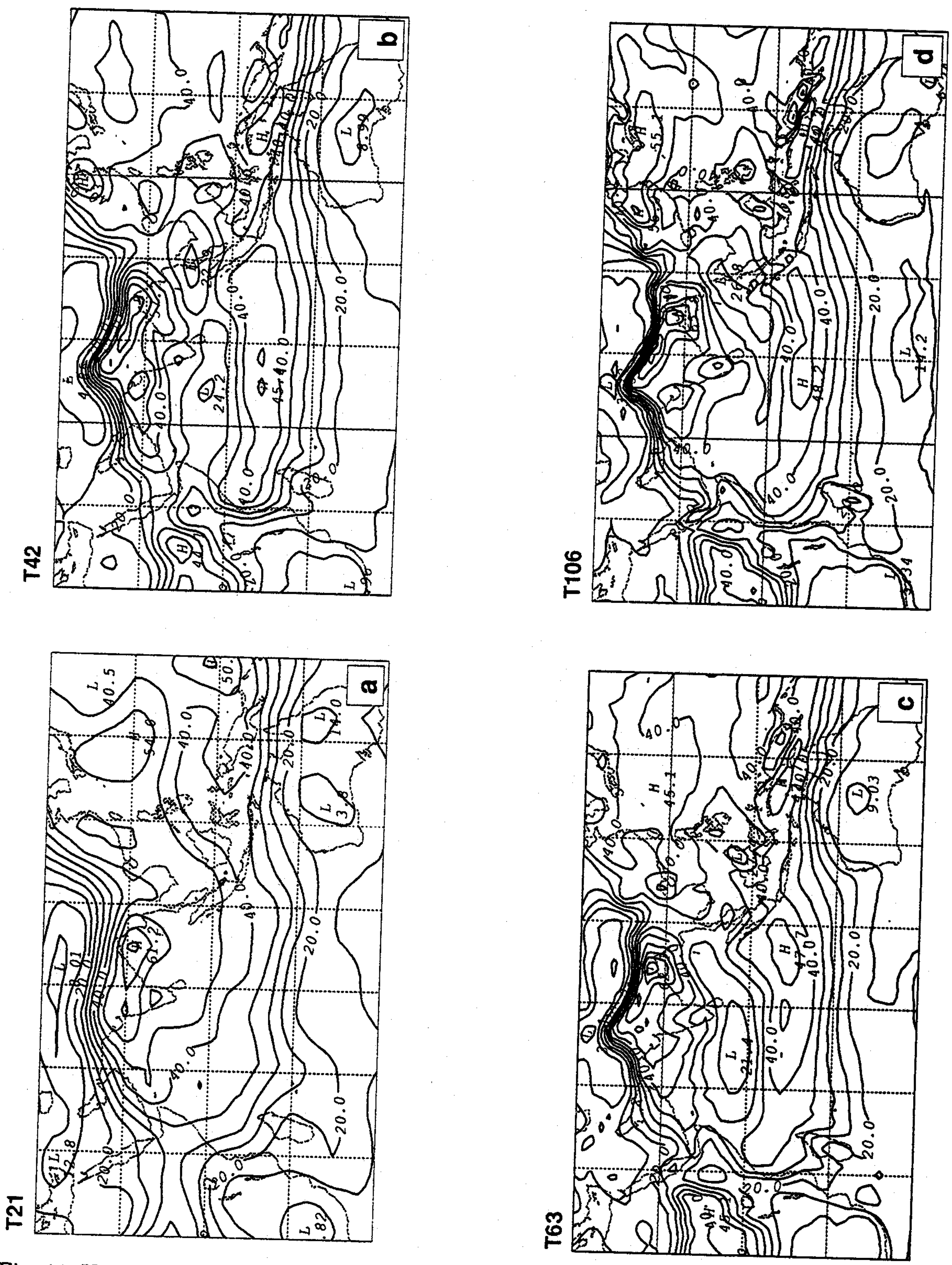


Fig. 11. Vertically integrated specific humidity for all model resolutions for JJA over the Asian monsoon region. Contour interval is 5 kg m^{-2}. (a) T21, (b) T42, (c) T63, (d) T106.

higher resolutions; the T21 data do not display this feature, and in the monsoon region over the oceans the T21 simulation is closer to the observed data seen in Fig. 10. From plots of the surface wind (not shown), it is clear that the region of minimum integrated water vapor corresponds to a wind speed minimum in both the observed and simulated atmospheres. However, the wind minima for T42 and higher are much lower than the observed, while the minimum for T21 is approximately the same magnitude. The higher resolution simulations typically produce a wind field with larger gradients and larger extrema. In this case the very low wind speeds in conjunction with the surface flux parameterization evidently inhibit the flux of moisture to the atmosphere from the sea surface, which cuts off the moisture flux needed to produce realistic convection. The reason for the underestimation of the Indian Ocean wind speed by the higher resolutions is not obvious.

d. Stationary waves

We next turn our attention to an examination of the stationary waves, defined as deviations from zonal symmetry of the time mean. These features are of fundamental importance to insure the fidelity of the simulation. The physical processes which contribute to the forcing of the zonal asymmetries include land/ocean temperature gradients, SST patterns, orographic features, radiative effects, synoptic transients and gravity wave breaking. The importance of evaluating the stationary wave aspect of the simulation has been emphasized by Wallace (1983).

In an attempt to measure the effect of resolution upon the stationary waves we present the deviations from zonal symmetry of the 250 hPa streamfunction, a field extensively documented in the JDP data. At the higher latitudes this field should closely resemble the geopotential deviations, but the streamfunction is more useful in the tropical regions. The JDP data set is an excellent standard to use, particularly in the Southern Hemisphere. Figure 12 presents the deviations from the zonal average of the 250 hPa streamfunction for both the Northern and Southern Hemisphere and for all four resolutions for the DJF season. Figure 13 is the same quantity for the JDP data. Figure 14 is the same as Fig. 12 except for the JJA season, while Figure 15 presents the JJA fields for the JDP data.

Comparing Figs. 12 and 13 it can be seen that all the resolutions present a credible simulation of the stationary features in this season. In comparison to the JDP data the T21 fields indicate an adequate simulation. The wave train across Canada

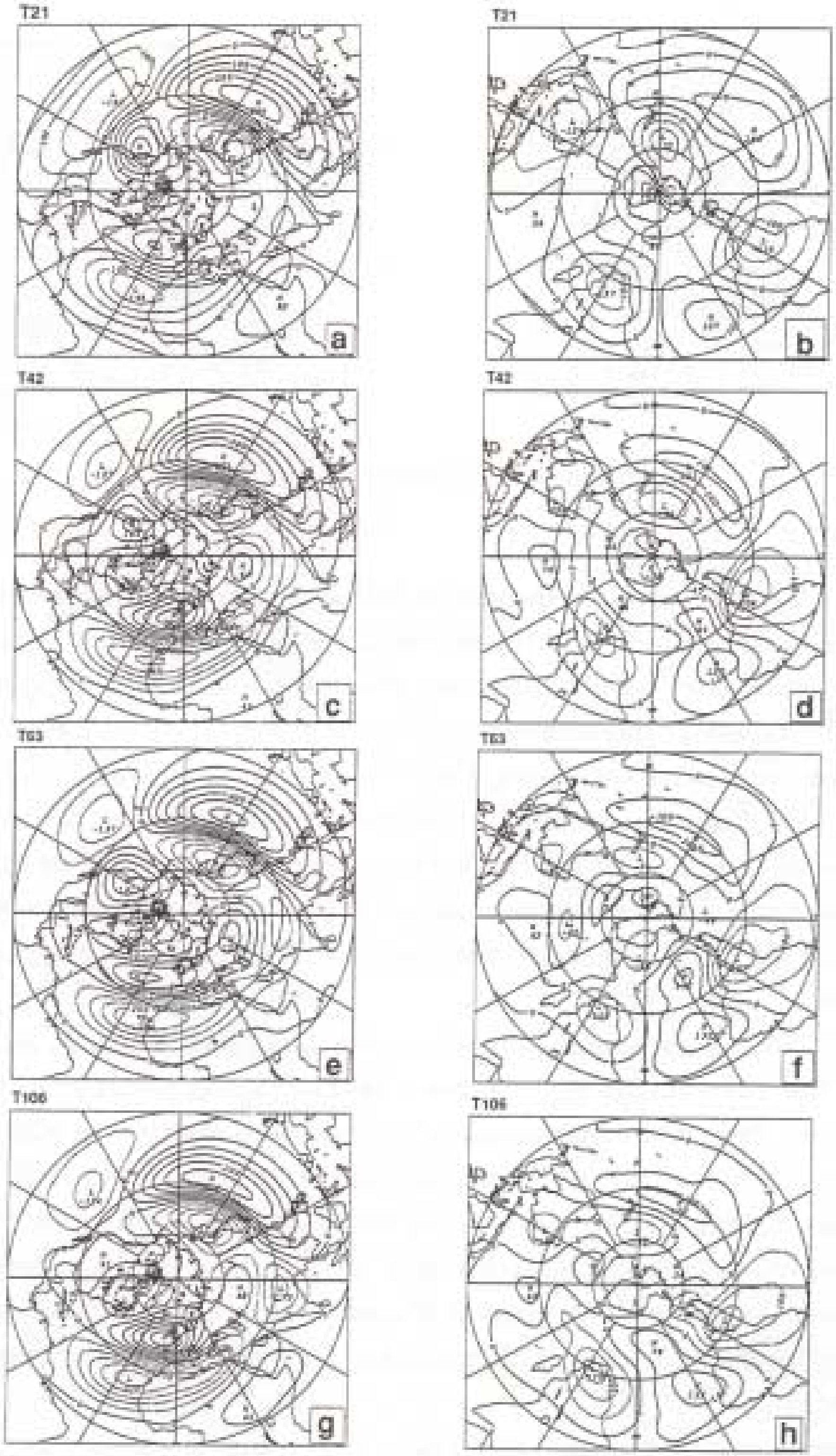
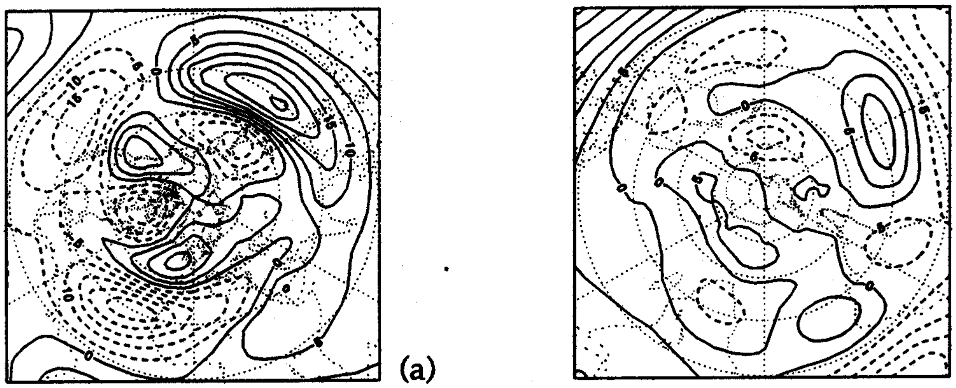


Fig. 12. Deviations from the zonally averaged streamfunction at 250 hPa for DJF for all model resolutions. Contour interval is 1.0 x 10^7 ms^{-2}. Dashed contours indicate negative values. (a) T21 Northern Hemisphere, (b) T21 Southern Hemisphere, (c) T42 Northern Hemisphere, (d) T42 Southern Hemisphere, (e) T63 Northern Hemisphere, (f) T63 Southern Hemisphere, (g) T106 Northern Hemisphere, (h) T106 Southern Hemisphere.



(a) (b)

Fig. 13. As in Fig. 12 except for the JDP data.

and into the Atlantic is most prominent at T63 and then weakens at T106. There is a consistent negative anomaly over the northern Indian subcontinent for all the resolutions, which reaches a rather significant maximum at T106. The proximity of this anomaly to the Tibetan Plateau might indicate a problem with the steep terrain, perhaps involving the gravity wave drag. On the whole, given the rather severe problems in the divergence field, the simulations of the stationary waves for this season are quite reasonable. The literature is replete with studies of the effects of tropical convection on the midlatitude stationary waves. In this case a rather egregious anomaly in tropical heating (over Amazonia) and the lack of heating over Indonesia lead to no obvious effects.

In JJA the northern hemisphere waves are again handled well. In the Southern Hemisphere the T21 simulation produces a field similar to the JDP data and there is a significant increase in the magnitude of the principal features in going from T42 to T106. The exact cause of this difference is difficult to sort out. A prime candidate for forcing the anomalous stationary waves is the very strong convection center evident in Fig.9 to the west of Central America; this feature represents a substantial energy source. This center is located in a region of strong easterlies, somewhat stronger than observed; this locale, we note, would inhibit the transmission of wave activity directly out of the Tropics.

Sardeshmukh and Hoskins (1988) have shown that the source for Rossby waves can extend out of the tropical easterlies via the advection of absolute vorticity by the divergent wind. Figure 16 is a plot the Rossby wave source described by Sardmesh-

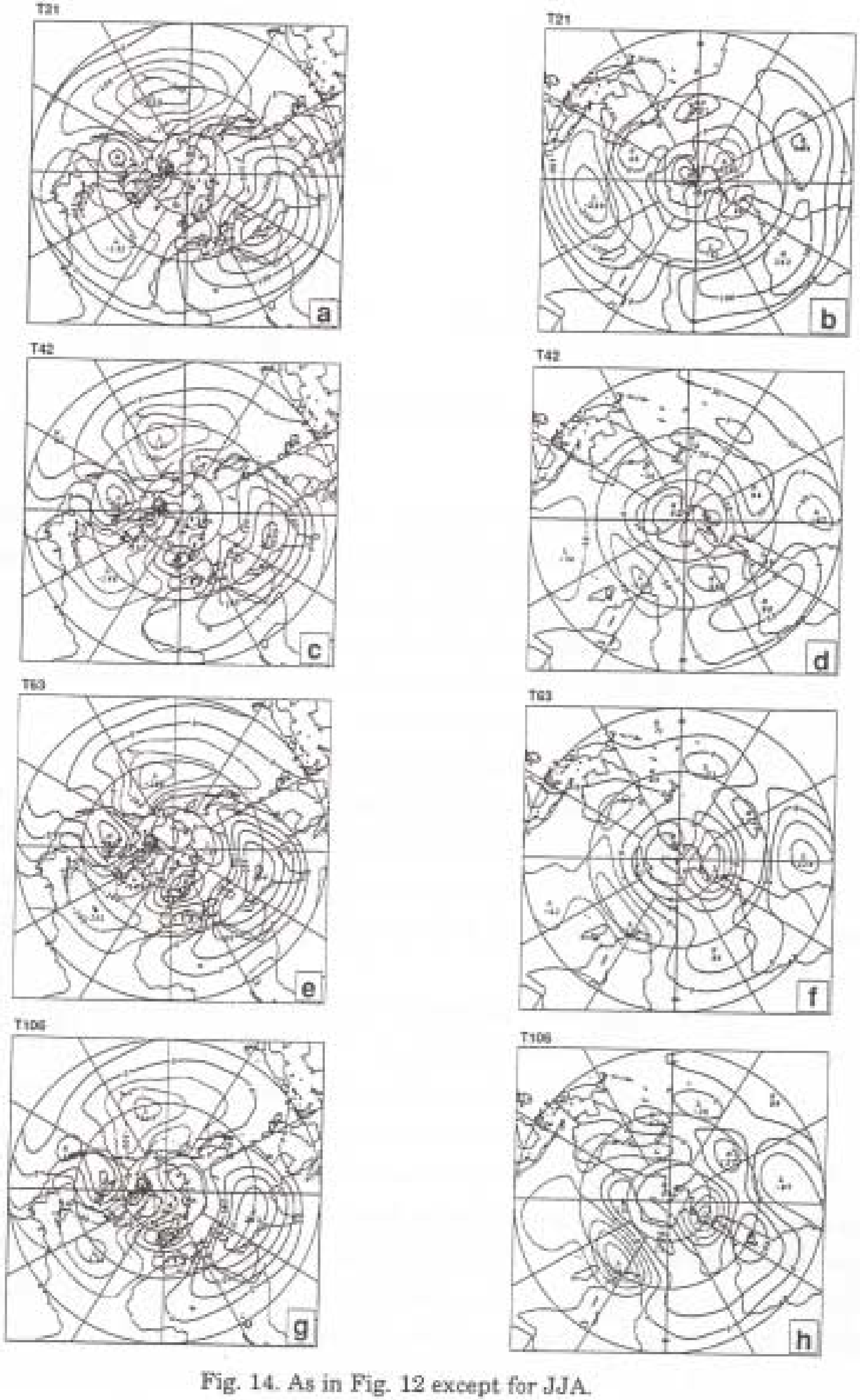


Fig. 14. As in Fig. 12 except for JJA.

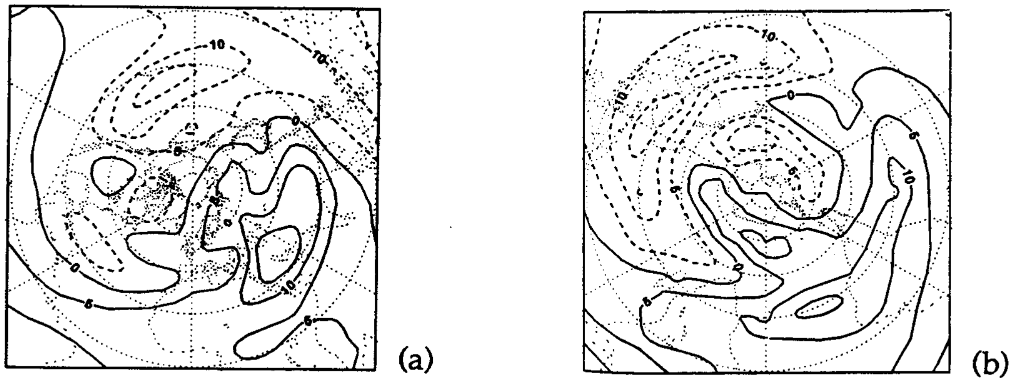


Fig. 15. As in Fig. 13 except for JJA.

mukh and Hoskins (1988) at 200 hPa for the four resolutions. The sources must extend beyond the tropical easterlies if the waves so generated are not doomed to die out locally. On Fig. 16 the zero line of the zonal wind has been sketched onto the T106 data and in this case it is apparent that the source attributable to the convection in Central America is entirely within the easterlies. Thus this prominent heating anomaly has little effect on the global wave structure. Note, however, that if this source were placed in the observed climatological wind field, the impact would have no doubt been substantial. The implication is that misleading results could be obtained by using a wave source (such as diabatic heating) in conjunction with an inappropriate zonal wind field. This particular integration is a good example of the compensation that can take place in a model (and perhaps the atmosphere) to minimize the impact of a heating anomaly.

Note that the Rossby wave sources in the Southern Hemisphere in Fig. 16 are significantly larger in the higher resolutions even though the divergent wind magnitudes are nearly equal amongst the higher resolutions. Figure 17 shows the absolute vorticity at 200 hPa for the JJA season for the four resolutions. The increase in the meridional gradient of this quantity is substantial as the resolution increases. The point is that even if the divergent wind is approximately the same for each resolution, the increase in the strength of the gradient of vorticity at higher resolutions makes the model sensitive to details in the divergence. That is, the lower resolution (T42, T63) errors in convection/divergence can perhaps be tolerated, but the same errors can lead to a poorer simulation at T106 by acting on the fine structure in the vorticity

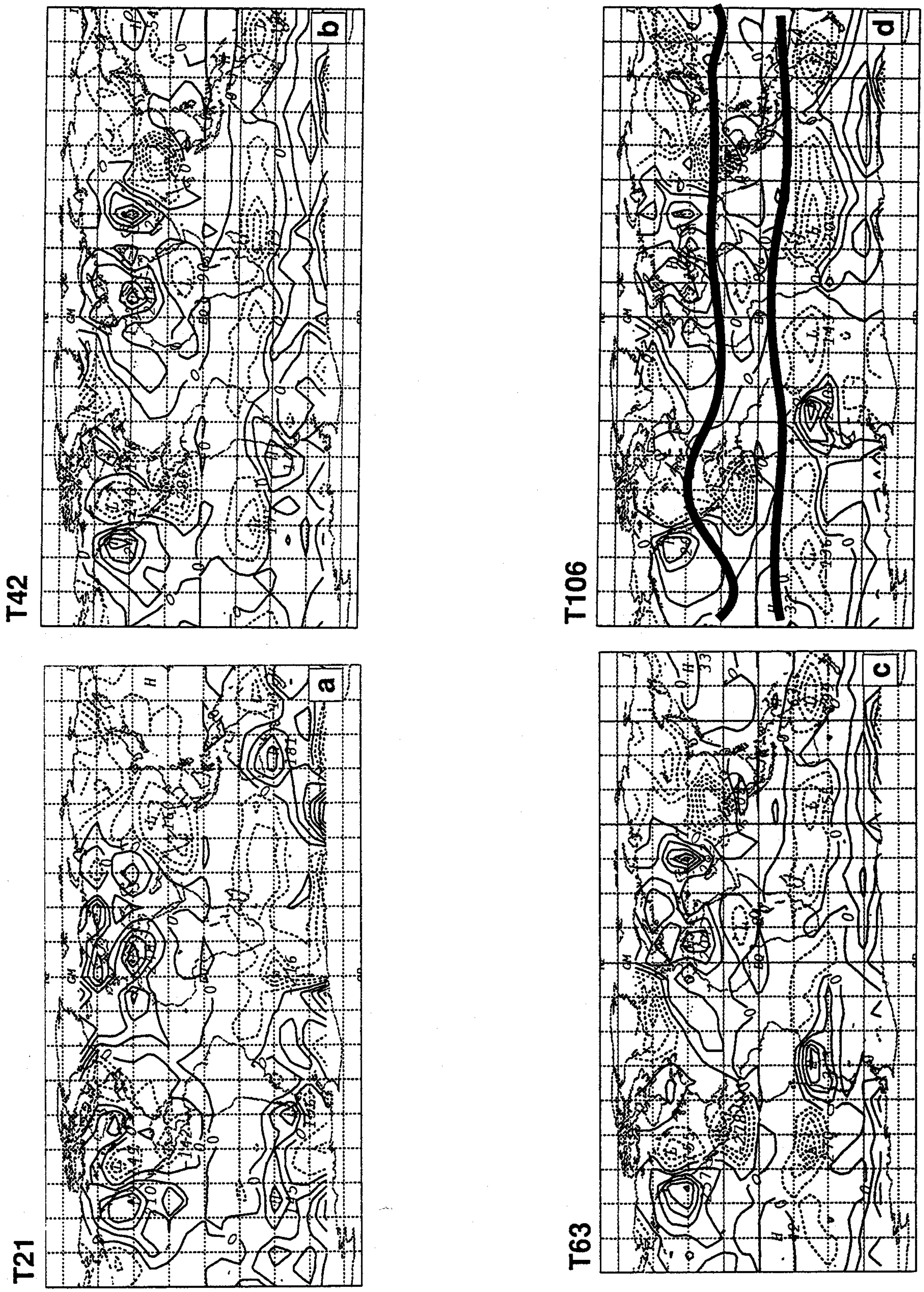


Fig. 16. Rossby wave source function at 200 hPa for JJA or all model resolutions. Contour interval is 0.5 s^{-1}. Dashed contours indicate negative values. (a) T21, (b) T42, (c) T63, (d) T106.

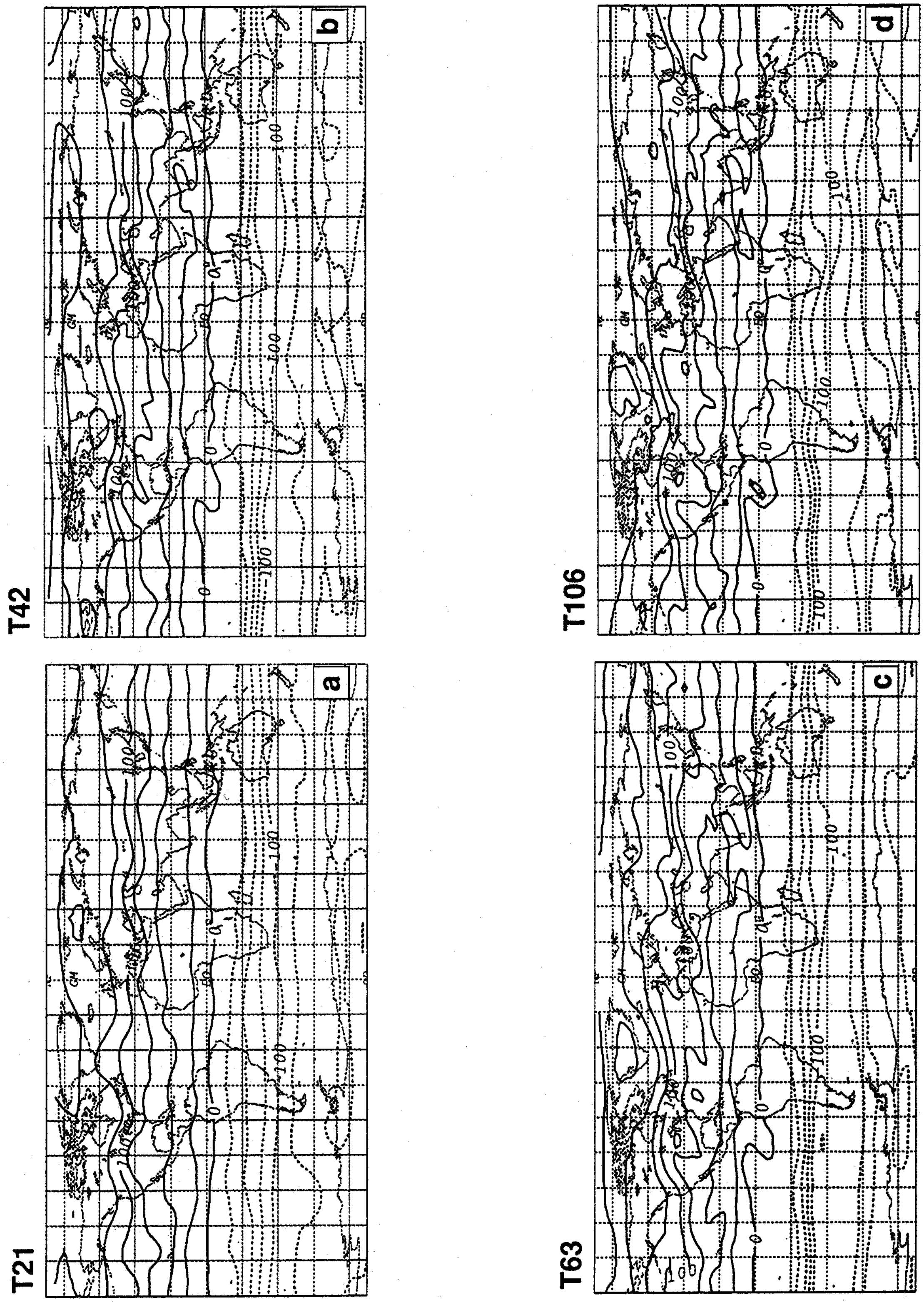


Fig. 17. Absolute vorticity at 200 hPa for JJA for all model resolutions. The zero contours of the zonal wind are plotted on the T106 figure. Contour interval is 0.5 x $10^{-4}s^{-1}$. Dashed contours indicate negative values. (a) T21, (b) T42, (c) T63, (d) T106.

patterns. Thus, over the southern Indian Ocean where the divergent fields are similar to the climatological means, the T106 Rossby wave sources are stronger. Also the vorticity gradient in Fig 17 has a rather low zonal wave number, but its impact in conjunction with the higher wavenumber divergence field can be critical for a good simulation of the higher wavenumber standing wave forcing. In studies of tropical convective effects on mid-latitude stationary waves, typically the absolute vorticity field is specified and the divergent tropical center is altered to assess the influence of the convection. In the model, however, the vorticity fields and the convection are not independent.

6. Conclusions and further discussion

The ECMWF operational forecasting model (cycle 33) was integrated as a climate model for 15 months with four different horizontal resolutions, T21, T42, T63 and T106. The initial conditions and boundary conditions were kept as nearly identical as possible within the limits imposed by the varying resolution. In this paper the results of the integrations are compared for the two solstitial seasons. It should be emphasized that the integrations were only carried out for 15 months. As a consequence, an attempt has been made to limit the inferences to those justifiable given the small sample size. From this experiment we have drawn the following conclusions:

The increase in resolution does not necessarily lead to a superior simulation, and in some instances a significant degradation was noted. The effectiveness of the parameterizations that are used are evidently dependent on scales resolved by the model. In this case the convective parameterization performed best at the T21 resolution. The increased resolution also increases the sensitivity of the model dynamics to errors in the physical parameterizations. The present simulation is not especially good, but the increased resolution did not improve matters; in fact, increased resolution made matters worse on the large scale in the Tropics. On smaller scales the higher resolution runs provide useful detail, usually in the regions where local orographic forcing was important. The mid-latitude MSLP fields generally were superior in the T106 simulation. The implication is that increased resolution cannot take the place of the proper formulation of the model physics (consistent with the resolution being used), although high resolution can provide useful detail in local regions.

The most common measures considered in resolution studies are the eddies with respect to the zonal and time means, the reasoning being that the fine scales would resolve the smaller eddies, leading to improved simulation. However, the large scale meridional gradients of vorticity are probably of rather low wavenumber and would not be reflected in the eddy quantities. Presumably, correctly simulating the intensity and position of this gradient is a sensitive parameter in the real atmosphere. The smaller scale divergent/vertical motion fields acting in conjunction with the sharp vorticity gradients can have a dramatic impact on the large scale climatological stationary wave pattern.

It appears that this particular model, in combination with the results of Tibaldi et al. (1990), establishes error patterns in the first 30 days or so of integration which are characteristic of those at 15 months. This indicates that the model slips into its own stable climatology rather quickly.

The character of the simulation does not change substantially in going from T42 to T106. There is a distinct qualitative break in going from T21 to T42, but above T42 the differences are not large and in this particular case at T106 the differences can be deficiencies. It would seem that T42 resolution provides an adequate simulation for most climate purposes. The differences in T42 - T106 are less than the differences typically seen between control runs and $2xCO_2$ simulations. This indicates that resolution differences would not obscure the effects of CO_2 doubling, all else being equal; the implication is that T42 would be adequate for a doubling experiment. Some caution must be noted with the very large differences above 200 hPa. As noted by Boville(1990) and Mahlman and Umscheid(1989), the largest differences between resolutions often appear in the stratosphere. The implication is that if stratospheric interaction in important, then T42 could not handle this adequately even if the necessary levels were added. The simulation might even be detrimentally affected by using higher resolution if proportionate care was not taken in modeling the stratosphere.

The northern hemisphere standing wave patterns are quite robust compared to those in the Southern Hemisphere. One might expect that the orographic and thermal forcing represented by the specified SST patterns are so overwhelming that the dynamics only have to be approximately correct to reproduce the climatological patterns. For the Southern Hemisphere the balance between transient, orographic and thermal forcing is more delicate, and it is in this hemisphere that the simulations should be carefully evaluated to provide a vigorous test of the fidelity of the models.

In general, one gets the impression that the T106 simulation provides accurate detail in local regions where the orographic boundary forcings dominate, while in regions where the model solution is more determined by internal dynamics it is more likely to go wrong. The implication is that one should not be fooled into thinking that the model is as good as it seems in certain localized regions. The situation for the southern hemisphere stationary wave is an example of the model solution deteriorating with resolution when not dominated by boundary influences as in the northern hemisphere stationary pattern. If detailed regional climate differences are important, perhaps a high resolution grid nested in the coarser (T42) grid would prove adequate.

The criticisms of this simulation using the ECMWF model should not be taken as shortcomings of the forecast potential of the model. The ECMWF model is an operational, medium range forecast model intended to produce ten day forecasts. The fact that it could be run virtually unchanged from its operational configuration for 15 months and produce a credible climate simulation is a tribute to the care and expertise that went into its formulation and implementation. Recent modifications to the ECMWF model have been directed to the problems of the excessive easterlies and the location and morphology of the tropical convection. Reformulation of the moisture flux parameterization at low wind speeds has substantially changed the model tropical circulation simulation, Miller et al. (1992). This is a rather daunting example of model sensitivity to a seemingly minor modification in the representation of physical processes.

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