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On the mean-meridional circulation during the summer and winter monsoon seasons

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ABSTRACT. Computation of the mean-meridional circulation within the framework of Kuo's model is carried out for the northern hemisphere and for the globe, for winter and summer seasons. It is inferred that the forcing due to heating plays a dominant role as far as the Hadley cell is concerned. From the computation of global mean-meridional circulation it is concluded that the direct effect of southern hemispheric mechanical forcing on the northern hemispheric circulation is not significant. But the thermodynamical forcing has a great influence on the northern hemisphere circulation.

1. Introduction

The study of Mean Meridional Circulation (M.M.C.) was undertaken by a number of investigators, *e.g.*, Eliassen (1951), Mintz and Lang (1955), Kuo (1956), Gilman (1964, 1965), Holopainen (1965), Vernekar (1967), Saltzman and Vernekar (1968), Saltzman (1964, 1968) as it is one of the factors in determining the climate of a region.

Synoptic studies indicate that the global general circulation has a profound effect on monsoon behaviour, Ramaswamy (1962). The tropical Hadley Cell of the M.M.C. is an important constituent of the monsoon circulation. The variations in M.M.C., it is felt, can introduce variations in the monsoonal behaviour. Hence a quantitative theory of the M.M.C. seems to be essential to understand the monsoonal behaviour. Here the aim of the authors is to compute the M.M.C. during both the summer and winter seasons based on a most general model given by Kuo (1956). We shall now go through the details of the model.

2. The details of the model adopted

Notations used being the same as that of Kuo (1956), the following are the equations of the model in (λ, ϕ, p, t) system.

The first equation of motion

$$cu_1 = z_0 v_1 - w_1 \frac{\partial u_0}{\partial p} - \chi \tag{1}$$

The second equation of motion

$$cv_1 = -fu_1 - \frac{1}{a}\frac{\partial \phi_1}{\partial \phi} \tag{2}$$

The hydrostatic equation

$$\frac{\partial \phi_1}{\partial p} = -\frac{RT_1}{p} \tag{3}$$

The continuity equation

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(v_1 \cos\phi) + \frac{\partial w_1}{\partial p} = 0 \tag{4}$$

The thermodynamic energy equation

$$cT_1 + \frac{1}{a}\frac{\partial T_0}{\partial \phi} v_1 + \Gamma_0 w_1 = H \tag{5}$$

where,

$$\chi = g\frac{\partial \tau_{xz}}{\partial p} + \frac{1}{a\cos^2\phi}\frac{\partial}{\partial \phi}(\overline{u'v'}\cos^2\phi) + \frac{\partial}{\partial p}(\overline{v'w'}) \tag{6}$$

$$H = \frac{Q}{C_p} - \frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(\overline{v'T'}\cos\phi) - \frac{\partial}{\partial p}(\overline{w'T'}) \tag{7}$$

With the help of the continuity Eqn. (4), the meridional and vertical velocities are defined in terms of stream function ψ as follows :

$$v_1 = \frac{1}{a\cos\phi}\,\frac{\partial\psi}{\partial p},$$

$$w_1 = \frac{-1}{a\cos\phi}\,\frac{\partial\psi}{\partial\phi} \tag{8}$$

Equations (1) to (8) can be suitably combined to arrive at the final governing equation which is of elliptic type.

$$\frac{\partial A}{\partial p}\,\frac{\partial\psi}{\partial p}+\frac{2R}{a^2 p}\,\frac{\partial T_0}{\partial\eta}\,\frac{\partial^2\psi}{\partial\eta\,\partial p}+ +\frac{R}{a^2}\left(\frac{\partial}{\partial p}\,\frac{1}{p}\,\frac{\partial T_0}{\partial\eta}\right)\frac{\partial\psi}{\partial\eta}-\frac{R\Gamma_0}{a^2 p}\,\frac{\partial^2\psi}{\partial\eta^2} =\frac{R\partial H}{ap\partial\eta}+\frac{f}{\cos\phi}\,\frac{\partial\chi}{\partial p} \tag{9}$$

where,

$$A=\frac{fz_0+c^2}{\cos^2\phi} \tag{10}$$

$$\Gamma_0=\frac{\partial T_0}{\partial p}-\frac{RT_0}{p\,c_p} \tag{11}$$

In (9) χ and H as defined in Eqns. (6) and (7) represent mechanical and thermodynamical forcings respectively. The input parameters of the model are $\bar{u}_0$, $\overline{T_0}$, $\overline{u'v'}$, $\overline{v'T'}$, τ_{xz} and Q. Kuo has solved Eqn. (9) by two methods, (1) by the Green's function method after making the following assumption which are A = constant, $\partial T_0/\partial\eta$ = constant, $\Gamma_0=-\beta/p, \beta$ = constant etc (2) by Relaxation method. The domain of the solution is defined by the boundaries $\phi=0°$, $\phi=90°$N, $p=1000$ mb, $p_0=0$ mb. The boundary conditions are in general $\psi=0$ on all the boundaries. The variation of τ_{xz} with respect to p is assumed to be the same as given by Kuo (1956).

$$\tau_{xz}=\tau_{x0}\,e^{\,\beta(p/p_0-1)} \tag{12}$$

where β is a constant.

Now we shall briefly describe the models, the methodology adopted and results obtained by earlier workers and see how they differ from that of Kuo (1956). The most general assumptions made by these workers are $c=0$, $\phi_1=0$, hence $T_1=0$, $u_1=0$. The variation of τ_{xz} with respect to p differs from each other. For example, whereas Kuo (1956) assumes an exponential decrease of stress which approaches zero at the top ($p=0$), Gilman (1965) considers a linear decrease making it approach zero at 850 mb only. With the assumption $\phi_1=0$, Gilman's (1965) set of equations becomes over-determined. Gilman (1965) used the method of variation of parameters to solve the simultaneous equations for the vertical motion forced only by the large scale horizontal transient eddy flux of momentum, $\overline{u'v'}$ and stress, τ_{xz}. Vernekar (1967) calculated M.M.C. using the separation of variables method to solve the final governing equation derived from the quasi-geostrophic vorticity equation and thermodynamic energy equation for a frictionless and adiabatic atmosphere using large scale horizontal transient eddy fluxes of momentum and heat ($\overline{u'v'}$ and $\overline{v'T'}$ respectively) as forcings. Holopainen (1967) considered only the effect of large scale horizontal transient eddy flux of momentum $\overline{u'v'}$. Though all the computations yield an M.M.C. with three cells (the direct cells in the tropics and polar regions and an indirect cell in the middle latitudes) for the winter season, they differ quantitatively. For, Kuo (1956) gets a maximum meridional velocity of 1 m/sec in the Hadley cell near the surface, whereas Vernekar (1967) gets 60 cm/sec within the indirect Ferrel cell near the surface. Gilman (1965) for the southern hemisphere winter season gets strongest meridional velocity of 1.6m/sec in the Hadley cell near the surface. Holopainen (1967) gets 2 m/sec in the Hadley cell near the surface. Such quantitative differences are mainly attributed to the differences in forcings, the variation of τ_{xz} with respect to p, the treatment of the Coriolis parameter f and the models adopted. With this brief review of the earlier works we shall now turn to the discussion of some of the results.

3. Discussion of the results

3.1. *Comparative results*

For comparison purposes in Figs. 1 and 2 are given the results by two methods.

(1) The Green's function method.

(2) The Relaxation method for Kuo's (1956).

Conditions and data

$$\left(\frac{1}{a}\,\frac{\partial T_0}{\partial\eta}=-1.0\times10^{-5}\,{}^0K/\text{m},\ A=\text{constant}\right)$$

$B=318°K$, $f=1.0\times10^{-4}$/sec in $f\dfrac{\partial\chi}{\partial p}$, as given by Kuo). We note the following :

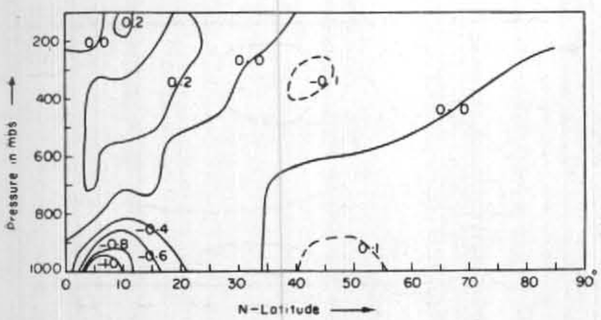

Fig. 1. Green's function method for Kuo's conditions

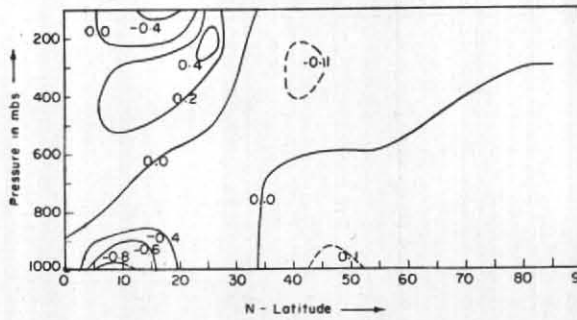

Fig. 2. Relaxation method for Kuo's conditions

(v_1 in m/sec, $f=10^{-4}$/sec=constant. Inforcing term $f\dfrac{\partial\chi}{\partial p}$ β=2.5)

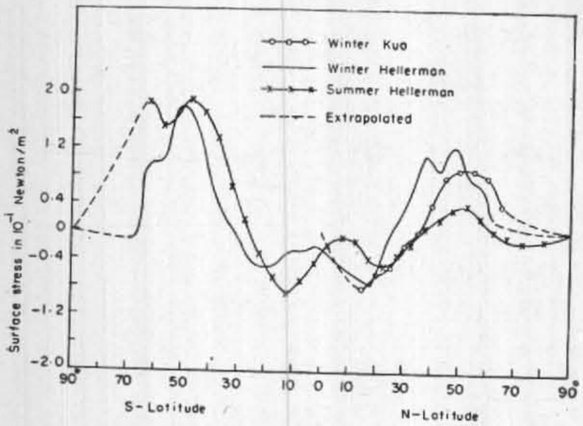

Fig. 3. Surface stress in 10^{-1} Newton/m^2

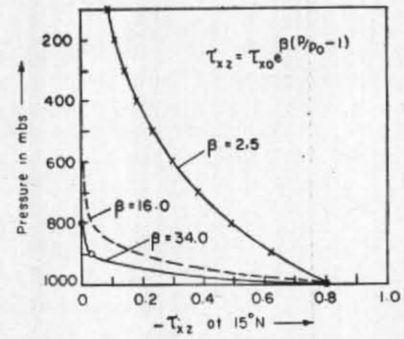

Fig. 4. —τ_{xz} variation with respect to p, in 10^{-1} Newton/m^2 for different values of β

(1) Both the methods give similar results.

(2) The Relaxation method gives a slightly weaker solution. It may be due to the further approximations involved in Green's function method as well as the differences in the boundary conditions.

(3) The maximum meridional velocity occurs in the Hadley cell and is about 1 m/sec.

(4) The direct Hadley cell and the indirect Ferrel cell are the most pronounced cells.

In view of the quantitative closeness of the results by both the methods, the Relaxation method only was utilised for further calculations.

In the above calculations f was assumed to be a constant in the forcing $f\,(\partial\chi/\partial p)$. Since such an assumption overestimates the forcing at the equatorial latitudes, in all the numerical experiments described hereafter the Coriolis parameter f is not kept a constant, but is allowed to vary naturally.

3.2. *The Northern Hemispheric M.M.C. (N.H.M.M.C.) in winter due to* χ *forcing alone*

For the winter, N.H.M.M.C is computed using the best available data of the input parameters $\overline{u_0}$, $\overline{T_0}$, $\overline{u'v'}$ released by Oort and Rasmusson (1971). The surface stress τ_{xo} given by Kuo (1956) as shown in Fig. 3 was utilised. The variation of τ_{xz} with respect to p given by Kuo's (1956) formula (12) for different values of β is shown in Fig. 4. τ_{xz} approaches zero at a lower level as β value increases. The M.M.C. was computed for different values of β as described in the following experiments.

Experiment 1

Here β is assumed to be the same as that used by Kuo (1956), β=2.5. Friction constant $C=.5\times10^{-5}$/sec. Fig. 5 shows the computed v_1 field. We notice the following :

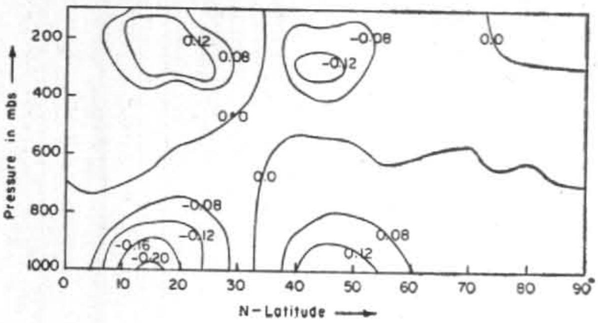

Fig. 5. v_1 in m/sec for winter with χ as forcing, β=2.5

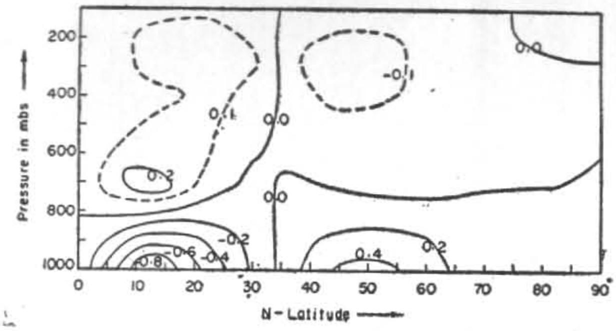

Fig. 6. v_1 in m/sec for winter with χ as forcing, β=16.0

(1) The response is weaker than in Kuo's (1956) study where f is kept constant in the forcing term. The meridional velocity of about only 20 cm/sec occurs at the surface in the Hadley cell about 15°N latitude.

(2) The Hadley cell and the Ferrel cell are of comparable intensity.

(3) The intensity of computed Hadley cell is weaker in comparison to the observations of Oort and Rasmusson (1971) indicating that H part of the forcing must be of considerable importance for the direct cell atleast.

Experiment 2

This is similar to experiment 1 except for the β value in τ_{xz} variation. Here it is β=16.0. Fig. 6 depicts the computed v_1 field. When Fig. 6 is compared with Fig. 5, the following points can be noticed :

(1) The intensity of mean-meridional velocity increases with the increase of β value, the maximum being 0.9 m/sec in the tropical Hadley cell and 0.4 m/sec in the middle latitudes Ferrel cell near the surface.

(2) The tropical Hadley cell is stronger compared to middle latitudes Ferrel cell.

(3) The maximum return current occurs at a much lower level than in experiment 1.

Experiment 3

Here the β value is made still large compared to the above two experiments (β=34·0). Fig. 7 describes the computed v_1 field.

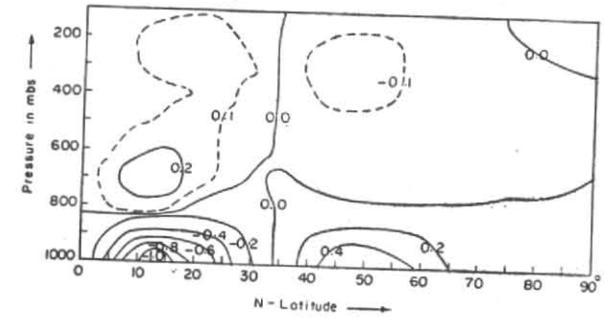

Fig. 7. v_1 in m/sec for winter with χ as forcing, β=34.0

(1) The velocities have slightly increased.

(2) The maximum meridional velocity is of the order of 1 m/sec in the Hadley cell near the surface.

(3) At higher levels there is no significant changes from experiment 2.

The return current is very weak compared to observations. Hence it is inferred that the strength of the M.M.C. depends very much on the variation of τ_{xz}. If it approaches zero at a lower level, the M.M.C. strengthens at the surface, but is weakened aloft.

3.3. *The heating function*

Till now the effect of only the mechanical forcing χ on the M.M.C. is studied. We shall now compute the M.M.C. forced by the H forcing alone. H forcing consists of diabatic heating Q, the large scale transient fluxes of heat $\overline{v'T'}$ and $\overline{\omega'T'}$. Even if we assume that $\overline{\omega'T'}$ is simply related to $\overline{v'T'}$, an accurate estimate of Q (ϕ, p) is still not possible. Some recent estimate of $\overline{Q_\phi} = \frac{1}{P_s}\int_0^{P_s} Q\,(\phi,p)\,dp$ exists for different seasons,

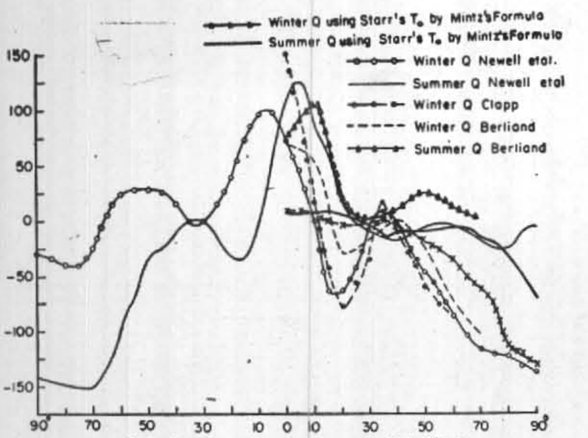

Fig. 8. Latitudinal distribution of mean diabatic heating, Q

Newell, Vincent, Dopplick, Ferruza and Kidson (1974). Earliear Gabites (1950), Pisharoty (1955), Berliand (1956), Clapp (1961), Davis (1963), Brown (1964) also gave estimates of $\overline{Q_\phi}$. Yale Mintz (1958) using a simple formula for heating function, which depends on the temperature difference between 1000 mb and 500 mb levels, computed zonal mean $\overline{Q_\phi}$.

The Mintz's (1958) formula was

$$\overline{Q_\phi} = \beta[\Delta T - \Delta T_m]$$

where,

β = constant, $\Delta T = T_{1000} - T_{500}$

$$\Delta T_m = (T_{1000})_m - (T_{500})_m$$

m stands for global mean

T = temperature

Diabatic heating estimated by some of these workers are shown in Fig. 8. The heating $\overline{Q\phi}$ according to Mintz's (1958) formula is too weak in the tropical region for both the seasons compared to that of Newell *et al.* (1974), Berliand (1956), Clapp (1961) and others. But the heating produced by Newell, *et al.* (1974) and Berliand (1956) agree very well with each other. Thus in the following experiments we prefer to utilise the diabatic heating given by Newell *et al.* (1974).

For the vertical distribution of diabatic heating, Q at any latitude we considered the following form :

$$Q(\phi, p) = \left[\frac{g}{P_s}\int_0^{P_s}\left(Q(\phi, p)\,\frac{dp}{g}\right)\right]F_Q$$

where,

$$F_Q = e^{-\gamma(1-p/p_s)}\left[c_1 \sin\frac{\pi}{2}\left(1-\frac{p}{p_s}\right)+c_2\right] \tag{13}$$

where γ, c_1 and c_2 are constants which can take different values. For different values of γ, c_2 we get different distribution of diabatic heating function F_Q as shown in Fig. 9. For $\overline{\omega' T'}$ values we used a relation given by Saltzman (1968) as follows :

$$\overline{v'T'} = \overline{\omega' T'}\left(\frac{\Gamma_0}{\dfrac{1}{a}\,\dfrac{\partial T_0}{\partial \phi}}\right)^{\pi} \tag{14}$$

where $\pi = 0{\cdot}75$ is a proportionality constant.

3.4. *The Northern Hemisphere M.M.C. (N.H. M.M.C.) for the Winter and Summer with H forcing alone*

Now we shall describe the results of a few experiments with H forcing alone. For these experiments we made use of the zonal mean heating $\overline{Q_\phi}$ given by Newell *et al.* (1974).

Experiment 4

In this experiment we computed M.M.C. for the winter, forced by H forcing alone. The diabatic heating Q (ϕ, p) is kept constant for all the pressure levels by taking $\gamma = 0$, $c_1 = 0$, $c_2 = 1{\cdot}0$. Fig. 10 shows the computed v_1 field. We notice the following :

(1) The Hadley cell induced by the H forcing is comparable at the surface to that induced by χ forcing with $\beta = 34{\cdot}0$.

(2) The Hadley cell v_1 velocity now compares favourably with the observations of Oort and Rasumsson (1971).

(3) The return current aloft is compaiable to the current at the surface.

Experiment 5

This experiment is conducted for the summer with H focing alone. The heating function is the same as in experiment 4 ($\gamma = 0$, $c_1 = 0$, $c_2 = 1.0$). The relevant summer data of $\overline{u_0}$, $\overline{T_0}$, $\overline{v'T'}$ were utilised. Fig. 11 describes the computed v_1 field. We notice the following :

(1) The summer circulation is weaker than the winter circulation near the surface.

(2) As in the case of winter, H forcing gives v_1 velocities comparable to the observations within the Hadley cell region.

(3) Aloft the maximum meridional velocity is of the order 0.8 m/sec.

(4) The return current is stronger than the surface current in the Hadley cell.

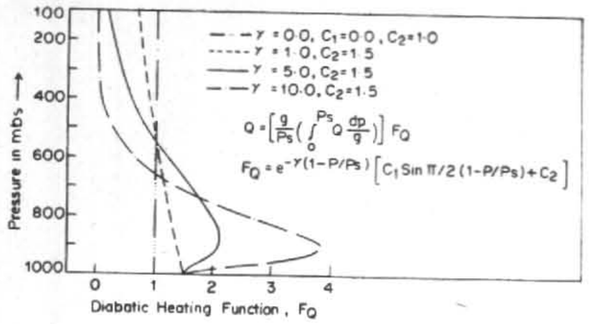

Fig. 9. Diabatic heating function F_Q for different values of γ, c_1, c_2

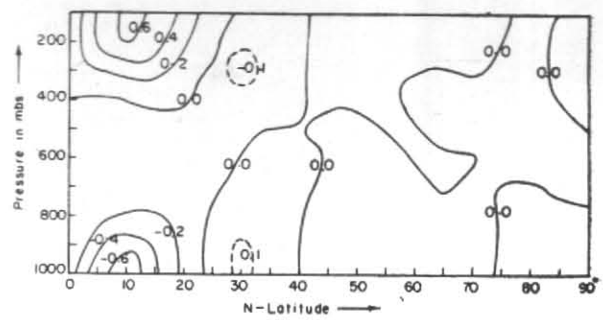

Fig. 10. v_1 (m/sec) for winter with H as forcing (γ=0.0, c_1 = 0·0, c_2 = 1·0)

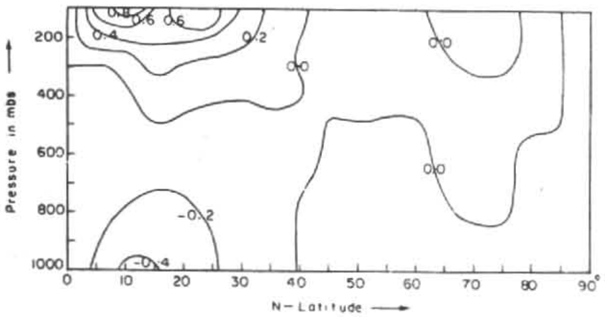

Fig. 11. v_1 (m/sec) for summer with H as forcing (γ=0·0, c_1 = 0·0, c_2 = 1·0)

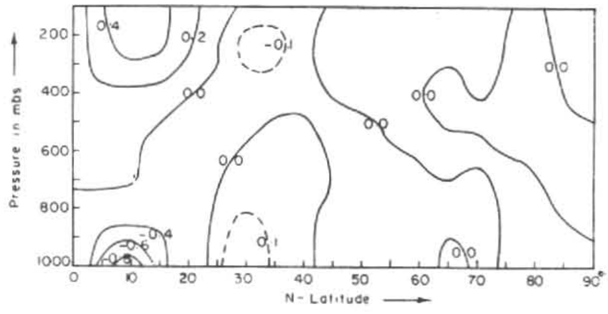

Fig. 12. v_1 (m/sec) for winter H with as forcings (c_2 = 1·5, γ = 1·0)

Experiment 6

Here we have assumed γ=1.0, c_2=1.5, so that Q is maximum at the ground and decreases slowly with height as shown in Fig. 9. Fig. 12 shows the computed v_1 field. We notice the following points.

(1) The circulation has intensified near the surface but has weakened at higher levels.

(2) The maximum meridional velocity is 0.8 m/sec in the Hadley cell near the surface.

Experiment 7

Here γ=10.0, c_2=1·5 as shown in Fig. 9. With these values of γ and c_2 the maximum heating $Q_{(\phi,p)}$ is at 900 mb and becomes very small from 400 mb onwards. Thus heating is concentrated in the lower level. The computed v_1 field is presented in Fig. 13. We notice the following :

(1) The strongest meridional velocity is of the order of 1.4 m/sec and occurs in the Hadley cell near the surface.

(2) The meridional velocities are very weak in the higher levels.

(3) The equatorward flow in the Hadley cell is confined between the surface and 850 mb instead of being spread upto 400 mb as in the case of constant heating.

3.5. *The global circulation for the northern hemisphere winter*

In the next step we attempt to investigate the effect of southern hemisphere forcings on the northern hemisphere. The following experiments illustrate the interhemispherical influences.

Experiment 8

In this experiment the northern hemispheric winter data were those used in experiment 1. The Hellerman (1967) surface stress is utilised. The meridional grid extends from 87.5°N to 87.5°S, with a grid interval of 5°. The vertical grid remains the same as in all the previous experiments.

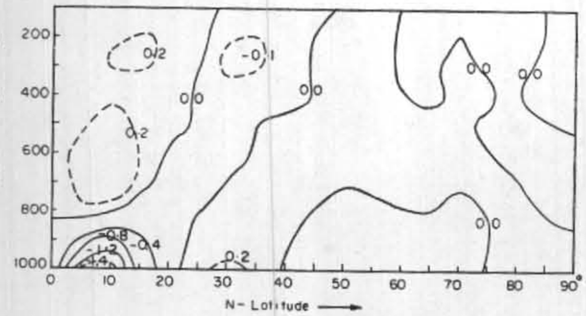

Fig. 13. v_1 (m/sec) for winter with H as forcing ($c_2 = 1{\cdot}5$, $\gamma = 10{\cdot}0$)

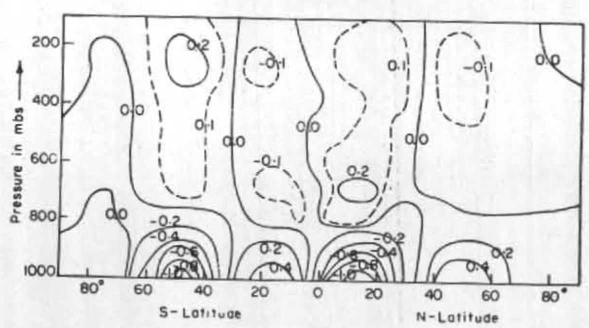

Fig. 14. Global v_1 (m/sec) for winter χ as forcing, $\beta = 34{\cdot}0$

For the southern hemisphere, data were taken from Newell *et al.* (1974). The value of β is that used in experiment 3. Figs. 14 and 15 show the computed v_1 and w_1 field. Comparing Fig. 14 with Fig. 7, we infer the following :

(1) As in the northern hemisphere experiment 3, the maximum meridional velocity prevails near the surface.

(2) Between the hemispherical experiment and the global experiment there is not much difference regarding pattern and strength of the circulation. Over the northern hemispheric circulation, the inclusion of the southern hemisphere did not give rise to significant changes. This shows that inter hemispherical influences do not act significantly through direct mechanical forcings alone. This does not mean that mechanical forcings such as friction are unimportant. They can indirectly introduce thermodynamic forcings by latent heat liberation by conditional instability of the second kind (C.I.S.K) processes.

(3) In the northern hemisphere the Hadley circulation is strongest with maximum meridional velocity of 1.1 m/sec, whereas in the southern hemisphere the middle latitudes indirect cell is stronger than the tropical direct Hadley cell.

(4) The meridional velocities in the southern hemispheric indirect cell are of the same order as those in the northern hemispheric Hadley cell.

(5) The rising branch of the Hadley cell is mainly situated in the summer hemisphere, the maximum vertical velocity being 0.08 cm/sec occurring around 5°S near the surface.

(6) The southern hemispheric circulation is stronger than that of northern hemisphere in terms of the vertical velocities near the polar regions.

Experiment 9

In this experiment M.M.C. is computed for the winter using H forcing alone. The diabatic heating $Q(\phi, p)$ is assumed to be a constant by taking γ=0.0, c_1=0.0, c_2=1.0. This is similar to the N.H. experiment 4. The v_1 and w_1 fields are shown in Figs. 16 and 17.

(1) The northern hemisphere Hadley circulation with maximum meridional velocity of about 1.8 m/sec occurring near the surface extends into the summer southern hemisphere upto 5°S. The return current is also quite strong with maximum meridional velocity of 1.1 m/sec at 100 mb.

(2) The inclusion of the southern hemispheric heating resulted in significant changes in the northern hemispheric circulation especially in tropics. For instance maximum meridional velocity in experiment 4 is about 0.8 m/sec while in this experiment the maximum is 1.8 m/sec. This shows that the interhemispherical influences act through thermodynamic forcings, which may arise due to mechanical forcings *via* C.I.S.K. type processes.

(3) In the middle latitudes the circulation is very weak thus indicating that χ forcing is very important.

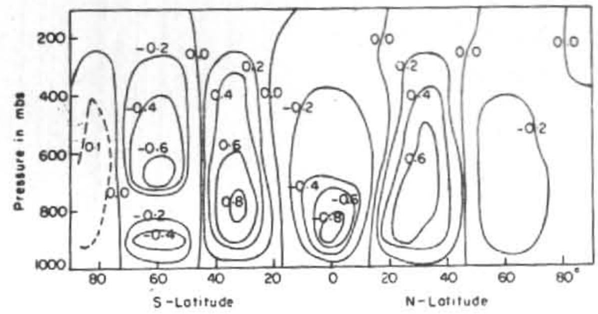

Fig. 15. Global ω_1 in 10^{-2} Newton/m^2/sec for winter with χ as forcing, $\beta = 34{\cdot}0$

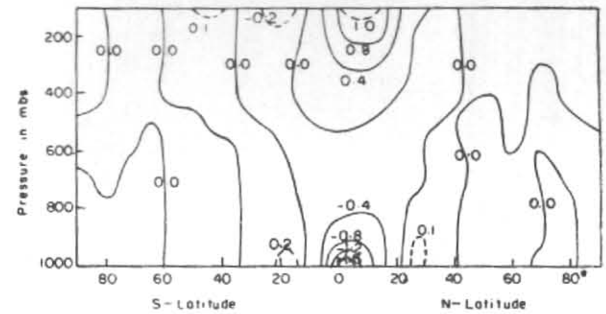

Fig. 16. Global v_1 (m/sec) for winter with H as forcing ($\gamma = 0{\cdot}0$, $c_1 = 0.0$, $c_2 = 1{\cdot}0$)

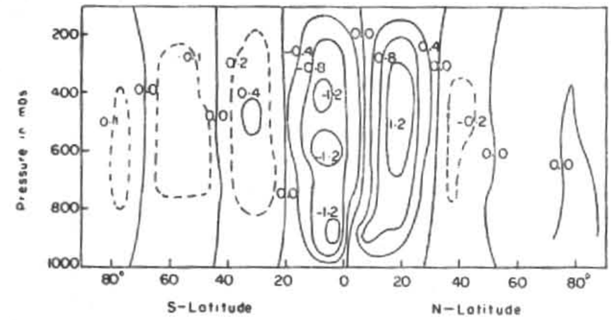

Fig. 17. Global ω_1 in 10^{-2} Newton/m^2/sec for winter with H as forcing ($\gamma = 0.0$, $c_1 = 0{\cdot}0$, $c_2 = = 1{\cdot}0$)

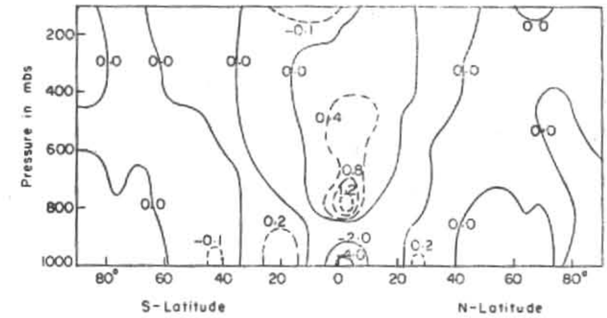

Fig. 18. Global v_1 (m/sec) for winter with H as forcing ($\gamma = 10.0$, $c_2 = 1{\cdot}5$)

(4) Just as in the previous experiment the rising branch of the Hadley cell is situated mainly in the summer-southern hemisphere.

(5) The velocities in the rising and sinking branches of the northern hemispheric Hadley circulation are almost of the same strength.

Experiment 10

This is similar to the above experiment but for the distribution of diabatic heating. Here we assumed $\gamma = 10.0$, $c_2 = 1.5$. The computed v_1 field is shown in Fig. 18. Comparing Fig. 18 and Fig. 13 we arrive at the following conclusions :

(1) Just as in the northern hemisphere experiment 7, the meridional velocities are strong near the surface the maximum being 4.7 m/sec in the Hadley cell.

(2) Between the hemispherical and global experiments the results show significant differences especially in the tropics as in experiment 9. For instance, the maximum meridional velocity in the hemispheric experiment is about 1.5 m/sec. The maximum in the global experiment is 4.7 m/sec.

(3) The return current of the Hadley circulation is weak the maximum being 1.3 m/sec occurring at 800 mb only. The Hadley cell is concentrated between 1000 and 500 mb. Thus the centre of the Hadley cell is much nearer to the surface when compared with the previous experiment.

3.6. *The Global circulation for the northern hemispheric summer*

Experiment 11

In this experiment the northern hemisphere summer data used for $\overline{u_0}$, $\overline{T_0}$, $\overline{u'v'}$ are from Oort and Rasmusson (1971). For the southern hemisphere we have utilised data from Newell *et al.* (1974). The surface stress being used is given by Hellerman (1967). β is the same ($\beta = 34{\cdot}0$). Global

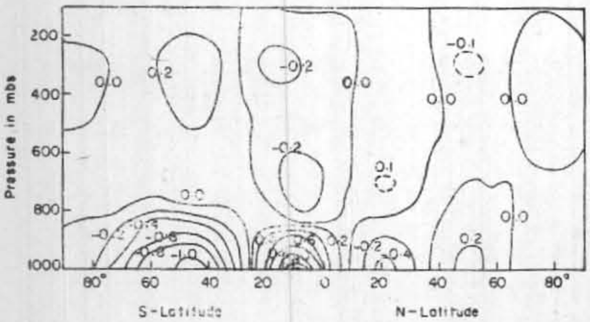

Fig. 19. Global v_1 (m/sec) for summer with χ as forcing, $\beta=34{\cdot}0$

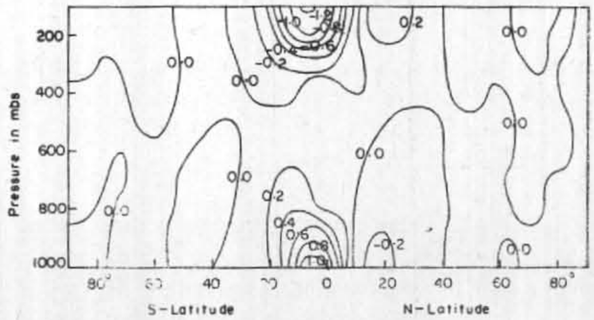

Fig. 20. Global v_1 (m/sec) for summer with H as forcing ($\gamma=0{\cdot}0$, $c_1=0{\cdot}0$, $c_2=1{\cdot}0$)

circulation computed is forced only by χ forcing. Fig. 19 describes the computed v_1 field. The following points are noticed :

(1) For the summer, the southern hemisphere Hadley circulation with maximum meridional velocity of 1.2 m/sec is stronger and extends into the northern hemisphere upto 10°N latitude.

(2) The return current is too weak as noticed in the winter experiment 3 with $\beta=34.0$.

(3) The southern hemisphere circulation is stronger than that of northern hemisphere.

(4) The summer circulation is weaker than the winter circulation.

(5) This experiment also shows that interhemispherical influences due to direct effects of χ forcing alone are not important.

Experiment 12

In this experiment the global circulation computed is forced by H forcing alone the diabatic heating $Q_{(\phi,p)}$ is assumed to be constant at all pressure levels. Computed v_1 field is shown in Fig. 20. Comparing Fig. 20 with Fig. 11 we notice the following points :

(1) The maximum meridional velocity of 1.2 m/sec occurs in the return current of the southern hemisphere Hadley circulation which extends into the northern hemisphere upto 10°N latitude.

(2) The middle latitudes circulation is too weak indicating the importance of χ forcing.

(3) As in the N.H. experiment 5, the return current of the Hadley cell is quite strong in this experiment also.

(4) Similar to other experiments, with H forcing, the inclusion of the southern hemisphere resulted in significant changes in circulation strength over the tropics. For instance the meridional velocity in the tropical regions is 0.4 m/sec at the surface in experiment 5 while it is only 0.2 m/sec in this experiment. Similar drastic changes can be seen aloft also.

4. Conclusions

We conclude the following from the results obtained above :

(1) The mechanical forcing alone, directly, cannot explain quantitatively the observed M.M.C. However, it is important for the middle cell and the polar cell.

(2) The pattern and the strength of the circulation is sensitive to the stress and heating distribution in the vertical.

(3) The forcing due to heating is of great importance as far as the Hadley cell is concerned. The constant distribution of diabatic heating along the vertical in the forcing due to heating gives rise to a Hadley cell where both the return current and the equatorward current are comparable in strength in which case the response resembles the observed circulation. But the return current of the Hadley cell is weak if the diabatic heating is such that the maximum is around 900 mb and becomes negligible from 400 mb onwards. This result has important implications on the results of numerical general circulation studies wherein the heating function shows a maximum near 900 mb level, *e.g.*, Manabe and Terpstra (1974).

(4) The effect of southern hemispheric mechanical forcing on the northern hemisphere circulation is not significant. But the inclusion of southern hemispheric forcing due to heating brought about a drastic change in the strength and pattern of the northern hemispheric circulation.

(5) In agreement with the observation, the M.M.C. response is stronger for the winter hemisphere than for the summer hemisphere.

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