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ANNUAL VARIATION OF MERIDIONAL FLUX OF SENSIBLE HEAT

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ABSTRACT :

The annual cycle of zonally averaged meridional flux of sensible heat and its divergence are discussed. The calculations are based on five year data from more than 500 radiosonde stations in the northern hemisphere. (Oort and Rasmusson, 1971).

In the annual mean, the meridional transport of sensible heat by the eddies shows double maxima in the vertical over middle and high latitudes and a counter gradient transport in the tropical mid-troposphere. The amplitude of the annual oscillation is also maximum over middle and high latitudes, occurring during January.

Divergence of meridional transport of sensible heat indicates that largest heating by the eddies occurs over the belt 60° - 70°N during April. This heating is found to be more due to standing eddies than due to transient eddies. The maximum diabatic heating over higher latitude occurring towards the end of July, as revealed by thickness analysis (Asnani and Verma, 1974) does not seem to be due to sensible heat transport.

The meridional transport of sensible heat by mean meridional circulation is such that the maximum heating occurs over the tropics near the surface and at 200 mb level during November.

INTRODUCTION :

During the recent years there have been studies describing the atmospheric general circulation, directly through a number of parameters. A few of these are those by Kung (1966 a,b, 1967, 1969, 1970), of kinetic energy, by Starr et al (1970), of angular momentum and by Van Loon et al (1968), of the zonal mean temperature and wind in the Southern hemisphere. It has been found that most of the annual variation of the parameters could be expressed by the annual mean and the first Fourier component of the annual variation. Wiin-Neilsen (1967) investigated the annual variation of available potential - energy and kinetic energy in both zonal and eddy form. In continuation, Wiin-Neilsen (1973) calculated the annual mean and the first few Fourier components of the annual variation using monthly mean values of the zonal wind, the meridional transport of momentum and sensible heat. Recently, the authors have completed a diagnostic study on the annual thickness (which is the same as temperature)

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oscillations in the troposphere of the Northern hemisphere. This study has revealed one interesting feature that the largest amplitudes in the annual temperature oscillation occur in middle or higher latitudes almost at the same time throughout the troposphere towards the end of July. The authors, therefore, decided to investigate further, this aspect of temperature distribution, which is essentially due to diabatic heating. Physical processes mainly responsible for diabatic heating are sensible heat transfer, latent heat release and radiation. (Since we are concerned with the whole of the troposphere, turbulent mixing may be reasonably neglected). We decided to investigate first some aspects of the sensible heat transfer. The present study deals with this.

There are two major mechanisms of transfer; the transfer by eddies (transient and stationary) and the transfer by the mean meridional circulation. We shall first consider in some detail the flux of sensible heat by these agencies.

2. Meridional Transport of Sensible Heat :

Following the notation that a bar (-) denotes the time average of any quantity, and a prime (′) the departure of a quantity from its time average. Likewise, let brackets (*) denote the average of any quantity with respect to longitude, and a star (*) the departure of a quantity from its longitudinal average. The field of northward motion may now be resolved according to the formulae.

$$v = \overline{v} + v' \ldots\ldots\ldots\ldots\ldots (1)$$

$$v = [v] + v^{*} \ldots\ldots\ldots\ldots (2)$$

On combining, which gives

$$v = [\overline{v}] + [v]' + \overline{v}^{*} + v^{*'} \qquad (3)$$

The terms in (3) are respectively the time-averaged or standing meridional circulation, the transient meridional circulation, the time-averaged or standing eddies and the transient eddies.

The long-term meridional transport of sensible heat may then be resolved into the amounts accomplished by the separate components of v , thus,

$$[\overline{vT}] = [\overline{v}][\overline{T}] + \overline{[v]'[T]'} + [\overline{v}^{*}\overline{T}^{*}] + [\overline{v^{*'}T^{*'}}] \; (4)$$

The second and fourth terms in (4) representing the transient eddy transports can be combined into one term, $[\overline{v'T'}]$. This term is regarded as the transport by the transient eddies.

Thus,

$$\left[\overline{vT}\right] = \left[\overline{v}\right]\left[\overline{T}\right] + \left[\overline{v}^{*}\,\overline{T}^{*}\right] + \left[\overline{v'T'}\right] \qquad (5)$$

where $\left[\overline{v}\right]\left[\overline{T}\right]$ = Meridional transport of sensible heat by mean meridional circulation.

$\left[\overline{v}^{*}\,\overline{T}^{*}\right]$ = Meridional transport of sensible heat by standing or stationary eddies.

$\left[\overline{v'T'}\right]$ = Meridional transport of sensible heat by transient eddies.

Oort and Rasmusson (1971) have given an exhaustive compilation and a critical discussion of the zonally averaged, monthly and seasonal statistics describing the atmospheric circulation in the Northern Hemisphere. The data covers the period from May 1958 through April 1963. In their earlier paper (Oort and Rasmusson 1970) they have shown that in the middle and higher latitudes, the net mean poleward transfer of the sum of sensible heat, latent heat and potential energy is small compared to the eddy poleward transfer of sensible heat. In other words, in the middle and higher latitudes, the energy transport is mainly in the form of sensible heat transported by eddies. The following points may be noted considering the meridional transport of sensible heat.

1] the transient eddy transport of sensible heat show two maxima in middle latitudes, one at about 850 mb level and the other at 200 mb.

2] the standing eddy transport is strong in winter and is insignificant in summer. This transport also shows 850 and 200 mb level maxima.

3] in low latitudes, the fluxes by the mean meridional circulation are large compared to those by the eddies. In the middle and higher latitudes, they are comparable. Near the equator, these are always directed towards the summer hemisphere.

3. Data Source :

The data of meridional transport of sensible heat by,

i) the transient eddies,

ii) the stationary eddies, and

iii) the mean meridional circulation, have been taken from 'Atmospheric circulation statistics' by Oort and Rasmusson, 1971. The data covers the 5-year period from May 1958 through April 1963. The values, zonally averaged and monthly mean, are given by these authors as a function of latitude between $10^{o}S$ and $75^{o}N$ and as a function of ~~highest~~ height between the earth's surface and 50 mb. The monthly flux data given by these authors and the values of divergence derived therefrom have been subjected to harmonic analysis by us and the results are discussed in the following paragraphs.

Data pertains to 00 GMT only. Therefore, the diurnal variation of the fluxes is not smoothed out. To that extent, the analyses may be viewd with reservation, especially in lower levels.

4. <u>Annual Variation of the Meridional Transport of Sensible Heat by the eddies (Transient + Stationary)</u>

Since it is established that eddies play an important role in energy transfer in middle and higher latitudes, it is desirable to examine in detail the annual oscillation in the meridional transport of sensible heat by the eddies and compare it with other similar studies. The usual technique of Fourier analysis in time has been utilised to describe the annual variations of the various parameters. Since these quantities depend upon time, latitude and pressure, we have described them using mean meridional cross sections.

Annual Mean :

Figure 2 (a) shows the computed annual mean of the meridional transport of sensible heat by the eddies as a function of latitude and pressure. The unit is $msec^{-1}\ ^{\circ}c$. The distribution is similar to that given by Wiin-Neilsen (1973) and reproduced in Figure 3 (a) for comparison. (Data period of Wiin-Neilsen was - February 1963 to January 1964). We observe two maxima in middle latitudes, one around 850 mb level and the other around 100 mb level. The significant feature of the counter-gradient transport of sensible heat by the eddies in the tropical mid-troposphere is very well revealed. This means that the colder temperatures are transported to the region of warmer temperatures. Within this layer zonal available potential energy (ZAPE) will be converted to eddy - available potential energy (EAPE).

Annual Oscillation :

i) The distribution of amplitude of the annual oscillation of eddy transport of sensible heat, shown in Figure 2 (b) is quite similar to the annual mean transport in middle latitudes. It shows that in these latitudes, the amplitude of annual oscillation is largest in these regions where the annual mean has also the largest value.

It is in general agreement with Wiin-Neilsen's analysis as shown in Figure 3 (b).

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ii) Figure 2 (c) shows the phase of the annual oscillation. In a broad zone of $25^{\circ}N - 65^{\circ}N$, there is a winter maximum in the sensible heat transport. North of $40^{\circ}N$, the maximum transport is in January, south of $40^{\circ}N$, the maximum transport is in February. This shows a marked difference from Wiin-Neilsen's finding as depicted in Figure 3 (c), which shows December maximum between $40^{\circ}N$ and $60^{\circ}N$ and January maximum south of $40^{\circ}N$. The cause of this discrepancy seems to lie in the fact that we have used five year data where as Wiin-Neilsen's data consisted of only one year.

Another significant point to be noted in phase distribution is that there is a north-south progression of the annual wave from $40^{\circ}N$ to $20^{\circ}N$. South of about $20^{\circ}N$, the phases appear variable, presumably due to the relatively small values of the amplitudes.

Vertically averaged fluxes :

Let us examine the values of the vertically averaged flux for certain latitudes, reproduced from Oort and Rasmusson (1971) in table 1. Apart from giving the broad idea of the relative role of transient eddies, stationary eddies and mean meridional circulations, from equator to $60^{\circ}N$ in January and July, we can get some idea of the amplitudes of the annual oscillation. The numbers shown in circles are obtained by subtracting July value from the January value and taking modulus of it. The value may be taken as double the amplitude of the annual oscillation. Between equator and 15°N, MMC is dominant and eddies are not significant. Between 30°N and 60°N, the eddies are about 3 to 4 times larger than MMC and in higher latitudes, it is the stationary eddies which are more significant than the transient eddies.

5. Annual variation of the divergence of the transport of Sensible Heat (Transient + Stationary)

Since the aim of the present study is to examine the heating caused by these transports of heat, it is necessary to calculate the divergence of the meridional transport of heat. Our basic data of the meridional transport of sensible heat by eddies and mean meridional circulation were used for calculating the divergence. These values of the divergence were then subjected to harmonic analysis to obtain the annual mean and the amplitude and the phase of the first harmonic. We obtained other harmonics as well, but our present interest is in the annual oscillation; hence we confine our remarks to the annual mean and the first harmonic only.

5.1 Annual Mean of the divergence of meridional transport of Sensible Heat :

(a) By Transient Eddies (TE) : In the annual mean, the transient eddies show small convergence or heating in tropical middle and upper troposphere and much larger convergence in middle and higher latitudes as shown in figure 4 (a). At about 60°N, there are two maxima in the vertical; one at 850 mb level and the other at 200 mb level. The maxima value is -40×10^{-7} Deg. $Csec^{-1}$. Between 15°N and 40°N, there is divergence or cooling by TE, again showing two maxima at almost the same levels of 850 mb and 200 mb and values of the same order of magnitude as higher latitude heating.

(b) By Stationary Eddies (SE) : The tropical-mid-tropospheric heating (convergence) and the sub-tropical and mid-latitude cooling by stationary eddies is much less marked compared to that by transient eddies as shown in Figure 4 (b). But the higher latitude heating is very well marked with stronger lower and upper tropospheric maxima (now at about 65°N) compared to that by transient eddies, the lower tropospheric maxima reaching the value of -50×10^{-7} $^{o}C\ sec^{-1}$. The whole heating belt seems to have shifted polewards (north of 50°N) compared to the respective heating belt by the transient eddies (north of 45°N). The gradient of the heating in the vertical is very small, but sufficiently large in the horizontal at any level.

The additive heating effect of the two eddies clearly indicates that amongst the two, transient eddies are more important south of 50°N. North of it, stationary eddies are more important.

(c) By Mean Meridional Circulation (MMC) : As shown in Figure 4 (c), there are three distinct vertical zones - (i) of heating at equatorial and tropical latitudes, (ii) of cooling at sub-tropical and middle latitudes and (iii) again of heating in higher latitudes. Each zone has two maxima, one at the surface and the second at about 200 mb level separated by a zone of opposite sign at mid-troposphere. The values of the maxima decrease towards pole. A significant mid-tropospheric heating over the latitudinal belt of 25°N - 40°N is noteworthy, which may be the effect of Tibetan high.

The relative role played by the eddies and the mean meridional circulation in heating the troposphere through sensible heat transfer can be easily inferred. From equator to 40°N the heating/cooling is predominantly due to MMC. Eddies are more important north of 40°N, except in the lowest troposphere and around 200 mb level between 50°N and 60°N, the MMC shows larger effect. The sub-tropical mid-tropospheric heating by MMC is exceeded by cooling effect of eddies (particularly transient) so that in the resultant, the area shows cooling.

5.2 Annual oscillation of the divergence of meridional transport of sensible heat

The horizontal divergence of zonally averaged meridional transport of sensible heat reduces to

$$\nabla\cdot\left[\overline{vT}\right] = \frac{\partial}{\partial y}\left[\overline{vT}\right]$$

It gives the rate of change of temperature.

This rate of change of temperature can be represented as a periodic phenomenon given by

$$\frac{\partial T}{\partial t} = A \cos(\omega t - \epsilon)$$

where A = Amplitude

ϵ = phase

Integrating, we get

$$T = \frac{A}{\omega} \sin(\omega t - \epsilon)$$

$$= \frac{A}{\omega} \cos\left\{\frac{\pi}{2} - (\omega t - \epsilon)\right\}$$

$$= \frac{A}{\omega} \cos\left\{\omega t - (\epsilon + \frac{\pi}{2})\right\}$$

noting that $\cos(-\theta) = \cos\theta$

i.e. $\frac{\partial T}{\partial t}$ wave lags behind T wave by $\frac{\pi}{2}$ (quarter of the period; in the present case this will be equal to 3 months). This phase relationship between T and $\frac{\partial T}{\partial t}$ is shown in Figure 5.

In the present analysis, the phase indicates the time of occurrence of the maximum.

Interpretation of phase :

In the present analysis, the phase value corresponds to the time of occurrence of maximum divergence of sensible heat transport i.e. of maximum cooling. Hence, to get the time of occurrence of maximum heating, 180° will be added to the computed phase value. Again, as we have seen in the preceding paragraph, 90° will have to be added to get the time of occurrence of the maximum temperature. Hence, 270° (equivalent to 9 months) will be added to the computed phase value of heat flux divergence to get the time of occurrence of the maximum temperature.

The phase diagrams, which are drawn to indicate the time of occurrence of maximum cooling rate should thus be interpreted accordingly to get the time of occurrence of the maximum temperature. For example, if the phase is indicated by 1 (i.e. time of occurrence of maximum cooling rate is 1st January), the time of occurrence of the maximum temperature will be 1 + 9 = 10 or 1st of October, and so on.

6. Amplitude and phase of annual oscillation :

Amplitude and phase of the first harmonic will give us an idea of distribution of annual oscillation in temperature in space and time due to sensible heat transport. Let us examine this distribution which is accomplished by the following mechanisms :

By Transient Eddies :

Amplitude of the annual oscillation of the divergence of meridional transport of sensible heat by transient eddies as a function of latitude and pressure is given in Figure 6 (a). The amplitudes are very small over the equatorial region and in the middle troposphere over higher latitudes. It is highest in upper and lower troposphere over mid-latitudes.

Phase of the annual oscillation of divergence of the meridional transport of sensible heat by transient eddies as a function of latitude and pressure, as shown in Figure 6 (b), illustrates large variability in time of occurrence of maximum heating. This is always associated with small amplitude values. In the regions of largest amplitudes (viz. upper and lower troposphere over mid-latitudes) the phases, as shown in the figure, are 8 and 9. Hence, as stated earlier, to get the time of occurrence of maximum temperature 9 months is added to these. The time of occurrence of maximum temperature, in the regions of largest amplitudes, is thus between 1st May and 1st June.

By Stationary Eddies :

Amplitude and phase are shown in Figs. 6 (c) and 6 (d) respectively. Poleward distribution of amplitude

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is such that there are alternate regions of small and large values of heating. From 7.5°S upto about 30°N, the amplitudes are very small. Between 30°N and 45°N, the amplitudes are fairly large, with two maxima in the vertical over about 42½°N, one in the lower troposphere and the other above 200 mb level. Between 45°N and 55°N, the amplitudes are again small with minimum in upper troposphere. Between 55°N and 70°N, the amplitudes are largest with very pronounced lower and upper level maxima over 62½°N. Upper maximum is slightly less than the lower one. North of 70°N, the amplitude decreases.

The phases are not as variable as in the case of the transient eddies. As one can expect, except the regions of small amplitudes, where the phases are very variable, the regions of large amplitudes show consistent phase. In the first region of large amplitudes over mid-latitudes, the time of occurrence of maximum divergence is January and hence the maximum temperature in October. From this region, the annual wave in sensible heat transfer by stationary eddies seems to propagate northwards. In the second region of large amplitudes, between 55°N and 70°N, it reaches after six months. Divergence is maximum in July, hence temperature maximum due to this agency should occur in April. The annual waves of heating due to sensible heat transfer by stationary eddies in the two regions of large amplitudes (Around 40°N and 60°N) are in opposite phase.

It would be of interest to see the heating effect by both the eddies combined (Figures 6 (e) and 6 (f) and their relative role. In the sub-tropics and mid-latitudes, though the two eddies have comparable amplitudes (stationary eddies are of slightly higher amplitudes) but the stationary eddies show less variations in phase compared to transient eddies. In the higher latitudes it is predominantly due to stationary eddies as can be seen clearly when we compare amplitude and phase of stationary eddies with those of total eddies. In this region the transient eddies, though small, have phases such that they add to the amplitudes of the stationary eddies.

By Mean Meridional Circulation :

Amplitude and phase of the annual oscillation of the divergence of meridional transport of sensible heat by mean meridional circulation are shown in Figures 6 (g) and 6 (h). It is clear from the phase diagram that except for two near equatorial regions, of maximum amplitudes, where the heating maxima occur in November, elsewhere the phases are quite variable. One maxima is centered round $17\frac{1}{2}^{\circ}$N at the surface and extends upto about 900 mb level. The

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other maxima is centered round $12\frac{1}{2}^{\circ}$N at 200 mb level. The heating in the upper level maximum is much larger than the lower level maximum and it is about 5° latitude nearer to the equator. There is a striking symmetry around 2.5°N throughout the troposphere.

7. Concluding Remarks :

The main purpose of this paper has been to describe the annual variation of the zonally averaged meridional transport of sensible heat by eddies and mean meridional circulation and of their divergent field. The technique of Fourier - analysis in time was used to get the annual mean and the amplitude and phase of the first harmonic.

In the annual mean, the meridional transport of sensible heat by the eddies show double maximum in the vertical over middle and high latitudes and a counter-gradient transport in the tropical mid-troposphere. The annual oscillation is maximum, also over middle and high latitudes, occuring during January.

In the annual mean, the divergence field of meridional transport of sensible heat by eddies shows alternate heating and cooling from equator towards pole, with increasing intensity. The equatorial heating is very small. The intensity of sub-tropical cooling is about half the middle and higher latitude heating. Both these regions display the lower and the upper tropospheric maxima. Annual mean of the divergence of meridional transport of sensible heat by mean meridional circulation shows a three-cell structure with intensity decreasing from equator to pole.

The annual oscillation of the divergence of meridional transport of sensible heat by eddies is largest over the belt $60^{\circ}-70^{\circ}$N, the heating maxima occuring during April. The heating is more due to standing eddies rather than due to transient eddies. The maximum diabatic heating over higher latitudes occurring towards the end of July, as revealed by thickness analysis, does not seem to be due to sensible heat transport.

The meridional transport of sensible heat by mean meridional circulation is such that the maximum heating occures over the tropics near the surface and at 200 mb level during November.

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R E F E R E N C E S

Asnani, G.C. and Verma, R.K.	1974	'Annual and semi-annual thickness oscillations in the northern hemisphere' I.I.T.M. Research Report-20.
Kung, E.C.	1966.a	'Kinetic energy generation and dissipation in the large-scale atmospheric circulation'. Mon. Wea. Rev. 94(2), pp. 67-82.
-" -	1966.b	'Large scale balance of Kinetic-Energy in the atmosphere', Mon. Wea. Rev., 94(11), pp. 627-640.
-" -	1967	'Diurnal and long-term variations of the kinetic energy generation and dissipation for a five-year period'. Mon. Wea. Rev., 95 (9), pp. 593-606.
-" -	1969	'Further study on the kinetic energy balance'. Mon. Wea. Rev., Vol. 97, No.8, pp. 573-581.
-" -	1970	'On the meridional distribution of source and sink terms of the kinetic energy balance'. Mon. Wea. Rev. Vol. 98, No.12, pp.911-916.
Starr, V.P. et al	1970	'A method for the study of the zonal kinetic energy balance in the atmosphere'. Pure Appl. Geophysics, Vol. 80, pp. 346-358.
Van Loon, H. et al	1968	'An outline of the yearly and half-yearly components in the zonal mean temperature and wind between the surface and 100 mb in the southern-hemisphere'. Notos, Vol.17, pp. 55-62.

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Wiin-Neilsen, A.	1967	'On the annual variation and spectral distribution of atmospheric energy', Tellus, Vol. 19, No. 4, pp. 540-559.
-" -	1973	'A study of the annual variation of certain aspects of the atmospheric general circulation', Technical Report-002630-7-T, National Science Foundation, Washington, D.C.
Oort, A.H. and Rasmusson, E.M.	1970	'On the annual variation of the monthly mean meridional circulation', Mon. Wea. Rev., Vol. 98, No. 6, pp. 423-442.
- " -	1971	'Atmospheric circulation statistics'. NOAA professional paper 5, 323 pp.

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		EQ	15°N	30°N	45°N	60°N
TE	Jan.	-0·4	-0·8	4·7	6·9	8·6
	July	0·1	-0·3	0·3	4·1	4·8
	Annual Mean	-0·15	-0·55	2·5	5·5	6·7
	(circled)	0·5	0·5	4·4	2·8	3·8
SE	Jan.	-0·0	0·0	2·2	10·3	7·8
	July	0·1	0·1	0·2	-0·7	-0·6
	Annual Mean	0·05	0·05	1·2	4·8	3·6
	(circled)	0·1	0·1	2·0	11	8·4
TE+SE	Jan.	-0·4	-0·8	6·9	17·2	16·4
	July	0·2	-0·2	0·5	3·4	4·2
	Annual Mean	-0·1	-0·5	3·7	10·3	10·3
	(circled)	0·6	0·6	6·4	13·8	12·2
MMC	Jan.	-27·0	-23·0	4·0	7·0	-3·0
	July	26·0	-1·0	2·0	4·0	1·0
	Annual Mean	-0·5	-12·0	3·0	5·5	-1·0
	(circled)	53	22	2	3	4
Total TE+SE+MMC	Jan.	-27·4	-23·8	10·9	24·2	13·4
	July	26·2	-1·2	2·5	7·4	5·2
	Annual Mean	-0·6	-12·5	6·7	15·8	9·3
	(circled)	53·6	22·6	8·4	16·8	8·2

Values in circle = |(January value − July value)| ≡ Range of annual oscillations
Numbers represent averages for layer between 1012·5 & 75 mb.

Table: I. Meridional Transport of Sensible heat (units in °C m sec^{-1}) from Oort & Rasmussen. 1971.

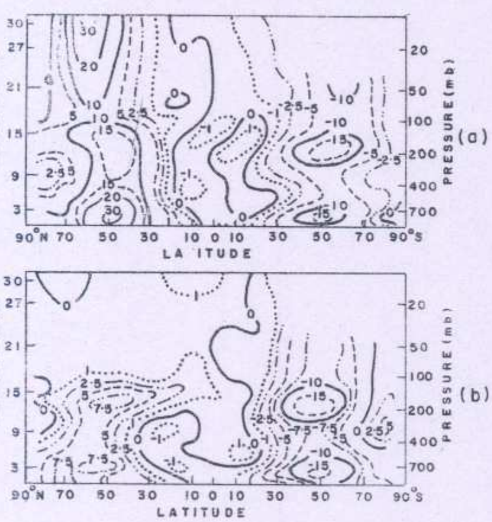
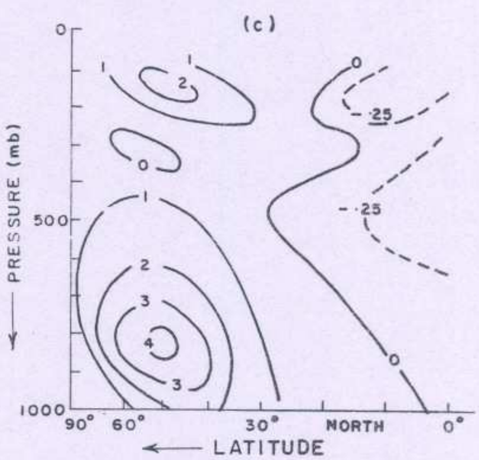


FIG.-1 (a) (b) (c): Transport of sensible heat by transient and standing eddies for (a) December - February. (b) June - August as estimated by Newell et. al. (1970). Only transient eddies available from 30S-90S. Unit: Deg. m sec^{-1}



(c) The vertical distribution of the average northward transport of sensible heat by the eddies as estimated by Peixoto (1960). The Unit is 10^{14} watts per hundred mb layer.

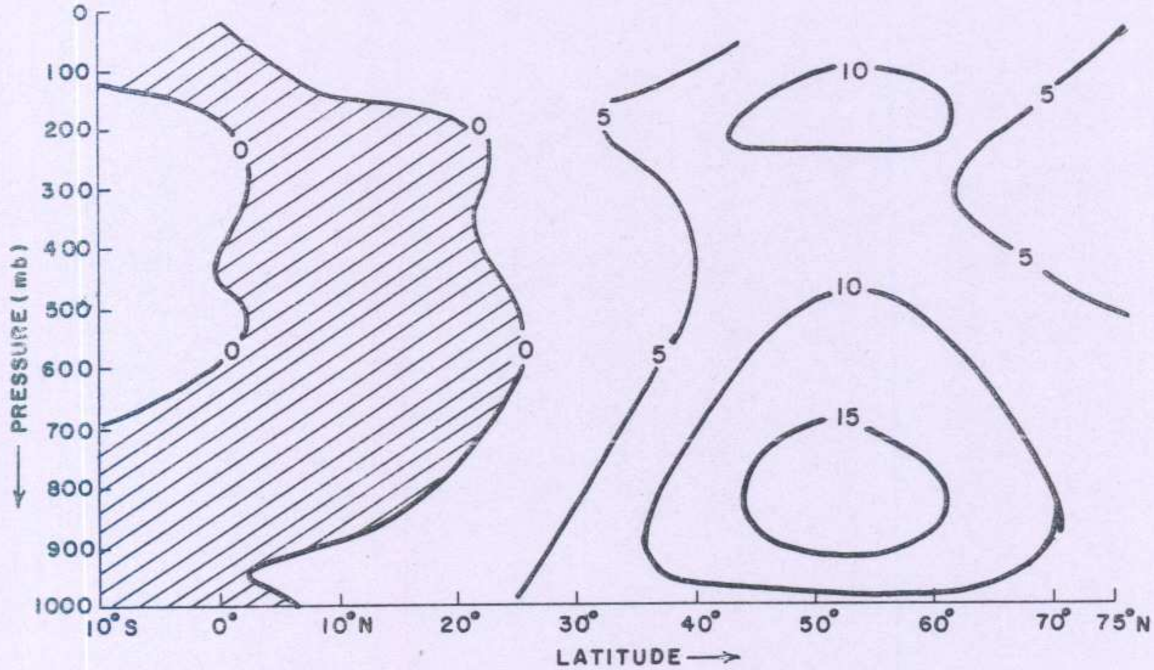


FIG-2(a) Annual mean of the meridional transport of sensible heat by the eddies as function of latitude and pressure. Unit : m sec^{-1} °C.

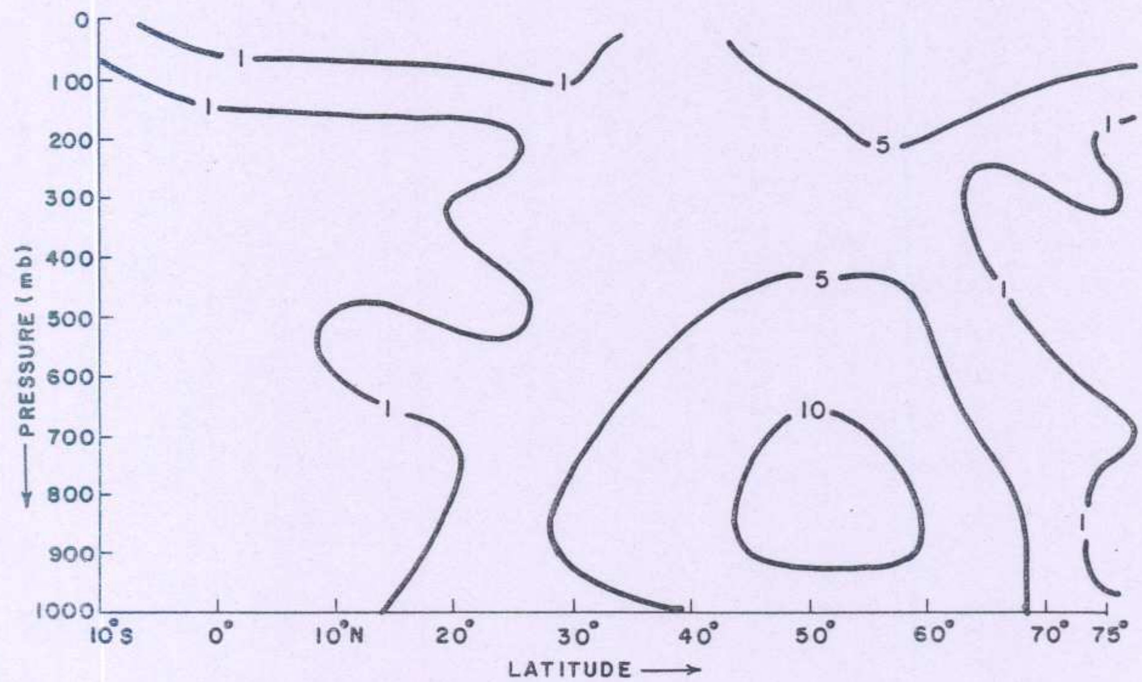


FIG.2(b): Amplitude of the annual oscillation of the meridional transport of sensible heat by eddies as a function of latitude and pressure. Unit: m sec^{-1} °C.

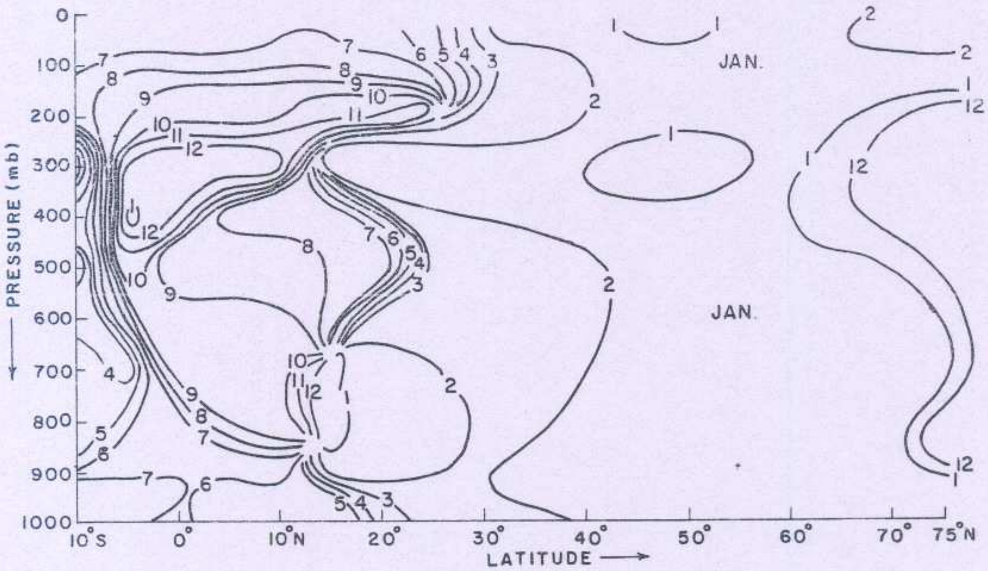


FIG.2 (c) Phase of the annual oscillation of the meridional transport of sensible heat by eddies as a function of latitude and pressure. 1 corresponds to 1st January, 2 corresponds to 1st February and so on.

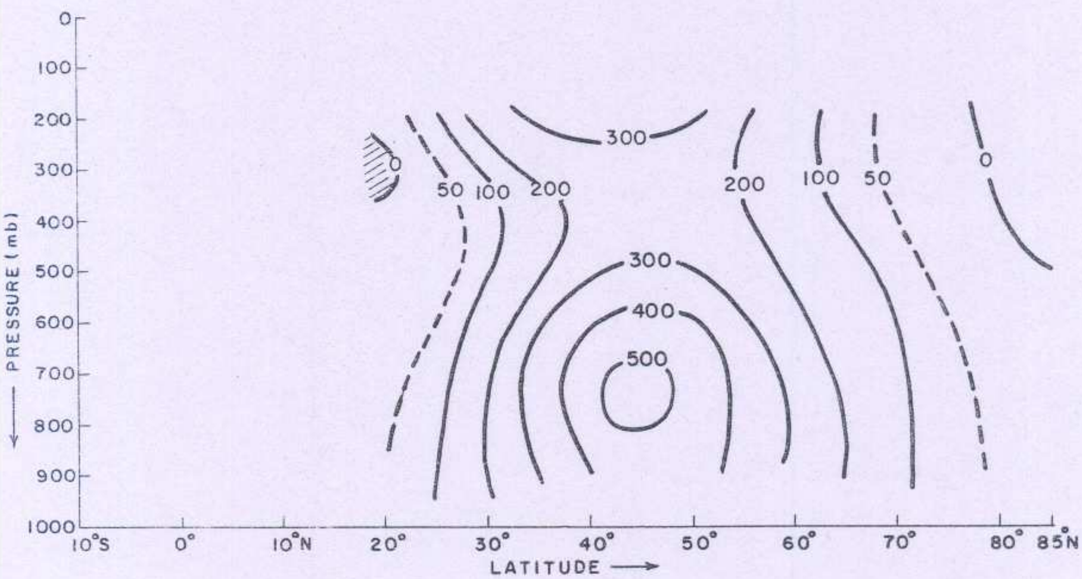


FIG.-3(a) Annual mean of the meridional transport of sensible heat by the eddies as a function of latitude and pressure as estimated by Wiin-Neilsen (1973). Unit: 10^8 Kj sec^{-1} cb^{-1}

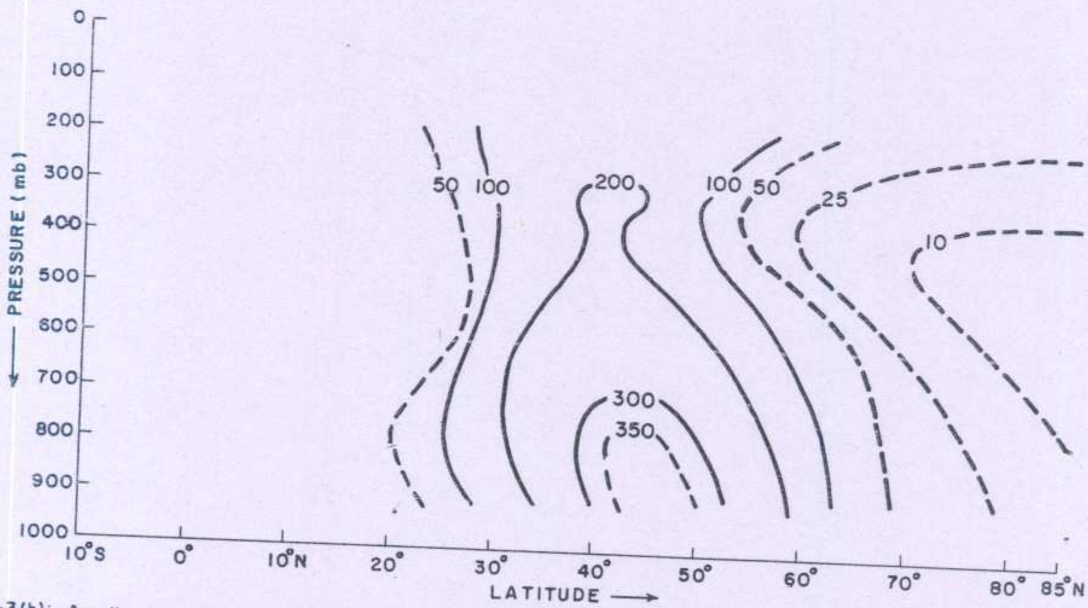


FIG.-3(b): Amplitude of the annual oscillation of the meridional transport of sensible heat by eddies as a function of latitude and pressure as estimated by Wiin-Neilsen (1973). Unit: 10^8 Kj sec^{-1} cb^{-1}

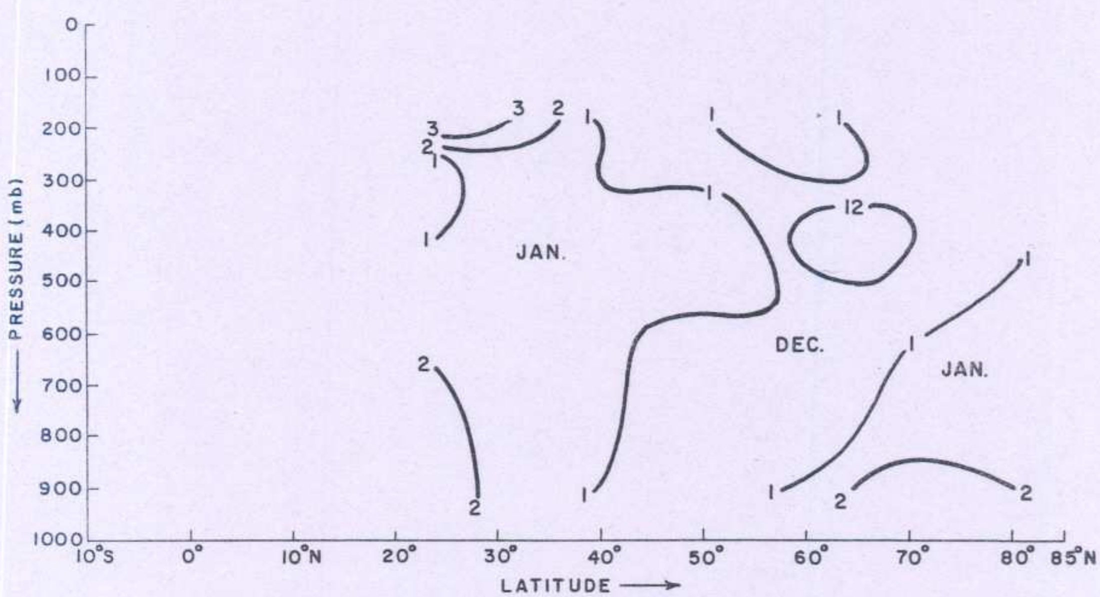


FIG.-3(c): Phase of the annual oscillation of the meridional transport of sensible heat by eddies as a function of latitude and pressure as estimated by Wiin-Neilsen (1973). 1 corresponds to 1^{st} January, 2 corresponds to 1^{st} February and so on.

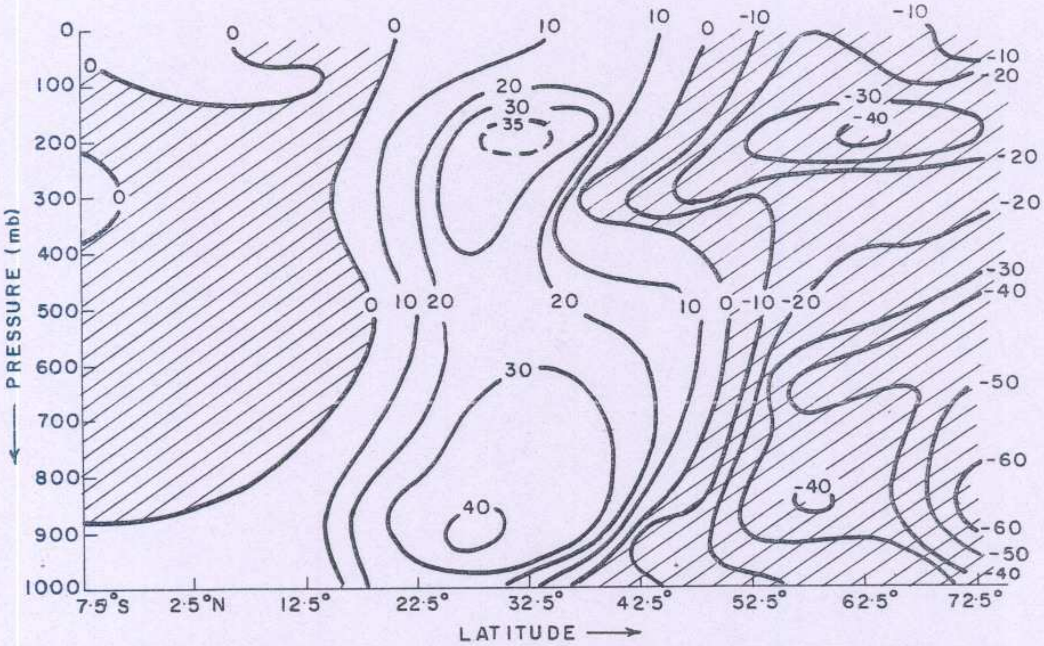


FIG.-4(a) Annual mean of the divergence of meridional transport of sensible heat by transient eddies as a function of latitude and pressure. Unit : 10^{-7} Deg.C.sec^{-1}

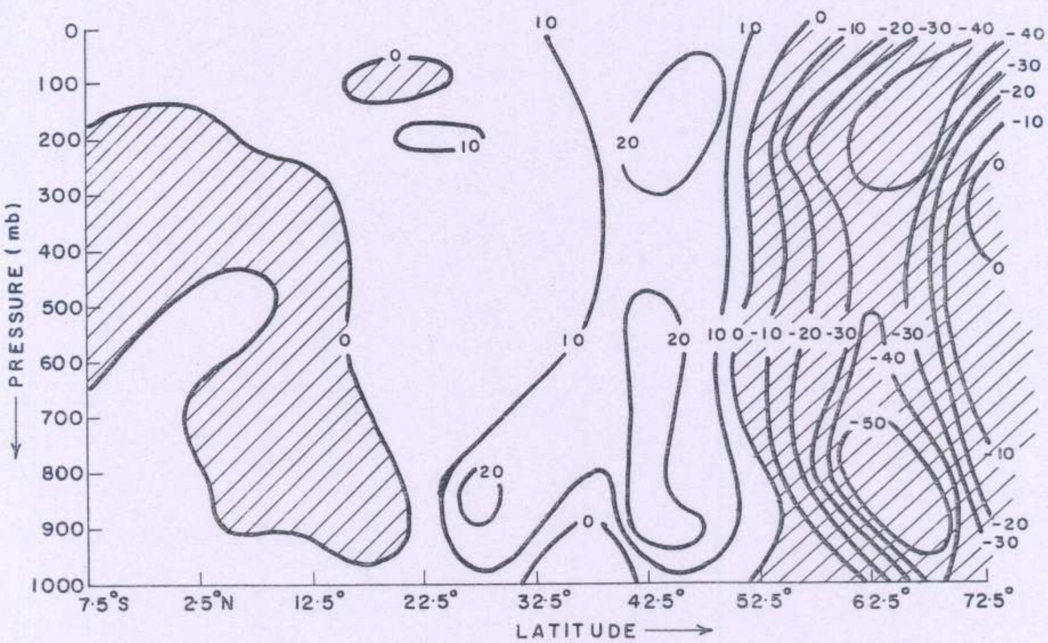


FIG.- 4(b): Annual mean of the divergence of meridional transport of sensible heat by stationary eddies as a function of latitude and pressure. Unit: 10^{-7} °C sec.$^{-1}$

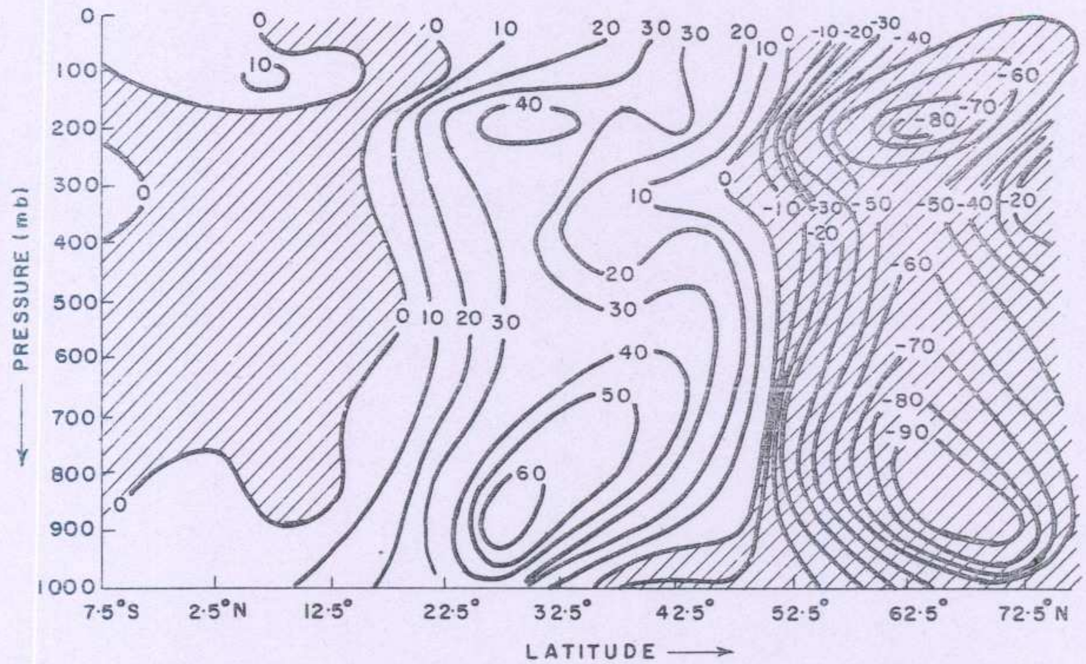


FIG. 4(c) Annual mean of the divergence of meridional transport of sensible heat by eddies (Transient + Stationary) as a function of latitude and pressure. Unit: 10^{-7} °C sec^{-1}.

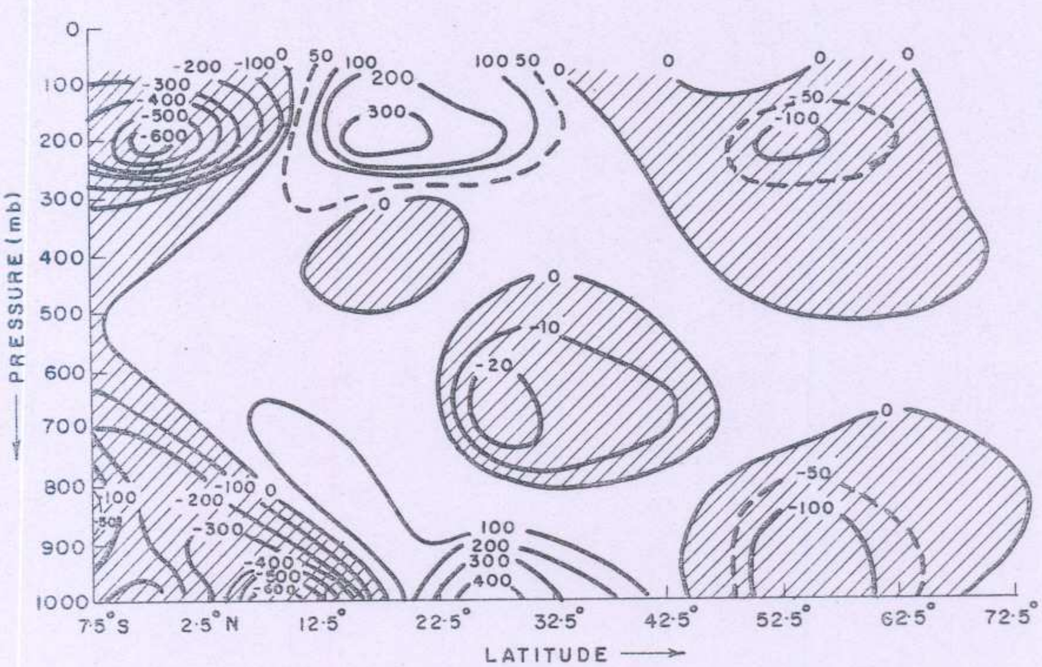


FIG.-4(d): Annual mean of the divergence of meridional transport of sensible heat by mean meridional circulation as a function of latitude and pressure. Unit 10^{-7} °C sec^{-1}.

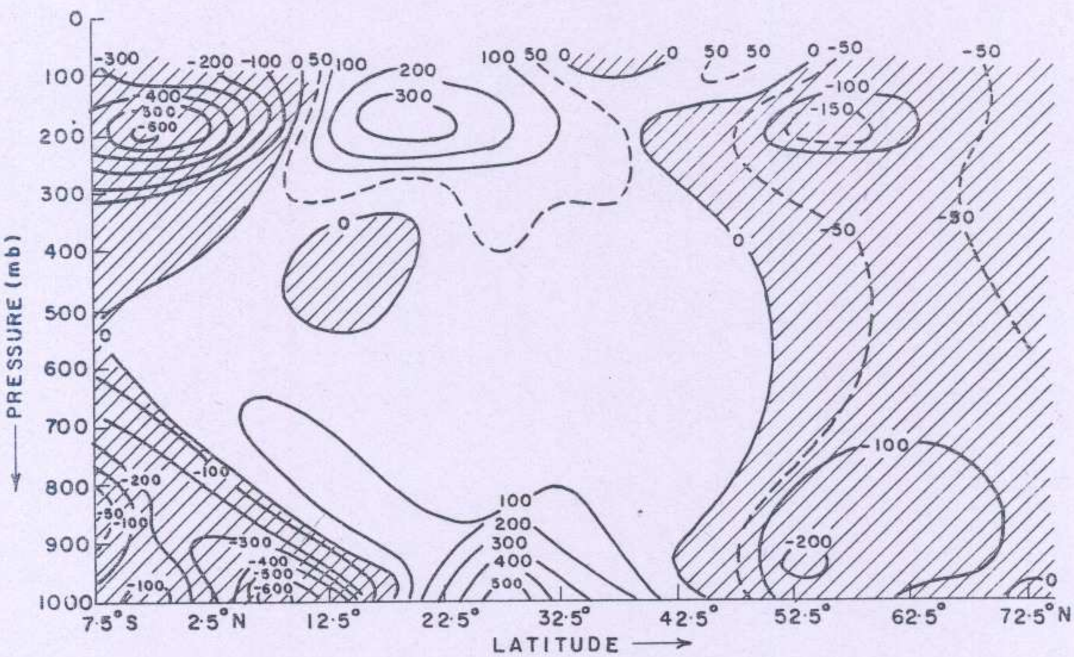


FIG.-4(e): Annual mean of the divergence of meridional transport of total sensible heat by eddies (transient + stationary) and mean meridional circulation as a function of latitude and pressure. Unit: 10^{-7} °C sec^{-1}.

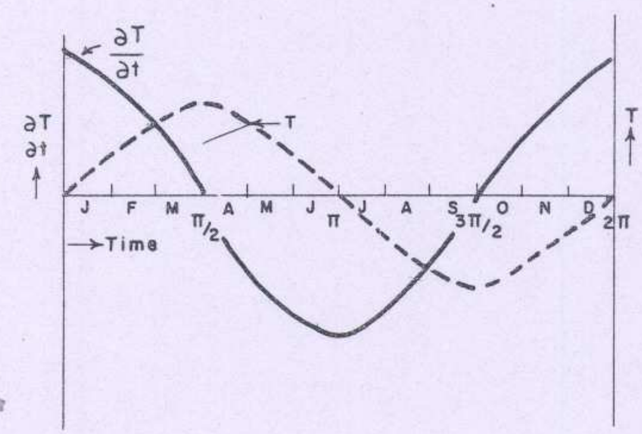


Fig. 5 : Phase relationship between T and $\frac{\partial T}{\partial t}$ in the annual oscillation.

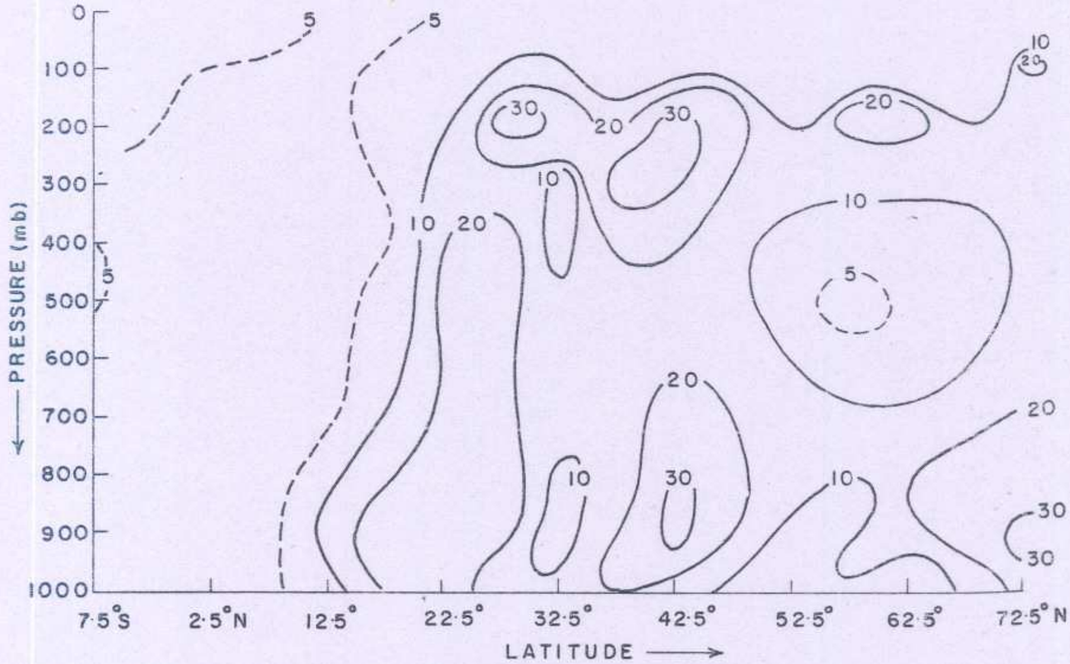


FIG.6(a) Amplitude of the annual oscillation of the divergence of the meridional transport of sensible heat by transient eddies as a function of latitude and pressure.
Unit: 10^{-7} Deg. C.sec^{-1}

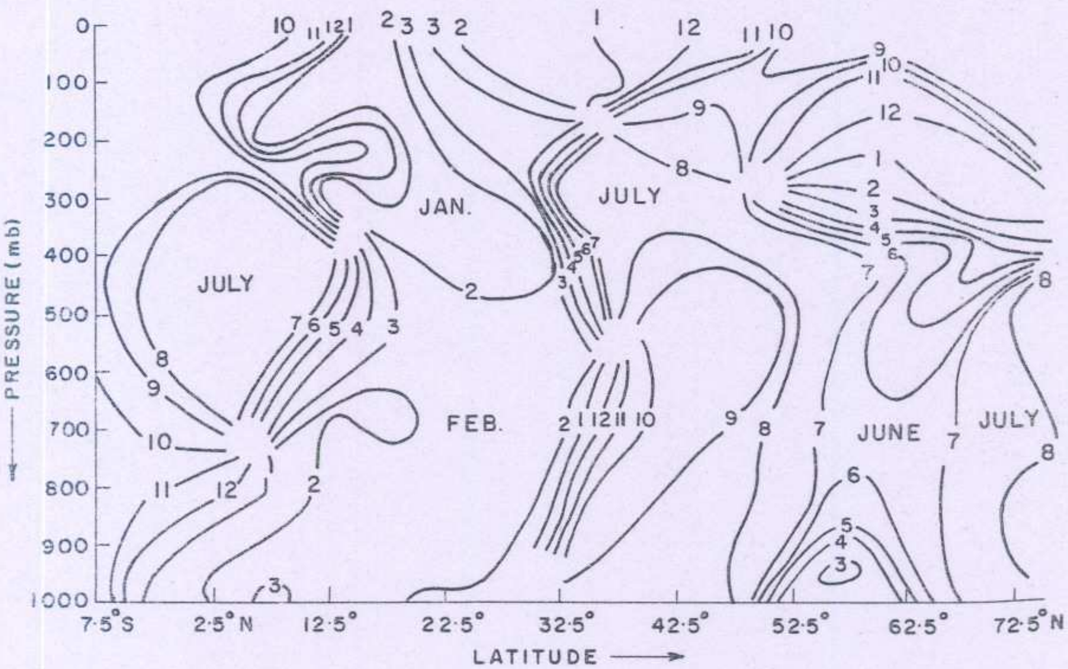


FIG. 6(b) Phase of the annual oscillation of the divergence of the meridional transport of sensible heat by transient eddies as a function of latitude and pressure. 1 corresponds to 1st January, 2 corresponds to 1st February and so on.

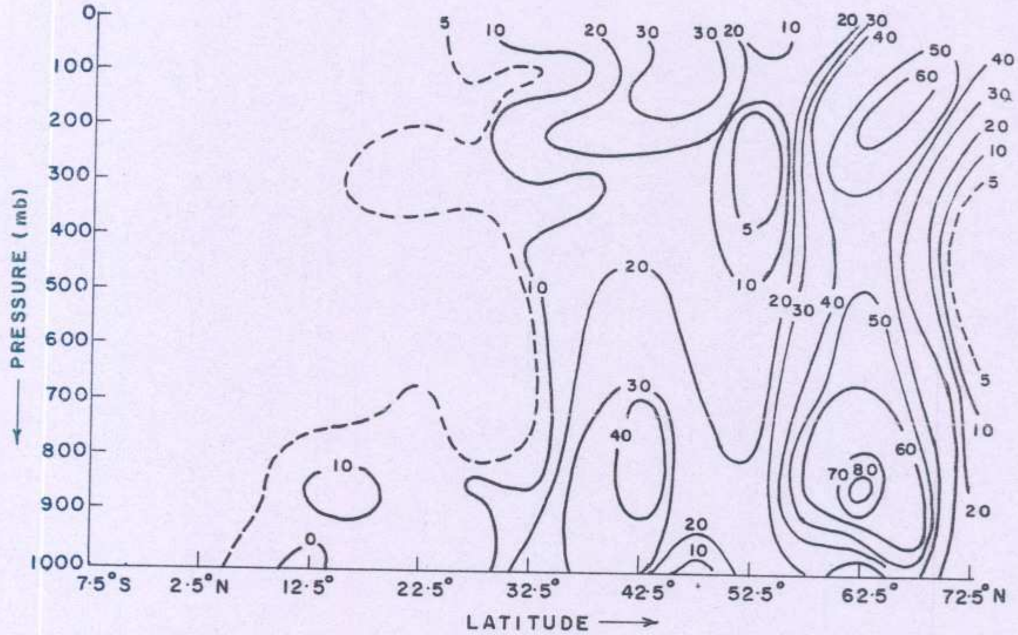


FIG.6(c): Amplitude of the annual oscillation of the divergence of meridional transport of sensible heat by stationary eddies as a function of latitude and pressure. Unit: 10^{-7} °C sec^{-1}.

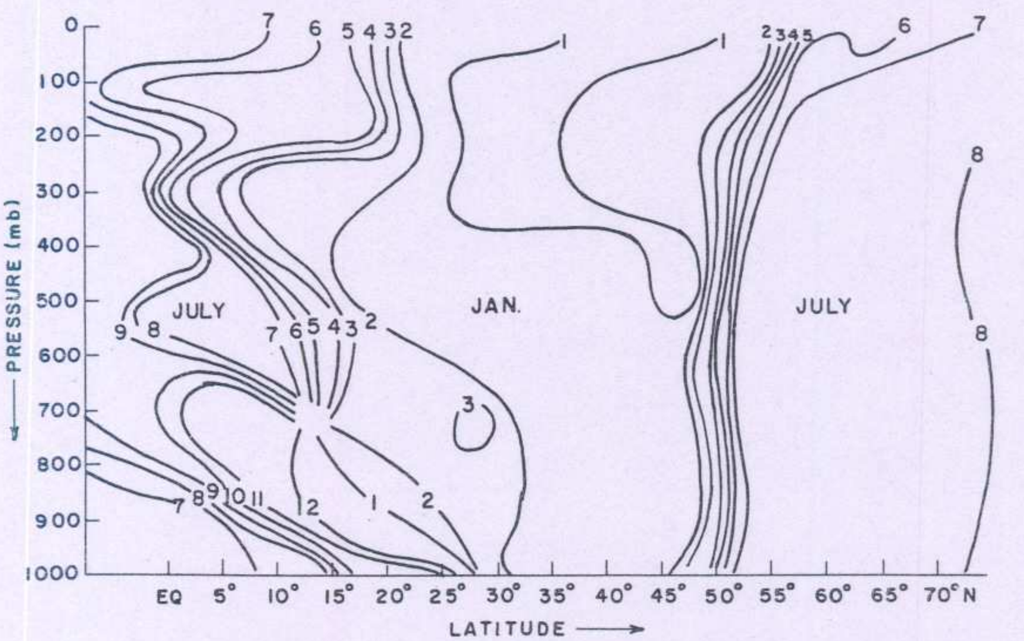


FIG.-6(d): Phase of the annual oscillation of the divergence of meridional transport of sensible heat by stationary eddies as a function of latitude and pressure. 1 corresponds to 1st January, 2 corresponds to 1st February and so on.

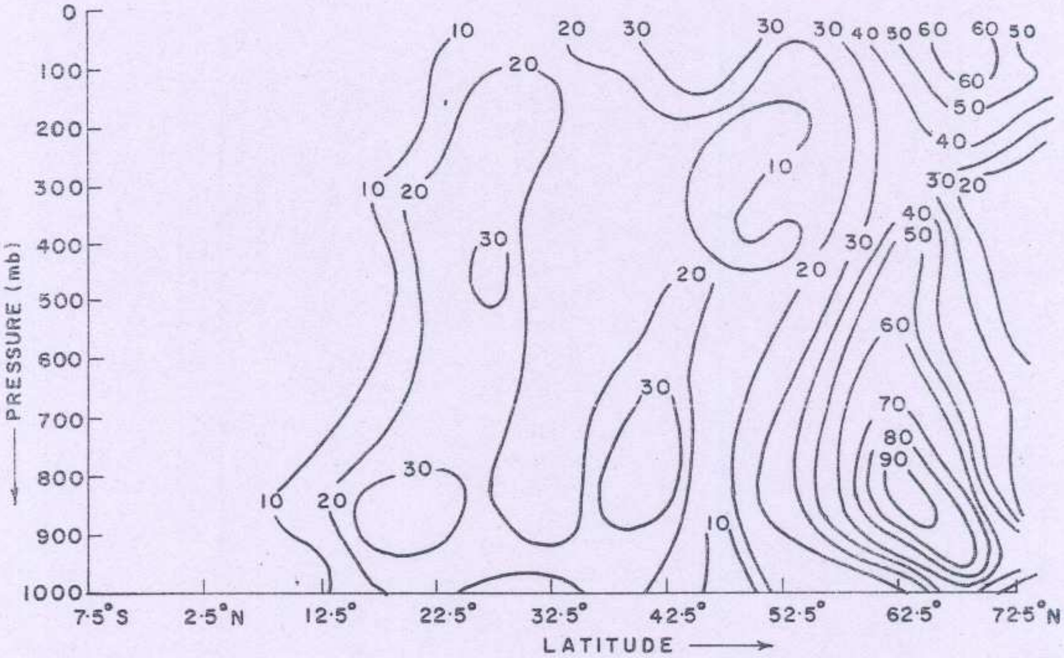


FIG.- 6(e) Amplitude of the annual oscillation of the divergence of meridional transport of sensible heat by eddies (Transient + Stationary) as a function of latitude and pressure. Unit: 10^{-7} °C sec^{-1}.

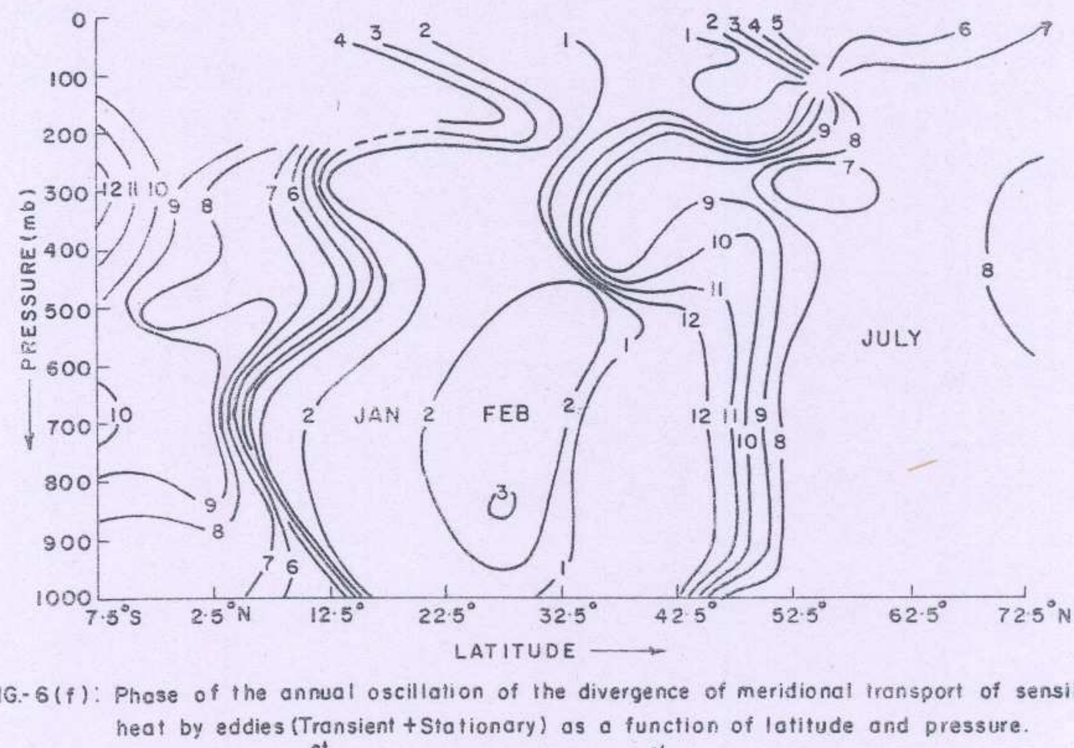


FIG.- 6(f): Phase of the annual oscillation of the divergence of meridional transport of sensible heat by eddies (Transient + Stationary) as a function of latitude and pressure. I corresponds to 1st January, 2 corresponds to 1st February and so on.

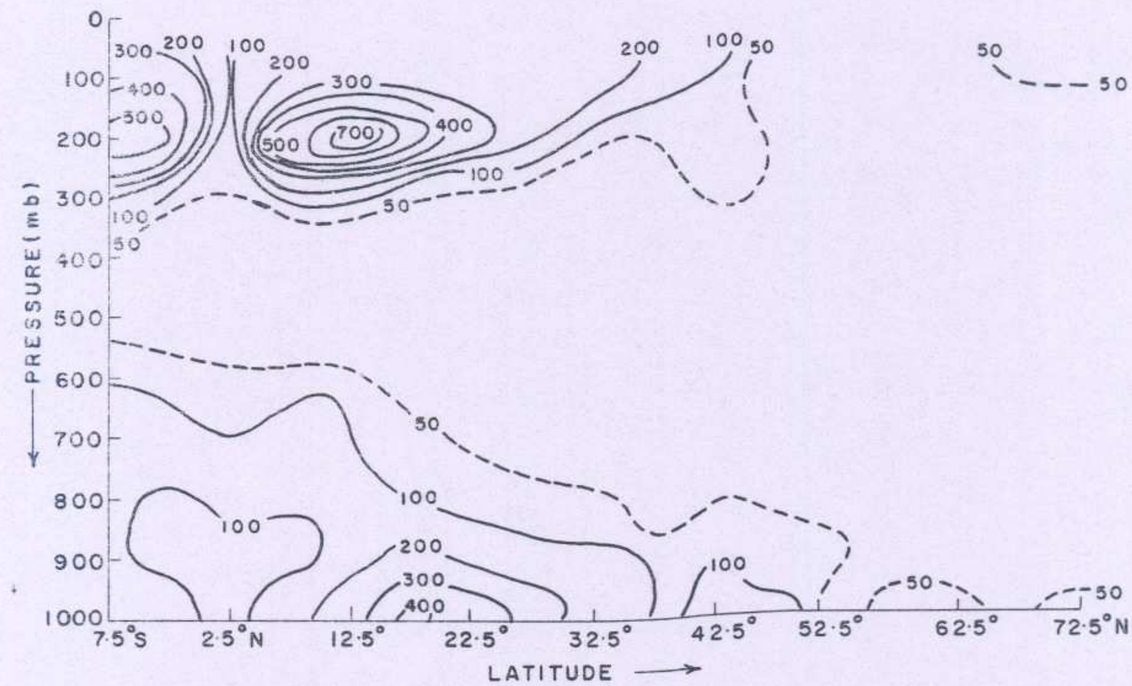


FIG. 6(g): Amplitude of the annual oscillation of the divergence of meridional transport of sensible heat by mean meridional circulation as a function of latitude and pressure. Unit 10^{-7} °C sec^{-1}.

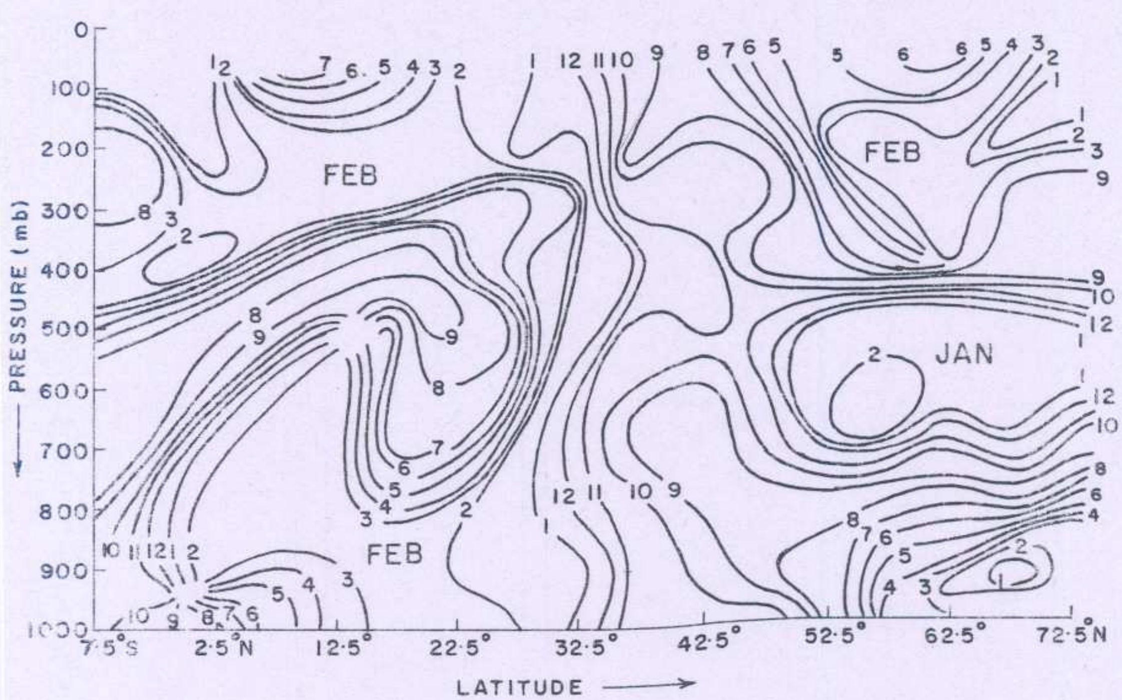


FIG.-6(h) Phase of the annual oscillation of the divergence of meridional transport of sensible heat by mean meridional circulation as a function of latitude and pressure. I corresponds to 1st January, 2 corresponds to 1st February and so on.

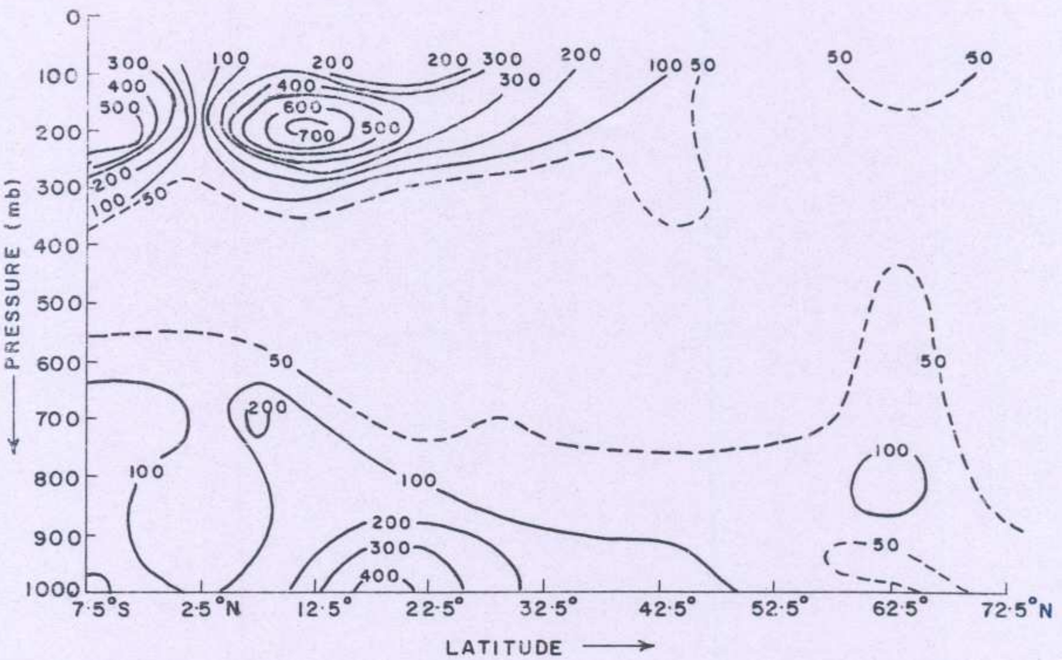


FIG.- 6(i) Amplitude of the annual oscillation of the divergence of meridional transport of total sensible heat by eddies (transient + stationary) and mean meridional circulation as a function of latitude and pressure. Unit: 10^{-7} °C sec^{-1}

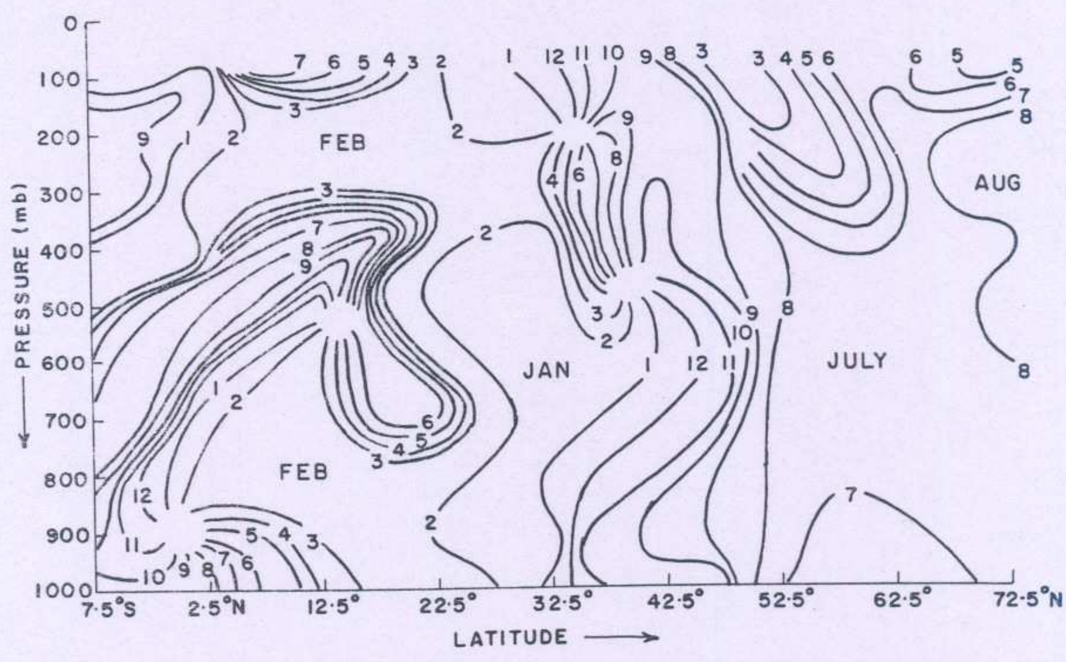


FIG.- 6(j): Phase of the annual oscillation of the divergence of meridional transport of total sensible heat by eddies (transient + stationary) and mean meridional circulation as a function of latitude and pressure. 1 corresponds to 1st January, 2 corresponds to 1st February and so on.