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Large-scale features of the summer monsoon during 1979

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सार — मासिक माध्य क्षेत्रीय तथा अनुरेखांश पवनें मौनेक्स वर्ष 1979 में अप्रैल से अगस्त मास के दौरान 48° दक्षिण तथा 48° उत्तर अक्षांशों के बीच 700 मिलिबार तथा 300 मिलिबार पर किए गए फोरियर विश्लेषण का विषय है। इन आयामों और अवस्थाओं से तरंग संख्या प्रभाव क्षेत्र में संवेग का अनुरेखांशीय परिवहन और तरंग से तरंग तथा तरंग से कटिबंधीय माध्य प्रवाह अन्तर्क्रिया अभिकलित की गई है। 1979 (कमजोर मानसून वर्ष) के लिए प्राप्त परिणामों की अन्य कार्यकर्त्ताओं द्वारा प्राप्त किए गए ऐसे ही परिणामों से तुलना की गई है। माध्य अनुरेखांशीय संचरण 20° दक्षिण तथा 20° उत्तर अक्षांशों के बीच संवेग के परिवहन के लिए महत्वपूर्ण है। भूमध्य रेखा तथा 10° उत्तर के बीच संवेग के अभिसरण के कारण वर्ष 1979 में मानसून के महीनों के दौरान ऊपरी क्षोभमंडल में पूर्वी पवनें कमजोर रह गई थीं। 1967 में इस क्षेत्र में संवेग का अपसरण है। 1979 में, उष्णकटिबन्धों में मानसून के महीनों में 1, 3 और 4 संख्या वाली तरंगें तरंग से तरंग की अन्तर्क्रिया के द्वारा अन्य तरंगों को तथा ऊपरी क्षोभमण्डल में माध्य कटिबन्धीय प्रवाह को गतिज ऊर्जा प्रदान करने वाले बड़े स्रोत हैं। दूसरी ओर तरंग संख्या 2 तरंग से तरंग की अन्तर्क्रिया द्वारा अन्य तरंगों के प्रति कुण्ड का कार्य करती है और कटिबन्धीय माध्य प्रवाह के लिए स्रोत का कार्य करती है। ऊर्जा शास्त्र व संचरण पैटर्नों की दृष्टि से 1979 और 1972 के वर्ष समान वर्ष (कमजोर मानसून वाले वर्ष) दिखाई पड़े जबकि 1967 इनसे भिन्न (एक प्रबल मानसून वर्ष) दिखाई पड़ा।

ABSTRACT. Monthly mean zonal and meridional winds are subjected to Fourier analysis for the Monex year 1979 during the months April through August between latitudes 48° S and 48° N at 700 mb and 300 mb levels. From these amplitudes and phases, meridional transport of momentum and wave to wave and wave to zonal mean flow interactions have been computed in wave number domain. The results obtained for 1979 (a bad monsoon year) have been compared with similar results obtained by other workers. Mean meridional circulation is significant for the transport of momentum between latitudes 20° S and 20° N. Convergence of momentum between the equator and 10° N, leads to weak easterlies in 1979 in monsoon months in the upper troposphere. In 1967 there is divergence of momentum in this region. In 1979, in the tropics, waves 1, 3 and 4 are greater source of kinetic energy to other waves *via* wave-wave interactions and to mean zonal flow in the upper troposphere during monsoon months, while wave 2 behaves as a sink to other waves *via* wave to wave interactions and source to zonal mean flow. The year 1979 shows similarity with 1972 (a bad monsoon year) in respect of energetics and circulation patterns but it shows contrast with 1967 (a good monsoon year).

1. Introduction

The First GARP Global Experiment (FGGE) and the monsoon experiment (MONEX) provide a large volume of meteorological data for the year 1979. Major findings of the Monsoon Experiment during 1978-79 have been described in International conference on monsoon experiment at Tallahassee, U.S.A., in January 1981 and Denspar, Bali, Indonesia in October 1981. Sikka and Grossman (1980) gave day to day evolution of the large scale atmospheric circulation features during the period 1 May to 31 August 1979. The large-scale planetary aspects of the monsoon were being studied for the first time in a quantitative manner as a result of FGGE and MONEX. The interhemispheric interactions during the northern summer and winter can be studied as large data are available in the data void region of the northern and southern hemispheric oceanic region. Murakami and Ding (1982) used Monex data of 1979 to study wind and temperature changes over Eurasia during the early summer of 1979. They correlated these changes with the onset of summer monsoon. The influence of heat, moisture and moist static energy on the onset and the activity of the Asian summer monsoon has been studied in detail using FGGE and Monex data of 1979 (Mohanty *et al.* 1982a, 1982b, 1983). Min and Horn (1982) obtained available potential energy in the northern hemisphere during the FGGE year of 1979.

Kanamitsu and Krishnamurti (1978) studied the large-scale features of two anomalous years 1967 and 1972. The year 1967 was good monsoon year and the year 1972 was the drought year in India. 1979 was also a bad monsoon year in India. Murakami (1981) studied the energetics in the wave number domain during three summer years in 1970-72 for four specified latitudinal belts. The present paper is a study of some aspects of large-scale circulation during 1979.

2. Data and method of analysis

Monthly mean zonal and meridional wind components are picked for the Monex year 1979 during the months April through August between latitudes 48°S to 48° N for the levels 700 mb and 300 mb at 5° Long. interval. The data are on a microfilm obtained from climate

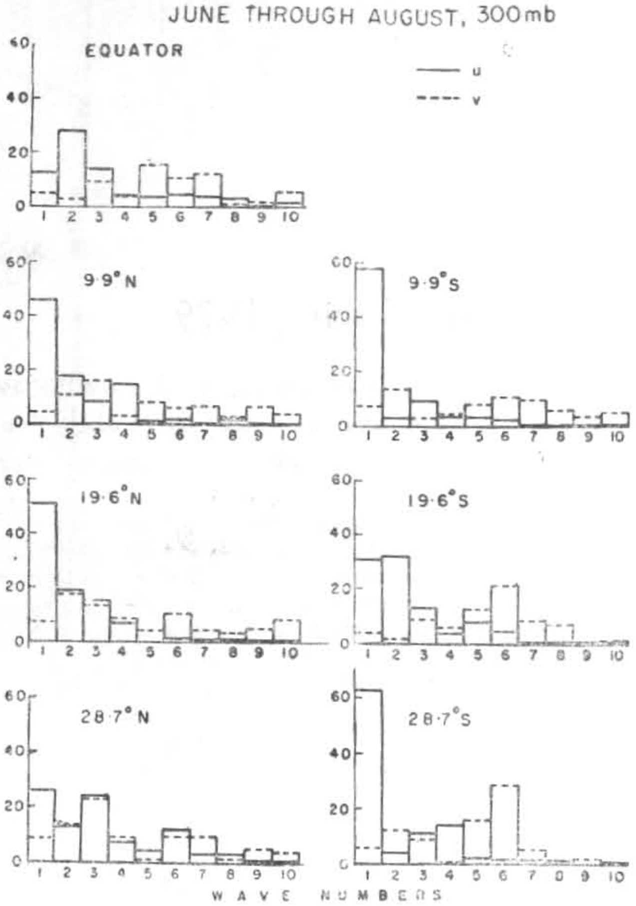


Fig. 1. Percentage variance of zonal harmonics of zonal wind and meridional wind spectra at selected latitudes for 1979 at 300 mb level during period June through August

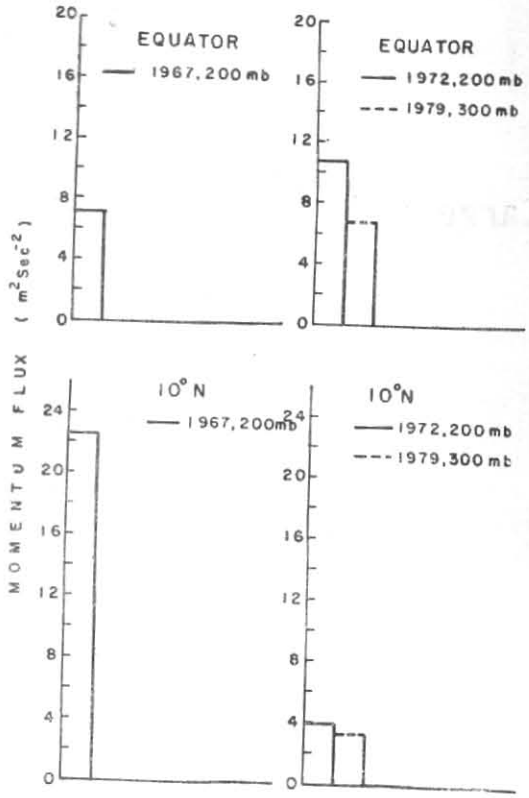


Fig. 2. Comparison of meridional flux of momentum by mean meridional circulation at 10° N and the equator for 1967 & 1972

analysis centre, National Meteorological Centre, U.S.A. The level 700 mb represents the lower troposphere and 300 mb represents the upper troposphere. Murakami and Ding (1982) observed the most significant changes in temperature and intensification of anticyclone at 300 mb level in early June 1979 at the Tibetan plateau, hence our choice of 300 mb level.

Using Fourier analysis, we have for zonal (U) and meridional (V) components

$$U\left(\lambda\right)=\left[\ U\ \right]+\sum_{m=1}^{\infty}\left(a_m \cos m\,\lambda+b_m \sin m\lambda\right) \qquad (1)$$

$$V\left(\lambda\right)=\left[\ V\ \right]+\sum_{m=1}^{\infty}\left(c_m \cos m\,\lambda+d_m \sin m\lambda\right) \qquad (2)$$

However, we truncate the Fourier analysis at $m=16$.

The amplitude R_m and phase ϵ_m of the mth wave is given by

$$R_m=\sqrt{a_m^2+b_m^2}\ ,\ \epsilon_m=\frac{1}{m}\ \text{arc tan}\ \frac{b_m}{a_m} \qquad (3)$$

for U component and by

$$R_m=\sqrt{c_m^2+d_m^2}\ ,\ \epsilon_m=\frac{1}{m}\ \text{arc tan}\ \frac{d_m}{c_m} \qquad (4)$$

for V component.

The meridional flux of momentum is given by

$$[\overline{UV}]=[\overline{U}][\overline{V}]+[\overline{U^*}\,\overline{V^*}]+[\overline{U'V'}] \qquad (5)$$

The three terms on the right hand side of Eqn. (5) are the fluxes associated respectively with mean meridional circulation, standing eddies and transient eddies. The eddy transport of angular momentum by standing eddies using Eqns. (1) to (4) is given by :

$$\left[\ \overline{U^*}\,\overline{V^*}\ \right]=\frac{1}{2}\sum_{m=1}^{16}\left(a_m c_m+b_m d_m\right) \qquad (6)$$

The transport by mean meridional circulation (MMC) is given by

$$[\bar{U}][\bar{V}] \quad (7)$$

Since we do not have daily values, we have not obtained transport due to transient eddies.

The flux of angular momentum across a latitude circle is given by

$$\frac{2\pi a^2 \cos^2 \phi}{g} \int_{p_1}^{p_2} \left[\overline{UV} \right] dp \quad (8)$$

Here,

[ ] Average over a latitude circle.

* Deviation from average over a latitude circle.

— Monthly time average.

′ Deviation from monthly average.

p_1 and p_2 Pressures at the higher and lower levels respectively.

a_m, b_m Cosine and sine coefficients of U Fourier series for mth wave.

c_m, d_m Cosine and sine coefficients of V Fourier series for mth wave.

m Wave number over a latitude circle ϕ.

Other symbols, here, have their usual meaning.

The amplitudes and phase values, obtained using Eqns. (3) and (4) are used for computing kinetic energy exchange in the following equation. The energy equation for eddy kinetic energy are essentially the same as used by Saltzman (1957 and 1970). Using the same notation (Saltzman 1970), we write,

$$\frac{\partial K(n)}{\partial t} = -M(n) + L(n) + C(n) - D(n), \quad (n=1, 2, 3, \ldots) \quad (9)$$

$K(n)$ gives the total kinetic energy of wave n, $M(n)$ indicates the rate of transfer of kinetic energy between the zonally averaged flow and eddies of wave number n, $L(n)$ indicates the flow of kinetic energy transfer to eddies of wave number n from eddies of all wave numbers. The $C(n)$ term represents the conversion of eddy available potential energy to eddy kinetic energy for wave number n. $D(n)$ is the dissipation term for wave number n. Since the vertical velocities are not available, we cannot compute these terms. From the scale consideration, $\int [U\omega]\, dm$ is much smaller than the term $\int [UV]\, dm$. We have not, therefore, computed term containing ω in $M(n)$ and $L(n)$. We have obtained $M(n)$ and $L(n)$ terms for various regions. The cyclic east-west continuityis observed as we have considered a latitude circle. The north sourth boundary is defined by 48°S-48°N.

A positive sign of $L(n)$ indicates a gain of kinetic energy of the wave due to interactions with all other waves. A positive sign of $M(n)$ indicates a transfer of kinetic energy from wave to zonal motion. All the above terms in Eqn. (9) are given in earlier paper (Awade *et al.* 1982).

3. Results

3.1. *Amplitude spectrum of zonal and meridional wind on selected latitude circles*

Fig. 1 shows the percentage variance plotted as a function of zonal wave number and is based on zonal harmonic analysis of monthly U and V components for the period June to August during 1979 at 300 mb level. Since similar features are shown at 700 mb level, we have not included this level.

Waves 1 and 2 are dominant in tropics between latitudes 20°S and 20°N. A very large proportion, between 40 to 70% of the total variance is accounted for by waves 1 and 2. Similar situation exists south of 20°S. However, north of 20°N, wave 3 also contributes to the total variance. The total variance accounted for by wave 1 north of 10° N is more than 40% in 1979. Kanamitsu and Krishnamurti (1978, hereafter called KK), also obtained the dominance of wave 1 for stationary part of spectrum in the tropical belt which they have attributed to the broad belt of upper easterlies that extends from the date line to the western Atlantic Ocean.

Fig. 1 (dashed lines) shows the corresponding spectrum for the V component. Here, we find long waves are not dominant unlike the zonal flow. Medium and short waves are also important. The V spectrum shows similar features in 1979 as shown by KK for the years 1967 and 1972.

3.2. *Meridional flux of momentum as a function of scale*

Fig. 2 gives the comparison of flux of momentum by mean meridional circulation for 1967, 72 and 79 at the equator and 10°N. Fig. 3 depicts the momentum flux at 700 mb and 300 mb level during the period June through August for the year 1979 at selected latitudes from 28.7°S to 28.7°N. Fig. 4 (a, b) shows the latitudinal variation of meridional flux of momentum for 1979 by the mean meridional circulation (MMC), and by standing eddy for 700 mb and 300 mb levels. The values obtained by Newell *et al.* (1971) for the period 1957-64 during June through August at these levels are also included for comparison.

700 mb — Meridional flux of eddy momentum and of MMC at 700 mb level is small when compared with the flux at 300 mb level. The mean meridional flux (MMC) at the equator is small. Wave 1 contributes to northward eddy transport and wave 4 contributes to southward eddy transport. Other waves are unimportant North of 10°N, transport by waves 1 and 2 is southward; other waves do not contribute. South of 10° S, the transport by vaves 1 to 4 is significant and it is southward (Fig. 3). Mean meridional flux of momentum is southward between equator and 20°N and northward north of 28°N. MMC is northward and large between

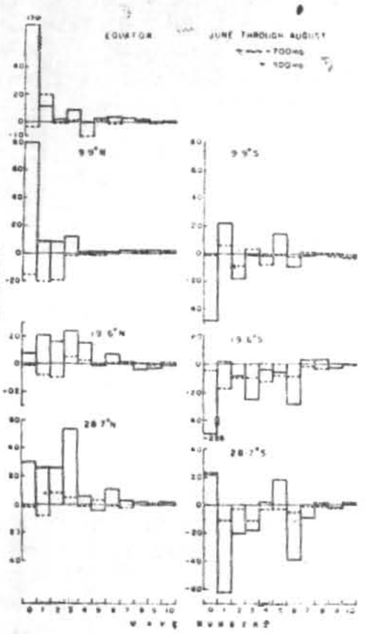


Fig. 3. Meridional flux of westerly momentum by various scales at selected latitudes during period June through August of 1979 at 700 mb and 300 mb level. Wave No. O denotes momentum flux by mean meridional circulation

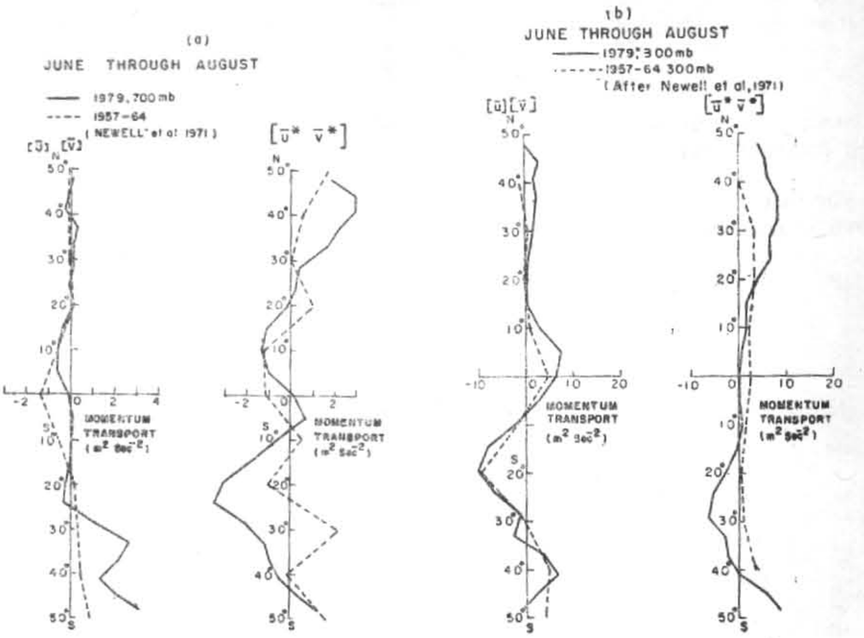


Fig. 4. Meridional transports of momentum due to mean meridional circulation $[\bar{u}]$ $[\bar{v}]$ and standing eddies $[\bar{u}^* \ \bar{v}^*]$ during period June through August of 1979 at (a) 700 mb and at (b) 300 mb level [Newell *et al.* (1971) values are shown by dotted lines]

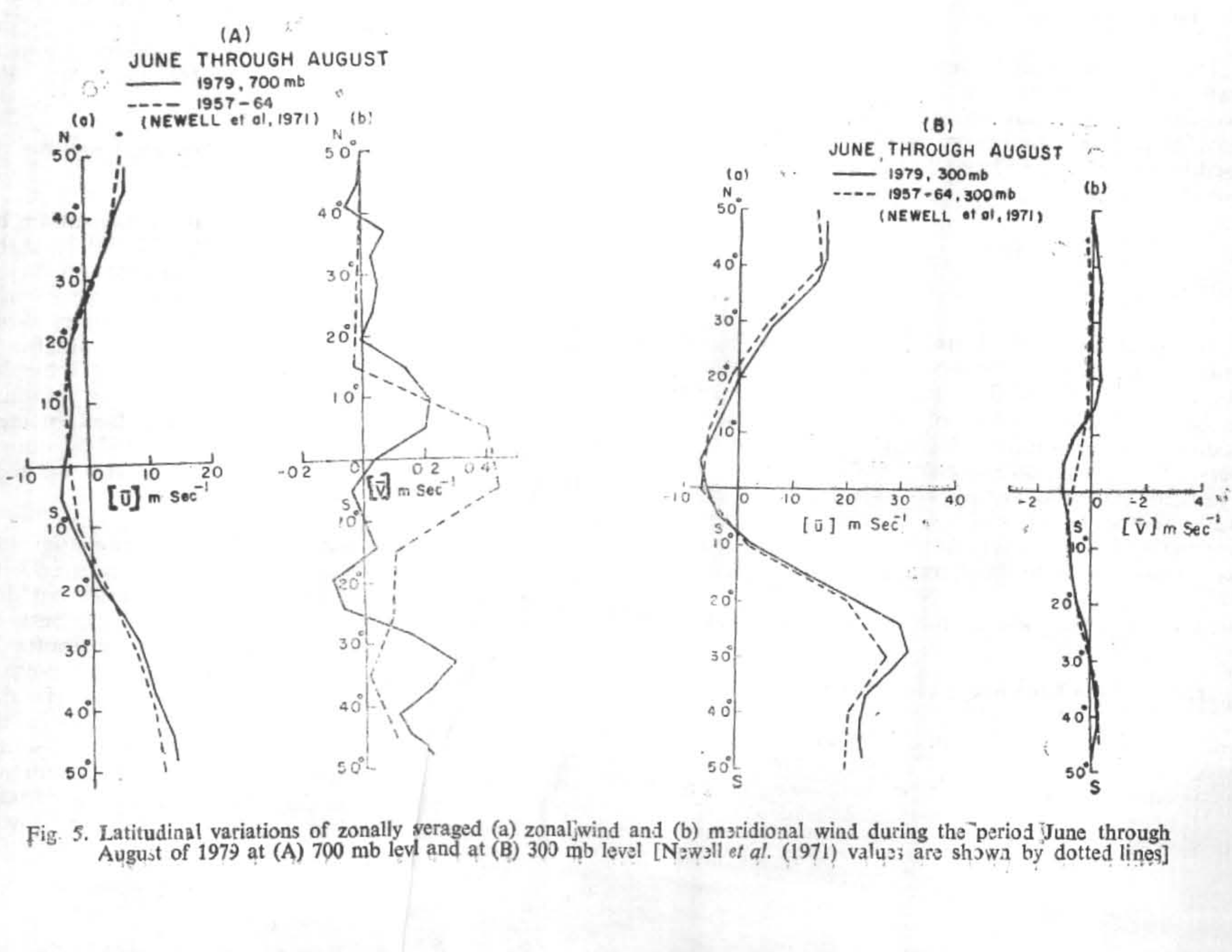


Fig. 5. Latitudinal variations of zonally averaged (a) zonal wind and (b) meridional wind during the period June through August of 1979 at (A) 700 mb level and at (B) 300 mb level [Newell *et al.* (1971) values are shown by dotted lines]

latitudes 25°S and 45°S, when compared with Newell *et al.* (1971) (Fig. 4a). The standing eddy transport between latitudes 10°S to 40°S is southward and large when compared with Newell *et al.* (Fig.4a).

300mb — Largest flux of momentum is carried between the equator and 10°N by the mean meridional circulation (MMC) (Figs. 3 and 4). This is in agreement with the results of KK. Waves 1 to 3 contribute to eddy flux but the magnitude is small. North of 20°N, waves 1 to 4 are prominent and transport is northward. However, MMC is less important. There is convergence of westerly momentum in 1979 between equator and 10°N. KK also obtained convergence between the equator and 10°N during 1972 (bad monsoon year) but divergence during 1967 (good monsoon year) (Fig. 2). This will have the easterly flow, weaker in 1979 and 1972 and stronger in 1967. This can be understood through the following mechanism for wave zonal mean flow exchange described by the term $C\ (K_Z,\ K_E) = [\bar{U}] \frac{\partial}{\partial y} [\bar{U}^* \bar{V}^*]$. In 1979, between latitudes 10°S and 20°S, the transport by MMC is southward and it is maximum at 20°S. The component due to the standing eddies at these latitudes by waves 1 to 4 is southward but the magnitude is small when compared to MMC. Waves 1 to 3 and 6 transport momentum southward at 28.7°S.

3.3. *Zonal and meridional wind*

Fig. 5 (A, B) shows the meridional distribution of *U* and *V* at 700 mb and 300 mb levels during the period June through August of 1979. We have depicted values obtained by Newell *et al.* (1971) for comparison. Summer mean stream line field and isotach field for 1979 at 300 mb are depicted in Fig. 6 (a, b).

700 mb — The zonal flow *U* is westerly at 700 mb level during the period June through August north of 26°N and south of 11°S (Fig. 5A). It is easterly between latitudes 11°S & 26°N. The maximum westerly wind is 6m/s at 45°N and 11m/sec at 45°S. The maximum easterly wind is 3-4 m/sec. The wind profile of Newell *et al.* (1971) and ours are in agreement.

The zonally averaged meridional wind *V* is southerly from equator to 40°N and between latitudes 25°S & 45° S. The maximum southerly wind is of order 0.2 m/s across 10°N and 0.3 m/s across 32°S. The southerly wind in Newell *et al.* (1971) extends from 45°S to 12°N and magnitude is twice of that in 1979. The meridional wind is weak at 700 mb level during 1979 between latitudes 25°S and 10°N.

300 mb — The zonal flow *U* is westerly north of 20°N with maximum (15 m/s) across 40°N (Fig. 5B). The flow is easterly between 7°S & 20°N with a maximum of 6 m/s across 5°N. The flow is westerly south of 7°S with maximum (31 m/s) across 30°S. There is a good agreement with the values obtained by Newell *et al.* (1971). The easterly flow in 1979 is slightly weaker than the average flow obtained by Newell *et al.* (1971).

KK also observed strong easterlies in 1967 and weak easterlies in 1972 at 200 mb. Easterlies are weaker in 1979 at 300 mb level compared to 1967. Krishna Rao (1981) noticed that 200 mb easterlies were strong in June, July and August in 1980 (good monsoon year) over the tropical belt when compared to the same period in 1979.

The zonally averaged *V* wind is northerly (negative) from 30° S to 14°N. The maximum northerly wind (1.0 m/s) is found at 3°N. It is southerly (positive) between 14°N & 40°N and it is of order 0.3 m/s. The northerly winds between equator and 10°N in 1979 are stronger than those obtained by Newell *et al.* (1971) (Fig. 5B).

Comparison of the summer stream line field of 1979 (Fig. 6a) for June through August at 300 mb level with stream line field of KK, we find that the anticyclone is around 85°E in 1967 while it is beyond 90°E in 1972 and 1979. Other normal features such as Mexican-high, mid-Atlantic, mid-Pacific troughs also show contrast in good and bad monsoon years.

3.4. *Mean wave-wave and wave-zonal mean flow interactions*

In section 3.3 we have given meridional distribution of zonally averaged *U* and *V* for computation of wave-wave *L*(*n*) and wave to zonal mean flow interactions *M*(*n*), during June through August at 700 mb and 300 mb levels. We have integrated wave-wave and wave-zonal mean flow interactions for various circulation region as follows:

(1) *Southern hemisphere* : 37.2°S-9.9°S : In this region *U* is westerly and *V* is northerly at 300 mb level.

(2) *Tropical belt* : 5° S-19.6°N : In this region *U* is easterly and *V* is northerly.

(3) *Sub-tropical belt* : 24.2°N-37.2°N : *U* is westerly and *V* is southerly.

(4) *Southern and northern hemispheric belt :* 37.2°S-37.2°N.

700 mb — Fig. 7(a, b) depicts wave-wave and wave zonal mean flow interactions at 700 mb and 300 mb level during June through August of 1979. In southern hemisphere belt at 700 mb level (37.2°S-9.9° S) all waves 1-16 lose energy to zonal flow. Long waves 1 to 4 are very prominent. Wave-wave interactions are very small compared to wave zonal mean flow interactions. waves 1, 3 and 5 are sink of energy for other waves and waves 2 and 4 are sources of energy for other waves *via* wave-wave interactions.

In the tropical belt (5°S-19.6°N), wave-zonal mean flow interactions at 700 mb level are small. Waves 1 and 4 gain energy from zonal mean flow, while waves 2 and 3 lose energy to zonal flow. Waves 5 to 16 show variable features. However, magnitude is small. Waves 1, 3 and 4 are sink of energy to other waves and wave 2 is a great source of energy to other waves *via* wave-wave interaction.

In subtropical belt (24.2°N-37.2°N), waves 1, 2, 3 and 5 lose energy to zonal flow, while wave 4 gains energy from zonal flow. Waves 1, 3, 4, 7 and 10 are source of energy for other waves while wave 2 is the sink for other waves *via* wave-wave interactions.

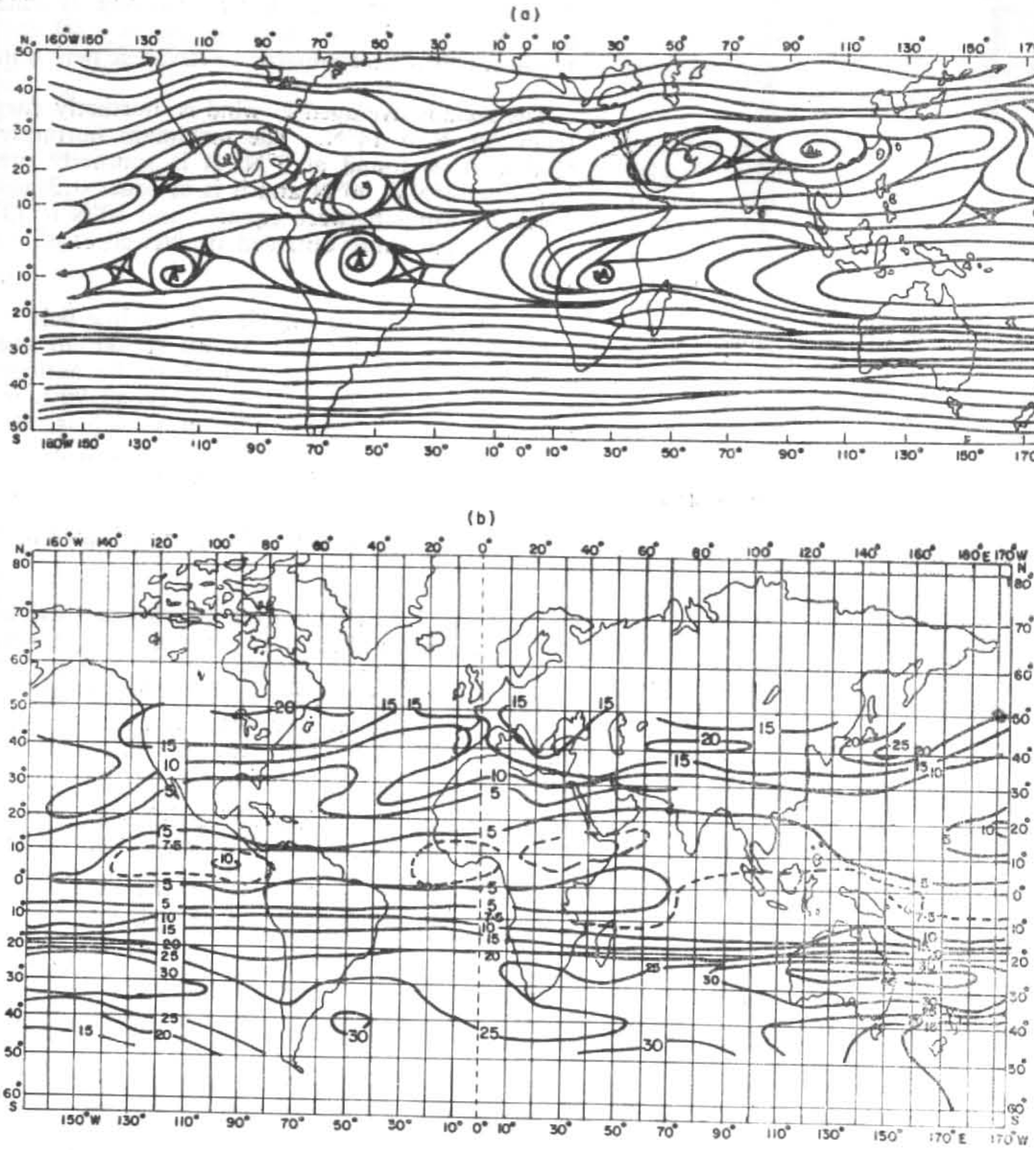


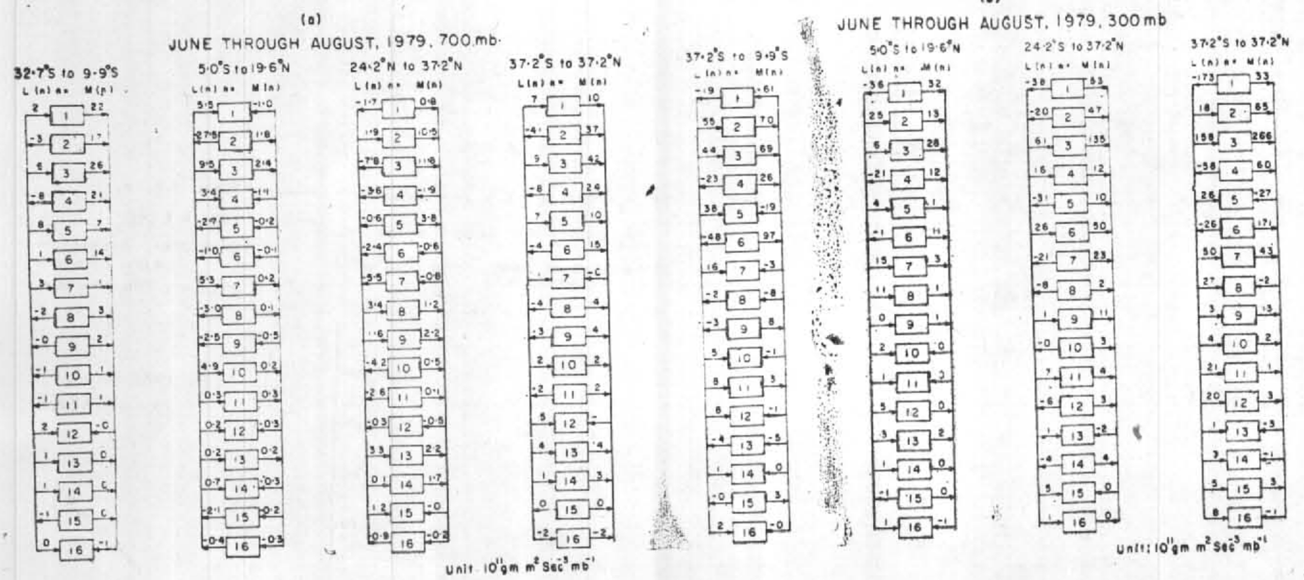
Fig. 6. Summer mean (a) stream line field and (b) isotach field for June through August of 1979 at 300 mb level (Units for isotach : m sec-1, Contour interval : 5 m sec—1)

For southern and northern hemisphere belt (37.2°S-37.2°N) all waves lose energy to zonal flow. Waves 1, 3 and 5 gain energy from other waves, while waves 2, 4 and 6 lose energy to other waves *via* wave-wave interactions.

300 mb — In the southern hemisphere belt (37.2°S to 9.9°S), waves 1 and 5 gain energy from zonal mean flow through wave-zonal interactions, while waves 2, 3, 4 and 6 lose energy to zonal flow. Waves 2, 3 and 5 gain energy from other waves *via* wave-wave interactions while waves 1, 4 and 6 lose energy to other waves *via* wave-wave interaction.

In the tropical belt (5.0°S-19.6°N), waves 1 to 4 lose energy to zonal flow through wave-zonal flow interactions and waves 1 and 3 are prominent. As far as wave-wave interactions are concerned waves 1 and 4 lose energy to other waves while waves 2, 3, 7 and 8 gain energy *via* wave-wave interactions.

In subtropical belt (24.2°N to 37.2°N), waves 1-16 contribute energy to zonal mean flow. Waves 1, 2, 3, 6 and 7 are prominent, and wave 3 contributes the maximum energy to the zonal flow. Waves 1, 2, 5 and 7 contribute energy to other waves, while waves 3, 4 and 6 gain energy from other waves *via* wave-wave interactions. Waves 1 and 2 together are source of energy for other waves and zonal flow. This is in agreement with earlier result (Awade *et al.* 1982). Wave 3 is the greatest source of energy to zonal mean flow and the greatest sink for other waves *via* wave-wave interactions. This also agrees with the earlier result for this wave (Awade *et al.* 1982). Our results for 1979 broadly agree with those of Murakami (1981) for long waves. These waves together are the source to other waves and to zonal mean



[*Read* : 37. 2°S instead of 32.7°S in (a) & 24.2°N instead of 24.2S° in (b)]

Fig. 7. Energy exchange between waves $L(n)$, between waves and zonal mean flow $M(n)$, over various latitudinal belts at (a) 700 mb level and at (b) 300 mb level during period June through August of 1979

TABLE 1

Latitudinal variation of meridional flux of momentum by mean meridional circulation (MMC) and by standing eddies (S.E.) for 1979 at 700 mb and 300 mb levels during period April and May

Latitude	700 mb			300 mb		
	MMC	S.E.	Total	MMC	S.E.	Total
28.7°S	−5.2	−35.2	−40.4	−32.7	−146.4	−179.1
19.6°S	−5.8	−48.8	−54.6	−191.3	−44.5	−235.8
9.9°S	9.3	−22.1	−12.8	−90.2	−85.6	−175.8
Equator	−15.2	−48.7	−63.9	21.4	0.2	21.6
9.9°N	−33.4	2.4	−31.0	12.3	34.0	46.3
19.6°N	0.3	0.5	0.8	222.1	211.5	433.6
28.7°N	12.3	25.6	37.9	102.2	185.4	287.6

Unit : 10^{17} gm $m^2 sec^{-2} mb^{-1}$

flow in both the studies for tropical and subtropical belts.

In belt (37.2°S to 37.2°N), waves 1-4 and 6 and 7 lose energy to zonal flow, wave 3 loses the maximum energy to zonal flow. Waves 1, 4 and 6 lose energy to other waves, while waves 2, 3, 5, 7 and 8 gain energy from other waves *via* wave-wave interaction. Here also, wave 3 gains maximum energy from other waves. Thus wave 3 seems to be greater source of energy for zonal flow and also a greater sink of energy for other waves *via* wave-wave interactions.

3.5. *Meridional flux of momentum and wave to wave and wave-zonal mean flow interactions during pre-monsoon months (April and May)*

Table 1 gives the meridional flux of momentum of 1979 at selected latitudes due to mean meridional circulation (MMC) and standing eddies during the period April and May at 700 mb and 300 mb levels. Fig. 8 gives wave to wave and wave to zonal mean flow interactions in wave number domain over the tropical and subtropical regions during pre-monsoon period at 300 mb level.

3.5.1. *Meridional flux of momentum*

700 mb — The flux of momentum between latitudes 28.7°S to 28.7°N during pre-monsoon and monsoon months of 700 mb level are of the same order. At the equator, flux of momentum by both MMC and standing eddies are significant. The eddy flux is larger than MMC flux. At 10°N, the flux by MMC is southward and significant. At 20°N flux by MMC and eddy flux are small. North of 28°N, the eddy flux is northward and significant. South of equator, eddy flux is southward and significant, when compared to flux by MMC. Waves 1 and 2 are prominent. At 10°S, flux by eddy is southward and large. South of 28°S, flux by MMC is small and eddy flux is southward and large. Wave 3 is prominent. South of the equator, eddy flux of momentum is southward and large compared to MMC. Waves 3 to 6 are also prominent at these latitudes.

300 mb — The flux of momentum at the equator by MMC is northward and large. North of 20°N, the flux by MMC and eddies are significant. Waves 1-3 contribute to eddy flux at these latitudes. The flux by MMC and SE is southward and large between latitudes 10°S & 20°S. South of 10°S, waves 1 to 6 contribute significantly to southward flux of momentum. North of 28°N and south of 28°S flux of MMC and eddy fluxes are

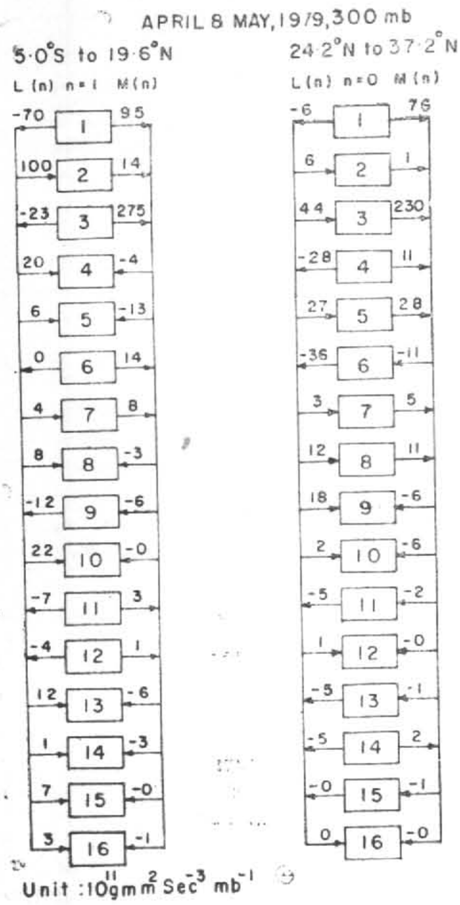


Fig. 8. Energy exchange between waves $L(n)$, between waves & zonal mean flow $M(n)$, over various latitudinal belts during the period April and May of 1979 at 300 mb level

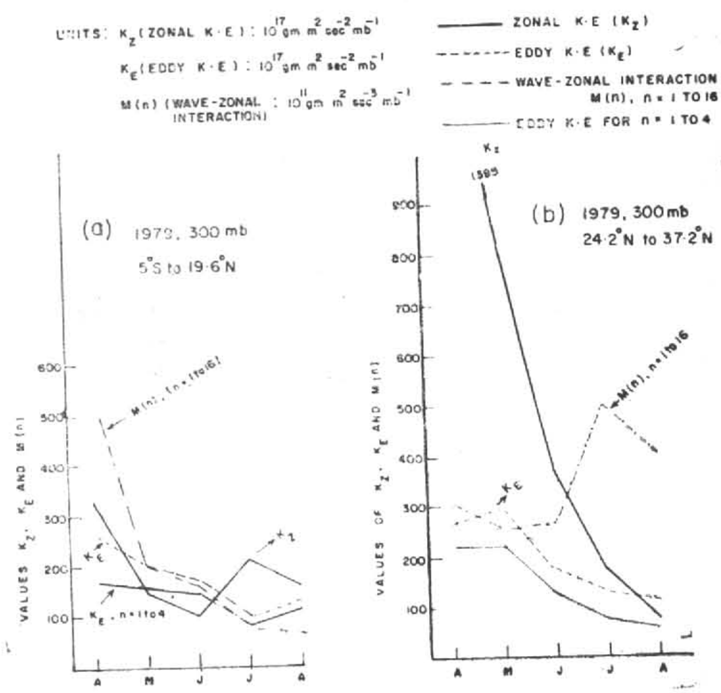


Fig. 9. Values of zonal K. E., Eddy K. E. and wave zonal interactions for (a) tropical region and (b) subtropical region at 300 mb level for April through August for the year 1979

poleward. There are signficant changes from pre-monsoon to monsoon period in the fluxes between latitudes equator and 28°N. The flux of momentum is northward and large between equator and 10°N during June through August when compared to April and May. However, the flux is northward and large north of 20°N during April and May when compared to flux during June through August.

3.5.2. *Wave to wave and wave to zonal mean flow interactions*

300 mb — Interaction terms for April and May are small at 700 mb level. Hence, we have presented the results for the tropical belt and sub-tropical belt at 300 mb level.

In the tropical belt (5° S to 19.6° N), waves 1 to 3 lose energy to zonal flow. Waves 4 to 16 are not significant. Wave 3 is more intense in pre-monsoon than in monsoon months. Waves 1 and 3 lose energy to other waves *via* wave-wave interactions. While wave 2 gains energy from other waves.

In subtropical belt (24.2° N to 37.2°N) waves 1, 3 lose energy to zonal flow and other waves are not significant. During period June through August of 1979, these waves are intense. In addition, other waves (waves 5 to 8) are also significant. In April and May waves 3 and 5 gain energy from other waves *via* wave-wave interaction. Waves 4 and 6 lose energy to other waves. During the period June through August waves 1 and 2 are more intense than during April and May of 1979.

3.6. *Zonal and eddy kinetic energy*

Fig. 9 represents monthly values of the zonal and eddy kinetic energy for (a) tropical and (b) subtropical, regions at 300 mb level for 1979. Monthly values of wave-zonal interactions for waves 1-16 are also given.

3.6.1. *Tropical region*

Zonal kinetic energy (K_Z) has decreased from April to June. This is due to large decrease of westerlies north of 10° N. There is increase in K_Z from June to July due to intensification of easterlies during that period. In August K_Z decreases due to decrease in easterlies, compared to July. Eddy kinetic energy (K_E) decreases from May to July but the decrease is less compared to the decrease in K_Z. There is slight increase in K_E from July to August. Long waves (waves 1 to 4) contribute significantly to eddy *K.E.* Wave-zonal interactions (Waves 1-16) follow decreasing trend as shown by K_Z from April to June. From July to August, wave zonal interaction decreases but K_Z increases. This may be due to the fact that apart from K_E to K_Z conversion, there may be large conversion from A_Z to K_Z.

3.6.2. *Subtropical region*

Zonal kinetic energy is one order more in this region than in the tropical region. Zonal kinetic energy decreases throughout from April to August. It is two orders larger in April than in August. This is due to decrease in the strength of westerlies from April to August in this region. Eddy kinetic energy is of the same order as in the tropics. It also steadily decreases from April to July and then there is slight increase in August. Long waves contribute significantly to eddy K.E. Wave-zonal interaction is constant from April to May and then steadily increases from June to August. In July there is decrease in K_Z from June to July while in $M(n)$, there is increase from June to July.

4. Conclusions

The primary conclusions during 1979 circulation are summarised here :

(*i*) waves 1 and 2 are dominant in the spectrum of zonal component of wind of 1979 during the period June through August in the upper troposphere. However, waves 1 to 10 are prominent in the spectrum of meridional wind component.

(*ii*) Mean meridional circulation is significant for the transport of momentum between latitudes 20°S and 20°N.

(*iii*) There is convergence of momentum between the equator and 10°N during the period June through August of 1979.

(*iv*) Waves 1, 3 and 4 are source of kinetic energy and wave 2 is sink of kinetic energy to other waves as well as to zonal mean flow in the tropics (5° S to 19.6°N) during monsoon months of 1979 in the upper troposphere.

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References

Awade, S.T., Totagi, M.Y. and Bawiskar, S.M., 1982, 'Wave to wave and wave to zonal mean flow kinetic anergy exchanges during contrasting monsoon years', *Pure and Appl. Geophys.*, **120**, pp. 463-482.

Kanamitsu, M. and Krishnamurti, T.N., 1978, Northern summer tropical circulations during drought and normal monsoon months', *Mon. Weath. Rev.*, **106**, pp. 331-347.

Krishna Rao, P., 1981, 'Comparison of satellite derived radiation budget measurements over Monex during 1979 and 1980', Proc. of the International Conf. on early results of FGGE and large-scale aspects of its monsoon experiments, Geneva, pp. 6-30 to 6-36.

Min, K.D. and Horn, L.N., 1982, 'Available potential energy in the northern hemisphere during the FGGE year', *Tellus*, **34**, pp. 526-539.

Mohanty, U.C., Dube, S.K. and Sinha, P.C., 1982 (a), 'On the role of large scale energetics in the onset and maintenance of summer monsoon-I : Heat Budget', *Mausam*, **33**, pp. 139-152.

Mohanty, U.C., Dube, S.K. and Sinha, P.C., 1982 (b), On the role of large scale energetics in the onset and maintenance of summer monsoon-II : Moisture budget, *Mausam*, **33**, pp. 285-294.

Mohanty, U.C., Dube. S.K. and Singh, M.P., 1983, 'A Study of heat and moisture budget over the Arabian Sea and their role in the onset and maintenance of summer monsoon,' *J. Met. Soc. Japan*, **61**, pp. 208-221.

Murakami, T., 1981 'summer mean energetics for standing and transient eddies in the wave number domain, *Monsoon Dynamics*,' Cambridge University Press, Cambridge, pp. 65-80.

Murakami, T. and Ding, Yi-Hui., 1982, 'Wind and temperature changes over Euresia during the early summer of 1979', *J. Met. Soc. Japan*, **60**, pp. 183-196.

Newell, R.E., Kidson, J.W., Vincent, D.G. and Boar, G.J., 1971, '*The general circulation of the tropical atmosphere and interactions with extratropical latitudes,* **I,** The MIT Press, Cambridge, USA.

Saltzman, B. 1957, Equations governing the energetics of the large-scale of the atmospheric turbulance in the domain of wave number, *J. Met.,* **14**, pp. 513-523.

Saltzman, B., 1970, 'Large scale atmospheric energetics in the wave number domain, *Rev. Geophys. Space Phys.,* **8,** pp. 289-302.

Sikka, D.R. and Grossman, B., 1980, 'Summer Monex Chronological Weather Summary,' International Monex Management Centre, New Delhi, pp. A 21-49.