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On the efficiency of meridional eddy transport processes during the major stratospheric warming of January 1977

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ABSTRACT

Correlation coefficients between the meridional wind and zonal wind and meridional wind and temperature measure the efficiencies of eddy transports of momentum and heat, respectively. Efficiencies are calculated in terms of these correlation coefficients for the major warming event of January 1977. It is found that the eddies are more efficient in transporting heat than in transporting momentum. Further, the efficiency of heat transport increased substantially before the meridional temperature gradient reversed. Increase of efficiency in heat transport is found to be related to the increased westward tilt of a wave in the height field. Since this tilt is known to be associated with vertical propagation of wave energy, interesting connections are inferred between the efficiencies of eddy transports, wave structure and energetics during a stratospheric warming.

1. Introduction

One of the most spectacular atmospheric phenomena which has received much attention in recent years is the so-called stratospheric sudden warming. Sudden warming occurs during some winters in high latitude regions of the stratosphere. It occurs during the polar night when there is no apparent heat source. In a major warming event it is not unusual to find the mean temperature of the stratosphere increasing at "an explosive" rate of 10 °C day^{-1} and within a week the normal temperature gradient (with higher temperatures in the middle latitudes and lower values at the pole) is reversed. Associated with the reversal of the temperature gradient, the strong westerly circumpolar jet stream that exists before warming gets completely destroyed and easterlies are created.

Several observational studies concerning the energetics of the warming event (Reed et al., 1963; Murakami, 1965; Muench, 1965; Julian and Labitzke, 1965, etc.) revealed that the warming is probably caused by planetary scale waves, mainly wave numbers 1 and 2, generated in the troposphere. It is observed that the sequence of events which leads to a warming event is triggered by an unusually large flux of wave energy from the lower levels into the stratosphere. Numerical models, notably that due to Matsuno (1971) which considered increased wave activity preceding the onset of warming as an important ingredient, also confirm the notion that the warming is forced by waves from below. The convergence of heat and momentum fluxes of the vertically propagating wave produces an indirect meridional circulation. The action of the Coriolis torques on this circulation then weakens the zonal westerly winds in the stratosphere. Since the waves have higher amplitudes at greater heights because of lower density, the deceleration of the westerlies is more pronounced at higher levels, where the easterlies appear first. The consequent situation of the existence of an easterly flow above the westerly inhibits further upward propagation of the waves (Charney and Drazin, 1961) and creates a large easterly acceleration in the vicinity of zero wind line. This drastic destruction of the westerly jet is accompanied by the sudden increase of temperature and the easterly region descends until easterlies replace the normal westerlies in the entire polar stratosphere.

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Matsuno's (1971) model was rather successful in reproducing many of the observed features of the warming event. The starting point of the Matsuno mechanism, as mentioned above, is the increased wave activity and associated transports of momentum and sensible heat. Does this mean, then, that the eddies become efficient in transporting heat and momentum preceding a warming event? In the present note, we calculate the efficiency of the eddy transports at the 50 and 30 mb levels for the major warming event of January 1977, and the results show that the eddies do, indeed, become more efficient before the warming event.

2. Definition of efficiency and data

Oort and Rasmusson (1971) used the degree of correlation between the meridional velocity v, and the parameter to be transported (in the present case zonal velocity u, or temperature T) as a measure of the efficiency. Thus, the definition of the efficiency is given by

$$E_1 = \frac{\overline{v' u'}}{\sqrt{\overline{v'^2}}\sqrt{\overline{u'^2}}} \quad (1)$$

$$E_2 = \frac{\overline{v' T'}}{\sqrt{\overline{v'^2}}\sqrt{\overline{T'^2}}} \quad (2)$$

where a bar "—" represents the zonal average and the prime represents the deviation from the zonal mean. Equations (1) and (2) measure the efficiency of the eddies in transporting momentum and heat, respectively. Oort and Rasmusson calculated the efficiencies using 5 years of data. Srivatsangam (1975) also calculated the efficiencies of the eddy transports. However, both Oort and Rasmusson and Srivatsangam did not discuss the efficiencies of the eddy transports during a stratospheric warming event. We use (1) and (2) to compute the efficiencies for the major warming event of January 1977.

The basic data used in the present study are the geopotential heights and temperatures interpolated carefully from 50 mb and 30 mb synoptic charts prepared by the Free University of Berlin (1977) for the synoptic time 00 GMT (kindly provided by Dr K. Labitzke). Both temperature and geopotential heights are interpolated at 10° longitude intervals for the first 19 days of January 1977. Interpolation becomes difficult at higher latitudes and over oceanic regions. Since stratospheric processes are dominated by very long waves, it is felt that the present data are of sufficient accuracy to resolve these waves south of about 75° N. Since major changes during a stratospheric warming take place in the high latitudes, the present analysis is extended only up to 40° N. Grid point data are subjected to zonal harmonic analysis and (1) and (2) are evaluated by summing the contributions of the first ten harmonics, although the first two harmonics dominated. For this purpose (1) and (2) are expressed in terms of the harmonic amplitudes and phases. Thus (1) can be written as

$$E_1 = \frac{\displaystyle\sum_{k=1}^{10} \frac{A_k^v A_k^u}{2} \cos\,[k(\lambda_k^v - \lambda_k^u)]}{\left[\displaystyle\sum_{k=1}^{10} \frac{(A_k^v)^2}{2}\right]^{1/2} \left[\displaystyle\sum_{k=1}^{10} \frac{(A_k^u)^2}{2}\right]^{1/2}} \quad (3)$$

where A_k^v and A_k^u represent amplitudes of v and u component (calculated geostrophically from the height field) and λ_k^v and λ_k^u are the corresponding phases of the kth zonal harmonic. A similar expression can be obtained for E_2 replacing the amplitudes and phases of u by those of T in (3).

It should be noted here that the zonal wind component u is calculated using a centered finite differencing of 10° latitude and as such involves some errors. This makes the computations of the eddy momentum transport somewhat less reliable. On the other hand, calculation of sensible heat transports does not involve finite differencing errors and should be more reliable.

3. Results and discussion

Studies describing some general aspects of the warming of January 1977 have already been made. Quiroz (1977) discussed the vertical extent of this warming while O'Neill and Taylor (1979) have given a synoptic account of the event in addition to some discussion of its dynamical features.

During the unusual winter of 1976–77 four warmings occurred (Schoberl, 1978): the first in November 1976, the second in the middle of December 1976, the third around January 8, 1977 and the fourth and final warming in March 1977.

Of all these warmings, the third was the most intense and possessed all the characteristics of a mid-winter major warming. Thus, we focus our attention on this warming.

Tables 1 and 2 give the values of the efficiencies E_1 and E_2 for the first 19 days of January 1977, at four latitudes, at the 30 and 50 mb levels, respectively. The last columns give the average of all the four latitude values for each day, weighted with respect to the length of the latitude circle. These tables show several interesting features. At 30 mb E_2, in general, is higher than E_1. That is, eddies transport heat more efficiently than momentum. Further, E_2 varies substantially, having high values in the first week then decreasing for the next few days, showing a tendency to increase again around the 18th and 19th. E_2 remained mostly positive, showing that the heat transport is towards the pole. Only at 70° N did it become negative after the 10th. The recovery to the normal temperature gradient that occurred by late January is probably associated with this southward heat transport. High values of E_2 are found around the 6th and 7th at almost all latitudes, reaching a value of 0.94 on the 7th at 50° N. Mean values are also high on these days. As mentioned earlier, the mean temperature gradient reversal occurred around the 8th. This shows that the eddies do become increasingly efficient in transporting heat preceding the maximum phase of the warming event.

Variability of E_1, in general, is less compared to that of E_2. However, it is of interest to note that it remained mostly negative at all latitudes showing a southward transport of momentum. This southward momentum transport seems to have contributed to the destruction of the westerly jet and the creation of easterlies (O'Neill and Taylor, 1979).

Table 2 shows similar characteristics at the 50 mb level also, although E_2 values, in general, are less.

From the above discussion it is seen that one interesting feature of the eddies is the increase of their efficiency in transporting heat northward before the warming took place. How do the eddies organize themselves to become more efficient? From (1) and (2) it could be seen that the calculation of the efficiencies involves not only the transport but also the standard deviations (variances). Table 3 gives the momentum and sensible heat transports at the 30 mb level, while Table 4 shows the variances. Characteristic

Table 1. *Efficiencies of meridional eddy transports of momentum (E_1) and heat (E_2) at 30 mb*

	Latitude									
	40° N		50° N		60° N		70° N		Mean	
Jan. 77	E_1	E_2	E_1	E_2	E_1	E_2	E_1	E_2	E_1	E_2
1	0.39	0.31	0.21	0.43	0.17	0.58	0.39	0.56	0.19	0.50
2	0.47	0.43	0.23	0.39	0.07	0.53	−0.16	0.57	0.14	0.49
3	0.16	0.25	−0.05	0.25	−0.18	0.41	−0.35	0.49	−0.09	0.38
4	−0.04	0.18	−0.14	0.73	−0.28	0.71	−0.36	0.55	−0.20	0.59
5	0.29	0.34	0.04	0.90	−0.20	0.75	−0.28	0.47	−0.08	0.62
6	0.13	0.46	−0.11	0.91	−0.25	0.76	−0.24	0.48	−0.14	0.66
7	0.32	0.68	−0.03	0.94	−0.21	0.67	−0.24	0.34	−0.08	0.61
8	0.34	0.57	−0.10	0.89	−0.14	0.46	−0.11	0.29	−0.05	0.51
9	0.24	0.50	−0.25	0.79	−0.18	0.44	−0.07	0.15	−0.10	0.41
10	0.24	0.54	−0.19	0.70	−0.22	0.28	−0.32	0.07	−0.16	0.32
11	0.29	0.46	−0.09	0.42	−0.17	0.09	−0.24	−0.12	−0.09	0.14
12	0.21	0.44	−0.02	0.42	−0.11	0.14	−0.23	−0.08	−0.06	0.19
13	−0.15	0.66	−0.12	0.49	−0.17	0.20	−0.20	−0.13	−0.13	0.27
14	−0.13	0.54	−0.14	0.50	−0.24	0.22	−0.26	−0.04	−0.16	0.28
15	−0.21	0.36	−0.08	0.42	−0.22	0.36	−0.53	0.09	−0.17	0.32
16	−0.17	0.29	−0.28	0.41	−0.41	0.07	−0.63	0.04	−0.31	0.22
17	0.03	0.46	−0.14	0.51	−0.38	0.38	−0.44	−0.01	−0.21	0.37
18	−0.33	0.69	−0.38	0.69	−0.27	0.27	−0.12	−0.28	−0.30	0.47
19	−0.25	0.87	−0.49	0.79	−0.41	0.29	−0.23	−0.13	−0.36	0.61

Table 2. *Same as Table 1 but at 50 mb*

	Latitude									
	40° N		50° N		60° N		70° N		Mean	
Jan. 77	E_1	E_2	E_1	E_2	E_1	E_2	E_1	E_2	E_1	E_2
1	0.25	0.49	0.08	0.49	0.01	0.47	0.08	0.33	0.07	0.42
2	0.34	0.36	0.03	0.67	−0.21	0.43	−0.46	0.31	−0.05	0.42
3	0.20	0.33	−0.14	0.76	−0.33	0.59	−0.47	0.35	−0.19	0.50
4	0.27	0.37	−0.08	0.86	−0.32	0.70	−0.33	0.41	−0.15	0.59
5	0.34	0.28	0.05	0.83	−0.24	0.75	−0.22	0.45	−0.06	0.61
6	0.10	0.72	−0.16	0.84	−0.27	0.80	−0.23	0.43	−0.15	0.65
7	0.21	0.70	−0.05	0.77	−0.16	0.63	−0.18	0.32	−0.07	0.57
8	0.31	0.47	−0.19	0.71	−0.17	0.43	−0.18	0.24	−0.09	0.44
9	0.40	0.56	−0.22	0.69	−0.22	0.33	−0.11	0.20	−0.08	0.38
10	0.33	0.64	−0.16	0.63	−0.23	0.26	−0.28	0.03	−0.13	0.30
11	0.22	0.66	−0.12	0.56	−0.19	0.30	−0.22	0.11	−0.11	0.34
12	0.14	0.53	−0.03	0.46	−0.16	0.21	−0.27	0.07	−0.08	0.30
13	−0.23	0.54	−0.14	0.44	−0.10	0.27	−0.10	0.18	−0.13	0.34
14	0.10	0.55	−0.18	0.46	−0.18	0.19	−0.22	−0.01	−0.09	0.30
15	0.42	0.24	0.12	0.40	−0.01	0.22	−0.24	0.13	0.08	0.27
16	−0.05	0.67	−0.06	0.68	−0.17	0.28	−0.40	−0.08	−0.11	0.47
17	0.07	0.78	−0.05	0.65	−0.10	0.26	−0.10	0.17	−0.03	0.50
18	−0.03	0.75	−0.10	0.79	−0.15	0.38	−0.12	−0.26	−0.08	0.63
19	−0.05	0.86	−0.26	0.77	−0.32	0.45	−0.27	−0.06	−0.19	0.71

Table 3. *Transports of momentum ($\overline{v'u'}$), and heat ($\overline{v'T'}$) at 30 mb*

	Latitude									
	40° N		50° N		60° N		70° N		Mean	
Jan. 77	$\overline{v'u'}$	$\overline{v'T'}$	$\overline{v'u'}$	$\overline{v'T'}$	$\overline{v'u'}$	$\overline{v'T'}$	$\overline{v'u'}$	$\overline{v'T'}$	$\overline{v'u'}$	$\overline{v'T'}$
1	26.7	6.7	31.6	31.3	30.1	84.0	36.2	109.2	30.3	46.5
2	29.2	12.8	34.8	24.5	14.6	83.4	−12.4	108.1	21.2	46.3
3	6.8	6.4	−4.8	10.3	−25.5	45.5	−29.3	84.3	−9.2	28.1
4	−1.6	4.3	−12.0	30.9	−38.4	92.0	−53.8	110.3	−20.7	47.6
5	15.8	10.4	3.6	57.6	−40.2	115.4	−54.8	117.7	−10.9	63.6
6	9.8	14.3	−13.3	71.0	−55.4	127.8	−64.3	119.3	−22.6	71.7
7	25.0	23.9	−3.5	71.8	−52.1	106.0	−63.1	78.0	−13.7	64.1
8	21.5	17.4	−11.3	68.1	−35.9	76.3	−21.0	58.5	−7.1	51.3
9	15.1	14.6	−27.4	51.3	−45.8	72.7	−15.3	29.2	−15.2	40.2
10	10.6	13.2	−19.3	41.6	−51.5	46.5	−49.2	13.3	−20.9	28.7
11	11.1	9.6	−10.6	31.3	−34.6	13.7	−25.4	−19.3	−10.8	12.4
12	9.8	11.6	−3.7	44.5	−24.2	28.6	−30.6	−12.6	−7.8	21.1
13	−5.6	16.5	−20.1	47.6	−28.5	35.3	−16.8	−13.3	−16.6	25.1
14	−5.1	12.6	−19.4	36.5	−31.2	26.5	−17.1	−4.3	−16.8	20.0
15	−5.7	6.8	−8.2	27.7	−21.7	35.1	−23.1	6.1	−12.6	19.0
16	−6.4	6.7	−32.7	40.3	−45.6	8.1	−22.2	2.0	−25.0	15.9
17	1.1	15.0	−16.6	44.6	−37.6	35.9	−26.2	−1.0	−16.7	25.7
18	−13.9	30.5	−27.9	71.9	−21.1	23.4	−5.3	−13.1	−18.2	34.2
19	−14.6	48.5	−38.1	80.7	−32.8	25.4	−8.3	−3.7	−24.4	44.7

Units		
	$\overline{v'u'}$:	$m^2 s^{-2}$
	$\overline{v'T'}$:	$m s^{-1} K$

Table 4. *Variances of meridional wind* ($\overline{v'^2}$), *zonal wind* ($\overline{u'^2}$) *and temperature* ($\overline{T'^2}$) *at 30 mb*

	Latitude														
	40° N			50° N			60° N			70° N			Mean		
Jan. 77	$\overline{v'^2}$	$\overline{u'^2}$	$\overline{T'^2}$	$\overline{v'^2}$	$\overline{u'^2}$	$\overline{T'^2}$	$\overline{v'^2}$	$\overline{u'^2}$	$\overline{T'^2}$	$\overline{v'^2}$	$\overline{u'^2}$	$\overline{T'^2}$	$\overline{v'^2}$	$\overline{u'^2}$	$\overline{T'^2}$
1	31.6	151.1	14.9	75.2	289.9	69.2	193.8	169.5	107.9	436.3	19.7	85.8	141.8	175.1	61.9
2	37.5	101.1	23.9	74.7	306.7	53.3	196.1	202.6	126.5	395.4	14.5	89.7	137.9	169.4	65.1
3	34.0	51.9	20.9	53.6	150.1	32.8	130.4	149.5	96.2	350.4	19.9	84.7	109.2	96.9	50.5
4	28.2	70.3	21.7	60.5	122.2	29.3	174.6	109.9	95.3	351.7	62.8	113.7	119.3	92.9	54.3
5	35.6	85.5	26.3	81.5	119.9	50.5	216.6	182.3	108.5	456.9	85.4	132.2	153.1	117.0	68.4
6	30.8	177.9	31.0	104.0	143.2	58.0	233.6	214.1	120.0	454.9	158.8	133.5	161.4	173.3	74.1
7	44.5	141.7	27.6	90.0	136.4	64.7	202.1	309.6	125.2	404.4	168.3	128.2	147.4	181.8	75.3
8	36.0	112.9	25.5	94.0	134.0	62.9	236.6	280.3	118.4	347.6	38.3	116.0	144.7	154.1	70.7
9	41.0	101.3	20.6	88.0	137.5	47.8	245.9	256.9	110.0	446.8	100.4	88.3	161.8	146.3	58.6
10	29.8	63.9	19.9	71.3	140.3	49.1	239.8	230.7	110.2	368.6	66.0	90.8	140.0	123.2	59.2
11	27.3	55.9	16.1	111.4	129.7	50.1	264.9	158.2	97.6	293.5	39.2	83.5	144.7	97.3	54.2
12	35.3	60.7	20.2	184.0	134.4	61.9	449.7	103.9	91.5	298.8	61.1	86.6	210.1	91.5	58.1
13	30.7	50.2	20.7	152.4	187.0	61.6	387.7	72.3	83.5	136.4	54.3	79.3	161.0	94.9	55.3
14	29.2	55.3	18.9	109.2	190.8	49.8	231.2	71.3	60.9	122.7	35.3	77.4	111.3	94.6	46.0
15	27.5	27.6	12.8	95.8	120.4	45.2	184.1	53.0	52.8	72.6	26.5	62.2	88.7	59.7	38.5
16	38.4	36.9	13.6	163.3	85.2	59.8	267.4	49.9	49.3	42.8	28.6	52.5	125.9	51.9	40.7
17	57.4	30.7	18.9	161.9	82.9	46.8	187.3	51.6	48.7	104.1	34.4	53.0	123.3	50.9	38.7
18	65.6	27.7	30.3	147.3	35.8	73.8	149.6	42.3	51.0	57.8	34.1	39.0	106.6	34.3	48.6
19	82.0	40.6	38.0	151.9	40.2	68.8	154.8	42.5	49.5	30.4	42.9	28.5	110.4	41.3	48.0

Units:		
	$\overline{v'^2}$:	$m^2 s^{-2}$
	$\overline{u'^2}$:	$m^2 s^{-2}$
	$\overline{T'^2}$:	K^2

features at the 50 mb level are very similar to those at the 30 mb level therefore further discussion is limited to the 30 mb level only.

From Tables 3 and 4 it can be seen that large variances of u are associated with small transports of momentum. This probably made E_1 values less as noted earlier. Heat transport increased at all latitudes from about January 3 to 6 (Table 3). During this period, variances of temperature and meridional wind component also increased (Table 4). Thus, the increase of E_2 during this period indicates that the rate of increase of heat transport is more than the rates of increase of the standard deviations of v' and T' (or equivalent variances). This has an interesting implication regarding the vertical structure of the eddies. The transport of heat by a geostrophic and hydrostatic wave can easily be derived as

$$\overline{v'T'} = -\frac{pf}{Rk}\overline{v'^2}\frac{\partial\delta}{\partial p} \tag{4}$$

where k is the zonal wave number, f is the Coriolis parameter, p is the pressure, R is the gas constant for dry air and δ is the phase angle of wave number k in the height field. Equation (4) shows the well-known relationship that a wave which has a westward slope with height ($\partial\delta/\partial p < 0$) transports heat northward (in the Northern Hemisphere). In the case of stationary waves, this northward transport of heat implies a vertical transport of wave energy as first pointed out by Eliassen and Palm (1961).

It was mentioned above that the $\overline{v'T'}$ increased at a higher rate than $\overline{v'^2}$ before warming. Hence from (4) it can be seen that for single wave, at a particular latitude and pressure level, the westward slope increases. This increase of slope could be interpreted in terms of the relative movement of the waves in two levels, say the upper troposphere and stratosphere (Hartman, 1977). The increased slope leads to increased upward flux of energy and also to increased conversion from mean to eddy available potential energy in the westerlies which increase with height. These two energy sources support the increased wave activity at the stratospheric levels prior to the warming.

From the last three columns of Table 4 it is seen that all the three variances increased from about January 3 to 6. The sum of $\overline{v'^2}$ and $\overline{u'^2}$ is a measure of eddy kinetic energy, while $\overline{T'^2}$ can be taken as a measure of eddy available potential energy.

Increase of these forms of energy gives some justification to the above-mentioned sequence of events.

It should be pointed out that the relationship between the westward slope of the height field and the corresponding energy exchange is considered to be valid for a stationary wave. However, this relation and the other arguments based on the considerations of a single wave should more generally be qualitatively correct for the warming situation discussed here.

4. Conclusions

Efficiencies of eddy transport of momentum and sensible heat are calculated in terms of the correlation coefficient between the meridional wind and zonal wind and temperature for the major warming event of January 1977. It is found that the eddies, in general, are more efficient in transporting heat than momentum. Further, the efficiency of the eddies in transporting heat increased substantially as the warming event developed, reaching a correlation coefficient of 0.9 on some days. Next an attempt is made to understand how the eddies organize themselves to become more efficient. Increase of efficiency is found to be due to increased westward tilt of the eddies. The structure of the waves could be related to the energetics of the warming events through some known relationship. Thus, the calculation of efficiencies revealed some interesting connections to the dynamics of the stratospheric warmings.

The present study is restricted to one warming event. It would be worthwhile to extend the analysis to other major and minor warmings.

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