The Association between Latitudinal Temperature Gradient and Eddy Transport. Part I: Transport of Sensible Heat in Winter

HARRY VAN LOON

National Center for Atmospheric Research,[1] *Boulder, CO 80307*

(Manuscript received 28 August 1979, in final form 16 January 1979)

ABSTRACT

When the total eddy transport of sensible heat in middle latitudes of the Northern Hemisphere increases in winter, the zonally averaged temperature gradient in the subtropics tends to increase, while the temperature gradient decreases in the same latitude as, and north of, the given total eddy flux. This effect is associated mainly with the flux in the quasi-stationary or mean waves. In agreement with this relationship between temperature gradient and heat transport, the correlation between the total eddy flux divergence and zonally averaged *temperature* in middle latitudes is strongly negative; and the main contribution to this negative correlation also comes from the quasi-stationary eddies. When the mean-eddy flux increases at middle latitudes, the transient-eddy flux tends to decrease over the region of weaker gradients to the north of the stronger mean-eddy flux and to increase to the south of it; and conversely when the mean-eddy flux weakens. From the association between total eddy transport and temperature gradients it follows that the gradients at lower latitudes are negatively correlated with those at higher latitudes.

In the Southern Hemisphere, where the quasi-stationary eddies in temperate latitudes transport little sensible heat, the relationship between total eddy flux and zonally averaged temperature gradient is determined principally by the transient-eddy flux.

All the associations above refer to seasonal averages.

1. Introduction

One may observe in Fig. 9 of van Loon and Williams (1977) that the zonally averaged temperature gradient at 700 mb near 50°N decreased over several winters while the poleward flux of sensible heat in eddies increased in the same latitudes; i.e., the two quantities were negatively correlated. It is well known that eddy flux of sensible heat dominates the horizontal transfer of heat through middle into high latitudes, but as far as I could ascertain, there is no empirical study in the literature of the relation between meridional temperature gradient and sensible heat flux in eddies. The only mention of the subject is a remark by Nyberg (1954) who observed that for daily values, "There is a small correlation between the ZI at 500 mb and the convergence of V_gT at the zone 50–60°N. However, it is negative as is also that between V_gT and the zonal index $ZI_{1000-500}$ of the relative contours 1000–500 mb."

This study first briefly describes the seasonal mean and variability of the total eddy transport of sensible heat and its components: the mean-eddy transport and the transient-eddy transport. The description covers the 29 years from the winter (December, January, February) of 1948–49 till the winter of 1976–77, and uses mainly the pressure-heights and temperatures at 700 mb since this is the level for which the longest series of daily analyses is available. It was shown early (White, 1951; Nyberg, 1954) that the peak of the horizontal eddy transport of sensible heat in the troposphere lies below the 700 mb level; judging by Oort and Rasmusson's (1971) diagrams the peak is near 850 mb, and the values at 700 mb are ~10% lower than those of the maximum below [see also Starr and Wallace (1964) and Newell *et al.* (1974)]. After the description of the mean and variability, the association between latitudinal temperature gradient and sensible heat flux in both hemispheres is examined for the purpose of providing information which can be used in the parameterization of eddy heat fluxes in seasonal climate models.

2. Data

The data are from the daily 700 mb maps analyzed at the U.S. National Meteorological Center for the Northern Hemisphere and at the Australian Meteorological Office for the Southern Hemisphere. The geostrophic transport of sensible heat by the eddies was obtained in the following way: For each day in the 29 winters the meridional component of the geostrophic wind at every 5° of latitude and longitude was multiplied by the temperature deviation

---

[1] The National Cancer for Atmospheric Research is sponsored by the National Science Foundation.

0027-0644/79/050525-10$06.50

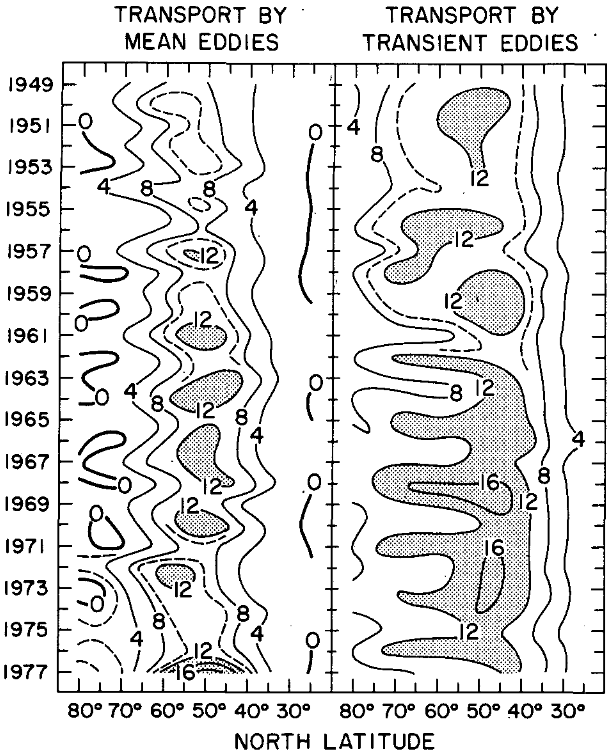


FIG. 1. The zonally averaged transport of sensible heat by the mean eddies (left) and transient eddies (right) at 700 mb in winter (°C m s⁻¹).

from the latitude mean at the same point. The daily value of this product is the total eddy transport, the sum of the transient-eddy and mean-eddy transports, since $[V_g] = 0$. The same product computed from the seasonal means of temperature and meridional geostrophic wind is the contribution by the mean eddies, $\bar{v}^*\bar{T}^*$, where the bar denotes the seasonal average. The share of the total provided by the transient eddies, $\bar{v}'\bar{T}'$ was obtained by subtracting $\bar{v}^*\bar{T}^*$ from the seasonal mean of the daily total eddy transport.

The zonally averaged temperature gradient used below is defined as

$$[\Delta T] = [T]_{\phi} - [T]_{\phi+10},$$

where the brackets represent the zonal average. In winter $[\bar{T}]$ always decreases poleward over the region in question, 20–80°N, and the zonally averaged heat transport by eddies in the same latitudes is poleward both for the transient-eddy flux, mean-eddy flux, and the total eddy flux $[\bar{v}'\bar{T}' + \bar{v}^*\bar{T}^*]$. A positive correlation between gradient and flux therefore means that the poleward flux of sensible heat is bigger with a large than with a small poleward fall of temperature; a negative correlation means that the flux is bigger with a small poleward fall of temperature.

3. Mean and variability of eddy heat fluxes

A time series of the total eddy flux at 700 mb for the years 1949–72 can be seen in van Loon and Williams (1977). Its mean and transient components are shown in Fig. 1 with the years 1973–78 added. The transient eddy contribution is usually the bigger one but in a few instances the mean-eddy transport exceeds it near 50°N, such as in the early 1960's, 1970, and particularly in 1977 when the mean eddies transported over 20 units at the peak whereas the transient flux hardly exceeded 12 units.

North of 45°N the two types of flux varied such that when the one was large the other was usually small (see also Oort, 1977). The amount of negative correlation is shown in Fig. 2 where the mean-eddy flux is correlated with the transient-eddy flux. The negative correlation coefficients become statistically significant ($r = 0.36$ is the 95% confidence level) at 40°N, and the largest negative correlations are

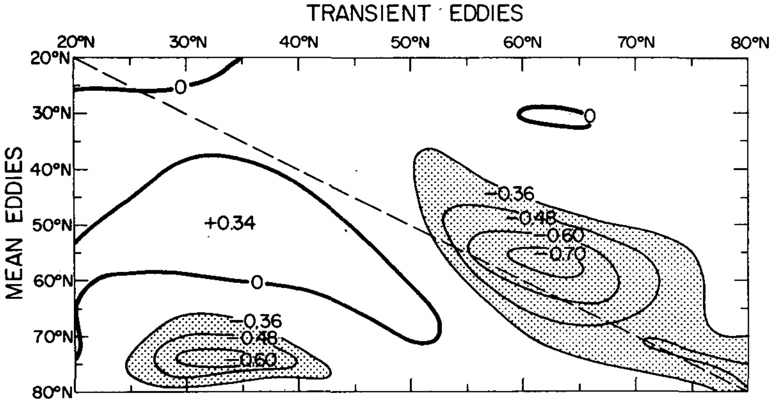


FIG. 2. Correlation of the zonally averaged mean-eddy transport of sensible heat at 700 mb in winter with the transient-eddy transport. The 95% confidence limit is 0.36, the 99% limit 0.48.

with $[\bar{v}'\bar{T}']$ 5–10° north of the parallel of the mean-eddy transport. For instance, the mean-eddy transport in 55°N is correlated at −0.50 with the transient-eddy flux at 55°N, but at −0.72 with the flux in 60°N, and −0.67 in 65°N. This relationship will be further described below.

There is one more region where the mean-eddy flux is significantly negatively correlated with the transient-eddy flux. The largest values here are between $[\bar{v}^*\bar{T}^*]$ at 70–75°N and $[\bar{v}'\bar{T}']$ at 30–35°N: $r = -0.66$. This negative correlation reflects the tendency for a southward displacement of cyclonic activity when pressure is high over the arctic, and the tendency for the subtropical highs to be well developed when the lows at high latitudes are deep (see, e.g., van Loon and Rogers, 1978). The largest transport of sensible heat into the arctic by the mean eddies thus occurs when the Icelandic low is well developed (van Loon and Williams, 1976).

The 29-year averages of $[\bar{v}^*\bar{T}^*]$ and $[\bar{v}'\bar{T}']$ at 700 mb are shown in Figs. 3 and 4 for winter and summer with vertical bars denoting the standard deviations from the average. The main features are known from other studies, for instance Oort and Rasmusson (1971): the total poleward eddy flux is much larger in winter than in summer and almost all the mean poleward eddy flux in summer is accomplished by transient eddies. The two types of eddies transport the same average amount of sensible heat poleward in winter at 50–55°N. Elsewhere, the transient-eddy flux dominates. The interannual variation is large (cf., Oort, 1977); in winter one standard deviation of $[\bar{v}^*\bar{T}^*]$ in the latitudes of biggest transport (45, 50 and 55°N) amounts to 28, 21 and 17%, respectively, of the mean. For $[\bar{v}'\bar{T}']$ in the same three latitudes the percentages are 15, 14 and 13. As a percentage of the mean, the interannual variability of $[\bar{v}^*\bar{T}^*]$ at other latitudes is much larger than that of $[\bar{v}'\bar{T}']$.

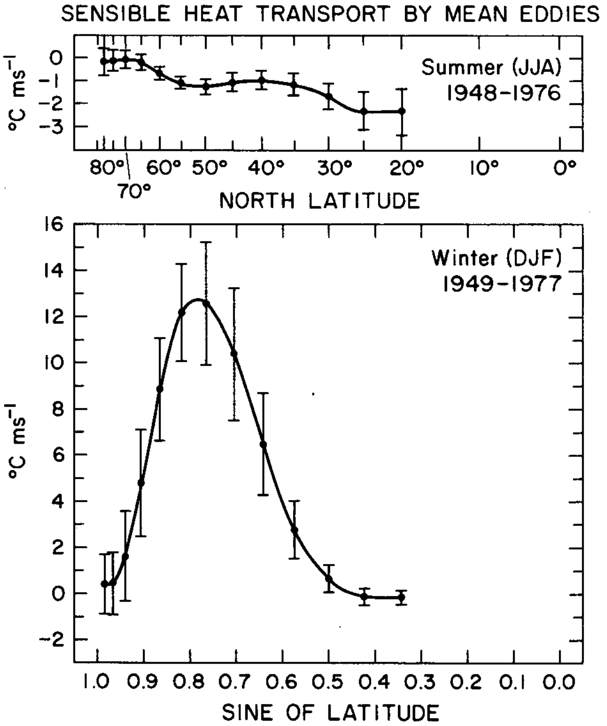


FIG. 3. The zonally averaged 29-year means of mean-eddy transport of sensible heat (°C m s⁻¹) in summer and winter at 700 mb. The vertical bars are one standard deviation above and below the mean.

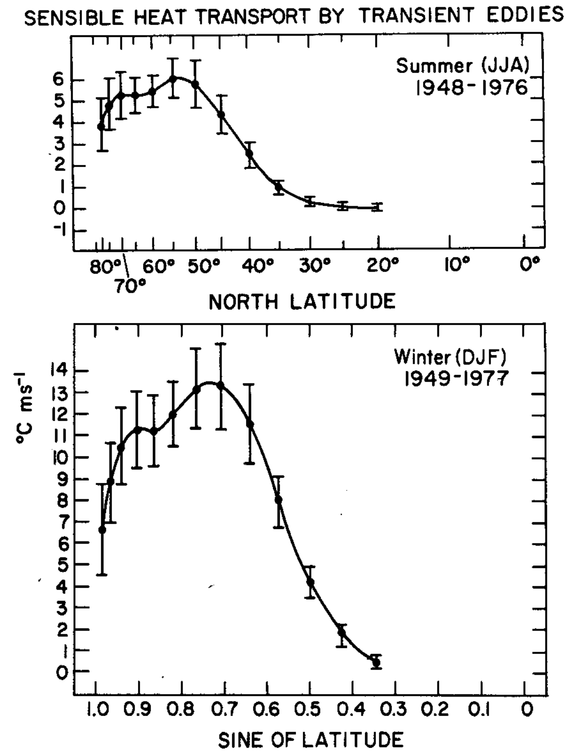


FIG. 4. As in Fig. 3 except for the transient-eddy transport.

Two other mean quantities need to be described. One is the zonally averaged temperature gradient per 10° latitude (Fig. 5), obtained from the monthly mean maps in Crutcher and Meserve (1970). This is the long-term gradient and not the gradient used in the correlation which, of course, is the gradient of the single winters. The second curve in Fig. 5 is the sum of the amplitudes of the seasonal mean zonal harmonic waves 1–4 at 700 mb, added without regard to phase. It indicates the size of the mean eddies in different latitudes, and just as the transport in the mean eddies culminates at 50°N, so do the combined amplitudes of the four waves. This does not in itself explain the position of the largest $[\bar{v}^*\bar{T}^*]$ since the size of the transport depends not only on the amplitude of the wave but also on the size of the temperature deviations from the latitude mean and on

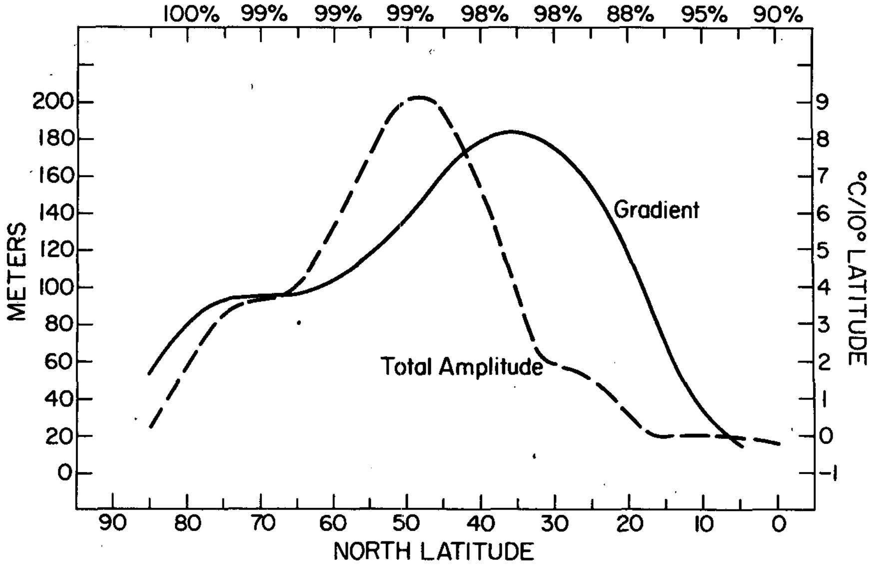


FIG. 5. The zonally averaged gradient (solid line) at 700 mb in winter (°C per 10° latitude) and the sum of the amplitudes of the first four zonal harmonic waves (dashed line) at 700 mb in winter, added without regard to phase. The percentages at every tenth parallel is the part of the total spatial variance of 700 mb height for which the four waves account.

the position of the temperature deviations with respect to the pressure wave.

4. Eddy heat transport and meridional temperature gradient at 700 mb

The association between the zonally averaged total transport of sensible heat by eddies and the zonally averaged gradient of temperature over 10° of latitude is illustrated in Fig. 6. Between the two dashed lines the transport in a 10° zone is correlated with the gradient for the same zone. North of 40–45°N the flux is negatively correlated with the gradient in the area of and north of the flux, with the largest negative correlation between the flux and the gradient immediately to its north. However, the flux is significantly *positively* correlated with the gradient to its south, and the distance between a specified flux and the latitude of the biggest positive correlation coefficient is 15–20°. In addition, the flux in the subtropics is significantly positively correlated with the gradients in the arctic, which in turn are negatively correlated with the flux in 55–60°N.

If one correlates the gradients with each of the two components of the total eddy flux it is immediately apparent that the principal features of the total eddy flux correlations in Fig. 6 derive from the mean-eddy fluxes (cf. Figs. 6 and 7). The zonally averaged temperature gradients to the north and south of the

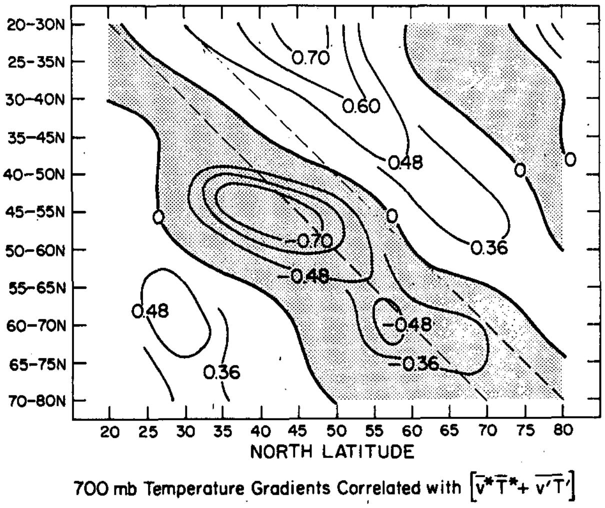


FIG. 6. The mean zonally averaged temperature gradients at 700 mb in 29 winters correlated with the mean total eddy heat flux. The 95% confidence limit is 0.36, the 99% limit 0.48.

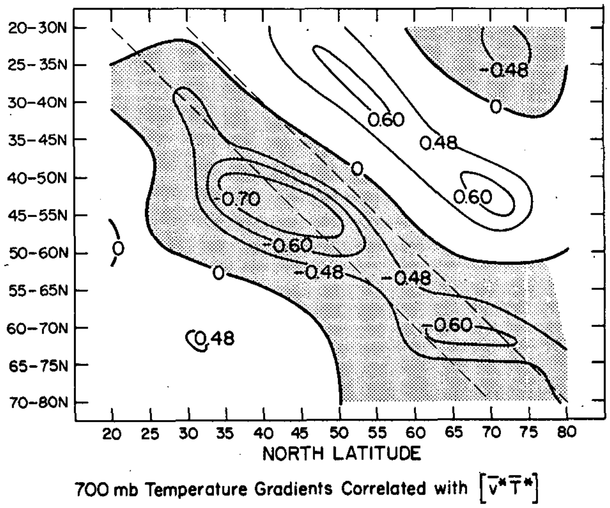


FIG. 7. As in Fig. 6 except for the mean-eddy flux.

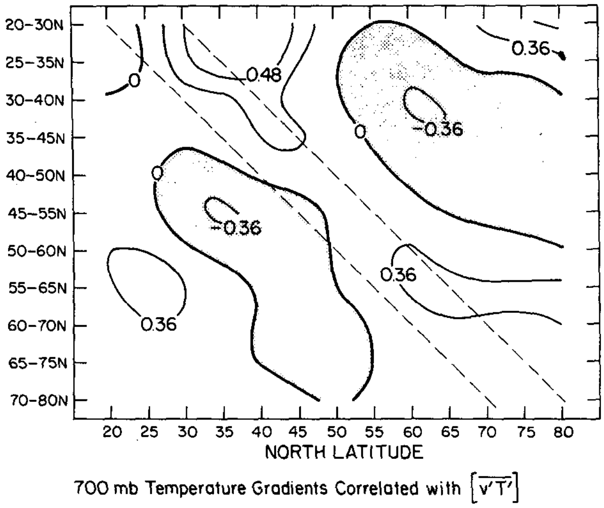


Fig. 8. As in Fig. 6 except for the transient-eddy flux.

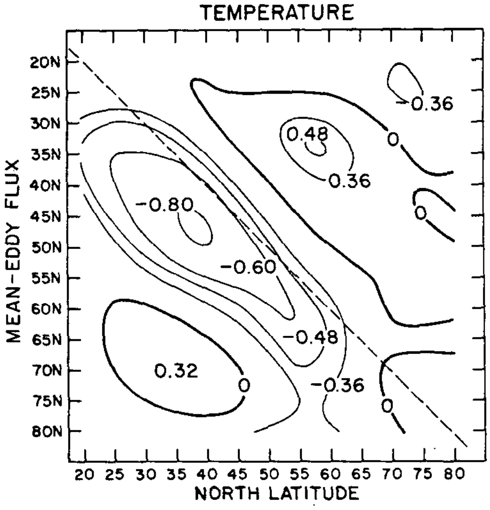


Fig. 10. As in Fig. 9 except for the mean-eddy flux.

largest poleward transport of sensible heat by the mean eddies are highly associated with this transport in the sense that when the transport goes up the gradient tends to increase to the south and decrease near and to the north of the latitude of the transport, and conversely when the transport goes down.

With this in mind we may return to the negative correlation between $[\bar{v}^*\bar{T}^*]$ and $[\overline{v'T'}]$ (Fig. 2) with the largest negative correlation coefficient (−0.72) between the mean-eddy flux at 55°N and the transient flux at 60°N. Since stronger $[\bar{v}^*\bar{T}^*]$ in middle latitudes is associated with weak gradients immediately to its north (Fig. 7) and since baroclinic instability is proportional to the temperature gradient, cyclonic activity and therefore transient eddy flux will weaken to the north of the strengthened $[\bar{v}^*\bar{T}^*]$. To the south of the stronger $[\bar{v}^*\bar{T}^*]$ the increased gradients tend to be accompanied by increased $[\overline{v'T'}]$, which is expressed by the positive correlations to the left of the diagonal in Fig. 2.

The correlations between gradients and transient-eddy fluxes (Fig. 8) reach statistical significance in comparatively few places. The correlation between a gradient and the transient-eddy flux in the same latitudes is positive, but the largest positive values lie just northward of the gradient in question.

Since the total eddy transport is positively correlated with the gradient to its south and negatively correlated with the gradient to its north, it is obvious that increasing total eddy heat flux in temperate latitudes is associated with decreasing temperature. The correlation between flux and zonally averaged temperature is given in Figs. 9–11. It is evident (Fig. 9) that when the total eddy transport is large in a specified latitude the temperature generally drops, in particular about 5° south of that latitude; the biggest correlation coefficient, −0.92, is between the

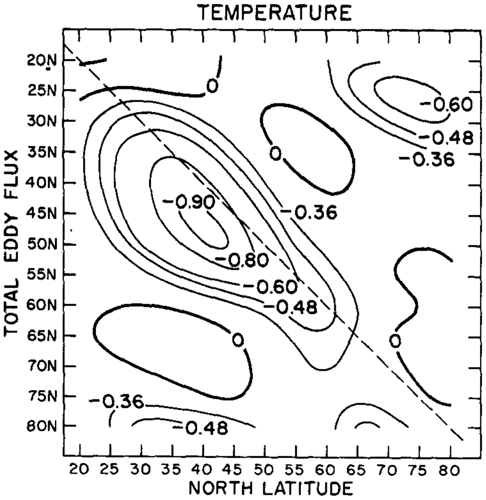


Fig. 9. The zonally averaged, seasonal mean total eddy flux in 29 winters correlated with the zonally averaged temperature.

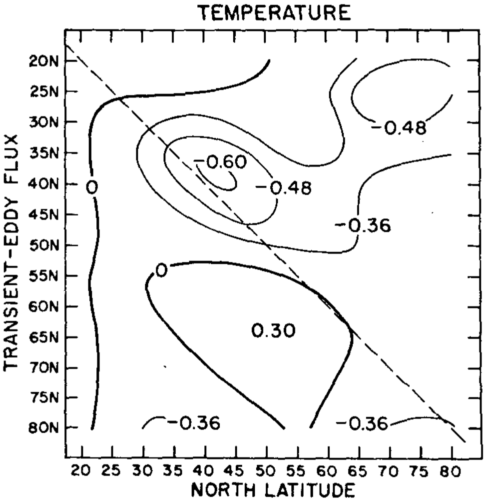


Fig. 11. As in Fig. 9 except for the transient-eddy flux.

total eddy flux at 45°N and the temperature at 40°N. The largest negative correlations between mean-eddy transport and temperature (Fig. 10) are distributed as those for the total eddy flux and reach −0.80 between the flux at 45–50°N and temperature at 35–40°N. In contrast, the largest negative correlation values for the transient eddies (Fig. 11) are for the transport in 30–50°N correlated with the temperature slightly to its *north*; the coefficient reaches −0.60 for transient-eddy flux at 40°N and temperature at 45°N.

The association between divergence of the eddy transport of sensible heat and zonal mean temperature is shown in Table 1. The measure of the divergence used in the table is defined as the transport at the higher latitude minus that at the lower latitude, i.e.,

$$D = (\overline{vT})_{\phi+10} - (\overline{vT})_{\phi}.$$

Where the divergence of heat flux is strongest (30–50°N, cf. Figs. 3 and 4), the size of the largest negative correlation coefficients for the divergence

TABLE 1. Correlations between zonally averaged flux divergence in total, mean and transient eddies and zonal mean temperature. A value of $r = 0.48$ is the 99% confidence limit. The underlined coefficients are significant beyond the 99% level. Compare with Figs. 9–11.

Flux divergence	Zonal mean temperature										
	20°N	25°N	30°N	35°N	40°N	45°N	50°N	55°N	60°N	65°N	70°N
20–30°N											
Total	−0.16	−0.46	−0.62								
Mean	−0.39	−0.49	−0.42								
Transient	0.12	−0.16	−0.40								
25–35°N											
Total		−0.57	−0.73	−0.80							
Mean		−0.56	−0.56	−0.55							
Transient		−0.23	−0.49	−0.62							
30–40°N											
Total			−0.69	−0.84	−0.88						
Mean			−0.62	−0.72	−0.68						
Transient			−0.29	−0.40	−0.52						
35–45°N											
Total				−0.73	−0.89	−0.90					
Mean				−0.73	−0.84	−0.75					
Transient				−0.06	−0.16	−0.32					
40–50°N											
Total					−0.06	−0.35	−0.56				
Mean					−0.43	−0.64	−0.70				
Transient					0.42	0.35	0.18				
45–55°N											
Total						0.55	0.24	−0.08			
Mean						0.12	−0.18	−0.42			
Transient						0.71	0.63	0.44			
50–60°N											
Total							0.42	0.09	−0.05		
Mean							0.01	−0.29	−0.34		
Transient							0.64	0.61	0.47		
55–65°N											
Total								0.13	−0.02	−0.03	
Mean								−0.15	−0.25	−0.15	
Transient								0.53	0.46	0.42	
60–70°N											
Total									0.13	0.05	0.07
Mean									0.09	0.03	0.01
Transient									0.06	0.02	0.08

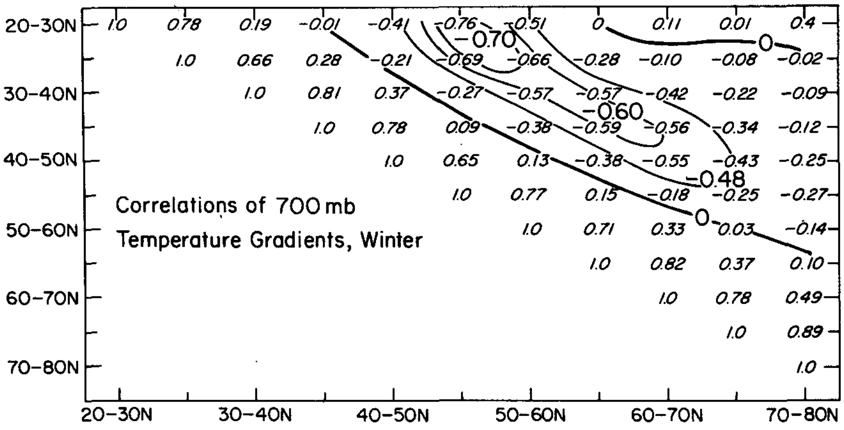


FIG. 12. The correlation matrix for the mean zonally averaged temperature gradient (°C per 10° latitude) at 700 mb in 29 winters.

of total eddy flux is determined mainly by the divergence of the mean-eddy flux. South of 50°N the negative correlation for the mean-eddy flux divergence is highest at the middle latitude in a 10° belt of latitude, whereas that for the transient eddies is highest at the upper latitude. The divergence of total eddy flux shows the largest correlation at the upper latitude too. North of about 50°N where the eddy flux on the average converges (Figs. 3 and 4), the total and transient-eddy flux divergences are positively correlated with the temperature at the lowest latitude in the 10° belt, whereas the mean-eddy flux divergence remains negatively correlated.

The fact that a given total eddy heat flux is negatively correlated with the zonally averaged temperature gradient on one side and positively correlated with the gradient on the other side (Fig. 6), implies that the gradients at lower latitudes are oppositely correlated with gradients at higher latitude. The correlation matrix for the zonally averaged gradients over 10° of latitude (Fig. 12) shows that the biggest negative correlation coefficient, −0.76, is between the gradients 20–30°N and 45–55°N, which lie on either side of the peak in the gradient at 30–40°N (Fig. 5).

There is another interesting aspect of the positive correlation between eddy heat flux through middle latitudes in the lower half of the troposphere and the gradients to its south. When the flux is strong and the latitudinal gradient in the subtropics is steep, according to the thermal wind relationship the west–east component of the wind in the subtropical upper troposphere must also be stronger, to the extent that the lower level eddy fluxes determine the gradients (thermal wind). Naturally, there are other factors which are connected with the gradient, and Figs. 6 and 7 show that the eddy fluxes explain only 64% of the variance in the gradient where the correlations are biggest. Nevertheless, the mid-latitude, low-level transport of heat in eddies must have a perceptible influence on the subtropical jet stream.

5. Mean-eddy flux in relation to wavenumbers

The part of the mean-eddy transport which is done by each of the first six zonal harmonic waves is given in Table 2A. The main carriers are the first three waves, and at the peak of $[\bar{v}^*\bar{T}^*]$—50–55°N (cf. Fig. 3)—45–50% of the average transport is done by wave 2 alone. The changes from one winter to another, however, are large as the comparison of the winter of 1975–76 with that of 1976–77 indicates: during the latter winter wave 2 transported 4.3 times more heat than during the former (Table 2B); the standard deviation of flux at 50°N is 1.1°C m s^{-1} for wave 1, 2.5 for wave 2 and 1.4 for wave 3. All

TABLE 2. (A) The $[\bar{v}^*\bar{T}^*]$ transported by each of the first six harmonic waves in winter (°C m s^{-1}). (B) The same for the winters of 1975–76 and 1976–77 for the first three waves. (C) The correlation coefficients for 10° gradients correlated with the mean-eddy flux in the first three waves.

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5	Wave 6
A						
35°N	0.7	0.5	1.6	−0.1	0	0.2
40°N	1.5	2.0	2.9	−0.2	0.2	0.1
45°N	2.6	3.9	3.6	0.1	0.1	0.1
50°N	3.2	5.6	3.2	0.5	0	0
55°N	2.8	5.9	2.8	0.5	0.1	0
60°N	2.0	4.6	2.0	0.3	0	0.1
65°N	1.3	2.5	0.9	0	0	0
B						
50°N 1975–76	2.7	2.9	4.4			
1976–77	4.0	12.4	4.1			
C						
G 45–55°N/*F* 40°N	−0.57	−0.65	−0.61			
G 60–70°N/*F* 65°N	−0.43	−0.53	0.11			
G 30–40°N/*F* 55°N	0.58	0.43	−0.04			
G 40–50°N/*F* 70°N	0.44	0.50	−0.13			

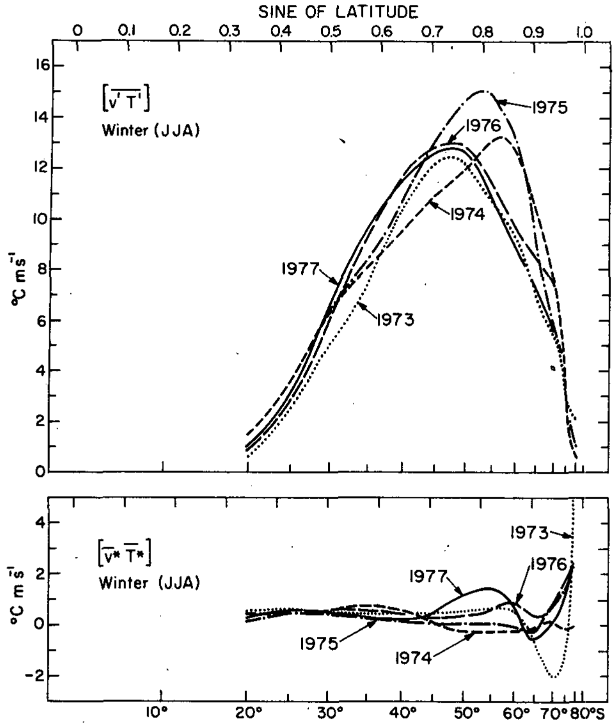


FIG. 13. The zonally averaged transport of sensible heat by the transient eddies (above) and mean eddies (below) in the Southern Hemisphere at 700 mb in five winters (°C m s⁻¹).

three zonal harmonic height waves in January at 700 mb reach their peak near 50°N where their average amplitudes are 64 m for wave 1, 56 m for wave 2, and 62 m for wave 3. Wave 2 thus transports more sensible heat poleward on the average despite its smaller amplitude. This is partly because its mean temperature wave is larger: 5.2°C against 4.8°C for wave 1 and 3.4°C for wave 3 at 50°N, and partly because the average phase difference between the height and temperature waves is somewhat more favorable for wave 2 than for the two other waves: 16.1% of a wavelength against 15.3% for wave 1 and 12.5% for wave 3; 25% of a wavelength being the optimum phase difference.

It is also of interest to see how the individual waves contribute to the biggest correlation coefficients between gradient and mean-eddy flux in Fig. 7. Except for the instance of the flux at 40°N and gradient between 45 and 55°N, when all three waves contribute significantly, nearly all of the high correlation coefficients are due to the flux in waves 1 and 2 (Table 2C).

6. Eddy fluxes in the Southern Hemisphere

The transient and mean eddy transport of sensible heat at 700 mb during five winters in the Southern Hemisphere is shown in Fig. 13. The size of the transient-eddy flux outside the Antarctic is remarkably similar to that of the transient-eddy flux in the Northern Hemisphere (cf. Fig. 4), but the total eddy flux is smaller than in the Northern Hemisphere because the mean-eddy flux is much smaller than in the Northern Hemisphere. This is not because of the level chosen for comparison [see Fig. 17 in van Loon and Williams, (1977)] nor is it because of a lack of mean eddies in the Southern Hemisphere (van Loon and Jenne, 1972). It is because the temperature and pressure waves over the southern oceans nearly coincide (van Loon *et al.*, 1973). As an example of this the phases of temperature and height wave 1 are given in Table 3 at the latitudes where the amplitude of the height wave reaches its peak. The largest poleward transport is accomplished when temperature-wave 1 lies 90° west of height-wave 1, a condition which is reached in the lower troposphere of the Northern Hemisphere owing to the influence of the extensive continents but not in southern middle latitudes where the sea is continuous round the hemisphere (van Loon *et al.*, 1973).

In the Northern Hemisphere the general shape of the correlation pattern between total eddy flux and gradient was determined by the correlation between the mean-eddy flux and the gradient (Figs. 6 and 7). Since in the Southern Hemisphere the mean eddies play such a small role in the total transport of sensible heat by eddies (Fig. 13), one would expect that the correlation between the transient-eddy flux and gradients in that hemisphere would largely determine the pattern of the correlation between gradient and total eddy flux. The available sample for the Southern Hemisphere (five years) is too small to establish correlation values, but one may nevertheless perform the correlation computations to get an idea of which type of wave influences more the association between total flux and gradient.

TABLE 3. The phases (longitude of ridge) of temperature and pressure wave-number 1 at the latitude of largest amplitude in the troposphere.

Pressure level (mb)	55°S July			50°N January		
	Temperature	Height	Difference	Temperature	Height	Difference
1000	140°W	131°W	9°	75°W	57°E	132°
850	130°W	129°W	1°	47°W	35°E	82°
700	149°W	135°W	14°	38°W	17°E	55°
500	151°W	135°W	16°	39°W	5°W	34°

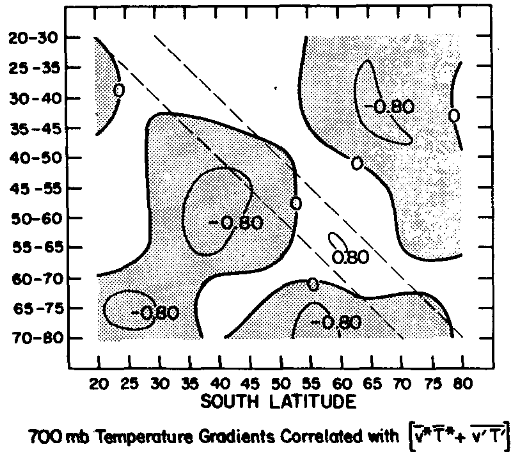


FIG. 14. The mean zonally averaged temperature gradients at 700 mb in five winters in the Southern Hemisphere correlated with the mean total eddy heat flux.

The first thing to note is that the shape of the pattern for the transient wave correlations (Fig. 15) is by and large the same as that in the Northern Hemisphere (Fig. 8). The second is that the pattern of the total eddy flux correlations (Fig. 14) is similar to that of the transient flux correlations.

Correlations obtained from such a small sample must be viewed with caution, but it is worth commenting on four features in Fig. 15 that are borne out by synoptic experience:

- When the subtropical gradients are steep (25–45°S), the transient-eddy flux in latitudes higher than 50°S tends to be weak.
- When the gradients in middle southern latitudes are steep (45–60°S) the transient-eddy flux at lower latitudes is weak.
- When the gradients in 50–65°S are steep the transient-eddy flux is strong in the same latitudes.

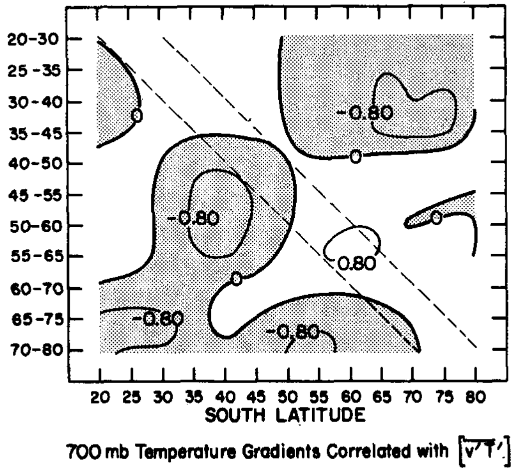


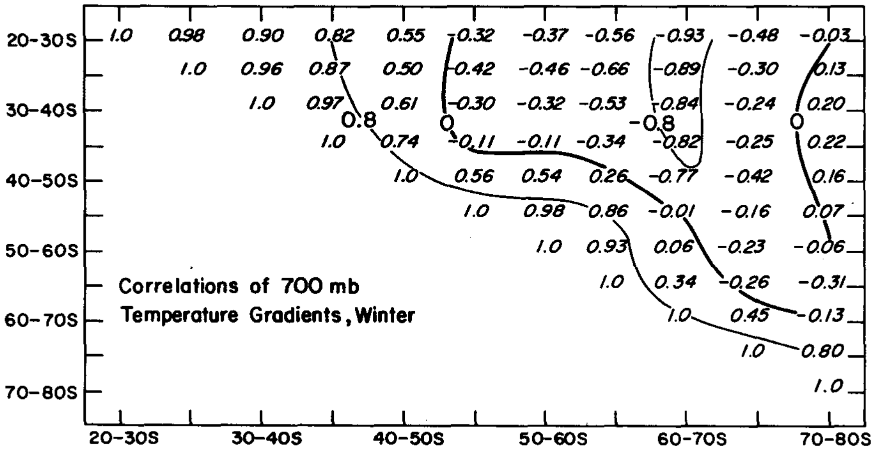
FIG. 15. As in Fig. 14 except for the transient-eddy transport.

- The transient fluxes in 40 and 60°S must be negatively correlated since they are oppositely correlated with the same gradient (50–60°S, Fig. 15).

From these relationships one may deduce that there is a tendency for an inverse relationship between the zonally averaged gradient in the subtropics, 20–40°S, and the gradient in the subantarctic at about 65°S. A correlation matrix between gradients over 10° of latitude (Fig. 16) outlines this inverse relationship between zonally averaged gradients in the Southern Hemisphere.

7. Conclusion

1) In the Northern Hemisphere the zonally averaged, total eddy transport of sensible heat in the lower half of the troposphere in winter is related to the zonally averaged temperature gradient in such a way that when the poleward transport in middle latitudes increases, the gradient in the subtropics



	20-30S		30-40S		40-50S		50-60S		60-70S		70-80S
20-30S	1.0	0.98	0.90	0.82	0.55	-0.32	-0.37	-0.56	-0.93	-0.48	-0.03
		1.0	0.96	0.87	0.50	-0.42	-0.46	-0.66	-0.89	-0.30	0.13
30-40S			1.0	0.97	0.61	-0.30	-0.32	-0.53	-0.84	-0.24	0.20
				1.0	0.74	-0.11	-0.11	-0.34	-0.82	-0.25	0.22
40-50S					1.0	0.56	0.54	0.26	-0.77	-0.42	0.16
						1.0	0.98	0.86	-0.01	-0.16	0.07
50-60S							1.0	0.93	0.06	-0.23	-0.06
								1.0	0.34	-0.26	-0.31
60-70S									1.0	0.45	-0.13
										1.0	0.80
70-80S											1.0

FIG. 16. The correlation matrix for the mean zonally averaged temperature gradient (°C per 10° latitude) at 700 mb in five winters in the Southern Hemisphere.

tends to increase while the gradient immediately to the north of the eddy flux decreases; and conversely when the eddy flux abates. This effect of the changes in the total eddy flux can be ascribed principally to the influence of the mean, or quasi-stationary, eddies.

2) In agreement with these relationships between eddy transport of sensible heat and gradients, the correlation between the total eddy transport and the zonally averaged temperature in middle latitudes of the Northern Hemisphere is negative. The largest negative correlation coefficient is −0.92 between the transport at 45°N and the temperature at 40°N. Also in this instance the main contribution to the correlation comes from the mean eddies.

3) When the mean-eddy flux in middle latitudes of the Northern Hemisphere increases and the gradient to its north at the same time decreases, the transient-eddy transport in the latitudes to the north of the specified mean-eddy flux tends to decrease. There is thus a negative correlation between mean-eddy flux north of 40°N and the transient-eddy flux 5–10° of latitude north of the specified mean-eddy flux.

4) In the Southern Hemisphere, the mean waves in temperate latitudes transport little sensible heat poleward because the pressure and temperature waves are nearly in phase. Therefore, the configuration of the correlation matrix between temperature gradient and total eddy flux in this hemisphere is determined almost entirely by the transient eddies.

5) Since the total eddy flux in the Northern Hemisphere is negatively correlated with the gradients to its north and positively correlated with the gradients to its south, it follows that the zonally averaged gradients at lower latitudes are negatively correlated with those at higher latitudes.

6) In van Loon and Williams (1977) we showed that during the overall cooling between 20 and 80°N in winter from the 1940's to the 1970's, the zonally averaged temperature contrast at the surface increased between the tropics and the arctic. At 700 mb the zonal mean temperature dropped the most at 45°N and hardly at all at 20 and 80°N. In agreement with the increased 700 mb temperature gradient south of 45°N, the number of cyclones increased south of 45°N while it decreased north of 45°N during the period. The surface temperature trends, in general, were such as would be compatible with the observed circulation changes at sea level. At 700 mb the poleward transport of sensible heat by eddies rose by nearly 40% during the period at 45°N. In concurrence with the correlations shown in this paper, the gradients increased south of the biggest rise in eddy heat transport and decreased to the north as the temperature dropped in the region of largest increase of flux. This region coincided with the largest rise in mean-eddy flux, whereas the largest rise in transient-eddy flux took place to the south where the gradient increased [Fig. 7 in van Loon and Williams (1977)]. These results and the results of the present study cast doubt on the validity of the way eddy heat fluxes generally are parameterized in seasonal climate models. The parameterization of the fluxes are made in terms of surface temperature gradients which, as mentioned above, are not necessarily representative of the baroclinic zone of the troposphere. Furthermore, it is assumed that the eddy flux is proportional to the gradient, i.e., that the correlation between the two is positive. As shown above, this is not so with respect to the total eddy transport and the mean-eddy transport.

In the subsequent parts of the study the connections described above for seasonal and zonal averages will be examined for other periods and the contributions from different longitudes will be outlined.

Acknowledgment. I am grateful to Will Spangler of NCAR for his invaluable help in handling the data and computations.

REFERENCES

Crutcher, H. L., and J. M. Meserve, 1970: Selected-level heights, temperatures, and dewpoint temperatures for the Northern Hemisphere. NAVAIR 40-1C-52 rev., Chief Naval Operations, Washington, DC, 17 pp. plus charts.

Newell, R. E., J. W. Kidson, D. G. Vincent and G. J. Boer, 1974: *The General Circulation of the Tropical Atmosphere and Interactions with Extratropical Latitudes*, Vol. 2. The MIT Press, 371 pp.

Nyberg, A., 1954: Meridional heat transport on a part of the Northern Hemisphere in November 1947, July 1949, and February 1950. *Arch. Meteor. Geophys. Bioklim.*, **A7**, 99–113.

Oort, A. H., 1977: The interannual variability of atmospheric circulation statistics. NOAA Prof. Pap. 8, U.S. Govt. Printing Office, Washington, DC, 76 pp.

Oort, A. H., and E. M. Rasmusson, 1971: Atmospheric circulation statistics. NOAA Prof. Pap. 5, U.S. Govt. Printing Office, Washington, DC, 323 pp.

Starr, V. P., and J. M. Wallace, 1964: Mechanics of eddy processes in the tropical troposphere. *Pure Appl. Geophys.*, **58**, 138–149.

van Loon, H., and R. L. Jenne, 1972: The zonal harmonic standing waves in the Southern Hemisphere. *J. Geophys. Res.*, **77**, 992–1003.

——, and J. Williams, 1976: The connection between trends of mean temperature and circulation at the surface: Part I. *Mon. Wea. Rev.*, **104**, 365–380.

——, and ——, 1977: The connection between trends of mean temperature and circulation at the surface: Part IV. *Mon. Wea. Rev.*, **105**, 636–647.

——, and J. C. Rogers, 1978: The seesaw in winter temperatures between Greenland and northern Europe. Part I: General description. *Mon. Wea. Rev.*, **106**, 296–310.

——, R. L. Jenne, and K. Labitzke, 1973: Zonal harmonic standing waves. *J. Geophys. Res.*, **78**, 4463–4471.

White, R. M., 1951: The meridional flux of sensible heat over the Northern Hemisphere. *Tellus*, **3**, 237–243.