On the standing-eddy sensible heat transport reversal in the polar region of the northern hemisphere during winter

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ABSTRACT

Harmonic analysis of the standing-eddy transport of sensible heat in the Northern Hemisphere polar latitudes shows that the equatorward sensible heat transfer in these latitudes in January is due to different zonal harmonics at different latitudes and isobaric levels. A comparison of the transports of sensible heat by the standing eddies, up the meridional temperature gradient, in the midlatitude lower stratosphere and the polar troposphere, shows that these up-gradient transports are due to different mechanisms. The former is caused by a relative maximum of time-and-zonal average temperature in the midlatitude stratosphere which owes itself to the mean meridional circulation, and does not involve any meridional changes in the structure of the standing eddies; but the latter is due to cross-latitude changes in the direction of tilt of the vertical axis of the standing eddies.

Symbols not defined in the text

a	= mean radius of the Earth
c_p	= specific heat at constant pressure of dry air
E	= degrees east (longitude)
f	= Coriolis parameter
g	= acceleration due to gravity
n	= 1, 2, 3, ..., number of a zonal harmonic
N	= degrees north (latitude)
p	= pressure
R	= gas constant for dry air
v	= meridional velocity of the wind
W	= degrees west (longitude)
z	= the height of an isobaric surface
λ	= longitude
ϕ	= latitude
– (bar)	= symbol for time-averaging
[ ]	= symbol for zonal averaging
*	= symbol for differencing a local value from the zonal mean for a variable
$\|x\|$	= modulus of x

1. Introduction

The accepted theory of heat transport in the atmosphere derives from the fact that the long-range thermal equilibrium of the planet has to be maintained by a poleward advection of heat, which would remove the excess energy accumulated in the low latitudes by radiative processes, and would compensate for the energy losses continuously suffered by the high latitudes through radiative transfers. According to this theory the poleward transport of heat must reach its maximum magnitude in the winter of a given hemisphere, when the capacity of the polar region to compensate for its radiative losses becomes nil under the influence of the polar night; this is in agreement with observations.

Hence it might be expected that in the winter hemisphere both the transient and the standing eddies would transport heat poleward everywhere in the atmosphere. (Here we shall refer to eddies which appear on daily charts, but disappear in time-averaging over a month as transient eddies, and eddies which do not thus disappear as standing eddies.)

However, this is not true. Transient eddies do transport heat in the poleward direction at all latitudes in the winter hemisphere. But north of 70 N, the tropospheric standing eddies transport sensible and latent heat equatorward in all winter months (see Oort & Rasmusson, 1971).

Here we shall confine our analyses to January, 1970. The data available to us consisted of

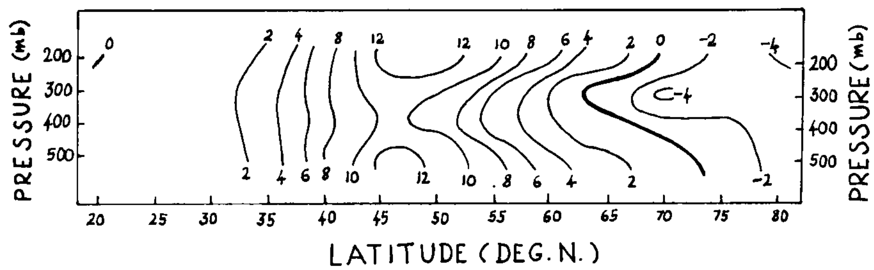

Fig. 1. $[\bar{v}^*T^*]$ in January 1970. Units: Deg Abs mps.

the United States National Meteorological Center (NMC) geopotential height distributions for the 700, 500, 400, 300, 200 and 100 mb levels between 20N and 80N. From these data the monthly-mean distributions of the heights of isobaric surfaces for the above-mentioned levels were derived, from which the monthly-average values of virtual temperature can be obtained for the 500, 400, 300 and 200 mb levels by the use of the hydrostatic equation and the equation of state. Hence the term 'sensible heat' in this paper stands for

$$c_p T = c_p \tau (1 + w\varepsilon^{-1})(1 + w)^{-1}$$

where T is the virtual temperature of atmospheric air, τ the observed dry-bulb temperature, w the mixing ratio and ε, the ratio of the molecular weight of water vapour to the molecular weight of dry air, is of the value 0.622. The above equation may be reduced to

$$c_p T \doteq c_p \tau + c_p \tau w \varepsilon^{-1}$$

by neglecting w (but not $w\varepsilon^{-1}$) compared to unity in the first equation. Therefore

$$c_p T \doteq c_p \tau + c_{pv} w \tau$$

where c_{pv} is the specific heat at constant pressure of water vapour, since

$$c_{pv} \doteq c_p \varepsilon^{-1}$$

Therefore the term 'sensible heat' in this paper stands approximately for the sum of the sensible heat of dry air and the sensible heat of water vapour.

The monthly-mean values of v^* were obtained from the distributions of $\bar{z}^*$ through the use of the geostrophic approximation. From these data and the data on $\bar{T}^*$, the values of $[\bar{v}^*\bar{T}^*]$ are readily calculated, and are presented in Fig. 1. These data clearly reveal the standing-eddy sensible heat transport reversal in the polar latitudes, at 70N and north of that latitude.

2. The pressure, longitude distributions

In Figs. 2, 3 and 4 we present the (λ, p) distributions of $\bar{T}^*$, $\bar{v}^*$ and $\bar{v}^*\bar{T}^*$ for 60N, 70N and 80N respectivey. It is seen from these data that the field of $\bar{T}^*$ of the high-latitude atmosphere is mainly due to the first zonal harmonic at the 300 mb and 200 mb levels. It is of further interest to note that at these levels (where the influence of *local* topography becomes negligible) $\bar{T}^*$ is positive almost everywhere in the western hemisphere and negative almost everywhere in the eastern hemisphere. Thus the distribution of $\bar{T}^*$ at the 300 mb and 200 mb levels in the polar region seems to be governed by the first zonl harmonic of the *Earth's* topography which is forced by the Himalayas and has nodes at 10W and 170E approximately. (For detailed maps of the first three zonal harmonics of the Earth's topography see Van Mieghem, 1961.)

The data on $\bar{v}^*$ in Figs. 2 to 4 reveal the importance of the second zonal harmonic in the distribution of this parameter in the zone 70N to 80N; and the data on $\bar{v}^*\bar{T}^*$ in these diagrams show that sensible heat is generally transported poleward in the sector 80W–0–70E, and equatorward in the remaining sector. From a simultaneous consideration of the data on $\bar{v}^*$ and $\bar{T}^*$ in Figs. 2 to 4 it can be further ascertained that the poleward transport of sensible heat in the sector 80W–0–70E consists of poleward warm advection in the western sector (10W–80W) and of equatorward

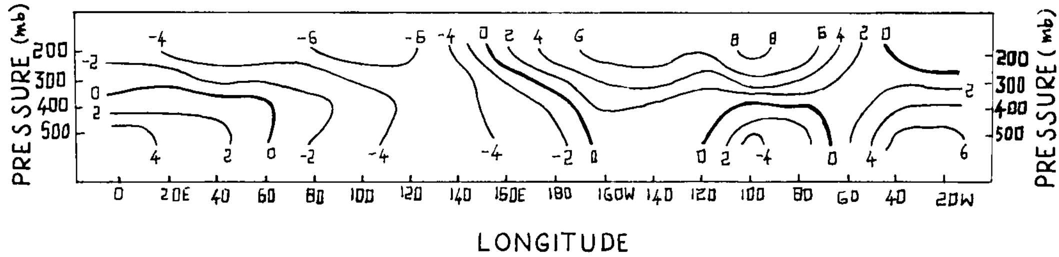

Fig. 2a. The pressure, longitude distribution of $\bar{T}^*$ in Jan. 1970 at 60N. Units: Deg Abs.

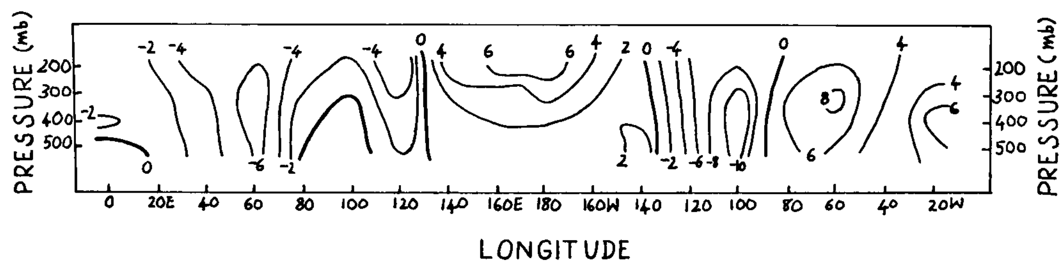

Fig. 2b. The pressure, longitude distribution of $\bar{v}^*$ in Jan. 1970 at 60N. Units: mps. (Some contours between 80 W and 100 W have been omitted for clarity.)

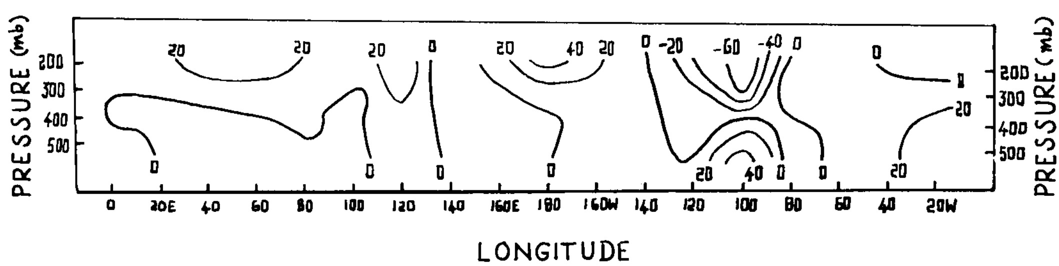

Fig. 2c. The pressure, longitude distribution of $\bar{v}^*\bar{T}^*$ in Jan. 1970 at 60N. Units: Deg Abs mps.

cold advection in the eastern sector (0–70E). The equatorward sensible heat transport over 80E–180–90W, on the other hand, is due to poleward cold advection in the sector 80E–180, and equatorward warm advection in the sector 90W–170W.

3. Wave-number analysis

In Table 1 we present the zonal-harmonic components of $[\bar{v}^*\bar{T}^*]$ in January 1970 from 60N to 80N. Data for only the first four harmonics are presented because the higher wave numbers do not play an important role in the standing-eddy transport of sensible heat. The data in Table 1 presents a rather complex picture of the standing-eddy transport of sensible heat up the meridional temperature gradient, the contribution by each harmonic being unique, dependent both upon latitude and isobaric level. The following statements could, however, be made concerning the harmonic analyses at the 300 mb and 200 mb levels: Wave-number 1 withdraws the largest amount of sensible heat from the polar circulation at 80N, but the negative sensible heat transport from 60N to 70N is largely due to wave-number 2.

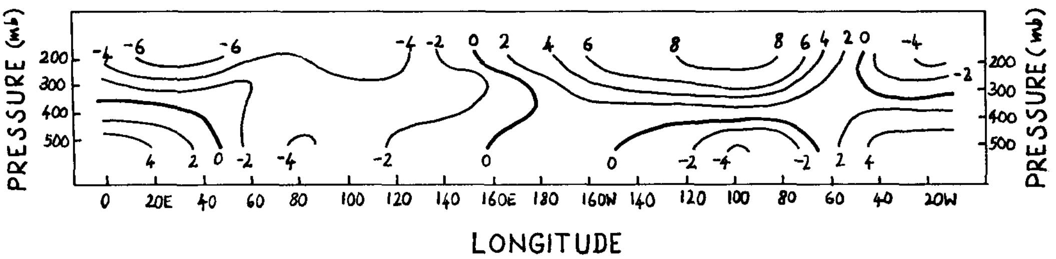

Fig. 3a. The (p, λ) distribution of $\bar{T}^*$ in Jan. 1970 at 70N. Units: Deg Abs.

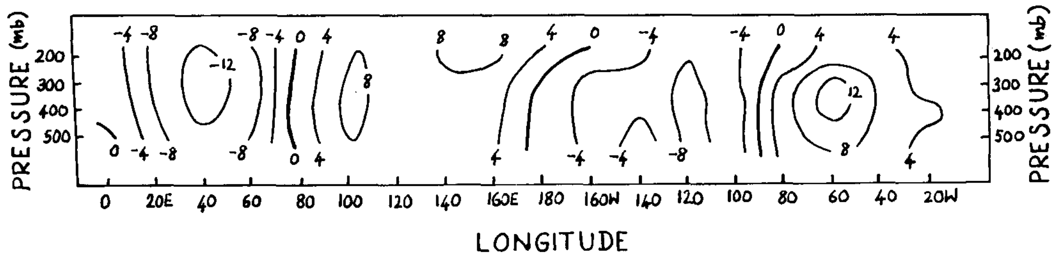

Fig. 3b. The (p, λ) distribution of $\bar{v}^*$ in Jan. 1970 at 70N. Units: mps.

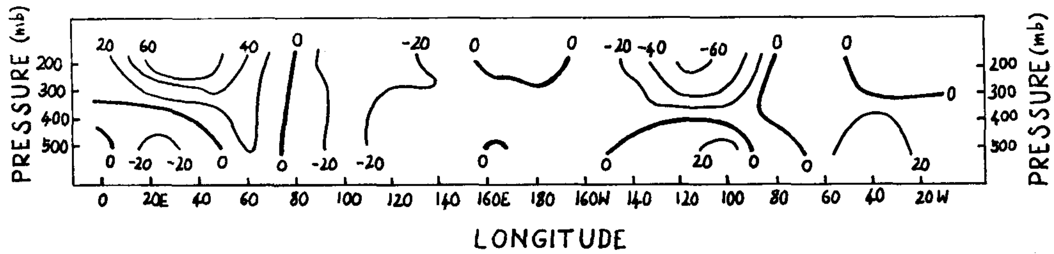

Fig. 3c. The (p, λ) distribution of $\bar{v}^*\bar{T}^*$ in Jan. 1970 at 70N. Units: Deg Abs mps.

4. Some basic differences between the up-gradient transport of sensible heat in the midlatitude stratosphere and the polar troposphere

The importance of the zonal harmonics 1 and 2 in the equatorward (and hence up-gradient) transport of sensible heat in the Northern Hemisphere polar region below the 200 mb level might appear to be related to the stratospheric polar vortex, which consists largely of wave-numbers 0 and 1 when unbroken, and of wave-numbers 0 and 2 when broken (Reed et al., 1963). It is indeed true that during January 1970 both the broken and the unbroken polar-night vortex structures prevailed on different days. However, it should be noted that at and above the 100 mb level the standing-eddy transport of sensible heat is poleward and down the meridional temperature gradient in the polar region (see Oort & Rasmusson, 1971).

The up-gradient transport of sensible heat at the 100 mb and 50 mb levels is located in the region adjoining 50N, as shown by the Oort & Rasmusson statistics (*op. cit.*) The occurrence of a relative maximum of $[c_p \bar{T}]$ near 50N is due to the adiabatic compression resulting from the two-cell meridional circulation at these lower-stratospheric levels, with rising motions in the tropical and polar regions and sinking motions in the middle latitudes (Miyakoda, 1963). Hence

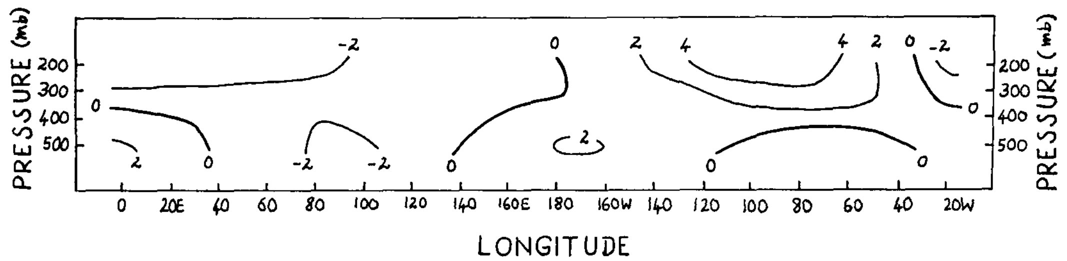

Fig. 4a. The (p, λ) distribution of $\bar{T}^*$ in Jan. 1970 at 80N. Units: Deg Abs.

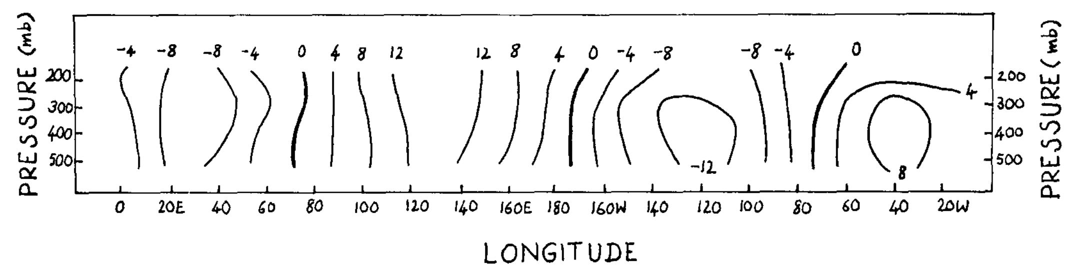

Fig. 4b. The (p, λ) distribution of $\bar{v}^*$ in Jan. 1970 at 80N. Units: mps.

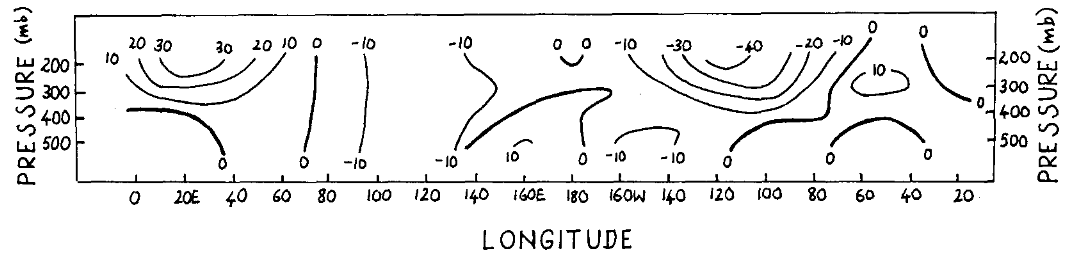

Fig. 4c. The (p, λ) distribution of $\bar{v}^*\bar{T}^*$ in Jan. 1970 at 80N. Units: Deg Abs mps.

$$c_p \frac{\partial[\bar{T}]}{a \partial \phi} > 0 \tag{1}$$

near 50N. But the standing-eddy transport of sensible heat itself is poleward at all latitudes at the 100 mb and 50 mb levels.

On the other hand,

$$c_p \frac{\partial[\bar{T}]}{a \partial \phi} < 0 \tag{2}$$

at all extratropical latitudes in the troposphere in January. Thus if we represent the distribution of standing-eddy heights upon isobaric surfaces by

$$\bar{z}^* = \sum_{n=1}^{\infty} C_n(p, \phi) \cos (n\lambda - S_n) \tag{3a}$$

$$= \sum_{n=1}^{\infty} (A_n(p, \phi) \cos n\lambda + B_n(p, \phi) \sin n\lambda) \tag{3b}$$

whereby

$$C_n = |(A_n^2 + B_n^2)^{1/2}| \tag{4}$$

and

$$S_n = \arctan (B_n/A_n). \tag{5}$$

Then from eq. 3a through the geostrophic approximation

$$\bar{v}_n^* = \frac{g}{fa \cos \phi} \frac{\partial \bar{z}_n^*}{\partial \lambda} = -\frac{g}{fa \cos \phi} nC_n \sin (n\lambda - S_n) \tag{6}$$

and through the hydrostatic approximation

Table 1. *Zonal harmonic components of* $[\bar{v}^* T^*]$ *in January 1970. Units: Deg Abs mps*

	60N	65N	70N	75N	80N
200 mb					
$n=1$	6.8	7.2	4.7	-.8	-4.9
$n=2$	-1.9	-5.4	-5.6	-1.5	1.1
$n=3$	1.1	0.4	-.2	-.5	-.1
$n=4$	0.0	0.0	0.2	0.1	0.0
300 mb					
$n=1$	3.4	3.2	1.1	-2.1	-4.7
$n=2$	-2.6	-4.8	-5.2	-.8	1.2
$n=3$	1.2	0.4	-.1	-.3	-.1
$n=4$	0.1	0.1	0.2	0.0	-.1
400 mb					
$n=1$	1.6	1.0	-.3	-1.5	-2.7
$n=2$	-.6	-.7	-.4	0.4	0.3
$n=3$	1.5	0.8	0.2	-.2	0.0
$n=4$	0.0	0.0	0.1	0.0	-.1
500 mb					
$n=1$	1.7	0.6	-.4	-.7	-1.0
$n=2$	1.2	1.1	1.3	-.3	-1.2
$n=3$	1.7	1.0	0.5	-.2	-.1
$n=4$	-.3	-.2	0.1	0.0	0.0

$$T_n^* = -\frac{g}{R}\left(\frac{\partial C_n}{\partial \ln p} \cos (n\lambda - S_n) + C_n \sin (n\lambda - S_n) \frac{\partial S_n}{\partial \ln p}\right) \quad (7)$$

From eqs. (6) and (7) then

$$[\bar{v}_n^* T_n^*] = \frac{n}{2} C_n^2 \left(\frac{\partial S_n}{\partial \ln p}\right) \frac{g^2}{Rfa \cos \phi} \quad (8)$$

From eq. (8) it is obvious that in the Northern Hemisphere for any given n,

$$[\bar{v}_n^* T_n^*] \gtreqless 0 \quad (9)$$

if and only if

$$\frac{\partial S_n}{\partial \ln p} \gtreqless 0 \quad (10)$$

respectively.

From the data in Table 1 it is therefore obvious that some of the zonal harmonic components of the polar tropospheric standing eddies must satisfy the requirements of eq. 10 oneway in some latitudes and in another in other latitudes while the sensible heat transport reversal is being accomplished in the polar region. Since the standing eddies themselves are constituted only of these components, a suitably defined *tilt* of the vertical axis of the standing eddies (see, for example, Lorenz, 1951) must also change its sign across latitude circles wherever the transport of sensible heat changes sign.

The above arguments show that the up-gradient transport of sensible heat in the midlatitude lower stratopshere (i.e., the 100 mb to 50 mb layer) and the polar troposphere are due to entirely different mechanisms. The former process is caused by the occurrence in the midlatitude stratosphere of a relative maximum of sensible temperature which is due to the mean meridional circulation in this atmospheric layer, and does not entail a meridional change in the structure of the eddies. On the other hand, the up-gradient transfer of sensible heat in the Northern Hemisphere polar troposphere by the standing eddies in winter arises only due to eddy-structure changes across latitude circles.

REFERENCES

Lorenz, E. N. 1951. Computations of the balance of angular momentum and the poleward transport of heat. Sci. Rep. No. 6, M.I.T. General Circulation Project, 34 pp.

Miyakoda, K. 1963. Some characteristic features of winter circulation in the troposphere and lower stratosphere. Department of Geophysical Science, University of Chicago, Tech. Rep. No. 14, 93 pp.

Oort, A. H. & Rasmusson, E. M. 1971. *Atmospheric circulation statistics*, Rockville, Md., U.S. Department of Commerce, 323 pp.

Reed, R. J., Wolfe, J. L. & Nishimoto, H. 1963. A spectral analysis of the energetics of the stratospheric sudden warming of early 1957. *J. Atmos. Sc. 20*, 256–275.

Van Mieghem, J. 1961. Zonal harmonic analysis of the Northern Hemisphere geostrophic wind field. International Union of Geodesy and Geophysics, Monographie No. 8, 57 pp.

ОБ ОБРАЩЕНИИ ЗНАКА ПЕРЕНОСА ТЕПЛА СТОЯЧИМИ ВИХРЯМИ В ПОЛЯРНЫХ ОБЛАСТЯХ СЕВЕРНОГО ПОЛУШАРИЯ В ТЕЧЕНИЕ ЗИМЫ

Гармонический анализ переноса тепла стоячими вихрями в полярных широтах северного полушария показывает, что перенос тепла в направлении к экватору на этих широтах в январе происходит благодаря разным зональным гармоникам на разных широтах и изобарических уровнях. Сравнение переносов тепла стоячими вихрями в направлении меридионального градиента температуры в нижней стратосфере умеренных широт и в полярной тропосфере показывает, что эти переносы вызываются различными механизмами. Первый вызывается относительным максимумом зонально и по времени осредненной температуры в стратосфере умеренных широт, который сам обязан происхождением средней меридиональной циркуляции и не зависит от каких-либо меридиональных изменений в структуре стоячих вихрей. Второй перенос возникает благодаря изменениям с широтой направлений наклона вертикальных осей стоячих вихрей.