A Laboratory Investigation of the Structure of Multiple Vortices

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Abstract

The structure of the multiple vortices formed in small scale atmospheric vortices is studied in a laboratory experiment. A guide vane type simulator is shown to be capable of producing the multiple vortices for large swirl ratios. The number of subsidiary vortices increases with the swirl ratio. A condition with 3 subsidiary vortices is examined closely with an improved smoke-wire and a two component hot-wire anemometer. Core sizes, velocity distributions and other properties of the subsidiary vortices are determined by the measurement. A subsidiary vortex rotates around the center of the parent vortex keeping its identity. But the ratio of the translational velocity of the subsidiary vortex to mean tangential velocity is about 0.9 in the layers far from the ground, and about 0.7 near the ground because of the vertical shear in the mean field. The cospectra between the two horizontal velocity components indicate that in the upper layers the subsidiary vortex transports momentum from the maximum velocity region of the parent vortex toward the center. The transport process is more complex near the ground.

1. Introduction

Non-axisymmetric structures are often observed in the small scale and mesoscale vortices in the atmosphere. Fujita (1967, see Fujita, 1970 and Fujita *et al.*, 1970), after examining the trochoidal tracks left on the ground by tornadoes, proposed that a tornado vortex consists of several small subsidiary vortices, which he called "suction vortices". In Ohmiya Tornado (near Tokyo, Japan in 1971), Fujita *et al.* (1972) found the evidence that the subsidiary vortices act as suction spots. Recently, a number of tornado photographs and movies have proved the existence of subsidiary vortices rotating in a parent vortex. Tornado damage statistics by Clare (see Snow, 1978) indicates that the tornadoes with the multiple vortex structure are more destructive. For instance, in Lubbock Tornado, Texas in 1970, 27 out of 28 deaths were found on the path of the subsidiary vortices (Fujita, 1970).

In the smaller scales, dust devils often

show the multiple structure (Hallett and Hoffer, 1971). In the meso-scale vortices, multiple vortex phenomena appear as multiple tornadoes in meso-cyclones. Agee *et al.* (1976) concluded from the damage tracks of tornadoes in Indiana and neighboring states on 3 April 1974, that there must have been multiple tornadoes rotating around each other in a parent meso-system. In the larger scales, tropical cyclones sometimes show non-axisymmetric structure which appears as elliptical eyes (Mitsuta and Yoshizumi, 1973) or polygonal eyes (Lewis and Hawkins, 1982).

The first simulation of the multiple vortex phenomena was succeeded in a laboratory experiment by Ward (1972) at National Severe Storm Laboratory in Oklahoma. He developed a simulator with two chambers, i.e., convergence and convection chambers. It had an exhaust fan to produce the updraft (therefore the convergent flow), and a rotating screen to provide the tangential velocity component to the incoming flow. Church *et al.* (1977) constructed a similar type of the simulator at

Purdue University with a larger dimension and more improved stability to remove the vortex wandering. Church *et al.* (1979) investigated the condition for various types of vortices including the multiple vortices as a function of the swirl ratio and the Reynolds number. However, there have been no works to quantify these observations except for a measurement of the surface pressure distribution obtained by Pauley *et al.* (1982).

A number of theoretical studies have also been made on the dynamic instabilities of axisymmetric flow. In the linear analysis of the columnar vortex, Snow (1978), and Staley and Gall (1979) found that the shear in the tangential velocity component allows the development of periodic disturbances. Walko and Gall (1984) extended the model to include the vertical variations. Ishikawa and Mitsuta (1981) extended these stability analysis to the anisymmetry in the typhoon vortices. These models gave some insights to the development of the multiple vortex phenomena. Recently the three dimensional numerical simulation done by Rotunno (1984) successfully produced the vortex splitting. However, because of the constancy of the viscosity in the model the turbulence in the vortex flow may not have been adequately expressed.

The main objective of this paper is to determine the flow characteristics of the multiple vortices. The vortex simulator developed here utilizes guide vanes to provide the tangential velocity component instead of the rotating screen adopted in the Ward type simulator. The guide vane type simulators developed in the past did not produce the multiple vortices. For instance, in the apparatus developed for the dust devil simulation (Fitzjarrald, 1973, or Mullen and Maxworthy, 1977) or tornado simulation (Monji and Mitsuta, 1983), a large vortex core was formed instead of the vortex splitting. Here, the conditions for the multiple vortex formation in a guide vane type simulation is searched in a more carefully designed apparatus. After choosing a particular condition, the structure of the multiple vortices, i.e., the velocity profiles of subsidiary vortices, relative position and size of the subsidiary vortices in

the parent vortex are examined. The interaction of the subsidiary vortices with the parent vortices, such as the translation of the subsidiary vortices and the energy exchange between the subsidiary vortices and the parent vortices is also a major interest of this research.

2. Apparatus and measurements

The outline of the simulator developed for this experiment is shown in Fig. 1. This was originally developed at Kyoto University by Mitsuta and Monji (1984) to investigate the small scale atmospheric vortices. Some modification was made to fit the present purpose. The flow to the measuring area is introduced by an exhaust fan located at the top of the

Fig. 1 Outline of the vortex simulator. Upper figure is the side view and lower figure the top view. The flow produced by the exhaust fan enters from the top surroundings (thick arrows), obtains angular momentum by guide vanes and enters to the convergence region and to the convection region.

apparatus. The inflow obtains the angular momentum by 1 mm thick aluminum plate guide vanes. The guide vanes have the size of 23 cm $\times$ 47 cm and were located at 48 positions at the radius of $r=80$ cm. The deviation angle (θ) of the guide vane from the radial direction is variable between 0 and 85 degrees. The swirl ratio defined as $S=\tan \theta / 2a$ (Davies-Jones, 1973), varies from 0 ($\theta=0^\circ$) to 4.6 ($\theta=85^\circ$), where $a=H/R$, H is the height of the inflow layer and R the radius of the updraft hole. H and R are fixed as 47 and 38 cm respectively in this experiment. The inflow velocity averaged over the inflow height varies from 0.2 cm/s to 40 cm/s at the outer end of the convergence chamber by changing the revolution rate of the exhaust fan. The Reynolds number defined as $Re=W_0 D/\nu$, where $D(=2R)$ is the diameter of the updraft hole and W_0 the average vertical velocity at the updraft hole, varies between $1.1 \times 10^3 \sim 8.3 \times 10^4$. Although bottom boundary of the apparatus is changeable, a smooth wooden surface was used in the present study.

The velocity was measured with a smoke-wire system and a two-component hot-wire anemometer. An improved smoke-wire system was developed to measure the structure of subsidiary vortices. The smoke emitting part (5 mm long) and non-emitting part (10 mm long) were placed alternately on a copper wire with a diameter of 0.1 mm in order to measure both the direction and the magnitude of the velocity. The smoke-wire was stretched horizontally across the convergence zone. The emitted smoke was illuminated by a stroboscope with the frequency of 7 Hz. A 35 mm still camera was installed at the top of the convection chamber looking down. A one-component hot-wire probe was installed a few mm below the smoke-wire and the output is recorded in order to monitor the flow situations near the smoke-wire. When the remote switch opened the shutter of the camera, the signal from the camera triggered the smoke-wire. The signal from the camera was also recorded together with hot-wire signal to indicate the timing and the length of the exposure. The height of the smoke-wire measurements were selected as 20, 10, 5 and

2 cm above the surface plate. The upward drift of the smoke caused by the convection due to the wire heating was approximately 5 cm/s in still air. With the sampling of the strobo light of 7 Hz, this causes the error of about 0.7 cm in the height of measurement.

Mean velocity field and the time variations of the velocity were measured by a hot-wire anemometer with two component probes (X-wire). Each probe had a diameter of 5 μ m and a length of 3 mm installed horizontally with the angle of 45 degrees to the tangential direction. The deviation of the flow direction from the tangential direction was measured as a function of the ratio of the output of two wires. The limit of the measurable angle with this method was about 30° from the tangential direction. Beyond this limit the disturbance from the wire supports prevents the accurate measurements. This measurement system also has a limit for existence of the vertical flow component. Under the particular condition indicated in the following section, the average horizontal velocity (V_h) is about 5 times as large as the vertical velocity W . The error in V_h caused by W component is approximately 2%. The calibration of the hot-wire anemometers was made in a small wind tunnel with an ultra-sonic anemometer as a reference anemometer. The calibration was supposed to be accurate down to a few cm/s. However, in the small velocity range less than 10 cm/s, the hot-wire anemometer can not hold its calibrated values for a long period. It was always necessary to make a calibration just before the measurements.

The hot-wire measurements were made at the radii of $r=10, 15, 20, 25, 30$ and 35 cm and at the heights of $z=2, 5, 10, 15$ and 20 cm. The measurement in the region closer to the center was omitted because the intensity of turbulence is large and beyond the limit of the hot-wire measurement. Each signal from two hot-wire amplifiers (KANOMAX Model 1010) was recorded on the magnetic tapes through a PCM recorder (TEAC PU-400). The signal was processed digitally using the pre-memorized hot-wire calibration curves by a computer. Three measurements were made

on different days. Most of the results shown in the following sections are the average of the three measurements.

Flow visualization was made with a mineral oil smoke generator (TEM System E). The generated smoke was introduced into the flow field from the center of the bottom plate.

3. Formation of the multiple vortices.

Various types of vortices are formed depending on the combination of the fan speed and the guide vane angle. These two variables combined with the apparatus configuration are organized into two parameters; the Reynolds number and the swirl ratio as defined in the previous section. The swirl ratio S was found to be an important parameter for the similarity of the vortex flow as shown by Davies-Jones (1973). For instance, the diameter of the vortex core generated in laboratories depends uniquely on S (Baker and Church, 1979; Mitsuta and Monji, 1984). The type of the vortex also depends on S . The type of the generated vortices in the present apparatus is shown as a function of Re and S in Fig. 2. When S is small, a narrow laminar vortex is formed. The increase of S causes a vortex breakdown followed by a turbulent two cell vortex, which has a downward motion in the axis surrounded by an upward motion. Further increase in S causes a splitting of vortex into multiple vortices. The number of the subsidiary vortices increases with S . The dependency of the vortex type on Re is also seen in Fig. 2, but it is not distinct except for the low Re region.

This result can be compared with that obtained by Church *et al.* (1979) in the rotating screen type simulator at Purdue University. Although the ranges of the Reynolds number in both experiments are different and therefore a comparison in a strict sense may be difficult, the variation of the vortex formation with the swirl ratio is similar in both simulators. This means that both the guide vane and the rotating screen method provide similar boundary conditions for the dynamic process of the vortex. However, different turbulent characteristics in the dif-

Fig. 2 The variation of the type of the vortex as a function of the Reynolds number and the swirl ratio. The boundary of the one cell and two cell structure is indicated by a thick solid curve. The area bounded by a dashed curve in the upper right corner is the region where the turbulence is too large to recognize any organized motion. The circles, triangles and other small symbols indicate the observed point.

ferent apparatus may result in the different nature for the multiple vortices. Leslie (1977) showed the effect of the surface roughness on the vortex splitting. His result indicates that the larger swirl ratio is required to cause vortex splitting when the surface boundary is rougher.

One particular condition $Re=3.2 \times 10^3$ and $S=2.3$ was chosen for the detailed analysis. This is the state of the multiple vortices with 3 subsidiary vortices. The photographs of the 3 subsidiary vortices at four heights taken from above are indicated in Fig. 3. The smoke-wire appears as a dashed line in these photographs. At $z=20$ cm, the multiple vortices are well recognized and each subsidiary vortices are clearly seen. At $z=5$ cm, the subsidiary vortices contains more turbulent components. Near the bottom surface, although the 3 subsidiary vortices are identifiable, the shape of the vortex is vague.

Fig. 3 Visualized 3 subsidiary vortices at 4 different heights, (a) $z=20$ cm (layer 15~25 cm), (b) $z=10$ cm (5~15 cm), (c) $z=5$ cm (2~8 cm) and (d) near the surface (0~2 cm). These 4 photographs were taken at different times. The smoke-wire which appears as dashed lines, is taken together to indicate the scale i.e., each white segment is 1 cm long and the mark + shows the apparatus center.

4. Structure of multiple vortices

Examples of the time variations of velocity measured by the hot-wire anemometer are indicated in Fig. 4. The variations with the frequency about $f=0.8/s$ is predominant through most of the field. This frequency is confirmed by the flow visualization as that associated with the rotation of the 3 subsidiary vortices around the center of the parent systems. However, at some locations especially near the bottom, a frequency slightly larger than $f=0.2/s$ (about one third of the frequency in the higher levels) is more predominant. This means that the flow energy is not equally distributed among the 3 subsidiary vortices near the surface.

The radial distribution of the mean tangential velocity measured with the hot-wire anemometer is shown in Fig. 5, and also in the r - z plane in Fig. 6. We see that the mean flow field is apparently two dimensional except for the layer several cm above the ground. For the given swirl ratio ($S=2.3$) the ratio of the radius of the maximum velocity (r_m) and the radius of the updraft hole (R) is about 0.7 at the height greater than 10 cm, which is approximately equal to that obtained in the experiment by Baker and Church (1979).

The velocity field of the subsidiary vortices is measured with the smoke-wire. Fig. 7 is the velocity vector distribution at 4 heights. Only 1/3 of the whole horizontal measuring area is indicated. In this figure the center of the subsidiary vortex is fixed in the middle of the sector, and the position of the smoke-wire changes relatively to the subsidiary vortex center. This position is determined by the timing pulse from the smoke-wire operation recorded with the periodic variation of the hot-wire signal as mentioned in Section 2. In Fig. 7(a) we see that the velocity at both end of the sector varies almost linearly with radius, but it is distorted remarkably in the middle of the area indicating the influence of the subsidiary vortex. To see the structure of the subsidiary vortex more clearly, the radial mean of the angular velocity for individual smoke-wire measurement multiplies

Fig. 4 The examples of the velocity variations measured with the two component hot-wire anemometer. The left figure is the radial component and the right figure the tangential component.

Fig. 5 The radial distribution of the mean tangential velocity.

Fig. 6 The distribution of the mean tangential velocity (cm/s) on r - z plane.

by the radial coordinates is subtracted and shown in Fig. 7(b). In the upper levels ($z=20$ or 10 cm), the deviations from the mean clearly show the wind field associated with

the subsidiary vortex. For the lower levels ($z=5$ or 2 cm), however, the flow field is more disorganized and it is not easy to recognize the subsidiary vortex. The dashed circles in Fig. 7(b) indicate the approximate position of the smoke filled core of the subsidiary vortices appeared in Fig. 3.

For the height of $z=20$ cm, three cases in which the smoke-wire operated just when the center of a subsidiary vortex was at the wire are averaged and shown in Fig. 8. The subsidiary vortex center defined as the middle point of the positive and the negative peak of the tangential component of the subsidiary vortex is located at around $r=20$ cm (Fig. 8(b)). The radial component also changes sign around this point from positive to negative as r increases (Fig. 8(a)). Therefore, the flow is convergent in the subsidiary vortices and may be acting as a suction spot as suggested by Fujita, although further research near the bottom surface is required. By comparing Fig. 8(b) and Fig. 5, we see the followings: The rotation of the subsidiary vortex near its center is approximately a solid body rotation with angular velocity about 25% larger than that of the parent vortex. The core size of the subsidiary vortex is about 1/5 of that of the parent vortex. The outer maximum of the subsidiary vortex is located at the same radial position as that of the

Fig. 7 (a) Velocity vector field of the flow associated with the subsidiary vortex measured with the smoke-wire at 4 levels. (b) The radially averaged angular velocity subtracted. The dashed circles indicate approximate position of the visualized core of the subsidiary vortex in Fig. 3.

parent vortex. The maximum tangential velocity of the subsidiary vortex (about 10 cm/s) is approximately about $1/4$ of that of the parent vortex (about 40 cm/s). This means that the instantaneous peak gust of the multiple vortices is about 25% larger

than that of a single vortex. This also means that about $1/2$ of the maximum velocity variation in the multiple vortices is due to the passage of the subsidiary vortices.

For lower levels, the flow visualization indicates that the location of the subsidiary

Fig. 8 The radial distribution of the velocity components of the subsidiary vortex measured at $z=20$ cm by the smoke-wire; the radial component (upper figure), the tangential component (lower figure).

vortex is closer to the center and the core size is smaller. The location of the center of the subsidiary vortex is approximately $4/5$ the parent vortex core radius in the all measured layers. As examples are shown in Fig. 4, velocity fluctuations associated with the subsidiary vortices vary with height. The largest fluctuations are seen at around $z=5$ cm. At this level, the fluctuations associated with the subsidiary vortices occupy more than $1/3$ of the velocity of the parent vortex.

5. Interaction of the subsidiary vortex with the mean field

The visualized subsidiary vortex rotates around the center of the parent vortex by keeping its identity. However, since the mean field varies with height as shown in Fig. 5, the propagating velocity of the subsidiary vortices relative to the mean tangential velocity varies with height. The propagating angular velocity of the 3 subsidiary vortices under the present condition is 1.7 rad/s, which makes the propagating tangential velocity at $r=20$ cm (the approximate passage radius of

the subsidiary vortices) is 34 cm/s. This is approximately 10% less than the mean tangential velocity at this radius in the layer above $z=10$ cm. However, in the layer near the surface, it is about 30% less. Therefore, at any height the subsidiary vortices travel slower than the mean flow. The stability theories of rotating flow discussed by many authors (e.g. Snow, 1972 or Rotunno, 1984), also predict the slower phase speed of the disturbances compared to the basic flow. For example, according to the simplest theory by Kelvin (see Rotunno, 1984), the ratio of the propagation velocity of the subsidiary vortex to that of mean state is $2/3$ in case of wave number 3. However, theories including the propagation of the subsidiary vortex in a mean flow with a vertical shear as the present case have not been developed.

The radial flux of tangential momentum is examined with the hot-wire anemometers. The distribution of the correlation between the radial (u) and the tangential (v) velocity component $\overline{u'v'}$ in the r - z plane is indicated in Fig. 9. The radial distributions of the correlation $\overline{u'v'}$ for $z > 10$ cm are similar at all levels. It has positive values (outward flux) both near the center ($r < 20$ cm) and the edge of the parent vortex ($r > 30$ cm) and negative values (inward flux) in between. The comparison of this distribution with the velocity distribution of the subsidiary vortex in Fig. 8 suggests that the subsidiary vortices transport momentum toward the center of rotation in

Fig. 9 The distribution of $\overline{u'v'}$ on the r - z plane. The shaded areas indicate the negative values (poleward transport). Unit of the number in the figure is $(\text{cm/s})^2$.

Fig. 10 The cospectra between u and v at different heights at $r=20$ cm.

these levels. In order to clarify this, the cospectra between u and v are computed. The examples of cospectra at $r=20$ cm are indicated for various height in Fig. 10. The values of the cospectra for the range $z>10$ cm have a distinguished negative peak at around the frequency associated with the passage of the subsidiary vortices. The momentum fluxes in the levels lower than 5 cm indicate quite different distribution compared to those at upper levels. The value of $\overline{u'v'}$ is positive for the subsidiary vortex core area (region between the peak of sub-vortex) at these levels.

The distribution of the flux divergence of the eddy momentum flux $\partial\overline{u'v'}/\partial r + 2\overline{u'v'}/r$ is indicated in Fig. 11. There is a flux divergence around $r\sim 30$ cm and flux convergence between the radius of 15 and 25 cm in the upper layers. This means that the subsidiary vortices obtain momentum from the mean field in the core region of the subsidiary vortex in these layers. Near the $z=5$ cm level, however, the situation is opposite. The subsidiary vortices act to obtain momentum from the mean field in the core region of the subsidiary vortices and add the momentum to the mean in the maximum velocity region of the mean field.

In the past, there was only one laboratory vortex measurement in which the momentum flux was measured. In the Ward's simulator, with $S=0.09$, Leslie (1979) obtained the results that the momentum flux ($\overline{u'v'}$) is negative (inward) throughout the measuring range and

Fig. 11 The distribution of the flux divergence $\partial\overline{u'v'}/\partial r + 2\overline{u'v'}/r$ on the r - z plane. The region of negative value (convergence) is indicated with hatch. The unit of the number is cm/s^2 .

the flux is convergent in the outer area of the vortex core near the surface ($z=1.4$ cm). Although his swirl ratio is much smaller than the present experiment and there was no vortex splitting, the turbulent eddies are found to add momentum to the mean flow in some region also in his experiment. Lilly (1969) examined the mean momentum field of Hoekner's (1960) analysis of Dallas Tornado, and found near the tangential velocity peak, above the lowest 30 m and also in the overall average, turbulent flux is adding momentum to the mean flow in the boundary layer, and concluded that this phenomena must be attributed to the effects of radial turbulent fluxes. He further suggested the possibility of asymmetries of the circulation must exist. In the present experiment, the inward momentum flux by subsidiary eddies might mean distortion of eddies in such a way that the central side of eddies proceeds ahead of the outer side. The asymmetry in the subsidiary vortex is apparent in the measurement by the smoke-wire as indicated by the top right figure of Fig. 7. However, it was not possible to visualize distinguished asymmetries by the smoke in Fig. 3. More adequate flow visualization is required for this purpose.

In this research, we only discussed the horizontal transport of momentum, since the flow is nearly two dimensional except for the layer near the ground. In order to discuss the momentum balance in the layer near

the surface, we have to consider the flow three dimensionally including the vertical transport. However, the structure of the surface boundary layer of the multiple vortices is too complex to deal with the present technique.

6. Conclusion

A laboratory experiment to investigate the structure of the multiple vortices in small scale and mesoscale atmospheric vortices is described. A guide vane type simulator is proved to be capable of producing multiple vortices as well as the rotating screen type simulator developed before. The conditions for the various type, i.e., one cell, two cell or multiple vortices is expressed as a function of the Reynolds number and the swirl ratio. The swirl ratio is more important parameter compared to the Reynolds number to describe the type of the vortices.

A flow condition with 3 subsidiary vortices is chosen for a close examination. An improved smoke-wire was used to measure the velocity field of the subsidiary vortices. The mean field and the velocity fluctuations were measured with a two element hot-wire anemometer. The summary of the structure of the multiple vortices in the layer near $z=20$ cm where they are well organized is as follows: The core size of the subsidiary vortices is approximately $1/5$ of that of the parent vortex.

The maximum tangential velocity of the subsidiary vortices is about $1/4$ of that of the parent vortex. This means that about $1/2$ of the maximum velocity variation in the multiple vortex is caused by the passage of the subsidiary vortices.

The structure of the subsidiary vortex varies with height. The turbulence is more predominant near the surface, and it was difficult to obtain the velocity distribution with the smoke-wire there. The fluctuations associated with the subsidiary vortices is more than $1/3$ of the velocity of the parent vortex near the surface. The flow visualization suggest that the location of the subsidiary vortex is closer to the center and the core size is smaller at the lower levels. The location of the center of the subsidiary vortex is approxi-

mately $4/5$ of the parent vortex core radius.

The translational velocity of the subsidiary vortex is slightly less than (about 90% of) the mean tangential velocity of the parent vortex in the layer far from the ground ($z>5$ cm). But, in the layer close to the ground where the mean tangential velocity is larger than the upper levels, the propagation speed of the subsidiary vortices is about 70% of the mean flow.

The radial transport of the tangential momentum is down the velocity gradient around the region of the maximum of mean flow except for the layer near the ground. The subsidiary vortices transport momentum from the peak toward the center of the parent vortex. The divergence of the radial flux of momentum is positive for the velocity maximum region of the parent vortices in the upper layers. However, near the ground surface, there are regions where the momentum is transported against the velocity gradient and also the region where the momentum of the parent vortex is fed by the subsidiary vortices. Further research on the boundary layer of the vortex flow including the vertical momentum flux is required to understand these transport mechanisms near the surface.

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複合渦の構造に関する室内実験

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大気中の中小規模の渦中に形成される複合渦の構造を室内実験によって調べた。案内羽根を用いて回転を与える実験装置を開発し、その中で複合渦の発生する条件を求めた。次に、3個の副次渦が発生する条件を選びその構造をスモークワイヤーと2成分の熱線風速計を用いて調べた。測定によって副次渦の渦核の大きさ、発生位置、風速分布その他の性質を求めて副次渦の構造とその主渦との関係を明らかにした。副次渦の移動速度は地面から離れた所では平均流速とほぼ同じか又は少し小さい程度であるが、地面近くでは平均流が上層より大きいので副次渦のほうが平均流より遅い速度で移動していることが分かった。流速の水平2成分の変動間のコスペクトルの計算によって大部分の領域で副次渦が主渦の最大風速域から中心の方向に運動量を輸送しているが、しかし地面近くではその逆も起こっており輸送形態は単純ではない事が分かった。