ROLL VORTICES IN THE PLANETARY BOUNDARY LAYER: A REVIEW *

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Abstract. Roll vortices may be loosely defined as quasi two-dimensional organized large eddies with their horizontal axis extending through the whole planetary boundary layer (PBL). Their indirect manifestation is most obvious in so-called cloud streets as can be seen in numerous satellite pictures. Although this phenomenon has been known for more than twenty years and has been treated in a review by one of us (R.A.Brown) in 1980, there has been a recent resurgence in interest and information. The interest in ocean/land-atmosphere interactions in the context of climate modeling has led to detailed observational and modeling efforts on this problem. The presence of rolls can have a large impact on flux modelling in the PBL. Hence, we shall review recent advances in our understanding of organized large eddies in the PBL and on their role in vertical transport of momentum, heat, moisture and chemical trace substances within the lowest part of the atmosphere.

1. Introduction

It is time for another review of instabilities, secondary flows, coherent structures, helical vortices, large eddies or rolls in the planetary boundary layer (PBL). The proliferation of terminology testifies to the common-place study of these phenomena. To save space, we shall refer to them generally as rolls or roll vortices, except to make a point.

The title of our review might suggest that we are treating any kind of organized roll vortices larger than the usual small-scale turbulence. Although research on "large eddies" or "coherent structures" is quite popular at present in turbulent boundary layers (see Liu, 1989 or Robinson, 1991 for recent reviews on the subject in engineering flows), we shall restrict our paper to horizontal roll vortices extending throughout the whole PBL). This kind of vortex can be best visualized by so-called cloud streets as in Figure 1, which have become common knowledge due to high resolution satellite pictures available on a routine basis (see Scorer 1986, 1990 for a collection).

The interpretation of this special type of cloud pattern can be easily achieved by assuming the existence of counter-rotating vortex rolls with axes approximately in the direction of the mean wind, as displayed schematically in Figure 2. Clouds

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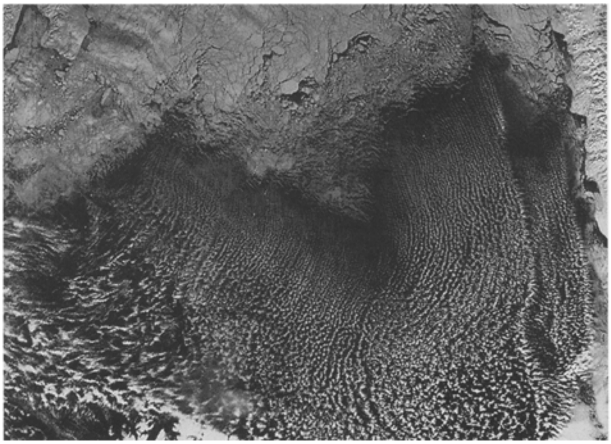

Fig. 1. Satellite picture of organized boundary-layer clouds during a cold air outbreak over the Barents Sea. NOAA 7, AVHRR, 6.4.1988.

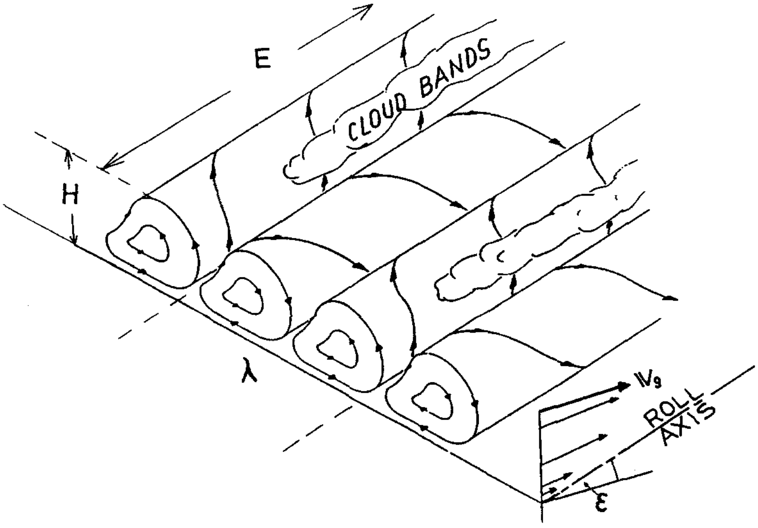

Fig. 2. Schematic of organized large eddies (horizontal roll vortices) in the PBL.

are formed above the updraft parts of the roll circulations; cloud-free areas are due to sinking motions. These facts have been known by glider pilots for a long time, as they used this special kind of upward motion organized in streets for long-distances soaring. An account of early flight reports and photographs of cloud streets taken from airplanes are given in Küttner (1959). These eddies in the PBL have been reviewed by Brown (1980). During the period 1970-1980 roll vortices were considered mainly as a good example of dynamical and thermal instabilities in geophysical flows. However, in the last decade, one has become aware that this special type of organized large eddies plays an important role in the vertical transport of momentum, heat, moisture and air pollutants within the PBL. This observation has also become evident in the molecular turbulent regime (Robinson, 1991). This has triggered renewed effort in investigating roll-like eddies with sophisticated instrumentation (e.g., Doppler radar, aircraft measurements) and numerical simulations. For this reason, we thought it useful to present information on the recent development of this kind of boundary-layer research. As most of the work performed before 1980 has already been covered by Brown (1980), we shall not include all earlier papers.

Another recent review on this subject has been published by Mikhaylova and Ordanovich (1991). These authors also provide information about research on coherent structures in the PBL performed in the former USSR, which has not been covered in our review.

Organized roll vortices are also observed frequently in the oceanic boundary layer, where they are known as Langmuir circulations. As we are focusing on atmospheric roll vortices, we might mention the review article by Leibovich (1983) and recent work on Langmuir circulations by Faller and Auer (1987) and Thorpe (1992) for readers interested in the oceanic counterpart.

2. Observations

2.1. OBSERVATIONAL METHODS

2.1.1. Satellite Observations

Cloud streets. Evidence on roll vortices has become widely available from numerous satellite pictures like the one displayed in Figure 1. The most impressive formation of cloud streets is obtained during so-called cold air outbreaks over the oceans. Satellite pictures of this type of situation have been used to evaluate the vertical and horizontal extent of cloud streets (e.g., Streten, 1975; Walter, 1980; Miura, 1986). Cloud streets are also common over land, but their streamwise extent (see Figure 2) is usually limited due to orographic effects. Observations of cloud streets over land have been analysed from satellite pictures by Küttner (1971), Weston (1980) and Müller *et al.* (1985). Prior to the satellite era, cloud streets were observed intensively by glider pilots and powered aircrafts. Documentation of cloud street pictures from these observational platforms can be found in Küttner (1959, 1971).

The results of these investigations can be summarized as follows (see also Figure 2):

vertical extent	H	1–2 km
wavelength	λ	2–20 km
aspect ratio	λ/H	2–15
downstream extent	E	10–1000 km
orientation of roll axis to mean wind	ε	−20° to +30°
life time	τ	1–72 h

There is a fairly wide range of parameters, especially for the wavelength and the aspect ratio. We shall not discuss all of these observations in detail but refer instead to the observations in Kelly (1984) and Christian and Wakimoto (1989).

The cloud streets are oriented more or less in the downwind direction. Much effort has been put into the exact evaluation of the angle between the roll axis and either geostrophic or mean boundary-layer wind, but the scatter is quite large. Much more discussion has been devoted recently to the observations of large aspect ratios (>10) which cannot be explained by the linear dynamic or the thermal instability mechanisms. We shall postpone this discussion to Section 3.1.

Other observations. Remotely sensed synthetic aperture radar (SAR) pictures of the ocean surface have long revealed linear patterns associated with atmospheric rolls (Thompson *et al.*, 1983). Gerling (1986) has spectrally analyzed the wavelength information obtained from a satellite SAR. He found a consistent peak in surface wave spectra at wavelengths of about 2 km. He assumed that this organization was imposed by atmospheric rolls and used the lines to assign wind directions to SAR implied wind speeds. These compared well with surface observations and satellite scatterometer wind vectors. It seems evident that the 2 km scale is atmospherically forced. The alternating convergence/divergence zones must impose sufficient perturbation on the surface stress field to augment or suppress the short gravity and capillary waves (cm-scale) to which the microwave radar responds. These observations in cloud-street-free regimes demonstrate the common occurence of rolls whose effects reach the surface.

There are also observations of crown fires leading to three-crown streets, which are of similar appearance as cloud-streets in aerial photographs (Haines, 1982). These streets are supposed to be formed by horizontal vortex rolls induced by surface heating (due to the fire) and wind shear, as is discussed for the case of cloud streets in Section 3.3.

2.1.2. *Radar and Lidar Observations*

Although cloud streets indicate the existence of large roll-like eddies in the PBL, quantitative measurements have only recently become accurate enough to warrant detailed examinations. In particular, associated secondary flow wind field measurements have become available due to single and dual doppler RADAR observations. These enable the detection of roll vortices even in the cloud-free PBL, as found in the observations of Kropfli and Kohn (1978), Reinking *et al.* (1981) or Rabin *et al.* (1982). With convective clouds present, RADAR and visual observation can

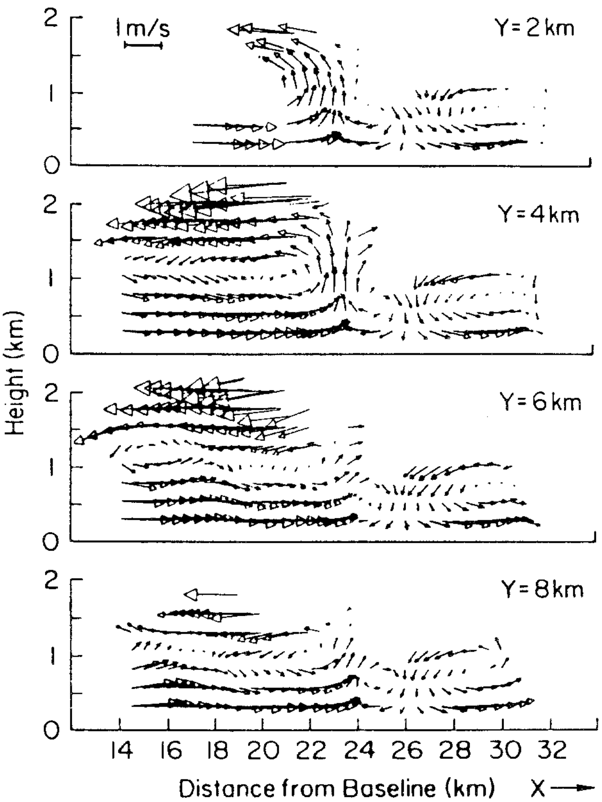

Fig. 3. Radar observations of roll circulations in the cloudless boundary layer (after Kropfli and Kohn, 1978).

be combined to evaluate secondary circulations as related to cloud street location. Examples of these studies are reported by Kelly (1982, 1984), Eymard (1985), Eymard and Weil (1988) and Christian and Wakimoto (1989). Roll circulations have even been observed during rain and snow with total cloud coverage (Puhakka and Saarikivi, 1986). An example of the wind field in a cross-section of a roll-like structure in the convective boundary-layer is given in Figure 3 (adapted from Kropfli and Kohn, 1978). In recent field investigations, organized roll vortices have also been observed by means of LIDAR instruments (Melfi *et al.*, 1985; Atlas *et al.*, 1986).

2.1.3. *Tower and Aircraft Observations*

Measurements of wind speed, temperature and moisture within boundary-layer rolls have been obtained from instrumented towers (e.g., LeMone 1973, 1976; Smedman, 1991). But as the height of these towers is usually much less than the PBL height, only the lower part of organized roll circulations can be captured. Also, as most often only one instrumented tower is available, one has to infer

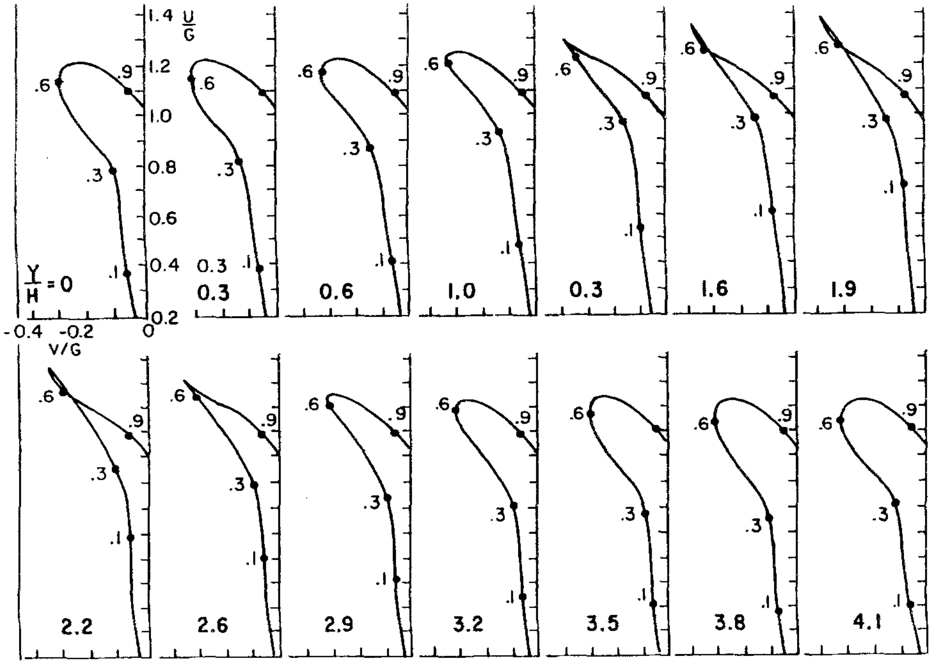

Fig. 4. Hodographs of the horizontal wind at different lateral positions in a PBL containing roll vortices (after Brown, 1970).

the structure of boundary-layer rolls by either additional satellite or ground-based cloud pictures or from spectral analysis of the data. In this case, one must assume the existence of quasi two-dimensional roll circulations. A point measurement can be skewed by the fact that rolls may drift past a point at various phase velocities, generally depending on stratification. In fact, this phase velocity of the rolls can reach zero for rolls driven primarily by convection (Brown, 1972). In this case, a point measurement can never resolve the rolls, or the mean wind profile, because only one of the velocity hodographs shown in Figure 4 would be observed.

In order to overcome these interpretation problems for horizontally non-homogeneous flows, it has become common in PBL research to use instrumented aircraft in order to cover larger horizontal areas. The field experiments including aircraft measurements have significantly increased our quantitative knowledge about the structure of large PBL eddies. Among these studies we mention the papers of Pennell and LeMone (1974), LeMone and Pennell (1976), Grossmann (1982), Walter and Overland (1984), Walter (1986), Atlas *et al.* (1986), Hein and Brown (1988), Chou and Ferguson (1991) and Martin and Bakan (1991).

Aircraft observations have also been evaluated with respect to small-scale organized structures (plumes, thermals) in the convective boundary layer by Williams and Hacker (1992).

2.1.4. Field Experiments

Whereas the earlier studies on roll vortices were more or less due to activities of single persons or groups, the need for data from different vertical levels over large horizontal extent in the PBL has led to several large field experiments. Some of those field campaigns were devoted in part to the investigation of horizontal roll vortices. Over the oceans, these include the experiments BOMEX (Grossmann, 1982), MIZEX (Walter and Overland, 1984), MASEX (Chou *et al.*, 1986), KONTUR (Brümmer *et al.*, 1985) and GALE (Chou and Ferguson, 1991). Over land the experiments PHOENIX II (Young, 1988; Schneider and Lilly, 1990) or COP-T 81 (Eymard and Weil, 1988) might be mentioned. In these field experiments large amounts of data on organized structures in the PBL have been gathered. This has especially improved the knowledge of the relative importance of rolls to PBL structure, mixing and fluxes. It has become apparent that rolls are ubiquitous in favorable situations, as discussed below, and cloud streets are simply a fortuitous flow visualization phenomenon. The rolls play a significant role in mixing, flux transport and entrainment processes in the PBL.

2.2. OBSERVED STRUCTURE

One of the important questions concerning rolls is: how often, and under what circumstances, are rolls found? Laboratory observations find rolls for neutral stratification and convection with shear. Theory suggests that rolls occur for all convection regimes in the presence of very little shear, and for the rotating frame of reference, for neutral and even slightly stable stratification. However, nearly all observations and field studies have been performed during cold air outbreaks over the sea or in the daytime PBL over land. This might imply that these large eddies are related to unstable stratification and hence to convective instabilities. As a measure of PBL stratification, the parameter z_i/L is usually evaluated, where z_i is the inversion height and L the Monin-Obukhov length (see Equation (12)). Deardorff (1972) and Grossmann (1982) related types of thermal convection to z_i/L as a stratification parameter with negative sign indicating thermal instability. They found that for $z_i/L \gtrsim -5$, convection might be found in the form of rolls, whereas three-dimensional convection cells will exist for $z_i/L \lesssim -25$ with some mixed type of organized convection in between.

As z_i/L is usually less negative for moderate winds and moderate surface heating and more negative for low winds and strong heating, it might be loosely said that cloud streets (roll vortices) will be observed for moderate unstable stratification. Indeed, evaluation of z_i/L for some of the observations quoted above gave $z_i/L \approx$ -6 to -15 for roll-like vortices. This has led to the suggestion that these rolls are always due to the interaction of thermal convection with boundary-layer shear flow. But in some cases, vortex rolls have also been observed for near-neutral stratification, $z_i/L \approx$ -2 say, e.g., Walter and Overland (1984) or Brümmer (1985). In these cases, roll vortices are assumed to be due to the so-called inflection-point

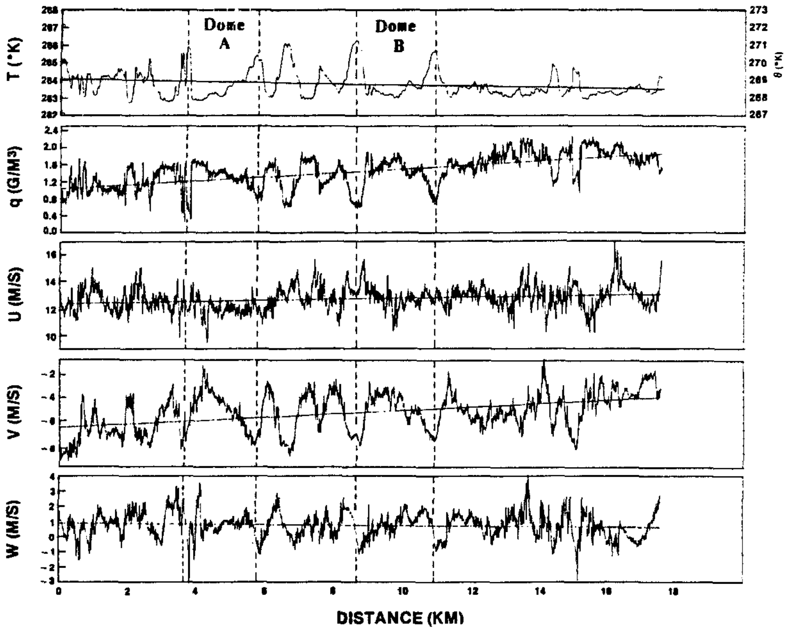

Fig. 5. Aircraft observations of the boundary layer at 770 m above sea level during the MASEX experiment. Flight leg is perpendicular to the mean wind (after Atlas *et al.*, 1986).

instability, which can operate whenever Ekman layer turning is imposed on the PBL, even under neutral stratification. These different types of instability will be discussed in Section 3.2.

Even without considering the physical mechanism of vortex roll development, it is evident from the observations that this type of large eddy routinely develops in an unstably stratified PBL which is heated at the surface. Hence, vertical motions of roll circulation must transport heat (and moisture) from the surface layer to the top of the PBL. One of the major aims of all experimental investigations is to partition the vertical fluxes in the PBL due to small-scale turbulence and organized large eddies (this is also true for numerical models which resolve large eddies explicitely, as will be discussed in section 4.1). The partitioning of fluxes (and variances) due to different scales of motion is not an easy task but might be performed by spectral analysis of the data or by conditional sampling methods (e.g., Chou and Zimmermann, 1989).

As an example, we shall present some results from aircraft measurements during cold air outbreaks over the marine atmospheric boundary layer, where the flight legs were perpendicular to the mean wind. Figure 5 shows data from the MASEX experiment (Atlas *et al.*, 1986) obtained near the inversion base at 770 m height. Periodic variations in temperature, moisture and wind components can be clearly seen, with wavelength between 500 m and 2 km. The power density spectra of the velocity components in Figure 6 also show several peaks which are related to these

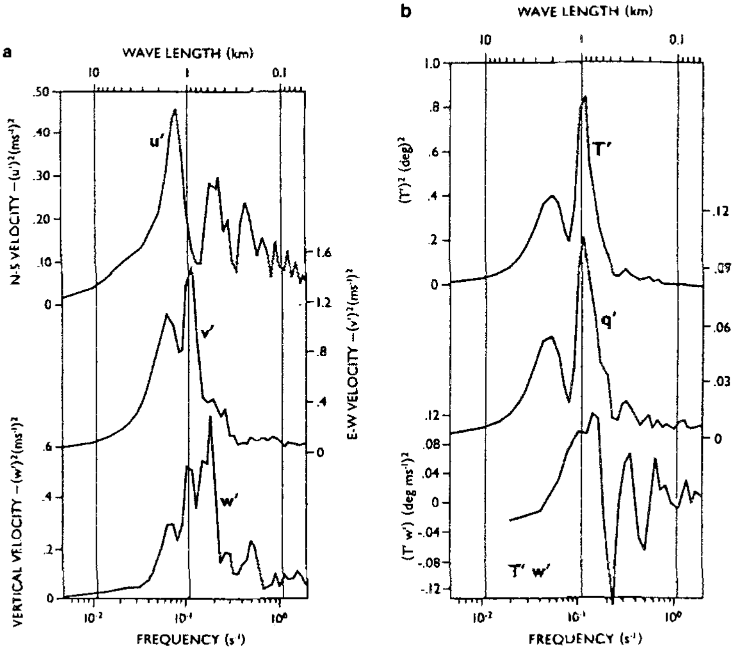

Fig. 6. Power spectra of wind, temperature, moisture and heat flux for the flight data shown in Figure 5.

distinct wavelengths. This kind of spectra is typical for all aircraft observations in convective boundary layers during cold air outbreaks (see references cited above). Although a roll-scale signal or the larger wavelength is clearly detectable, there are also contributions from smaller scale variances of wind, temperature and moisture fields. We might note that prior to the compaigns of Brown and Katz in the Arctic Ice Dynamics Joint Experiment (AIDJEX) and LeMone and Pennell, the low frequency signal of the rolls was not sought. In fact, it was routinely filtered out.

The mean vertical fluxes of momentum, heat and moisture can be attributed to vertical motions of different scales. This is nicely illustrated for the kinematic heat flux $\overline{w'\theta'}$ in Figure 7, which was obtained through bivariate conditional sampling of aircraft measurements during the GALE experiment by Chou and Zimmermann (1989). The different scales were attributed to small-scale turbulence (λ <200 m), to thermal plumes ($\lambda \approx$ 200 m–2 km) and to roll vortices ($\lambda > 2$ km). As can be seen from Figure 7, small-scale turbulence is more important in the surface layer, whereas the plume scale is effective throughout the lower half of the PBL. Roll vortices seem to contribute in the middle and upper layer of the PBL, although there is much scatter for the heat flux in these scales. These observational findings might be compared to results from numerical models (Figure 9), where partitioning of vertical fluxes due to small-scale (subgrid) turbulence and organized large-scale motions can also be found.

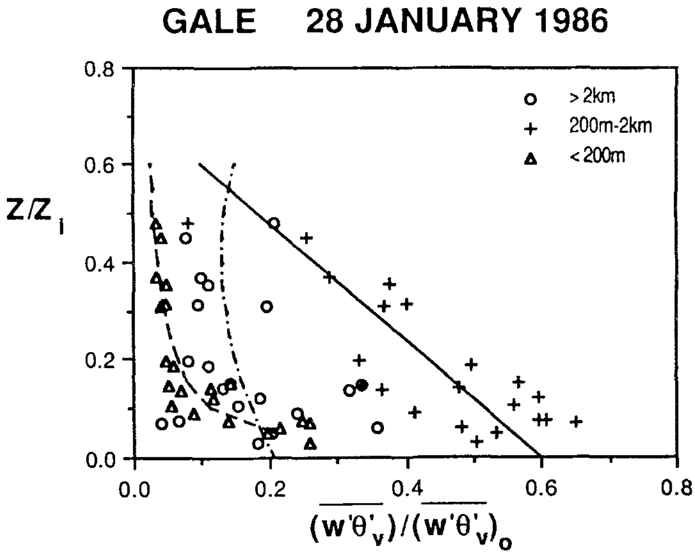

Fig. 7. Partitioning of mean vertical heat flux due to different scales of motion during the GALE experiment (after Chou and Zimmermann, 1989).

2.3. SUMMARY

Various types of data analysis have led to the picture that although organized cloud streets and hence roll vortices are clearly formed during cold air outbreaks over the oceans, they are only part of a multi-scale process in the PBL which includes surface-layer vortices, roll vortices, thermals and plumes. The last mentioned kind of organized structure has been discussed in some detail for the atmospheric surface layer by Wilczak and Tilman (1980), Wilczak and Businger (1984), Schols (1984) and Schols *et al.* (1985) and for the convective boundary layer by Williams and Hacker (1992). The roll-vortices (roll-like large eddies) are superimposed on these smaller scale structures and hence might be responsible for organizing thermal plumes into street-like features. One indication of this kind of scale-interaction might be found in all close-ups of satellite pictures of cloud streets, where individual clouds seem to be organized like "pearls on a string".

For these reasons, a single vortex-roll signal, as might be expected from theoretical considerations (see Section 3), will not often be found in an actual PBL. Instead, roll vortices are a part of a multi-scale vortex phenomenon, as discussed by Walter and Overland (1984), Hein and Brown (1988) and Chou and Ferguson (1991).

3. Theoretical Aspects

In the following we treat only mechanisms leading to quasi two-dimensional roll vortices in the PBL. As already discussed in Brown (1980), three effects are supposed to be responsible for such vortices: inflection-point instabilities, parallel instabilities and thermal instabilities.

From observations, it appears that the structures of rolls produced by dynamic and by convective instability are quite similar. Their wavelength is nearly the same, but their orientation with respect to the mean wind may vary by up to 30° and the intensity will change with source energy. The finite perturbation dynamic solution for the PBL includes the effects of stratification on the roll strength and orientation (Brown, 1972). Observations and theory also show that strong finite perturbations in the PBL can force very long waves ($\lambda \approx 15$ km) to establish an equilibrium solution (Mourad and Brown, 1990).

Before discussing these instability mechanisms in some detail, we give the basic underlying equations. Assuming horizontal homogeneity in the direction of the roll-axis (denoted by the x-coordinate), these may be written using the Boussinesq-approximation and first-order closure K-theory as follows (e.g., see Brown, 1991):

$$\frac{\partial u}{\partial t} + \vec{v}\cdot\vec{\nabla}u - f(v - v_g) + f^* w \cos\phi = \vec{\nabla}\cdot K_m \vec{\nabla}u \tag{1}$$

$$\frac{\partial v}{\partial t} + \vec{v}\cdot\vec{\nabla}v + f(u - u_g) - f^* w \sin\phi = -\frac{1}{\varrho_0}\frac{\partial p}{\partial y} + \vec{\nabla}\cdot K_m \vec{\nabla}v \tag{2}$$

$$\begin{aligned}\frac{\partial w}{\partial t} + \vec{v}\cdot\vec{\nabla}w + f^* v \sin\phi - f^* u \cos\phi &= \frac{1}{\varrho_0}\frac{\partial p}{\partial z} + \vec{\nabla}\cdot K_m \vec{\nabla}w + \\ &\quad + \frac{g}{\Theta_0}(\Theta - \Theta_0)\end{aligned} \tag{3}$$

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4}$$

$$\frac{\partial \theta}{\partial t} + \vec{v}\cdot\vec{\nabla}\Theta = \frac{\partial}{\partial y}K_h\frac{\partial \Theta}{\partial y} + \frac{\partial}{\partial z}K_h\frac{\partial \Theta}{\partial z} \tag{5}$$

where p is the small-scale pressure perturbation whereas the synoptic pressure gradient has been included as the geostrophic wind (u_g, v_g). The Coriolis terms $f(= 2\Omega \sin\varphi)$ and f^* $(= 2\Omega\cos\varphi)$ have been retained here for further reference. ϕ is the angle between the east and the vortex axis (x-coordinate). K_m and K_h are the small-scale turbulent diffusivities for momentum and heat, to be discussed later. If effects of water vapor on static stability are important, as over the oceans, an additional budget equation for specific humidity is needed and use of the virtual potential temperature Θ_v in the buoyancy term in Equation (3) is appropriate.

Equations (2) and (3) can be combined to a vorticity equation

$$\frac{\partial \zeta}{\partial t} + \vec{v}\cdot\nabla\zeta = f\frac{\partial u}{\partial z} + f^*\frac{\partial u}{\partial y}\cos\phi + \frac{g}{\Theta_0}\frac{\partial \Theta}{\partial y} + \text{Friction} \tag{6}$$

with

$$\zeta = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z},$$

where velocity and vorticity may be linked through a stream function ψ by

$$v = \frac{\partial \psi}{\partial z}, w = -\frac{\partial \psi}{\partial y}, \zeta = \nabla^2 \psi. \quad (7)$$

Equation (6) contains all three instability mechanisms mentioned and will be discussed later.

3.1. INFLECTION-POINT INSTABILITY

Without any roll circulation, the basic state is a steady state equilibrium flow between pressure, Coriolis and frictional forces, which depends only on the vertical coordinate. It is actually a boundary-layer shear flow with the special feature of directional turning with height due to the Coriolis force. The most simple state (for constant viscosity K) is the well known barotropic Ekman-flow, which may serve here as an example:

$$u(z) = V_g[\cos\varepsilon - \exp^{-\hat{z}}\cos(\hat{z} - \varepsilon)] \quad (8)$$

$$v(z) = V_g[-\sin\varepsilon + \exp^{-\hat{z}}\sin(\hat{z} + \varepsilon)] \quad (9)$$

where $\hat{z} = z/D$ and $D = \sqrt{2K_m/f}$ is the Ekman-height. ε is the angle between the x-axis and the geostrophic wind V_g. Now the vorticity of the background flow is simply $\zeta = -\partial v/\partial z$ or

$$\zeta(z) = -(V_g/D)\exp^{-\hat{z}}[\cos(\hat{z} + \varepsilon) - \sin(\hat{z} + \varepsilon)]. \quad (10)$$

In all cases, this vorticity profile exhibits a maximum, the magnitude of which depends on the angle ε of the roll axis to the geostrophic wind. This extremum coincides with an inflection-point in the velocity profile $v(z)$. Now it has long been known that shear flows with vorticity extrema are unstable with respect to small perturbations (Drazin and Reid, 1981), although this is just a necessary condition. Indeed this kind of instability was already noted by Kelvin and Helmholtz a hundred years ago, with the additional complication of stratification.

The inflection-point instability related to PBL shear flow has been treated extensively in earlier papers e.g., Lilly (1966), Faller and Kaylor (1966), Etling (1971), Brown (1972), Asai and Nakasui (1973), which are reviewed in Brown (1980). These investigations have been performed for the classical Ekman layer (8), (9) and indeed gave instability and roll development, where the most unstable mode was about $\varepsilon = 14°$ to the left of the geostrophic wind in neutral stratification. Mathematical treatment was based on the so-called Orr-Sommerfeld equation (e.g., Drazin and Reid, 1981), a linearized form of vorticity equation (6), with the addition of a rotating frame of reference term. This instability was generalized by

Brown (1980) to any turning wind profile (e.g., the "thermal wind") with a vorticity maximum.

Linear stability analysis for more realistic PBL wind profiles including surface roughness and variable eddy viscosity have been performed by Etling and Wippermann (1975) and by Criminale and Spooner (1981). In contrast to the former investigators, the latter propose an instability of the viscous type (Tollmien-Schlichting) as the reason for vortex rolls in the turbulent Ekman Layer. Recent accounts on the same problem have used simple non-linear spectral models for finding roll-like instabilities (Chlond, 1985; Stensrud and Shirer, 1988; Haack and Shirer, 1992), but their results do not differ much from earlier work.

All investigations agree more or less that the most unstable mean wind profiles led to roll vortices with wavelength about three times the boundary-layer height, hence the aspect ratio (width to height) was 3:1. As this was about the same as observed from cloud streets, it was assumed that the inflectionp-point was the cause of large eddies in the PBL (Brown, 1980). Although today most researchers attribute the formation of large eddies to forcing by thermal instability (heating of the surface), the aspect of inflection-point instability is still discussed (Brown, 1972; Brümmer and Latif, 1985; Etling and Raasch, 1987). Although roll vortex development due to inflection-point instability was also clearly obtained in two-dimensional numerical models (see Section 3.2), recent three-dimensional simulations of the Ekman layer (Coleman *et al.*, 1990) and of the PBL (Mason and Thomson, 1987) did not yield organized rolls under neutral stratification. Hence this introduces the possibility that strictly two-dimensional theory is not applicable to the inflection-point problem in a rotating boundary layer. Another explanation might be that inflection-points are very weak in a turbulent boundary layer. There is also the question of whether the decreased resolution or domain size limitations of 3-D models can properly resolve the inflection-point instability in neutral stratification.

3.2. PARALLEL INSTABILITY

In a neutrally stratified Ekman boundary layer, a second instability mode was found by Lilly (1966), which he termed "parallel instability". This mode only appeared if the equation for the along-axis velocity component u (Equation 1) was coupled to the vorticity equation (6). The effect of variations in u is transmitted to the cross-flow vorticity by the term $f\partial u/\partial z$ and can therefore be effective only in a rotating flow.

The parallel instability mode appeared with an angle $\varepsilon = -15°$ towards the geostrophic wind and had a larger wavelength $\lambda = 6H$ than the inflection-point mode. It was found also in the theoretical investigations of Faller and Kaylor (1966), Etling (1971) and Gammelsrod (1975). It was effective only for very low Reynolds numbers (high viscosity) and the growth rate was much smaller than for the inflection-point mode at higher Reynolds numbers.

Although these two vortex modes (inflection-point and parallel instability) have also been found in laboratory experiments (Faller and Kaylor, 1967; Caldwell and von Atta, 1970), the existence of the parallel mode in the atmospheric boundary layer might not be easily verified. For comparison of these studies with the PBL one has to introduce an "effective turbulent Reynolds number", i.e., a Reynolds number based on a mean eddy viscosity instead of molecular viscosity as in laminar flows. Etling and Wippermann (1975) did not find any sign of the parallel instability mode when using wind profiles based on Rossby-number similarity. This may be due to the fact that a (turbulent) Reynolds number can not be artificially varied in real flows, as the eddy viscosity varies with the background (geostrophic) wind itself. Hence, low Reynolds numbers might not be realized in the natural PBL. Also the results of linear stability analysis indicate that growth of the parallel mode is quite slow compared to that of the inflection-point mode, and the latter might mask the effect of the parallel instability in real world flows.

Nevertheless, recent investigations by Shirer (1986) and Stensrud and Shirer (1988) have argued in favor of the parallel instability mode. It was also proposed for interpretation of field observations (Shirer and Brümmer, 1986). But this was only assumed for near neutrally stratified cases, where convective instability is not dominant. We might mention in passing that in atmospheric shear flows induced by thermal wind (i.e., horizontal temperature gradient), an instability related to the earth's rotation is well established, called "symmetric instability" (e.g., Bennetts and Hoskins, 1979; Emmanuel, 1979). This instability produces roll-like two-dimensional circulations with axes parallel to the mean shear, and Coriolis-forces play a major role in this phenomenon. But these roll circulations are of much larger horizontal extent ($\approx$ 100 km) than the PBL rolls.

Finally one short remark might be given on the influence of the horizontal component of the Coriolis parameter ($f^* = 2\Omega \cos \varphi$) on the instability. Although this effect is usually neglected in atmospheric flow problems, it has been investigated by Etling (1971), Mason and Thomson (1987) and in detail by Leibovich and Lele (1985) and Coleman *et al.* (1990). Results show that the horizontal Coriolis force supports inflection-point instability for northerly flows and reduces growth rates for southerly flows. Although the theoretical investigations clearly show this effect, it is somewhat doubtful whether this can be identified among other instability mechanisms in the available observations of the real PBL.

3.3. CONVECTIVE INSTABILITY

Roll vortices in the PBL are most often observed in cold air outbreaks over water or during daytime over land. This led to early suggestions (e.g., Küttner, 1971) that roll-like eddies are mainly a result of thermal instability due to warm surfaces. This so-called Rayleigh-Bénard instability is inherent in nearly all fluid systems with unstable density/temperature stratification and is the cause of most of the convective clouds in the atmosphere. There is considerable discussion on roll versus cellular modes of convection. We are not going to discuss thermal convection here in detail but rather refer to review articles by Krishnamurti (1975), Busse (1978), Agee

(1982) or van Delden (1985).

Here we shall deal only with roll-like convection in the PBL. From linear analysis it is known that convection rolls will orientate their longitudinal axis in the direction of mean shear in a vertical shear flow (e.g., Asai, 1970; Kelly, 1977). As one nearly always has wind shear in the PBL, it is natural to think of thermal instability as a main cause of observed atmospheric roll-vortices as shown by cloud streets. Indeed, in earlier investigations on the stability of the unstably stratified Ekman layer (Etling, 1971; Brown, 1972; Asai and Nakasui, 1973) it was found that initial perturbations occur with growth rates larger than for the neutral inflection-point and parallel models. These most unstable convective modes were oriented more or less in the direction of the geostrophic wind but their wavelength was smaller than for the other modes. The aspect ratio was about 2 compared to 3 for inflection-point and 6 for parallel instability. The same trend was found also in linear stability analysis for the unstably stratified PBL by Wippermann *et al.* (1978) and in the nonlinear spectral model approaches by Shirer (1986) and Chlond (1987).

But one should be cautious in comparing results from linear stability analysis with observed structures, as finite amplitude convection is also controlled by nonlinear effects (a comparison of linear stability analysis and nonlinear numerical simulations is given in Mason and Sykes, 1982).

Although investigations have used the Rayleigh number

$$Ra = \frac{g}{\theta}\frac{\Delta\theta H^3}{K_m K_h} \tag{11}$$

as a criterion for the onset of roll convection in theoretical analysis, the use of z_i/L with

$$\frac{z_i}{L} = -\frac{z_i \kappa g \overline{(w'\theta_v')_0}}{\overline{\theta_v} u_*^2} \tag{12}$$

is a much more common measure for real atmospheric observations. Here z_i denotes the inversion height and L is the Monin Obukhov length for the surface layer in standard notation (the virtual potential temperature θ_v used in (12) account for moisture effects on static stability, especially over the oceans). Observations of thermal convection have been classified with respect to z_i/L as discussed in Section 2, where the roll-regime was found in the slightly unstably stratified regime at $-25 < z_i/L < -5$. But as observations of wavelength and aspect ratios of cloud streets are rather scattered (see Section 2.1), it is not easy to deduce the underlying mechanism of roll development, especially for near-neutral stratification, with $z_i/L \approx -2$ say. Indeed, some attempts to calculate energy conversion rates for observed roll perturbations from field measurements (LeMone, 1976; Brümmer, 1985) or from numerical simulations (Chlond, 1992) show some competitive relation between inflection-point instability (mechanical energy transfer) and convective instability (thermal energy transfer) under near neutral conditions.

One special problem in the discussion of thermal versus inflection-point instability is the existence of a capping inversion at height z_i in the convective PBL (Gossard and Moninger, 1975). This is most often neglected in both the linear and nonlinear stability analyses for both convective and dynamic instability modes. This is a particular problem for the convective instability criterion based on the Rayleigh number (11). It has been shown by Brümmer and Latif (1985) and by Etling and Raasch (1987) that the inflection-point instability is suppressed if the height of the inflection-point is larger than 0.6 z_i. In this case, additional thermal forcing is necessary in order to sustain roll vortices in the PBL. These theoretical findings have some support from observational data by Müller *et al.* (1985).

Hence it currently appears that under most circumstances large roll eddies in the PBL are driven by thermal instabilities. The observed wavelength and aspect ratios can be much larger than predicted by linear theory, as was noted by most investigators (see Section 2.1). Therefore the physical reason for the formation of roll vortices in the PBL is still a matter of discussion and we shall touch on this matter below.

3.4. LARGE-ASPECT RATIOS

Although convective instability is most often attributed to roll vortex development in the PBL, there is some discrepancy between predictions of linear theory and observations, especially regarding the spacing of cloud streets. In contrast to an aspect ratio of about 2 predicted by theory, observed ratios are most often in the range 4–6 and have been observed up to 15, especially during cold air outbreaks over the oceans (Miura, 1986; Walter, 1986) or in tropical regions (LeMone and Meitin, 1984). Some summaries of observed aspect ratios for horizontal roll vortices can be found in Kelly (1984) or Christian and Waikimoto (1989).

These discrepancies between theory and observations have stimulated some discussion on the cause of large aspect ratios (i.e., long wave lengths). Among the proposed effects we mention: nonisotropy in diffusion coefficients; nonlinear wave interaction; latent heat release; gravity wave interaction; nonlinearity. Nonisotropy between horizontal and vertical diffusion coefficients K_x and K_z was proposed by Priestley (1962) to account for the large cell diameter of atmospheric thermal convection. These arguments have been extended by Sheu et al. (1980) and Ray (1986) through numerical simulation and linear theory. Qualitatively the aspect ratio of convective cells increases for increasing K_x/K_z. But as vertical eddy diffusivities of order 10 m^2 s^{-1} and greater have to be used in PBL flows, one may wonder how horizontal diffusivities can be much larger than vertical ones. Hence one may not favor nonisotropy of the eddy viscosity as the main cause of large aspect ratios of PBL roll vortices.

Large aspect ratios have been observed over pack ice and during cold air outbreaks over the oceans in the downstream part of cloud street development. This has led to the idea that large wavelengths are due to nonlinear scale interactions within the original small-scale convective region at the upwind part of those out-

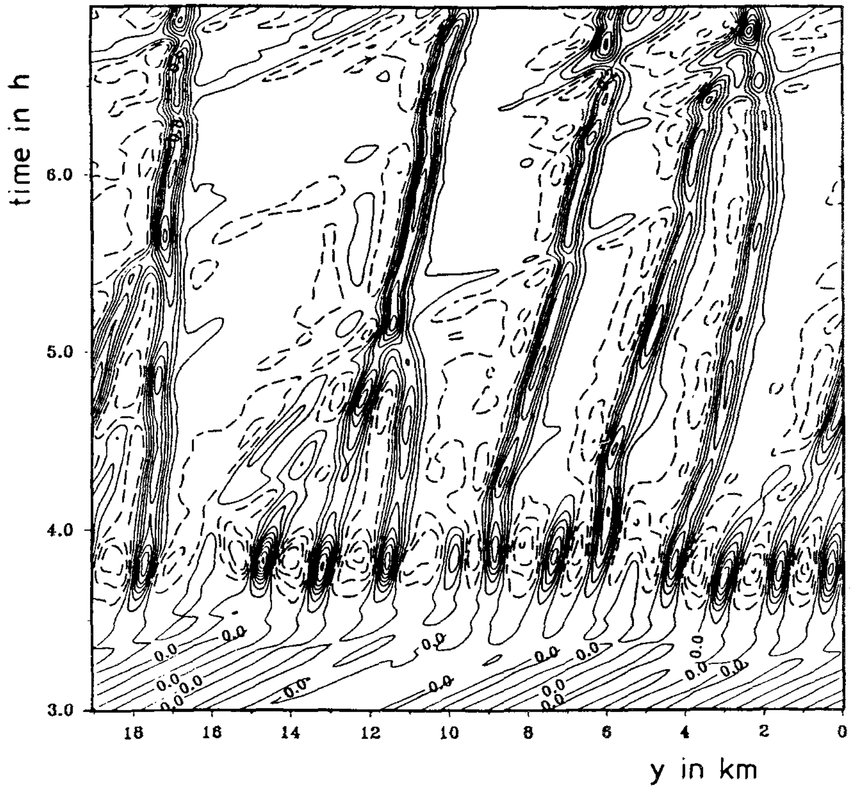

Fig. 8. Development of vertical velocity at mid boundary-layer depth as a function of cross-wind distance y and time during vortex roll formation (numerical simulation after Raasch, 1990b).

breaks (e.g., Walter and Overland, 1984). Indeed, recent theoretical investigations by Mourad and Brown (1990) have shown that these kinds of interactions will lead to increasing wavelength (aspect ratio) with time (downstream distance) even in a non-stratified PBL. This upscaling process may be similar to the phenomenon of vortex pairing which can be observed in free shear layers (Huerre, 1984), where initial Kelvin-Helmholtz waves can re-combine, leading to subharmonics of doubled wavelength. In addition, if there is a strong finite perturbation (e.g., a mountain or island), then a long wavelength may become the preferred wavelength.

Numerical simulations in two-dimensional vertical planes by Rothermel and Agee (1986), Zivkovic and Agee (1988), and Raasch (1990a) have indeed found grouping of rolls into larger size circulations as time increases. An example adopted from Raasch (1990a) is given in Figure 8, which might be interpreted as a numerical picture of cloud street development in cold air outbreaks, with merging of clouds downstream. Concerning these numerical simulations, one has to keep in mind that in two-dimensional models, there will always be some tendency for upscale energy transfer from so-called two-dimensional turbulence. Hence, some caution might be necessary in interpretating results from these models with respect to large aspect-ratio cells.

As yet another mechanism for explaining large aspect ratios in roll-like and mesoscale cellular convection (MCC), the release of latent heat has been put forward by several authors (e.g., Sheu *et al.*, 1980; Helfand and Kalnay, 1983; van Delden and Oerlemanns, 1982; Chlond, 1988; Sykes *et al.*, 1988), who found broader convective cells for cases with latent heat release compared to those in dry atmospheres. A study of these two cases for a cold air outbreak is given in Sykes *et al.* (1988) who found long wavelengths only for model runs with latent heat release. This may be contrasted to simulations by Raasch (1990a), as displayed in Figure 8, where wavelengths increasing with time were obtained even with a model of dry convection.

When convective plumes, or updraft areas of roll convection, impinge on the capping inversion which always accompanies shallow convective systems, undulations of the inversion layer might be induced. These undulations may then trigger gravity waves within the stably stratified layer aloft and these in turn might influence the convection cells below. This suggests that the spacing of roll vortices in the PBL might also be related to interaction with gravity waves aloft. A coupling was indeed found in the numerical simulations of Clark *et al.* (1986), Hauff and Clark (1989) and in a linear analysis by Sang (1991), but the relation of this mechanism to observed large wavelengths, e.g., during cold air outbreaks, may not be easily evaluated due to other mechanisms involved in the roll vortex problem.

In summary, the special problem of roll vortices in the PBL with large aspect ratios (10:1 or so), is not predicted by linear theory of inflection-point instability, parallel instability, or convective instability. Hence, some other nonlinear interactions must occur. There are some observational problems, too. Due to their low frequencies (hence very long flight paths required to resolve), the large aspect ratios are only found from pictures of cloud streets (e.g., Miura, 1986). In some field experiments, aircraft observations in the lower parts of the PBL often show smaller wavelengths at the same time (Walter and Overland, 1984; Atlas *et al.*, 1986). This could imply that cloud bands are formed above, e.g., only every third roll. Hence, it seems to be possible that large eddies in the PBL are a multi-scale phenomenon, as proposed by Walter and Overland (1984) and shown theoretically by Mourad and Brown (1990). However, all single effects as discussed above might come into play in order to create eddies with large aspect ratios in the real PBL.

3.5. FINITE PERTURBATION MODEL

The previous analyses have used the linear instability-maximum growth rate criterium for establishing roll characteristics. Brown (1970) postulated that the rolls come to equilibrium at a finite perturbation. By using the energy equation to establish an equilibrium criterium, he obtained an Ekman solution modified with finite perturbation roll vortices. The magnitude of the roll circulations depended on the energy source from kinetic energy though inflectional instability and from convection (Brown, 1972). Although the roll wavelength characteristics are established from an inflection-point instability, the shape of the rolls – counter rotating, nearly circular but sheared by the mean wind – are similar to observations in strongly convective regimes. They closely resemble the rolls produced in the numerical solutions which produce nonlinear equilibrium flows. This solution for the Ekman layer has been patched to a stratification-dependent logarithmic profile layer to produce a two-layer similarity model for the PBL. The effects of the rolls, stratification and thermal wind turning are parameterized in this model. It is interesting that the inclusion of the rolls in the Ekman layer of this solution allowed the derivation of a single parameter similarity solution (Brown, 1980). The fairly extensive verification and application of this model, which successfully predicts the effects of stratification on the classical similarity parameters, winds, and fluxes, indicates the importance of the rolls to these phenomena.

The latter is also true for large eddies in general not only for the special form of roll vortices. It is well known that more random large eddies of PBL scale dominate e.g., heat transport in the convective boundary layer (see discussion in Section 5) and they also have to be taken into account for parameterization in large-scale models. Some examples of parameterization of random large eddies in the PBL can be found, e.g., in Troen and Mahrt (1986), Moeng and Wyngaard (1989) or Chrobok *et al.* (1992).

4. Numerical Models

Besides theoretical analysis of equations of motion for the roll vortex problem by linear theory as discussed in Section 3, numerical models have been run for the full nonlinear problem. Indeed, Faller and Kaylor (1966) used a nonlinear simulation of the vorticity equation (6) for the Ekman-layer instability problem. They extended their work to the stratified Ekman layer (Kaylor and Faller, 1972) and showed the effects of thermal convection and gravity waves on inflection point instability. These earlier numerical simulations considered the case of an idealized Ekman layer with a constant viscosity and initial wind profiles after Equations (8, 9). Since the 1980's, many simulations have been performed using observed PBL profiles of wind, temperature and moisture as basic states. These will be discussed below.

4.1. TWO-DIMENSIONAL MODELS

The first modern numerical attempt to simulate the development of roll-vortices in the neutrally stratified PBL seems to be due to Mason and Sykes (1980) with a finite-difference model of the Boussinesq-equations (1)–(4). These authors extended their modelling to the unstably stratified PBL (Mason and Sykes, 1982; Mason, 1983; Mason, 1985), investigating various aspects of two-dimensional roll circulations. These investigators concluded that convective instability dominates the inflection-point instability for $z_i/L < -0.8$ and that latent heat release has no marked influence on vortex roll development. Comparisons to field experiments like KONTUR were also conducted (Mason, 1985).

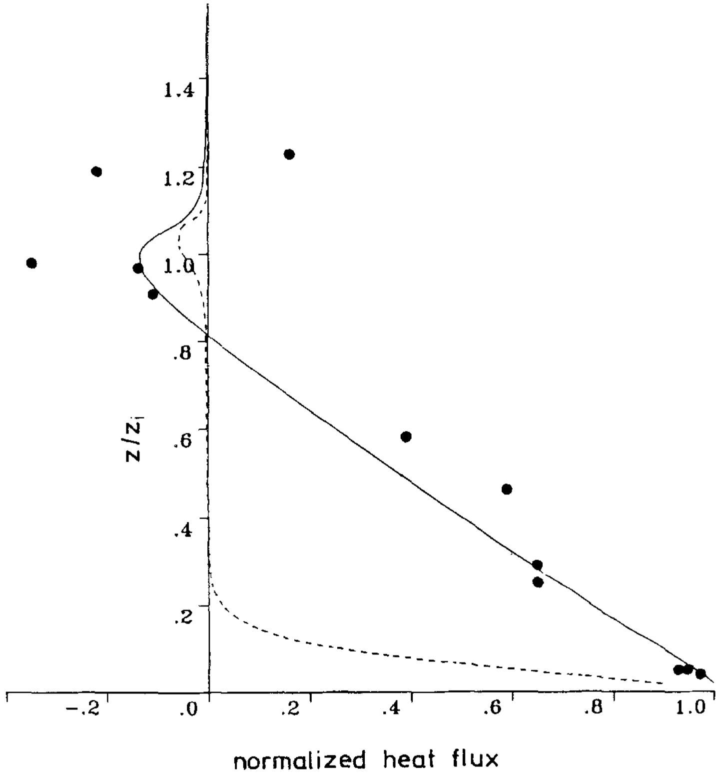

Fig. 9. Vertical heat flux in a convective boundary layer obtained from a two-dimensional model. — : total heat flux; - - - : subgrid scale heat flux; ● ● ●: Observations from MASEX (numerical simulation after Raasch, 1990a).

In general, these numerical simulations supported results from linear theory regarding the instability mechanisms. They also agree with the roll-equilibrium analytic model. But more importantly they provide information on vertical transport of momentum, heat and moisture within the PBL due to organized roll-like large eddies. One example for the vertical heat flux is shown in Figure 9 (adopted from Raasch, 1990a), which shows that most of the total heat flux is due to resolved scales, i.e., large eddies, and only near the surface does small-scale turbulence dominate.

Numerical investigations like those by Mason and Sykes have also been performed by Chlond (1987, 1988), with a spectral model based on the vorticity equation (6). Specific questions have been addressed in other papers. The role of diabatic heating, mean subsidence and viscous anisotropy on the aspect ratio of convective vortex rolls has been investigated by Sheu *et al.* (1980). The influence of latent heating on aspect ratio and cloud grouping was also treated in the model simulations of Chlond (1988) and Sykes *et al.* (1988). The effects of inflection-point instability versus convective instability in the presence of a capping inversion are discussed in Etling and Raasch (1987). The long-term development of two-dimensional convection, leading to nonlinear scale interactions and subsequent cell broadening has been simulated by Rothermel and Agee (1986) and Zivkovic and Agee (1989). Most of these points have already been discussed in the context of the physical aspects of roll-like eddies in Section 3.

Numerical simulations have also been performed for field experiments. These include MIZEX (Raasch, 1988), MASEX (Raasch, 1990a), KONTUR (Chlond, 1987; Mason, 1985; Raasch, 1990b) and GALE (Sykes *et al.,* 1990). These simulations were checked against cloud street pictures and aircraft measurements, especially with regard to vertical transports. In all of these simulations, one has to keep in mind that initial and boundary conditions as well as large-scale forcing (e.g., geostrophic wind, mean subsidence) are difficult to match between model requirements and observational possibilities. Hence, only gross characteristic features of roll-vortices in the PBL can be compared between real world data and numerical models.

One special shortcoming of all models discussed above is their implicit assumption that large roll-like eddies are homogeneous in the direction along the axis. This leads to a two-dimensional treatment of the problem in a vertical plane perpendicular to the mean wind, which allows for high resolution model runs at moderate computer time. But, in a two-dimensional model, thermal convection will always lead to roll-like solutions. In the case of zero background wind, one might expect three-dimensional convection cells in natural flows (although some studies suggest that randomly oriented groups of rolls may be the preferred mode).

It would be interesting to repeat some of the simulations described above with three-dimensional models to see whether the same large eddy structure would evolve. But simulation of a cold air outbreak at high resolution requires large computer resources and hence only a few three-dimensional numerical experiments have been performed so far. A short discussion on 3-D models will be given below.

4.2. THREE-DIMENSIONAL MODELS

4.2.1. *Large Eddy Simulation Models (LES)*

In recent years, so-called "large eddy simulation" (LES) models have been developed for turbulent boundary layers. To give an idea of the underlying motivation, consider a classical one-dimensional model of the PBL as has been used by numerous authors for flux studies. In these models, a horizontal average is taken over an infinite plane, hence all variables depend only on the vertical coordinate. The model equations like (1– 3) contain an eddy viscosity K_m, which must parameterize all diffusion effects of turbulence (including random large eddies and rolls) in the PBL. Hence no dominating eddies of the PBL are resolved in these models. There is also some question as to whether a continuum exists (and hence the Navier-Stokes equations) for large eddy diffusion modeling (e.g., Brown, 1981,1991).

In contrast to these one-dimensional models, LES models are three-dimensional with relatively fine resolution, say $\Delta = 50$ m, where Δ is the typical dimension of a grid-box. In LES models, the basic equations are averaged over these box sizes and only turbulence plus eddies within these boxes – called subgrid turbulence – need be parameterized. Hence, K_m in Equations (1) – (3) represents only transport properties of this subgrid turbulence. All other turbulent motions are resolved explicitly and all eddies with size $\lambda > 4\Delta$ are simulated directly. The term "large-eddy" refers to all eddies ranging from $\lambda = 4\Delta$ to $\lambda = H$, where H is the domain height. This kind of modelling approach is very popular in both meteorological and engineering fluid mechanics: a collection of different approaches is given in Schumann and Friedrich (1986).

In our review, "large eddy" refers to only those eddies which cover the whole PBL depth, such as roll-vortices. We are not discussing large-eddy structures which occur near walls, as in the surface layer, which are of major interest to engineering shear flow applications. In general the geophysical large-eddies occur at high Reynolds-numbers which are not accessible to direct numerical simulations (DNS) technologies (Robinson, 1991).

With respect to atmospheric applications, the first LES was designed by Deardorff (1972). This modeling approach was subsequently extended by Moeng (1984), Wyngaard and Brost (1984), Nieuwstadt and Brost (1986), Mason (1989) and Schmidt and Schumann (1989), just to mention some of the major groups. But of these models only a few have attempted to model roll vortices (see next section), and most solutions have been restricted to cases with no background wind and a convective boundary layer.

Although large eddies are also permanent features of the wind-less convective boundary layer (although not as organized as roll vortices), we shall not discuss the model results here in detail. We refer to the papers quoted above instead. We just illustrate a typical model result for the vertical velocity field in Figure 10, where a horizontal cross-section of the zero mean wind model domain is shown (adopted from Raasch and Etling, 1991). Updrafts are organized into spoke-patterns, which we may identify as "large eddies". The net effect of these organized large-scale convective cells is to transport heat (and also air admixtures) from the surface to the inversion. The vertical profiles of mean vertical heat flux (averaged over the model domain) are very similar to those shown in Figure 9, although the latter have been obtained with a two-dimensional model. The application of LES models has considerably improved the understanding of the turbulent convective boundary layer, especially with regard to vertical transport of heat, moisture and air pollutants. For example, this has led to the concept of top-down and bottom-up diffusion in the convective PBL (see Wyngaard and Brost (1984) for a summary). But as we are more interested in the development of large eddies in a PBL with mean wind, we shall restrict further discussion on LES models to these cases.

4.2.2. Neutral PBL

Three-dimensional numerical simulations of the non-stratified PBL have been performed by Mason and Thomson (1987) and Coleman *et al.* (1990). Mason and

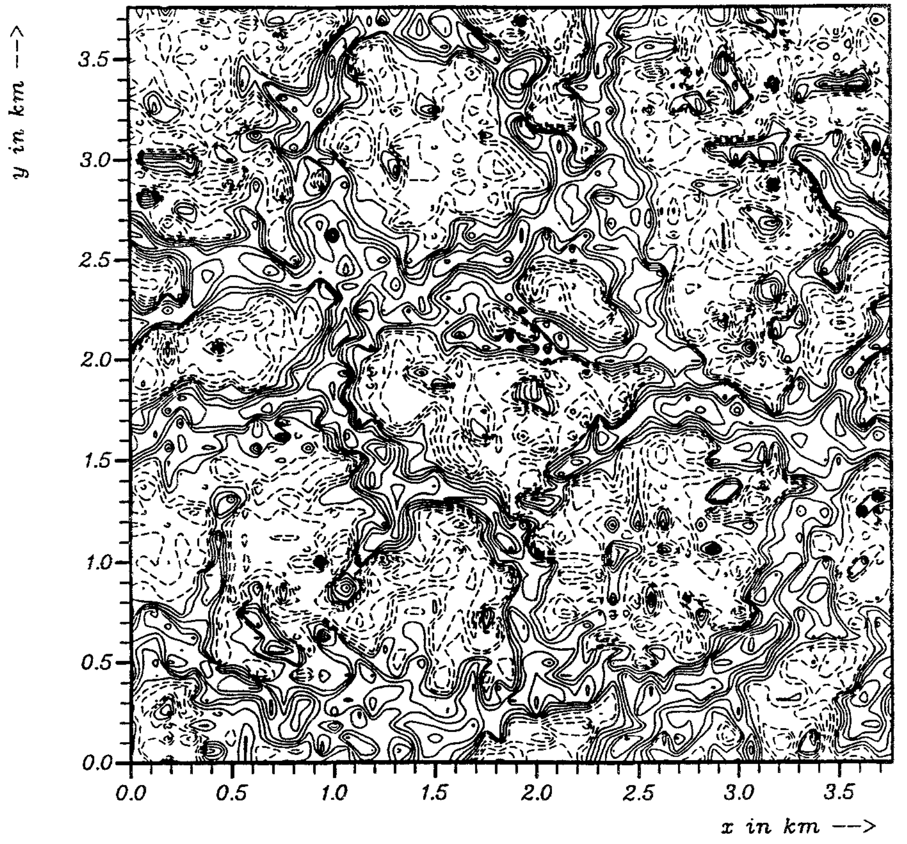

Fig. 10. Vertical velocity in a horizontal plane at 100 m above ground in a convective PBL without a mean wind. Numerical simulation using LES model (after Raasch and Etling, 1991).

Thomson used a large eddy simulation (LES) model with a surface layer obeying Monin-Obukhov similarity theory. Hence their basic state was a typical PBL wind profile similar to those used in linear stability analysis by Etling and Wippermann (1975). Although the authors expected to find organized roll-like eddies as in their earlier 2-D simulations (see Section 4.1), they did not find any clear signal of those rolls. Hence they argued that inflection-point instability does not lead to organized roll vortices in three-dimensional turbulent flows, disagreeing with results of linear theory and some observations. Earlier simulations with a LES model by Deardorff (1972) showed organized rolls for the neutral PBL only in a transient state.

Although their numerical results might have been restricted by the extent of the simulation domain, similar results were indicated by Coleman *et al.* (1990). These authors used a direct-numerical-simulation (DNS) model, which means they used a constant eddy viscosity in their model simulations. Hence their initial profile was the classical Ekman-spiral from Equations 8, 9 without a wall layer. Coleman *et al.* found longitudinal roll vortices only for low Reynolds-numbers ($\mathrm{Re} \approx 150$)

and for a single wavelength initial perturbation corresponding to the linearly most unstable normal mode. When they increased the Reynolds number up to $\approx$ 400 and/or used stochastic initial perturbations, no organized roll vortices could be clearly indentified. As a result, they also did not find signals of the inflection point instability in the finite-amplitude turbulent Ekman-layer. But there are difficulties in interpreting these DNS results. If the molecular viscosity ν of air is used, Re $\approx$ 400 (Re = $v_g z_i/\nu$) would imply a PBL height of only about 1 m with wind speed of about 1 cm s^{-1}. For realistic PBL parameters, the use of a molecular viscosity would give Re $\approx 10^6$. Their Re = 400 would imply a constant (eddy) viscosity $K \approx 25\ \mathrm{m}^2\ \mathrm{s}^{-1}$ for typical atmospheric wind and PBL height if the concept of an "effective turbulent" Reynolds number is applied. The analogy to atmospheric flow is thus strained.

The results of these numerical simulations do not provide a preferred explanation of roll vortices in the PBL due to inflection-point or parallel instability, as Coriolis forces were effective in both models. The question on whether or not the lack of instabilities appearing at neutral stratification is due to lack of vertical resolution, problems with Re scaling, or limited domain is still open. The limited domain size might be important because linear stability analyses predict a significant lateral wave phase speed ($\approx$ 2 m/s) for neutral stratification. The lateral extent of the domain and/or domain boundary conditions must be able to accommodate this traverse wave motion. Otherwise, the rolls might appear to be evanescent.

4.2.3. Unstable Stratification

Currently in three-dimensional model simulations, evidence for roll-vortices has been found only in the unstably stratified PBL. One of the early simulations by Deardorff (1972) showed roll-like structures for z_i/L =–1.5 and –4.5 but not for z_i/L =–25, but perhaps his model domain was too small ($\approx$ 5H). Becker (1987) also found convection organized in rolls for the PBL, but his model domain was even smaller ($\approx$ 3H) and the numerical method was upstream for the advection terms, leading to a large numerical diffusion (this could implicitely cause a "low Reynolds-number flow" as in Coleman *et al.* (1990), see discussion above). Sykes *et al.* (1990) simulated the situation of a cold air outbreak during the GALE experiments with 2-D and 3-D models. Whereas the 2-D model yielded organized convection rolls, as observed in the experiment, these rolls showed up in the 3-D model only at early integration times and disappeared later on. Sykes *et al.* attributed the non-existence of roll vortices in the 3-D model to the limited horizontal extent (6x6 km) of the model domain.

Recently Coleman (1990) extended his work on DNS simulations of the Ekman layer to the stratified case. Whereas he did not find roll vortices in the neutral Ekman layer (see above), these organized vortices showed up for moderate unstable stratification with -2.9 $< z_i/L < -0.4$, but not for the very unstable situation with $z_i/L = -27$. These results seem to support Deardorff's earlier work and also many observations in the PBL (see Section 2) that longitudinal roll vortices are found

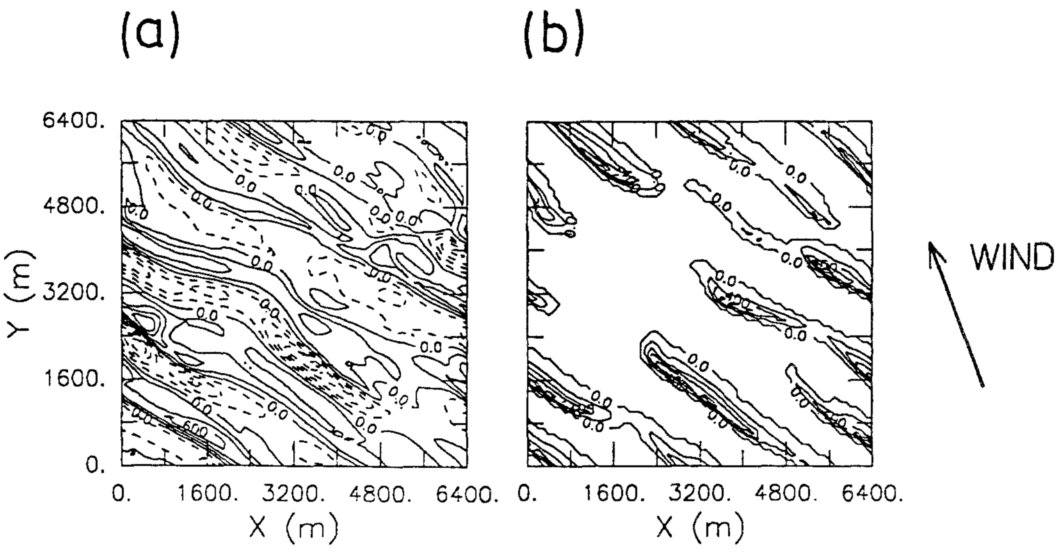

Fig. 11. Numerical simulation of coherent structures in the PBL during a cold air outbreak. Horizontal cross-sections at 350 m height: (a) vertical velocity, (b) liquid water content (after Chlond, 1992).

mainly in moderately unstable stratification.

The most recent three-dimensional simulation of the PBL seems to be due to Chlond (1992), who also included the effects of radiation and cloud physics. For the simulation of a cold air outbreak, he found longitudinal rolls in the PBL, although there were marked inhomogeneities in the direction of the roll-axis (Figure 11). This has to be compared with the case for the wind-less convective PBL shown in Figure 10. Through analysis of the energy equations, Chlond found two different mechanisms mainly responsible for the roll development: inflection-point instability due to lateral shear at the beginning of the cold air outbreak and convective instability due to surface heating at later times. The rolls were found in a rather shallow PBL with $z_i \approx 500$ m and under very strong winds ($v_g \approx 25$ m s^{-1}). The mean wind showed very strong veering with height leading to marked inflection-points in the lateral wind component. Under these circumstances, inflection-point instability might indeed lead to roll vortices in three-dimensional simulations, in contrast to the earlier investigations of Mason and Thomson (1987) or Coleman et al. (1990).

4.2.4. Summary

Three-dimensional LES simulations of the PBL indicate that convective instability takes the form of roll-like quasi two-dimensional eddies in the PBL. Rolls due to inflection-point instability have been found in shallow boundary layers with strong background shear. But in contrast to 2-D numerical results and observations of PBL rolls (as is most evident in cloud streets which extend over large domains and long times), they do not yet show up clearly as permanent features in three-dimensional models. This might be attributed to the limited horizontal extent of the model domain, which does not permit a "satellite view" of the simulated structures, where more or less linear features (rolls) can be identified more clearly than in close-up looks (Sykes et al., 1990). On the other hand, in various model studies, small domain size is found to encourage roll formation by restricting eddies which would break up rolls. There may also be difficulties accomodating the lateral drift of the rolls in a small domain. In the case of DNS, the restricted range of Reynolds number limits simulation capabilities of the PBL, unless one accepts the concept of a constant eddy viscosity in those models.

5. Large Eddies and Turbulence Closure

A major goal of the large field experiments described in Section 2 was to parameterize the vertical turbulent fluxes between the land/sea-air interface and the atmosphere in terms of average variables, e.g., mean wind and temperature gradients. This is necessary for the numerical prediction of intense cyclogenesis of the oceans (e.g., GALE) as well as for general circulation or climate models, where energy fluxes at the earth's surface are the main driving mechanisms.

In most of these models, turbulent transport is calculated by a gradient-transfer approach, which might be written for the turbulent heat flux as:

$$\overline{w'\Theta'} = -K_h \frac{\partial \overline{\Theta}}{\partial z}. \tag{13}$$

In (13) the overbar means an average over the grid-box of the model and (at least) over the computational time step. The coefficient K_h is called "eddy diffusivity for heat" in analogy with molecular heat transfer.

We shall not engage in a lengthy discussion of the so-called "K-theory", on which (13) is based, or of the vast literature on this turbulence closure problem. Some recent discussions can be found in Moeng and Wyngaard (1989), Weil (1990) and Chrobok et al. (1992). However, we shall comment on subgrid-scale closure with respect to large eddies in the PBL, as treated here.

If we consider a typical horizontal resolution of say $\Delta = 100$ km in the grid of a numerical weather prediction model, heat flux and mean temperature in Equation (13) are representative for an area of 10^4 km^2. Hence K_h is an effective diffusivity for all processes with scales less than 100 km. This includes surface-layer turbulence as well as organized convection as in the form of random cells or vortex rolls. Since K_h is usually positive definite, the gradient transfer approach (13) also implies that the heat flux (and similarly moisture and momentum flux) is always down-gradient.

But this is not always the case, as observations in the windless convective boundary-layer have shown. Indeed LES model results for these situations, as discussed in Section 4.4, find up-gradient fluxes in the middle and the upper part of

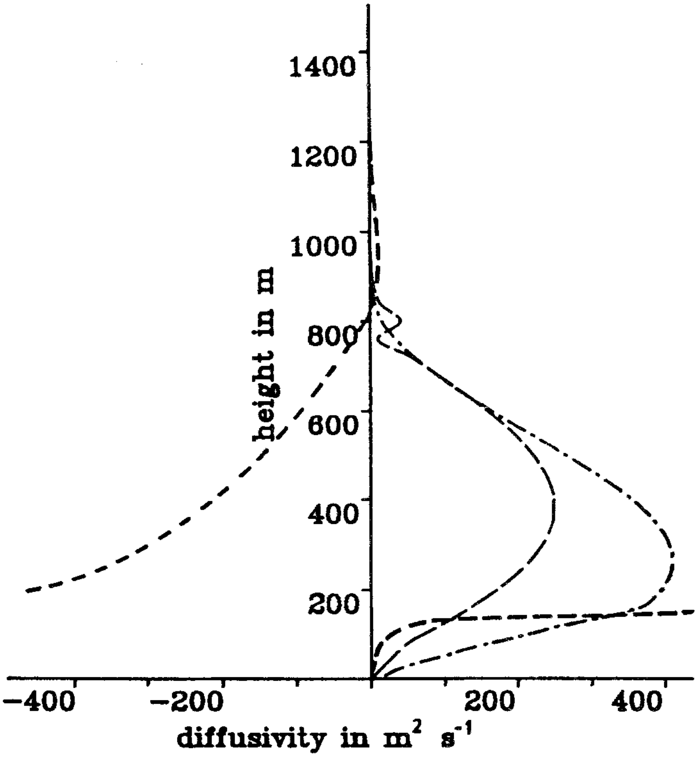

Fig. 12. Vertical profile of eddy diffusivity K_h in a convective boundary layer during a cold air outbreak. Model results: — — — transilient turbulence model; – · – · – K_h after Wyngaard and Brost (1986); - - - - derived from two-dimensional large eddy simulation (after Chrobok *et al.,* 1992).

the convective boundary layer. This would imply a negative heat transfer coefficient K_h, for a K-theory model, which is not physically possible. Separate evaluations of heat flux and temperature gradient from LES results would give extremely large (zero gradient) or negative values of K_h for the convective boundary layer (see, e.g., Weil, 1990). Hence, the simple concept of eddy heat transfer coefficient like (13) is not valid in the whole PBL (Brown, 1981). Part of the problem is that the derivation of mean flow parameters (e.g., $\partial\overline{\theta}/\partial z$) is not well defined when large eddies are present (e.g., see Brown, 1991), as there is no eddy-continuum. This has led to new concepts of turbulent diffusion such as top-down and bottom-up diffusion (Wyngaard and Brost, 1984) or transilient turbulence theory (Stull, 1991).

But with respect to parameterization of heat flux with a gradient transfer approach like Equation (13), boundary layer height and vertical heat flux are still predicted quite reasonably, if proper profiles for the eddy diffusivity K_h are used (see, e.g., Wyngaard and Brost (1984) and Chrobok et al. (1992). The proper representation of large eddies might be more important for momentum transfer, if the concept of eddy viscosity is applied to the PBL.

In the case of a boundary layer with roll vortices, similar problems with simple turbulence closure schemes may appear. But in contrast to the wind-less convective boundary layer, little effort has been put forward by LES modellers. Negative heat diffusivities have been found in two-dimensional simulations of roll convection during cold air outbreaks by Chrobok *et al.* (1992) as shown in Figure 12, and they can be expected in data evaluation of three-dimensional LES models of vortex rolls (still to be performed). Therefore many formulas for the vertical variation of K_h and similarly for the eddy viscosity K_m as proposed in the literature have to be considered with caution if applied to situations where large eddies are present in the PBL.

But of course numerical modeling of meso- and large-scale atmospheric phenomena cannot wait until a "correct" parameterization of boundary-layer fluxes is available for all situations, including large eddies formed during cold air outbreaks as an example. There have been attempts to model the roll effects with a pseudo K_m (e.g., Troen and Mahrt, 1986). However, it is preferable to model the rolls explicitly. Indeed a very simple model for including vortex rolls in the boundary-layer parameterization has already been proposed by Brown (1974b), and extensively checked against observations (Brown, 1978; Brown and Liu, 1982; Brown and Levy, 1985). This model has also been investigated as a boundary-layer model in general circulation models (Brown and Foster, 1991; Foster and Brown, 1991). Although this model also does not account for the up-gradient mean heat flux in the convectively driven PBL explicitly, it is in line with simple approaches for the CBL as proposed by Wyngaard and Brost (1984) and applied to situations of a cold air outbreak by Chrobok et al. (1992) (see also Figure 12).

The main point we would like to stress is that the transport properties of roll vortices (but also of more random large eddies) have to be taken into account for a successful parameterization of subgrid-scale fluxes in large-scale models. This is obvious if situations like cold air outbreaks over the oceans are to be simulated with the proper energy input from the lower boundary. However, on the basis of the considerable number of stability analyses of the Navier-Stokes equations for the PBL, and the finite perturbation analytic solutions, it appears that the rolls are predicted inevitably whenever modest winds and convection are present over flat, homogeneous surfaces. (Linear stability theory and a few observations indicate that the rolls should also be present for neutral and perhaps slightly stably stratified layers, while initial numerical simulations do not support these.) The advective flux of the large eddies is large and cannot be properly modelled with a diffusion coefficient. Thus if numerical models are to simulate the PBL properly, they must resolve the instabilities and generate the finite eddies, whether they are organized as roll vortices or are more of random nature.

Hopefully, LES modeling of these situations, together with observations from field experiments, will provide this kind of parameterization in a similar way, as has been demonstrated for the wind-less convective boundary layer in recent years.

6. Conclusions

In this review we have focused on those large eddies in the PBL which manifest themselves as quasi two-dimensional horizontal vortex rolls with axes oriented in the downwind direction. These rolls are most easily visualized indirectly by cloud streets organized parallel to the mean boundary-layer wind. They are observed quite impressivly on satellite pictures of cold air outbreaks over the oceans. As this kind of organized behaviour covers quite large areas for long durations during such situations, considerable vertical transport of momentum, heat, moisture and trace substances between the earth's surface (land and oceans) and the atmosphere takes place within these circulations. They clearly do not have properties of isotropic and homogeneous small-scale turbulence.

It is also possible that the organized roll vortices are present in much of the geophysical PBL for all moderate flows with modest unstable stratification. There are still many gaps between the linear stability analyses, the equilibrium finite perturbation models, and the numerical models. However, the preponderance of observations and theory indicate that the rolls are commonly present in the PBL. Hence, in order to model exchange processes of this kind in mesoscale or large-scale numerical models (weather forecast or climate studies), the use of simple eddy viscosity-type parameterizations is not appropriate without special considerations of large eddies. This has been recognized during many field experiments which have been performed in the PBL (mainly over the oceans) during the last decade. Evidence of transport properties of large eddies different from usual surface-layer turbulence has also been provided recently through small-scale numerical models of the PBL.

Concerning theoretical explanations on the formation of vortex rolls in the PBL, dynamic (inflection-point) instabilities and thermal (convection) instabilities are still assumed to play their roles under certain situations. In certain circumstances, wave-wave interaction becomes important. But it is now recognized that a single instability mode cannot explain the observed structure of large roll-like eddies in the real PBL. Instead it seems very likely that observed cloud streets are just flow visualizations of a multi-scale boundary-layer process containing dynamic and thermal instabilities as well as nonlinear interactions between various scales of motion.

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