Estimating the Orientation and Spacing of Midlatitude Linear Convective Boundary Layer Features: Cloud Streets

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ABSTRACT

Linear features in a clear convective boundary layer (CBL) over the North Atlantic Ocean were studied during a weak cold air outbreak using a down-looking airborne lidar. Sequential lidar profiles were placed together and color coded to provide images of aerosol and molecular scattering from below the aircraft to the ocean surface, over a 36-km segment of a flight track approximately 150 km off the coast of southern Virginia. The aircraft flew on a path approximately perpendicular to the expected orientation of cloud streets if they had formed. The lidar image clearly shows randomly sized convective cells in the CBL, grouping under the crests of a gravity wave in the stable troposphere. It is suggested that the wave develops as energetic convective cells in the CBL penetrate into the stable layer aloft and act as obstructions to the relative flow. An analytic study, published in 1965, demonstrates that vertical disturbances on the top of the CBL adjust to be in resonance with a horizontal gravity wave in the free troposphere. The results of the study along with an interpretation of the lidar images have led to the development of a simple conceptual model that is used to estimate the spacing and orientation of long linear convective features in the midlatitude CBL. In addition, the conceptual model can explain the change in cloud street patterns with increasing fetch, seen in satellite images. Comparisons with observations from this study and five other midlatitude field programs show good agreement. A suggestion for future research is presented.

1. Introduction

Long linear horizontal convective boundary layer (CBL) features, which frequently manifest as cloud streets, have been of scientific interest since Woodcock’s (1942) observation of soaring seagulls. Glider pilots take advantage of cloud streets to soar over long distances. Kuefeatures that, among others, have suggested that in order for gliders to continue to soar well above the CBL there would have to be internal gravity waves in the stable troposphere associated with these linear convective features. Reasons to study these interesting convective patterns include the following: 1) convective organization may lead to more efficient transfer of heat and moisture from the surface through the CBL and into the free atmosphere, and 2) cloud streets may generate vertically propagating gravity waves that can transfer their momentum aloft, thereby influencing atmospheric circulation in the upper troposphere.

Observational studies have been conducted over the last 40 yr to more fully understand the structure and dynamics of these linear convective features. Scientific interest increased with the advent of satellite imaging, which clearly shows the unique and unmistakable pattern of these clouds, which can cover an area of several hundred kilometers on a side. Satellite imagery also indicates how ubiquitous these cloud patterns are around the globe. Konrad (1970), using a high-powered radar, observed parallel lines of clear air convective cells in the CBL aligned along the mean low-level wind direction, having an aspect ratio of about 2:1 (aspect ratio is defined as the horizontal scale of convection divided by the depth of the CBL). LeMone (1973) analyzed tower and aircraft data acquired during a number of midlatitude field programs, which were suitable for studying long linear convective features in the CBL, and found that the spacing of these

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convective features ranged from 1.5 to 6.5 km with an aspect ratio of about 3:1 (see also LeMone 1976). LeMone and Meitin (1984) used tropical Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) observations to document broad cloud bands and their subcloud eddies. These cloud bands were shown, in a numerical simulation by Balaji et al. (1993), to be organized by tropospheric gravity waves. Walter and Overland (1984) studied linear convective features over the northern Bering Sea ice field made visible by steam fog from cracks and leads in the ice, and found that the features display five horizontal scales ranging from 0.3 to 30 km. Melfi et al. (1985) studied the CBL during a cold air outbreak over the North Atlantic Ocean using an airborne down-looking lidar, similar to that used in this study, and observed individual convective cells, each organized under the crests of an undulating CBL top, with an aspect ratio of 1.5:1–4:1:1. They suggest that interfacial wind shear at the top of the CBL may influence convective scales. Kuettner et al. (1987), as part of the Convective Waves Project, reported on a study investigating the interaction of cloud streets in the CBL with gravity waves in the free troposphere. The field program consisted of aircraft flights over cloud streets, which showed a correlation between measured vertical velocity oscillations at flight level, associated with wave action, and the location of clouds at the top of the CBL. In addition, they state, based on glider experience, that gravity waves tend to form when the winds aloft blow at a considerable angle to cloud streets, a condition expected during cold or warm air advection. Weckwerth et al. (1997) analyzed Doppler radar returns from the Convection and Precipitation/Electrification (CaPE) project to study long linear convective features and found that the spacing between the features scaled with increasing CBL instability, and that the orientation correlated well with the CBL wind direction. They used a three-dimensional numerical cloud model to simulate their observations (Clark 1977; Clark and Farley 1984). Atkinson and Zhang (1996) and Young et al. (2002) provide a review of other field programs and theoretical research conducted to study these linear convective patterns.

Theoretical studies of the lower atmosphere have been pursued in an attempt to better understand the conditions for the development and maintenance of long linear CBL features. Townsend (1965) developed an analytic description of the atmosphere, with the CBL top acting as obstructions to the flow of the stable atmosphere aloft, and found that the obstructions adjust themselves to be in resonance with the Brunt–Väisälä frequency of the stable layer, giving rise to horizontal gravity waves. Brown (1970), based in part on laboratory simulations of Faller (1965) and the theoretical work of Lilly (1966), focused exclusively on the CBL and developed a theory for linear convective features arising from instability associated with an inflection point in the vertical profile of the horizontal wind (see also Brown 1972). He showed that under certain conditions a series of parallel horizontal roll vortices develop in the CBL counterrotating one with the other. Even though he did not explicitly include clouds in his theory, he concluded that clouds would tend to form in the updrafts between each pair of vortices, resulting in long linear parallel cloud patterns. The theory can account for cloud street aspect ratios ranging from 2:1 to 4:1 and a cloud street orientation close to the low-level wind direction [see a review by Brown (1980)]. Etling and Brown (1993) provide a more recent review of roll vortices, pointing out other factors that may lead to their development, including parallel instability, convective instability, and gravity wave interactions. Mason and Sykes (1982) developed a two-dimensional numerical model that demonstrated a connection between roll vortices in the CBL and internal gravity waves in the stable atmosphere aloft. Clark et al. (1986), as part of the Convective Waves Project mentioned above, applied a two-dimensional numerical model (Clark 1977) to simulate the interaction between convection in the CBL and internal gravity waves. They found that CBL eddies that penetrate into the stable layer, in the presence of wind shear, can act as an obstacle to the flow aloft and thus initiate gravity waves in the free atmosphere, and that the waves, in turn, through a feedback mechanism, serve to organize the eddies. Hauf and Clark (1989) extended Clark’s previous work to three dimensions. Sang (1991) developed an analytic description of a two-layer atmosphere, which shows the development of convective rolls correlated with trapped internal gravity waves in the stable layer above (see also Sang 1993). More recently, Liu and Sang (2009) used an analytic solution of a two-layer atmosphere and found, for their study, that a suitable wind-direction shear at the top of the CBL is necessary for the development of long linear convective features in the CBL.

Based on the research reviewed above, there are three interrelated categories that may lead to the development of long horizontal linear convective features in the CBL that frequently manifest as cloud streets: 1) shear- and buoyancy-driven “classical” roll vortices with an aspect ratio limited to about 2:1–4:1, oriented close to the low-level wind direction, with no involvement of the stable atmosphere aloft (Brown 1970, 1972; LeMone 1973, 1976; Brown 1980; Walter and Overland 1984; Etling and Brown 1993; Weckwerth et al. 1997); 2) roll vortices
interacting with a gravity wave in the stable atmosphere aloft that may lead to a broader spacing and a wider range of orientations for cloud streets than expected for the classical case (Mason and Sykes 1982; Clark et al. 1986; Kuettner et al. 1987; Hauf and Clark 1989; Sang 1991, 1993; Eting and Brown 1993; Liu and Sang 2009); and 3) cellular convection in the CBL organized into horizontal linear features by a gravity wave aloft (Townsend 1965; Clark et al. 1986; Kuettner et al. 1987; Hauf and Clark 1989; Balaji et al. 1993). For this case, when the gravity wave wavelength matches the typical aspect ratio in the CBL of about 2:1–4:1, then the convective cells would be organized into long parallel lines, and if clouds formed they would appear as “pearls on a string” (Konrad 1970; Melfi et al. 1985). For a longer gravity wave wavelength, the horizontal linear features would be made up of bands of convective cells or clouds. The separation of these cloud bands could range from a few kilometers up to several tens of kilometers (LeMone and Meitin 1984; Walter and Overland 1984; Balaji et al. 1993).

This paper presents results from the Convective Waves Experiment (COWEX) conducted during the winter of 1990 over the North Atlantic Ocean. During the experiment a down-looking airborne lidar was used to observe the CBL. The lidar data clearly show, in remarkable detail, the convective structure of the CBL over the ocean and a gravity wave in the free troposphere that is highly correlated with the convection. These data, along with the Townsend (1965) study mentioned earlier, will be used to suggest a simple two-layer conceptual model that can be used to estimate the spacing and orientation of horizontal linear convective features in the midlatitude CBL. The conceptual model estimates will be compared with observations from several field programs conducted to study cloud streets.

The remainder of the paper is organized as follows: section 2 will present the plan of COWEX; section 3 will describe the airborne lidar system and its operation; in section 4 the lidar data will be presented and compared to the results of the Townsend (1965) study; section 5 will present the conceptual model and its implications; section 6 will compare the conceptual model estimates with several field campaign observations; and section 7, will provide a summary and the conclusions of the paper along with a suggestion for future research.

2. The Convective Waves Experiment

During the winter of 1990 a joint field experiment between the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Center for Atmospheric Research (NCAR) was conducted to study cloud streets during cold air outbreaks over the North Atlantic Ocean. Three aircraft participated in the experiment: the NASA Electra with a down-looking lidar and a gust probe, and the NCAR King Air and the NCAR Sabreliner, both with the standard complement of atmospheric instrumentation and a gust probe.

The plan for the field program was to fly flight legs over cloud streets, perpendicular to the long axis of the linear cloud structures, at three downfetch locations. The Electra was to fly at 3 km observing the structure of the CBL with the lidar while measuring vertical velocity fluctuations at flight level. The King Air and Sabreliner were to fly straight and level above the Electra, also measuring flight level vertical velocities. The objective was to correlate convective structure in the CBL with gravity waves aloft and to determine the vertical extent of these waves.

Unfortunately the winter of 1989/90 was unseasonably warm and during the deployment at Wallops Island, there were no cold air outbreaks with sufficient strength to develop a field of cloud streets. Nevertheless, toward the end of the deployment period, a modified mission was conducted on the afternoon of 17 February 1990, after the passage of a weak cold front. As previously planned, three flight legs were flown offshore, at successively longer fetch in a direction judged to be approximately perpendicular to the long axis of cloud streets if they had formed. The objective of this mission was to study the development of clear air convection over the ocean after a cold frontal passage, as a function of fetch, to determine if clear air convection showed an organization similar to that seen when cloud streets are present, and to assess whether these convective structures generate gravity waves in the stable free atmosphere aloft. Only a small segment of one of the flight legs will be presented and discussed in this paper.

3. Airborne lidar

The NASA–GSFC down-looking airborne lidar has been used in a number of CBL investigations (see Melfi et al. 1985). It consists of a 40-cm Newtonian telescope aligned with the output of a frequency-doubled Nd:YAG laser (wavelength 532 nm). The laser is fired at 10 Hz and, with a nominal aircraft speed of 130 m s\(^{-1}\), a vertical profile from below the aircraft to the ocean surface is acquired every 13 m. Each return profile, because of scattering by atmospheric molecules and aerosols, is digitized at 100 ns, thus giving a vertical resolution of 15 m. As a result, when the aircraft is flying straight and level the lidar data provide, in the plane below the aircraft, a pixelated view of atmospheric scattering, with each independent pixel having vertical and horizontal dimensions of 15 and 13 m, respectively.
4. Data and discussion

Lidar data acquired just after 2300 UTC on a flight heading of 55\(^\circ\) at an altitude of 3.7 km, approximately 150 km off the coast of southern Virginia, are shown in Figs. 1 and 2. Figure 3a provides profiles of potential temperature and relative humidity and Fig. 3b provides profiles of wind speed and wind direction. The data of Fig. 3 are from a rawinsonde launched at 2200 UTC 17 February 1990 at Wallops Island, Virginia, which is approximately 175 km northwest of the experiment area. A Geostationary Operational Environmental Satellite (GOES) image acquired during the experiment indicated essentially cloud-free conditions over the experiment area. Each lidar profile has been range corrected, color coded, and placed together sequentially to provide the images given in Figs. 1 and 2. Figure 2 consists of three panels, each 12 km long; it provides a view of the same data shown in Fig. 1 but in a more realistic perspective (height and distance scales nearly equal). The atmosphere above an altitude of about 2 km is aerosol free; therefore, the lidar signal (shown in the figures as dark blue) is due only to molecular scattering. Below 2 km an aerosol layer is seen (blue, yellow, and green) extending down to the top of the CBL at an altitude of 0.6–1 km. The CBL is the region extending from near the ocean surface up to an altitude of 0.6–1 km (violet, red, brown, and white).

The CBL seen in Figs. 1 and 2 consists predominantly of vertically oriented convective cells. The panels in Fig. 2 show that the larger cells are rounded on the upshear side (left side) and they show that wind shear in the upper CBL cause several of the cells to tilt downshear (to the right). In a well-mixed boundary layer the water vapor mixing ratio and the potential temperature are expected to remain nearly constant with altitude. As a result, the relative humidity will increase with height as shown in Fig. 3a. Aerosols, which are the principal cause of light scattering variations in the CBL, are hygroscopic (primarily salt spray from the ocean) and therefore grow in size as they move upward (increasing humidity) in the updrafts, and thus scatter the laser radiation more effectively (see Ferrare et al. 1998). These inferred updrafts extend from near the ocean surface up to the top of the CBL and are shown in Figs. 1 and 2, within the cells, as features changing color from red and/or brown near the surface to white near the top. The updrafts tend to be on the upshear side (left side) of the convective cells. On the downshear side, and near the top of the CBL, the aerosol scattering is less, as indicated by red and occasionally violet colors, and is likely due to the entrainment of dry and relatively clean air from the free troposphere.

Figures 1 and 2 show randomly sized convective cells ranging, in the horizontal, from a few hundred meters to several kilometers. (Some of the cells seen in Figs. 1 and 2 may, in fact, be larger than they appear since the lidar did not always sound through the center of each cell). The convective cells appear to have a full range of turbulent structure from the size of the cell down to the smallest scale observed (tens of meters). The images show that most of the convective cells tend to scale with the depth of the CBL with an aspect ratio of about 2:1. The randomly sized cells are observed in the figures to accumulate in three groups in the first 21 km of the images. These groupings consist of larger and likely more energetic cells that extend higher in altitude. The scale of these three groupings is on the order of 7 km. Beyond about 21 km the depth of the CBL is smaller.
There is one small cloud in Fig. 1 and the middle panel of Fig. 2 at 16 km into the flight track. Clouds produce very high scattering as seen by the white region at the top of the cell, and clouds also attenuate the signal coming from regions below the cloud. The attenuated region is seen in both figures as the blue–green stripes extending from below the cloud to the ocean surface. One sees a stronger lidar signal (white) in the updraft of the cloud-topped cell when compared to the updrafts of the other energetic cells. Because of the hygroscopic nature of the aerosols, the larger scattering likely indicates higher levels of moisture in this updraft. As a result, the updraft in this cell reaches saturation at an altitude below the tops of some of the other cells. If the lifting condensation level (LCL) were lower for the other cells (higher moisture in their updrafts), one would observe a small cloud at the top of each of the cells in the three groupings, giving rise to three evenly spaced groupings of clouds.

Above the CBL, in the free troposphere, the image of Fig. 1 shows the previously mentioned aerosol layer undulating in phase with the variation of the CBL top. It is suggested that this undulation in the aerosol layer is due to the presence of a gravity wave in the stable troposphere. It is also suggested that the wave develops as energetic convective cells in the CBL penetrate into the stable layer aloft and act as obstructions to the relative flow of the free troposphere. Figure 3b shows that the wind speed and direction in the boundary layer was approximately 10 m s\(^{-1}\) from 350°, and the wind speed and direction in the free troposphere was about 20 m s\(^{-1}\) from 300°. The interfacial wind shear vector between the CBL and the free troposphere was therefore 15.6 m s\(^{-1}\) pointing at 90°. Because, in Figs. 1 and 2, the relative wind aloft is blowing from left to right, it is further suggested that energetic convective cells will tend to grow under the wave crests, to support the wave, as it propagates down shear (from left to right). The wave seen in the image also causes undulations in the strong inversion cap at the top of the CBL. Energetic convective cells impinging on the inversion cap will tend to flatten out, thus becoming larger in the horizontal, and if energetic enough will continue to move up the sloping inversion cap to be under a wave crest. The convection beyond 21 km appears to be less energetic than the earlier convection, both because the CBL only extends to an altitude of 600 m and because the horizontal size of the convective cells in this region is less, tending to be on the order of 1 km. Beyond 21 km the convective cells do not appear to support or be influenced as much by the gravity wave; thus, the wave is seen to damp out.

The amplitude of the gravity wave in the image of Fig. 1, just above the CBL, is approximately 200 m, decreasing to about 50 m at an altitude of 2 km. A wave signature was not obvious in the gust probe data at the aircraft flight level (3.7 km). The lack of a wave signature at flight level was probably due to continued attenuation of the wave above an altitude of 2 km. The image shows little or no tilt of the gravity wave crests with height, leading one to speculate that the wave is a horizontal wave without a vertical component.

As mentioned in the introduction, several investigators have pursued numerical or analytic studies of the interaction between convection in the CBL and gravity waves in the free troposphere (Townsend 1965; Mason and Sykes 1982; Clark et al. 1986; Hauf and Clark 1989; Sang 1991, 1993; Balaji et al. 1993; Liu and Sang 2009).

The Townsend (1965) study treats the development of gravity waves in the stable atmosphere stimulated by a CBL under conditions similar to that observed during the acquisition of the lidar data shown in Figs. 1 and 2. He developed an analytical solution of an ideal atmosphere,
consisting of the top of a CBL that has vertical displacements, which he places at the surface, and two stable layers aloft. The lower stable layer in contact with the CBL top is his “troposphere” and the upper, more stable layer, is his “stratosphere.” He represents the vertical displacements at the top of the CBL by a superposition of time-dependent Fourier components that move at a uniform velocity. Upon matching boundary conditions he finds that, after a time—a long time compared to the period \( \tau \) of the troposphere where

\[
\tau = \frac{2\pi}{N},
\]

in which \( N \) is the Brunt–Väisälä frequency—the dominant modes of the vertical displacements in the CBL top have resonant frequencies very near \( N \). Since \( \tau \) is typically on the order of a few minutes in the lower troposphere, the resonant process takes about an hour to develop. He also shows that the phase velocity \( V \) of the generated waves is the vector difference between the flow velocity of the troposphere and the velocity of the CBL disturbances. Townsend notes from his study that the waves that develop in the stable troposphere have crests and troughs normal to \( V \), and wavelengths \( \lambda \) near

\[
\lambda = 2\pi|V|\left[-g/\rho(d\rho/dz)\right]^{-1/2},
\]

where \( V = V_{sh} - V_{bl} \) (in which \( V_{sh} \) is the interfacial wind shear vector, \( V_{ft} \) is the free troposphere vector wind, and \( V_{bl} \) is the boundary layer vector wind), \( g \) is the acceleration due to gravity, \( \rho \) is potential density, and \( z \) is altitude. Equation (2) can also be written in the more familiar form as

\[
\lambda = 2\pi|V_{sh}|\left[g/\theta(d\theta/dz)\right]^{-1/2},
\]

where \( \theta \) is potential temperature. To be precise, virtual potential temperature \( \theta_v \), which takes into account the effects of water vapor, is more appropriate than \( \theta \) in Eq. (3); however, the error in using \( \theta \) is small. The Brunt–Väisälä frequency of the stable troposphere is given as

\[
N = \left[9.8/280(0.008)\right]^{1/2} = 0.0167 \text{ Hz}.
\]

And from Eq. (1), \( \tau \approx 6 \text{ min} \). Substituting the above value of \( N \), along with the previously mentioned absolute value of the interfacial wind shear vector at the CBL top of 15.6 m s\(^{-1} \), into Eq. (5), one has for the gravity wave wavelength

\[
\lambda = \left[2\pi(15.6)/0.0167\right] = 5.85 \text{ km}.
\]

From the Townsend study, the estimated orientation of the wave crests and troughs is normal to the interfacial wind shear vector of 90° or in a north–south direction (180°). The orientation of the wave crests and troughs is 10° off the wind flow direction in the CBL and 60° off the wind flow direction of the free troposphere.

The mean CBL depth for the three cell groupings seen in Fig. 1 is about 0.8 km. This depth along with a horizontal scale of 5.85 km results in an aspect ratio, in the plane of the interfacial wind shear vector, of about 7:1, which is much flatter than expected for classical roll vortices (2:1–4:1). Therefore, the image of Fig. 1 most likely represents, as previously suggested, convection in the CBL initiating and then being organized by a gravity wave in the free troposphere.

Now the plane of the lidar image of Fig. 1 is at 55°, which is 35° from the plane perpendicular to the wave crests (estimated to be 90°). Taking this into account results in a wavelength observed by the lidar along the flight track as

\[
\lambda_o = \lambda/\cos 35° = 7.15 \text{ km}.
\]

The estimated value for the observed gravity wave wavelength of 7.15 km is very close to the 7-km wavelength seen in the image of Fig. 1.

5. A conceptual model of long linear convective structure in the CBL

Because of the good agreement between the estimated and the observed wavelength of the gravity wave shown in Fig. 1, a conceptual model for estimating the spacing and orientation of midlatitude long linear CBL features
will be introduced in this section, along with a discussion of its implications.

The conceptual model consists of a strong convectively mixed neutral/unstable CBL capped by an inversion and overlaid by a stable free troposphere. In the well-mixed CBL, for the purpose of the conceptual model, it is assumed that potential temperature, water vapor mixing ratio, and wind speed and direction each are constant with altitude from the surface layer up to the top of the CBL. The turning of the wind with altitude is assumed to be concentrated at the interface between the CBL and the free troposphere above. Also at the interface there is a discontinuous change in potential temperature (increase), water vapor mixing ratio (decrease), and wind direction and speed (increase). In the free troposphere, it is assumed that the potential temperature lapse rate is constant, that the mixing ratio decreases with altitude, that the wind speed increases with altitude, and that the wind backs (veers) with altitude during cold (warm) air advection. Energetic convective cells in the CBL penetrate into the stable atmosphere and act as obstructions to the flow aloft. Within a relatively short period of time (on the order of an hour) a gravity wave develops in the stable free atmosphere with a wavelength given by Eq. (5). Since convective cells in the CBL can adjust to gravity wave forcing, as mentioned earlier, a horizontal wave develops (Townsend 1965) that does not propagate energy and momentum aloft. [This is in contrast to mountain lee waves that develop as winds aloft flow over a fixed obstruction, whose scale is typically much longer than the horizontal wavelength given in Eq. (5). Therefore, mountain lee waves typically tilt and propagate energy and momentum vertically.] The wave in the free troposphere, initiated by energetic convective cells, propagates at its phase velocity, identical to and along the interfacial wind shear vector, with other energetic convective cells preferentially growing under the crests of the wave downshear. The crests and troughs of the wave, which are normal to the plane of the interfacial wind shear vector, advect downfetch, driven by the downfetch components of the wind in both the CBL and the free troposphere (fetch is assumed to be perpendicular to the plane of the interfacial wind shear vector). As a result, a gravity wave field develops with energetic convective cells under the wave crests, giving rise to a pattern of long linear parallel convective features, which may cover an area of several hundred kilometers on a side. For the conceptual model, the gravity wave wavelength becomes an estimate of the spacing of the long linear CBL features and the orientation of these features is estimated to be in a direction normal to the plane of the interfacial wind shear vector. Figure 4a, a view of the lower atmosphere looking at the plane of the interfacial wind shear vector, provides a sketch of the conceptual model described above and also a rendering of what is seen in the image of Fig. 1. Randomly sized convective cells grouped under the crests of a long-wavelength gravity wave. Tilting of the cells may occur in the upper CBL because of wind shear. When the LCL is low enough, clouds form at the top of each convective cell. (b) A conceptual view of (a), from above, showing clouds under a long-wavelength gravity wave. (c) A sketch of individual convective cells organized under a short-wavelength gravity wave. Tilting of the cells may occur in the upper CBL due to wind shear. When the LCL is low enough, clouds form at the top of each convective cell. (d) A conceptual view of (c), from above, showing clouds at the top of each convective cell resulting in a cloud street pattern that appears as “pears on a string.”

The fact that energetic convective cells can adjust to gravity wave forcing and that Townsend’s study shows that their height structure resonates with the Brunt–Väisälä frequency of the stable free troposphere aloft provides an expectation that the conceptual model may apply to a broad range of atmospheric conditions. With this in mind, a discussion of the implications of the conceptual model follows.

Cold air outbreaks over the ocean, after the passage of a strong arctic cold front, constitute the condition for one of the most frequent occurrences of large fields of long linear horizontal CBL features, which frequently manifest as cloud streets. During a cold air outbreak over the ocean the wind aloft blow generally out of the northwest. Because of the cold air advection the wind tends to back (turn counterclockwise) with altitude, resulting in the low-level winds being generally out of the north. If, as the
The conceptual model suggests and is often observed, most of this turning is concentrated at the interface between the CBL and the free troposphere, then there will be an opposing flow between the two layers in the plane of the interfacial wind shear vector. With arctic cold air blowing over relatively warm ocean water, there is ample heat and moisture flux at the surface to create the energetic convective cells needed to initiate and sustain the gravity wave. As the conceptual model suggests, a two-dimensional field of parallel linear convective features develops in the CBL, made visible by the clouds, which frequently form at the top of the most energetic convective cells.

The conceptual model can also explain the change in cloud street characteristics as a function of fetch seen in satellite images. Satellite images of well-developed cloud streets frequently show, as clouds first develop offshore, lines of individual clouds (pearls on a string) separated by a few kilometers. For this case, as the clouds first form offshore, during a cold air outbreak, the gravity wave wavelength would tend to match the typical CBL scale of convection (aspect ratio of 2:1–4:1), thus giving rise to individual clouds organized into long lines. A sketch of this conceptual model suggests and is often observed, most of this turning is concentrated at the interface between the CBL and the free troposphere, then there will be an opposing flow between the two layers in the plane of the interfacial wind shear vector. With arctic cold air blowing over relatively warm ocean water, there is ample heat and moisture flux at the surface to create the energetic convective cells needed to initiate and sustain the gravity wave. As the conceptual model suggests, a two-dimensional field of parallel linear convective features develops in the CBL, made visible by the clouds, which frequently form at the top of the most energetic convective cells.

The two cases, for the purpose of this heuristic demonstration, are summarized in Table 1. The last column in the table provides the estimated spacing and orientation of the linear convective features for both cases as the CBL deepens. As mentioned earlier, the spacing is determined using Eq. (5), and the orientation is set to be normal to $V_{sh}$. It can be noted from the last column of the table for case one that if the free tropospheric winds were as anticipated, then the spacing of the linear convective features would increase from about 3.7 km for a CBL depth below 500 m to about 9.9 km for a CBL depth below 3000 m. Because of the slight backing of the wind with altitude, the linear convective features would be reasonably straight, oriented at $180^\circ \pm 2^\circ$, as the CBL depth increases. For case 2, the last column of the table shows that the spacing of the linear convective features would increase from about 4.1 km for a CBL depth below 500 m to about 7.4 km for a CBL depth below 3000 m. The orientation of the long linear convective features, for this case, would start out pointing about $9^\circ$ west of due south (CBL depth below 500 m) and gradually curve to the east as the CBL depth increases to

### Table 1: A heuristic demonstration of the change in the spacing and orientation of linear convective features as a function of fetch using the wind profile given in Fig. 3b as a guide to anticipate the CBL and free-troposphere winds as the CBL deepens. The vector winds (winds pointing in the direction that the wind is blowing) shown in the table are as follows: $V_{bl}$ is the boundary layer wind, $V_{ft}$ is the free troposphere wind, and $V_{sh}$ is the interfacial wind shear.

<table>
<thead>
<tr>
<th>CBL depth (m)</th>
<th>$N$</th>
<th>$V_{bl}$</th>
<th>$V_{ft}$</th>
<th>$V_{sh}$</th>
<th>Spacing and orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–500</td>
<td>0.0167</td>
<td>10 m s$^{-1}$ at 170$^\circ$</td>
<td>15 m s$^{-1}$ at 130$^\circ$</td>
<td>9.7 m s$^{-1}$ at 89$^\circ$</td>
<td>3.7 km at 179$^\circ$</td>
</tr>
<tr>
<td>1000–1500</td>
<td>0.0167</td>
<td>10 m s$^{-1}$ at 170$^\circ$</td>
<td>20 m s$^{-1}$ at 120$^\circ$</td>
<td>15.6 m s$^{-1}$ at 91$^\circ$</td>
<td>5.9 km at 181$^\circ$</td>
</tr>
<tr>
<td>2000–2500</td>
<td>0.0167</td>
<td>10 m s$^{-1}$ at 170$^\circ$</td>
<td>25 m s$^{-1}$ at 115$^\circ$</td>
<td>20.9 m s$^{-1}$ at 92$^\circ$</td>
<td>7.9 km at 182$^\circ$</td>
</tr>
<tr>
<td>2500–3000</td>
<td>0.0167</td>
<td>10 m s$^{-1}$ at 170$^\circ$</td>
<td>30 m s$^{-1}$ at 110$^\circ$</td>
<td>26.5 m s$^{-1}$ at 91$^\circ$</td>
<td>9.9 km at 181$^\circ$</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–500</td>
<td>0.0167</td>
<td>8 m s$^{-1}$ at 175$^\circ$</td>
<td>15 m s$^{-1}$ at 130$^\circ$</td>
<td>10.9 m s$^{-1}$ at 99$^\circ$</td>
<td>4.1 km at 189$^\circ$</td>
</tr>
<tr>
<td>1000–1500</td>
<td>0.0167</td>
<td>10 m s$^{-1}$ at 170$^\circ$</td>
<td>20 m s$^{-1}$ at 120$^\circ$</td>
<td>15.6 m s$^{-1}$ at 91$^\circ$</td>
<td>5.9 km at 181$^\circ$</td>
</tr>
<tr>
<td>2000–2500</td>
<td>0.0167</td>
<td>12 m s$^{-1}$ at 165$^\circ$</td>
<td>25 m s$^{-1}$ at 115$^\circ$</td>
<td>19.7 m s$^{-1}$ at 86$^\circ$</td>
<td>7.4 km at 176$^\circ$</td>
</tr>
<tr>
<td>2500–3000</td>
<td>0.0167</td>
<td>15 m s$^{-1}$ at 160$^\circ$</td>
<td>30 m s$^{-1}$ at 110$^\circ$</td>
<td>23.4 m s$^{-1}$ at 80$^\circ$</td>
<td>8.8 km at 170$^\circ$</td>
</tr>
</tbody>
</table>
point about 10° east of due south (CBL depth below 3000 m).

As mentioned above, when the wavelength of the gravity wave aloft is longer than the typical CBL scale of convection (aspect ratio of 2:1–4:1), then multiple cells (or clouds if the updrafts have reached the LCL) may form under the wave crests, as seen in the image of Fig. 1 and the sketch of Fig. 4a. These clouds would not necessarily be aligned one with another but could develop randomly, with a higher number under the wave crests when compared to the wave troughs. In addition, the tops of the clouds above cloud base, the LCL, would tend to follow the shape of the wave. Depending on the height of the LCL an occasional small cloud might also form near the wave troughs. Thus, under these circumstances, a field of clouds might form with more, and slightly deeper, clouds grouped as long broad features separated by the longer wavelength of the gravity wave aloft (see Fig. 4c). As mentioned earlier, LeMone and Meitin (1984) studied broad cloud bands in the tropics. The patterns they observed are similar to Fig. 4b.

Viewed from a low earth-orbiting spacecraft the pattern shown in Fig. 4b (especially for low-resolution imagery) would appear to be widely separated cloud streets. Viewed, in the visible wavelength, from the relatively shallow angle of a geostationary satellite (since the satellite is located over the equator), an image of the pattern of Fig. 4b would show not only the tops but also the sides of the clouds. In this case, the image would display brightness changes associated with both the location and the depth of the clouds, and again would appear to be widely spaced cloud streets. However, from a relatively low-flying aircraft, the pattern of these broad linear cloud bands might be difficult to observe. The authors of this paper participated in another field experiment designed to study the spacing of cloud streets over the North Atlantic using the NASA–GSFC down-looking airborne lidar. Prior to departure, during the flight, and upon return of the aircraft, GOES imagery showed what appeared to be cloud streets in the experiment area. No one on the aircraft, including the authors, observed cloud streets while flying over the experiment area. Instead they saw a random field of shallow cumulus clouds. It is likely that the GOES instrument was imaging brightness changes associated with a linear variation of cloud depths. The subtle, but regular, changes in cloud depth, presumably organized by a long wavelength gravity wave, were impossible to observe from the aircraft.

For a strong cold air outbreak in the midlatitudes, the conceptual model would suggest a region of clear air immediately offshore, followed by a field of cloud streets (pearls on a string) with the street separation widening with fetch and then breaking up into wide bands of clouds. For cloud streets over land, the conceptual model would suggest a similar scenario. The necessary conditions for gravity wave organized cloud streets over land include a capping inversion, a strong heat and moisture flux at the surface, and a turning of the wind at the interface between the CBL and the free atmosphere.

6. Evaluating the conceptual model

This section will compare the conceptual model estimates with data from field experiments conducted over the last 25–30 yr. Unfortunately, very few field programs have published sufficient data to evaluate the conceptual model. Field data on the stability and winds in the free troposphere are frequently unavailable in these published reports. Table 2 lists some of the field programs that have provided sufficient information on the CBL and the stable atmosphere aloft to evaluate the conceptual model. The first six field programs presented in the table are midlatitude and the last three are high latitude. As mentioned earlier, the spacing of the linear convective features is estimated using Eq. (5), and their orientation is estimated to be normal to \( \vec{V}_{sh} \).

With regard to the orientation of the convective features, one finds when comparing the last two columns of Table 2 that with the exception of the two high-latitude field programs of Renfrew and Moore (1999) and Brümmers (1999), the estimated and observed orientation agrees to better than 12°, ranging from a low of 3° for Melfi et al. (1985) to a high of 12° for Weckwerth et al. (1999). The average difference between estimates and observations for these six field programs is 8°.

As far as the spacing of the convective features is concerned, the last two columns of Table 2 show that in four of the six midlatitude field programs the comparisons agree quite well, and the other two have estimated spacing slightly wider than that observed. The three high-latitude field programs also have estimated spacing similar to that observed, especially if one considers the spacing of the perpendicular cloud organization in the Brümmers (1999) study (see Müller et al. 1999). The average difference between the estimated and the observed spacing for all nine field observation cases is 8%. Important aspects of two of the field programs listed in the table are discussed below.

a. Melfi et al. (1985)

In Melfi et al. (1985), the power of the conceptual model was illustrated in their lidar observations of two areas, separated by a 15-km-wide low-level convergence zone (oriented generally in a north–south direction), which showed different horizontal CBL scales that were clearly related to their respective interfacial wind shear. Since the convergence zone was narrow, it is reasonable to assume...
Table 2. Comparison of conceptual model estimates of the orientation and spacing of long linear convective features in the CBL with observations from several published field programs.

The vector winds are as in Table 1.

<table>
<thead>
<tr>
<th>Field program</th>
<th>$\theta$ (K)</th>
<th>$d\theta/dz$ (K m$^{-1}$)</th>
<th>$V_{ld}$ at 170$^\circ$</th>
<th>$V_{ft}$ at 120$^\circ$</th>
<th>$V_{sh}$ at 90$^\circ$</th>
<th>Model spacing and orientation</th>
<th>Observed spacing and orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>280</td>
<td>0.008</td>
<td>10 m s$^{-1}$</td>
<td>20 m s$^{-1}$</td>
<td>15.6 m s$^{-1}$</td>
<td>7.15 km at 180$^\circ$</td>
<td>7.0 km$^a$</td>
</tr>
<tr>
<td>Melli et al. (1985)</td>
<td>274</td>
<td>0.01</td>
<td>11 m s$^{-1}$ at 185$^\circ$</td>
<td>11.7 m s$^{-1}$ at 211$^\circ$</td>
<td>7.1 m s$^{-1}$ at 278$^c$</td>
<td>2.35 km at 188$^c$</td>
<td>2.0 and 2.4 km$^b$ at 180$^c$ ± 5$^c$</td>
</tr>
<tr>
<td>Kelly (1984)</td>
<td>265</td>
<td>0.0156</td>
<td>11 m s$^{-1}$ at 125$^c$</td>
<td>16 m s$^{-1}$ at 150$^c$</td>
<td>6.1 m s$^{-1}$ at 12$^c$</td>
<td>2.45 km at 102$^c$</td>
<td>3–5 km at 110$^c$–120$^d$</td>
</tr>
<tr>
<td>Kueettner et al. (1987)</td>
<td>26 June 1985</td>
<td>307</td>
<td>12 m s$^{-1}$ at 170$^c$</td>
<td>15 m s$^{-1}$ at 100$^c$</td>
<td>15.7 m s$^{-1}$ at 54$^c$</td>
<td>12.9 km at 144$^e$</td>
<td>11–12 km at 135$^e$</td>
</tr>
<tr>
<td></td>
<td>3 July 1984</td>
<td>318</td>
<td>4.0 m s$^{-1}$ at 240$^c$</td>
<td>6.0 m s$^{-1}$ at 95$^c$</td>
<td>9.5 m s$^{-1}$ at 81$^c$</td>
<td>9.3 km at 171$^e$</td>
<td>8 km at 230–180$^f$</td>
</tr>
<tr>
<td>Weckwerth et al. (1999)</td>
<td>306</td>
<td>0.0075</td>
<td>2.5 m s$^{-1}$ at 160$^c$</td>
<td>2.5 m s$^{-1}$ at 225$^c$</td>
<td>2.68 m s$^{-1}$ at 282$^e$</td>
<td>1.12 km at 192$^c$</td>
<td>1-1.5 km at 170$^c$–180$^g$</td>
</tr>
<tr>
<td>Walter and Overland (1984)</td>
<td>265</td>
<td>0.0057</td>
<td>19 m s$^{-1}$ at 148$^c$</td>
<td>20.6 m s$^{-1}$ at 162$^c$</td>
<td>5.1 m s$^{-1}$ at 69$^c$</td>
<td>2.25 km at 159$^c$</td>
<td>1.3–1.7 km at 148$^c$–152$^{dh}$</td>
</tr>
<tr>
<td>Renfrew and Moore (1999)</td>
<td>259</td>
<td>0.0034</td>
<td>12.2 m s$^{-1}$ at 36$^i$</td>
<td>25.3 m s$^{-1}$ at 27$^i$</td>
<td>13.4 m s$^{-1}$ at 18$^i$</td>
<td>7.6 km at 108$^i$</td>
<td>4-5 km at 45$^i$, 7-10 km at 45$^{oi}$</td>
</tr>
<tr>
<td>Brümmer (1999)</td>
<td>264</td>
<td>0.02</td>
<td>17.3 m s$^{-1}$ at 190$^i$</td>
<td>8.1 m s$^{-1}$ at 183$^i$</td>
<td>9.0 m s$^{-1}$ at 184$^i$</td>
<td>2.1 km at 94$^i$</td>
<td>3.2–5.0 km at 190$^i$, 2.0 km at 100$^i$</td>
</tr>
</tbody>
</table>

$^a$ Present study: since the present study was conducted during clear-sky conditions, there was no independent measure of the orientation of the convection.

$^b$ Melli et al. (1985) states that the dominant scale of convection was 2 km. See text for an explanation of the two horizontal scales.

$^c$ Cloud streets were observed to the northeast of the experiment area in a satellite image given in Melli et al. (1985).

$^d$ 1200–1411 UTC 10 Jan 1981.

$^e$ Kueettner et al. (1987) shows that the aircraft was flying perpendicular to cloud streets on a heading of 45$^c$. Therefore the long axis of the streets would be at an azimuth of 135$^c$.

$^f$ Kueettner et al. (1987) shows that the aircraft was flying on a heading of 90$^c$, presumably perpendicular to the long axis of the cloud streets. This would make the streets oriented at an azimuth of 180$^c$.

$^g$ 1050 eastern daylight time (EDT) 14 Aug 1995.

$^h$ Walter and Overland (1984) find five scales of convection (1.3–1.7 km was in the aircraft spectra). They give cloud street orientation as 328$^c$–332$^c$, which is equivalent to 148$^c$–152$^c$.

$^i$ Renfrew and Moore (1999) find two scales of convection. Data are analyzed at the dropsonde location near longitude 52$^c$W.

$^{oi}$ 1209 UTC 24 Mar 1993 (see Müller et al. 1999). The 2.0-km scale at 100$^c$ is perpendicular to the principal cloud street pattern.
that the wind and stability in the free troposphere and the energy driving the convection were the same on both sides. The only difference on either side was that the CBL winds on the western side would have had a more westerly component when compared to the CBL winds on the eastern side. The wind in the free troposphere was blowing out of the northeast, so on the western side of the convergence zone there was a larger interfacial wind shear vector than on the eastern side. Consistent with the conceptual model presented earlier [see Eq. (5)], the undulations of the CBL top, observed by their lidar, to the west of the zone were of longer wavelength (spectral peak at 2.4 km with an aspect ratio of about 4.1:1) than the undulations to the east of the zone (spectral peak of 2.0 km with an aspect ratio of about 3.2:1). [See Figs. 3c and 14 (0–15- and 30–45-km spectra) of Melfi et al. (1985).] Also, since the wavelength of the presumed gravity waves in their study was within the typical scale of CBL convection (2–4 times the CBL depth), they observed only single convective cells under each wave crest. In their case, if clouds had formed one would have expected to see a pattern of cloud streets like pearls on a string, with a slightly wider spacing of the streets to the west of the convergence zone.

b. Kuettner et al. (1987)

On 3 July 1984 their aircraft flew into a cloud that topped the CBL. As the aircraft entered the cloud the winds abruptly shifted in speed and direction by 5 m s\(^{-1}\) and 230\(^{\circ}\), respectively. They found that the relative motion of the free troposphere against the cloud was 9 m s\(^{-1}\) from 265\(^{\circ}\). This is equivalent to a wind shear vector of 9 m s\(^{-1}\) pointing at 85\(^{\circ}\), very similar to that given in Table 2. (The wind vectors given in the table were derived from the published mean winds in the CBL and the free troposphere.) The abrupt change in wind clearly demonstrates the necessary condition for the obstacle effect clouds and/or strong convective cells can have on the flow aloft.

7. Summary and conclusions

The interpretation of airborne down-looking lidar data in conjunction with an analytic study by Townsend (1965) has led to the development of a conceptual model that can characterize long linear convective features in the CBL that frequently manifest as cloud streets. Images generated from the lidar data, which depict atmospheric scattering from just below the aircraft to the ocean surface, show three groups of randomly sized energetic convective cells in the CBL highly correlated with the crests of a gravity wave in the free troposphere. The data are consistent with energetic cells acting as obstructions to the flow of the stable atmosphere above. The wave that develops propagates downshear, with larger energetic cells under the three wave crests providing support to maintain the wave. Beyond the third grouping the convective activity in the CBL is noticeably less and the wave damps out. It is shown that the organized convection seen in the lidar data are consistent with an analytic treatment of the interaction of an undulating CBL top overlaid by a stable atmosphere as described by Townsend (1965). He found that time-dependent disturbances on the CBL top moving at a constant velocity relatively quickly (on the order of an hour) adjust to be in resonance with the Brunt–Väisälä frequency of the stable troposphere aloft. He shows that a horizontal gravity wave develops in the stable troposphere with a wavelength proportional to the magnitude of the interfacial wind shear vector at the CBL top and inversely proportional to the Brunt–Väisälä frequency of the stable atmosphere [see Eq. (5)]. A horizontal gravity wave does not propagate momentum aloft and therefore, in this case, long linear convective features in the CBL would not impact circulation in the upper troposphere. The predicted wavelength of the gravity wave and the lidar observed wavelength agreed remarkably well. As a result of the good agreement, a conceptual model was presented that can be used to estimate the spacing and orientation of long linear convective features in the midlatitude CBL, such as cloud streets. The model depends on energetic convective cells in the CBL that penetrate into a stable layer aloft and act as obstructions to the flow. As the wave propagates downshear, other strong convective cells preferentially grow to be under subsequent crests to support the wave. The wave crests and troughs are advected downshear by wind components of both the CBL and the free troposphere that are normal to the interfacial wind shear vector at the CBL top. As a result, a gravity wave field develops with convective cells under the wave crests resulting in long parallel convective features, which frequently manifest as cloud streets.

During a cold air outbreak, clear-air convective cells initially orient under the wave crests of the relatively short wavelength gravity waves. At some point down-fetch, clouds form on the tops of the convective cells under the wave crests and a field of cloud streets develop like pearls on a string. Farther downfetch as the CBL grows into stronger winds aloft, the gravity wave wavelength increases, and multiple cells orient under the crests, leading to a broadening of the cloud spacing with multiple clouds developing along the extension of the cloud street pattern.

The most important characteristics of the conceptual model, and those which are necessary for the development
of gravity wave organized long linear convective features in the CBL, are as follows: 1) a capping inversion at the CBL top, 2) strong heat and moisture fluxes at the surface giving rise to energetic convective cells that initiate and support the gravity wave aloft, and 3) turning of the wind at the interface between the CBL and the stable atmosphere above.

The estimates of the conceptual model have been compared with observations from this study and eight other field programs. With two exceptions (both high-latitude studies), the estimated spacing and orientation of cloud streets compared favorably with observations. Including all nine comparisons, the difference between the estimated and observed spacing was on average 8%. The average difference in orientation of the cloud streets for six of the observations when compared to the estimates was 8°.

In conclusion, the simple two-layer conceptual model can be used to estimate the orientation and spacing of long linear CBL features. It can account for the change in character of midlatitude cloud streets, as a function of fetch, during cold air outbreaks. The conceptual model allows for multiple scales within the CBL, as observed by others. Within the CBL, the conceptual model depends only on energetic convection, which is seen in the lidar image as randomly sized convective cells. Unlike the classical roll vortex theory, the conceptual model can account for cloud street orientations that differ significantly from the direction of the CBL wind, and for cloud street spacing wider than 2–4 times the depth of the CBL.

A field program specifically designed to further study the applicability of the conceptual model presented here should be conducted. The field program should include the following: 1) aircraft flights into and out of convective cells and/or clouds during a cold air outbreak/cloud street event to measure, as Kuettnert et al. (1987) did, the wind vectors into and out of the cells/clouds to obtain an accurate wind shear vector; 2) aircraft soundings to determine the stability of the free atmosphere just above the highest convective cells and/or clouds, 3) level flights over the cloud streets, perpendicular to their long axis with a down-looking lidar, to measure CBL structure, and a gust probe to confirm the presence of gravity waves in the stable atmosphere; 4) level flights within the CBL, also perpendicular to the cloud street’s long axis, to measure the scales of convective activity; 5) an estimate of surface fluxes; and 6) coincident satellite imagery to accurately determine the spacing and orientation of the field of cloud streets.

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REFERENCES


