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Review

Coupling of the Earth's Surfaces to the Lower Atmospheres

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Abstract: This brief review introduces some general properties of lower atmospheric motions that may be exploited by birds, linking historical findings and current knowledge from both observational and modeling perspectives. The relative importance of turbulent mixing resulting from wind shear and that from buoyant thermals is emphasized as well as the determinants of the geometry of the resulting vertical motions.

Keywords: turbulence and thermals; atmospheric boundary layer

Implications: The heated ground warms the adjacent air layer, provoking upward motion in newly buoyant air, called thermals. Mixing also results from strong changes in wind speed very near the surface. Wide variation in these vertical motions are elements of the avian atmospheric habitat that birds may exploit. The likelihood of regular patterns in vertical motions is associated with local surfaces heating the air.

1. Introduction

Birds have adapted to a range of atmospheric systems that provide sustained vertical velocities from the surface to considerable depths in the atmosphere. While humans are more likely to examine mean conditions and statistical properties, a bird may also seek clues for imminent lift, to aid in gaining altitude. For them, finding a living in the 'airspace habitat' [1] is an existential issue. They must exploit this atmospheric habitat efficiently to survive, seeking clues from the flow field itself to determine their launch decisions and guide their path through the air, a struggle highly particular to current conditions. When people refer to a 'bird's-eye view' they usually mean the prospect as seen from on high, but the backyard hen who scurries under the deck in response to seeing a shadow pass over the ground—be it a hawk or low-flying plane—also exercises its own 'avian eye'. This very brief review addresses some aspects of motions in the lower atmosphere that may be important to birds, largely from a scientific perspective. This necessarily means that the emphasis is on the general, when the particular geometry of the land and atmosphere is where the birds must make their determinations. The author anticipates that other articles in this issue focus on the peculiar aspects of avian behavior, how they make efficient use of their airspace habitat. Here the modest goal is to present an overview of some features of the lower atmosphere motions relevant to avian life.

2. Basic concepts about lower atmospheric density structure and winds

Wind results from horizontal variations in temperature and consequent pressure gradients. These variations are brought on by large scale weather systems or by local surface contrasts. In the atmospheric sciences, the boundary layer is considered to be that region in which the direct influences of the surface affect the state and dynamics of the atmosphere. Locally, the landscape surface texture—e.g., albedo, roughness, topography-- influences how the land heat and cools the lower atmosphere. Each bird species thrives in a preferred range of lower atmospheric conditions characterized by a range of horizontal winds, vertical motions, and temperature.

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2.1. Atmospheric stability, near-surface winds, and the origin of turbulence.

The strongest persistent gradients of wind speed, called shear, humidity and other variables occur near the ground. A viscous fluid cannot sustain strong wind shear without breaking down into smaller turbulent motions, called eddies. Turbulence, though apparently disordered, is not random—kinetic energy conducts down through ever smaller scales ultimately to be dissipated as heat. Though not random, atmospheric turbulence is most frequently described in statistical terms. This turbulent activity mixes the lower atmosphere, more or less intensely depending on how the average density changes with height. Meteorologists prefer to describe density using the potential temperature θ, whose profile is a mirror image of the density adjusted for the decrease in mean pressure with altitude—increasing θ means decreasing density.[1] A layer for which θ increases with height is referred to a 'stable', since it would take energy to move denser air vertically. In the opposite situation, the layer is 'convective', ripe for generating vertical turbulent motions, sometimes called thermals. We resist calling this condition 'unstable', since this situation persists over land for hours daily. The basic understanding of the origin and maintenance of turbulence was understood in the 1920's, formalized twenty years later using dimensional analysis by several scientists. Empirical confirmation of these concepts was realized over time as instrumental and computational capabilities improved. For the curious, Garstang and Fitzjarrald [2] present a historical overview.

Vertical motions in the lower atmosphere result either from wind-shear related turbulence or when the lower boundary is heated. Following Archimedes' Principle, what occurs during the day over land for example, and over large regions of the ocean, heat emanating from the surface both warms and mixes the lowest layer. A parcel of lower density air will be buoyant, experiencing an upward force. In the opposite situation, locally cooler air would move down. The ratio of the 'buoyant production' to the 'shear production' of turbulence is often described using z / L in the surface layer, where z is the height above the surface and L depends on the turbulent heat and momentum fluxes[2]. In the stable surface layer $z / L > 0$—nocturnal conditions over land, or air – sea temperature > 0 over water; $z / L < 0$ describes the convective surface layer. In the deeper boundary layer $h/L < 0$ describes convective conditions and $h/L > 0$ is its stable counterpart (see below). These ratios describe the relative importance of wind shear and buoyancy on mixing in the boundary layer.

2.2. Surface energy budget.

The dual heating and mixing roles of surface buoyancy effects determine the degree of mixing in the lower atmosphere. This warming depends during the daytime on incident solar radiation and its reflection and at all times on the net balance of thermal (infrared) radiation. How the sum of the components comprising the net radiative flux is distributed determines to what degree the surface heats the lower atmosphere, and how this 'available energy' is partitioned into directly heating the atmosphere (H), evaporating water from surfaces or through plants (LE) as well what is used to heat underlying soil and vegetation layers. This balance determines to what degree vertical motions in the boundary layer are generated (convective case) or suppressed (stable situation). Such is the genesis of the buoyantly-produced turbulent kinetic energy realized in the eddies that simultaneously warm and mix the lower atmosphere. Note that H and LE vary widely over the globe by latitude and season, and whether the surface is over land or water.

[1] A small correction to account for the effect of water vapor on air density is sometimes included in the *virtual* potential temperature $_v$.

[2] L is the Obukhov length. z/L gives information equivalent to that by the Richardson Number.

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2.3. Atmospheric surface layer.

Observation and dimensional analysis revealed that in the *atmospheric surface layer*, the size of turbulent eddies depends on the height above the surface, *z*. Here the mean wind profile varies approximately logarithmically with height Surface layer stability is identified by a ratio *z*/*L*, whose size indicates the relative importance of mixing by buoyant parcels to that caused by wind shear. At small *z*, only the latter dominates. The effects of buoyancy on the layer during convective conditions are dominant above for -*z*/*L* > 0.6 [3]. (For reference -*L* can be ≈ 50-100 m during the afternoon over land.) What the birds might profit most from is assessing the likelihood the imminent arrival of an updraft, whose typical structure (Figure 1) could give appropriate clues. Surface layer wind shear leads to 'tilted plumes', whose identity can be detected at the surface [4] Such a surface signature holds the clue to determining when a bird might launch to enter the coming updraft (Figure 1, [5]; see below). The key element for the birds is that there be regular *or* predictable motions, such that they might seek very short-term "forecasts". While many birds exploit the atmosphere above the surface layer, the albatross can soar for many kilometers staying within 20 m of the surface above the southern ocean, well within the surface layer [6-7].

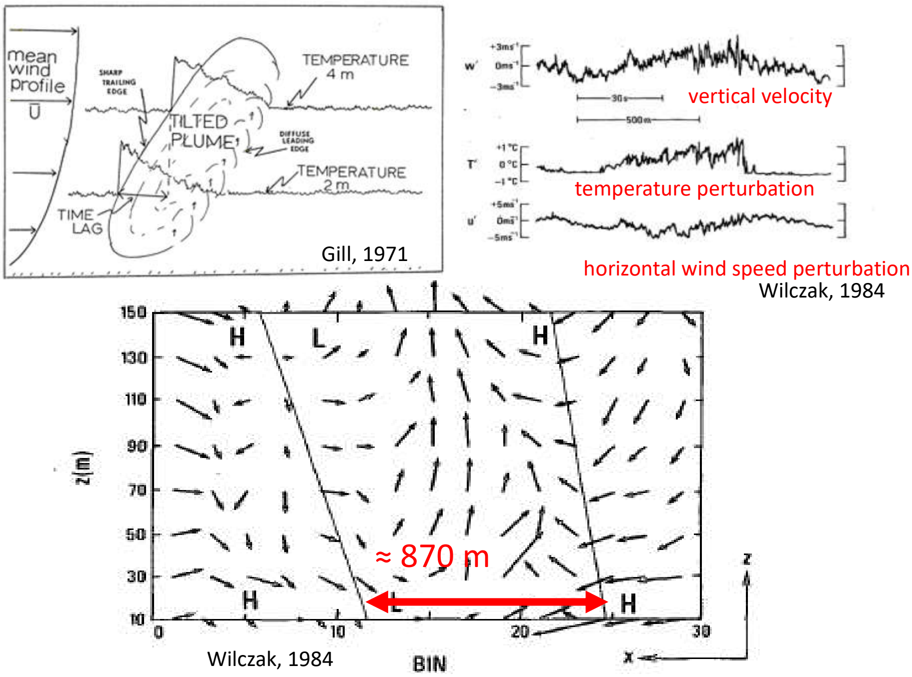

Figure 1. Large eddies leave a signature in the atmospheric surface layer that birds might recognize. These arrive as 'ramp events', shown in the schematic, upper left [4]. Upper right: time sequence of vertical velocity, temperature perturbation and horizontal wind as a ramp arrives at an observation point. Bottom: a composite of several such events, showing how it might be possible for a creature to anticipate an arriving updraft while still at the surface (Upper right and bottom images adapted from Wilczak [5]).

2.4. The boundary layer up to cloud base

In the deeper boundary layer, *h*/*L* < 0 describes the convective condition and *h*/*L* > 0 is its stable counterpart. The convective boundary layer (CBL) is one of the most successful idealizations in this field, largely because vigorous mixing averages the mean structure over many local surface inhomogeneities. The combined heating and stirring effects of surface buoyancy fluxes leads to a *mixed layer* in θ as well as in specific humidity *q* and other scalars (Figure 2, boreal forest). Mixed-layer structure has been seen nearly everywhere when the sensible heat flux *H > 0*, up to the thickness *h,* the level of a capping stable inversion base. The intensity of vertical mixing is described by the strength of buoyant updrafts. Improvements in observational and modeling capabilities in recent years

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illustrates details of the vertical motions that lead to the mixing (Figure 3, North American Great Plains). The vertical slices in that figure show how concentrated updrafts extend up to the inversion base at *h*, with the variance of the vertical velocity showing a mid-layer maximum both in the observations and in the computer simulations.

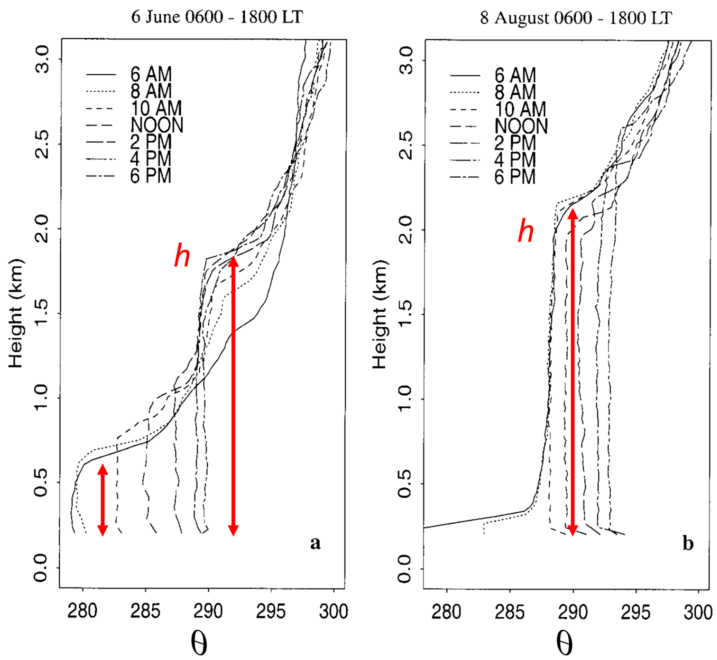

Figure 2. Evolution of the convective boundary layer CBL (mixed layer) thickness *h* on the first (left) after cold frontal passage and (right) on a day in which the convective layer grows into an established residual mixed layer from the previous day in the Canadian boreal forest (55.74°N, 97.86° W). Boundary layer growth is slower when it must act against a potential temperature (θ) inversion in the first case. The mixed layer *h* rises rapidly into the residual layer from the previous day in the second case [8].

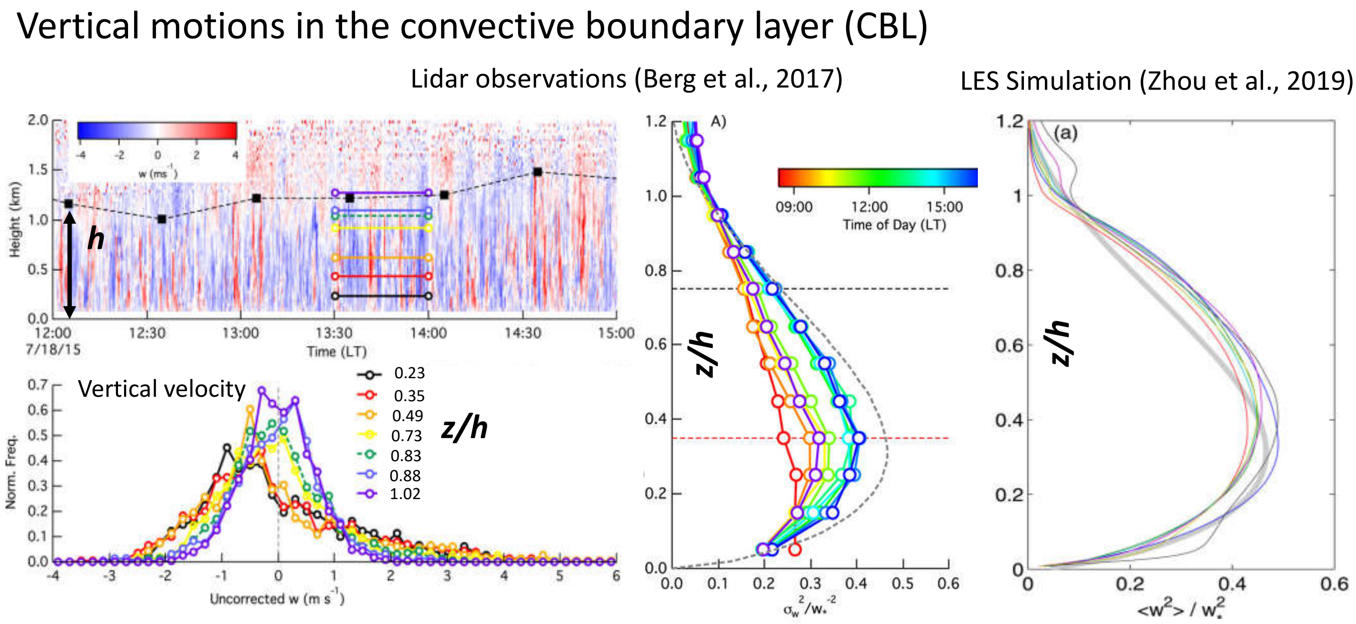

Figure 3. Vertical motions in the convective boundary layer (CBL). Top left: Doppler radar observations for a single day in Oklahoma showing upward (red) and downward (blue) motions in the layer in a vertical cross section. Bottom left: The distribution of vertical velocity changes with position within the CBL. Center: Observed lidar profile of the vertical velocity variance in the CBL. (Images adapted from [9]). Right: Large-eddy CBL simulation of the vertical velocity variance profile. (Image adapted from [10]).

2.5. Bulk thermodynamic and wind structure

Convective boundary layer growth is similar at many sites around the world. Over land, a regular diurnal cycle occurs. Figure 1 illustrates CBL growth in the boreal forest. A similar pattern is seen over the Amazon Rain Forest (Figure 4), each a response to buoyant forcing from the surface sensible heat flux. The temperature and humidity conditions within the CBL define the fair-weather cloud base as indicated above *h* by a small height interval. Over multiple days, the lower atmosphere over land at a midlatitude site shows somewhat regular features (Figure 5), interrupted at intervals by synoptic scale disturbances. One would think that if the birds are to exploit their environment, ‘surprises’ ought to be relatively rare. Note how a stable boundary layer forms at night, and the following day the surface heat flux promotes growth of the CBL, culminating in the case shown with clouds appearing. The vertical velocity upper boundary moves up as the capping inversion is eroded.

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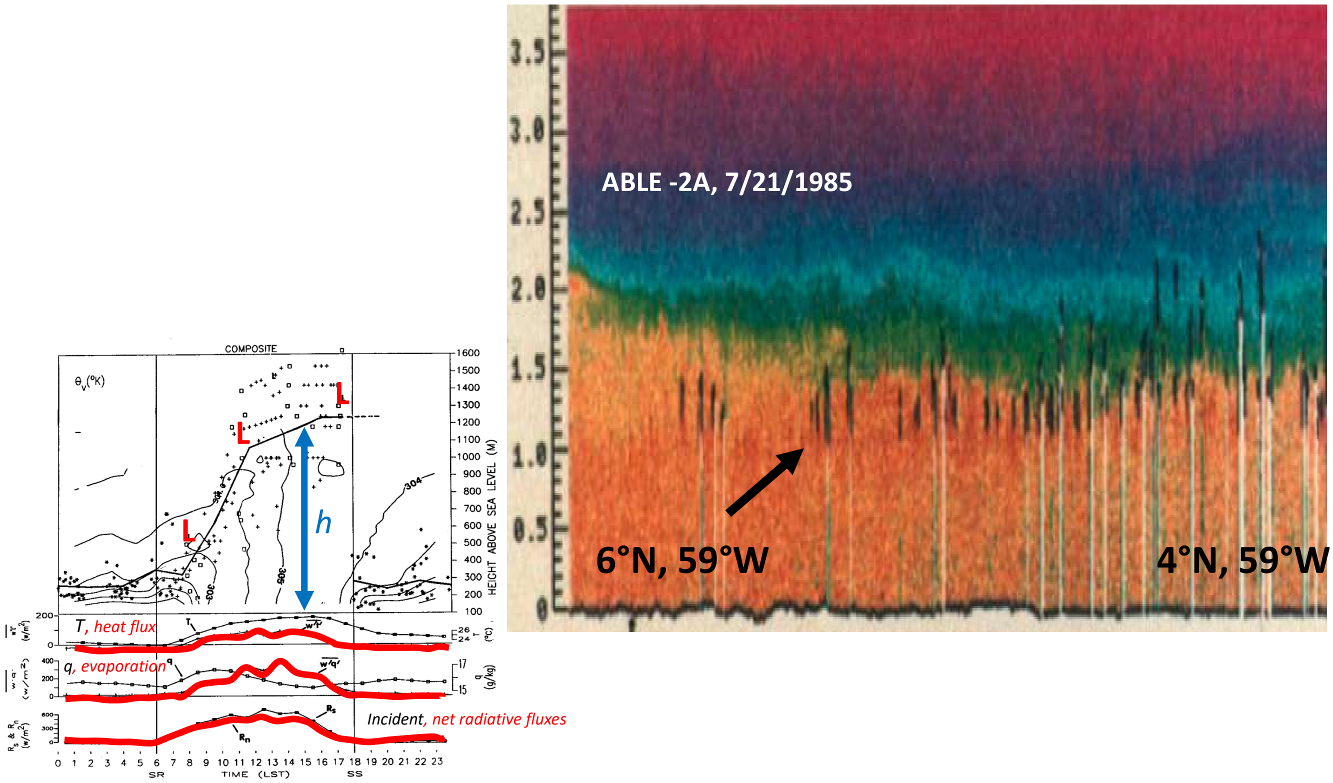

Figure 4. Left upper: The diurnal course of convective boundary layer ***h*** growth over the Amazon Forest (2.96°S, 59.93°W) shown at left in a composite of several days. "**L**" denotes the altitude of the lifting condensation level. Below left: the sensible heat flux that drives the growth and evaporation flux whose convergence helps determine **L** are illustrated (emphasis red). Right: Example of lidar-determined aerosol density (colors) cloud presence (black stripes, arrow) at midday during fair weather conditions during the same period as detailed in the boundary layer plot at left. (adapted from [11]).

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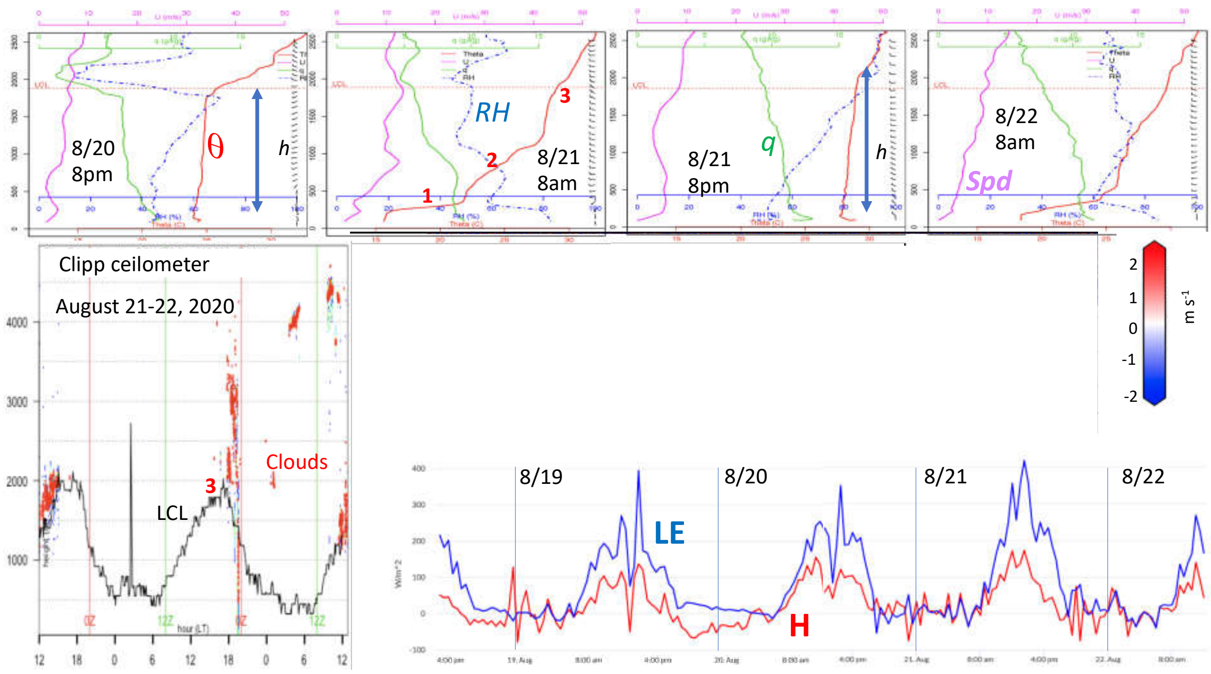

Figure 5. Mosaic of plots for a fair late summer day at Albany NY (42.65°N, 73.75°W) illustrate the links among surface forcing, lower atmosphere structure, thermals and clouds. Top row: Sounding profiles from the National Weather Service Forecast Office, Albany illustrate how the convective boundary layer (CBL) structure inlate afternoon (8pm LT, 0Z) on one day is transformed overnight into a stable boundary situation, with a residual layer above (8 am LT, 12Z early morning sounding). By late afternoon (8pm LT, 0Z) on the following day a slightly deeper mixed layer ***h*** is evident, and the sequence repeated overnight. Note the potential temperature θ, red and specific humidity q, green traces that illustrate the afternoon mixed layers. The Albany NYS Mesonet lidar observation of the CBL (center, right) shows a wide variation and appreciable magnitudes in the CBL vertical velocity over the day: red areas are updraft thermals; blue are downdrafts. Note that the vertical extent of the updraft increases throughout the day as the nocturnal stable layers are eroded in sequence by the turbulent mixing, a consequence of the surface sensible heat flux **H** (see "1", "2", and "3" in the plots), while the water vapor flux **LE** serves to help moisten the layer, defining the lifting condensation level (LCL). Fair-weather clouds appeared late in the day (lower left ceilometer record). [source: [12]; Flux and lidar Figures adapted from plots designed by N. Bassil and the staff at the NYS Mesonet. Other plots based on data from the National Weather Service. Ceilometer observations were made by the author. For details about the NYS Mesonet in general consult [13] and for the lidar network see [14].

2.6. Convective habit in the CBL

The magnitude of *-h/L* also describes the geometry of the eddies that mix the CBL, what we call the *convective habit* of the motions. Typical forms of these habits are cellular or linear roll structures. In 1940, Woodcock [15] published observations of herring gull soaring along the East Coast of North America: "*When a convection up-flow is found, the birds must lift themselves fifty, a hundred, two hundred feet* [15, 30, 60 m], *depending upon the strength of the up-flow and of the wind, before the rising rate of the air exceeds their own settling rate, and they are able to begin soaring. However, they detect the presence of the convection when they are flying just a few feet over the sea surface, for one sees them change abruptly from a wing-flapping horizontal flight to a steep climb, before they start the flying tactics characteristic of convection soaring*." Woodcock's insights [15-16] brought early understanding of how the marine boundary layer habit changed with the surface conditions were done through the clever use of observations of herring gull soaring. [15] He found that, for certain combinations of surface wind speed and air-sea temperature difference, birds changed their soaring from a linear to a circular pattern, from which he inferred the former to result from the presence of boundary layer roll circulations, the latter to that of cellular convection. Simpson noted the existence of cloud streets in the Caribbean region in the 1950's

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and 1960's indicated that there were particularly strong roll circulations (Figure 6), with the clouds describing regions of upward motion. In recent times, computer simulation has allowed for more detailed illustration of the eddies that mix the convective boundary layer for ideal conditions (Figure 7). Note how the *habit* of convective switches from linear to cellular behavior as buoyant forcing becomes more dominant. Salesky et al. [18] found that turbulence transported heat more efficiently and momentum less efficiently going from weakly to strongly convective conditions.

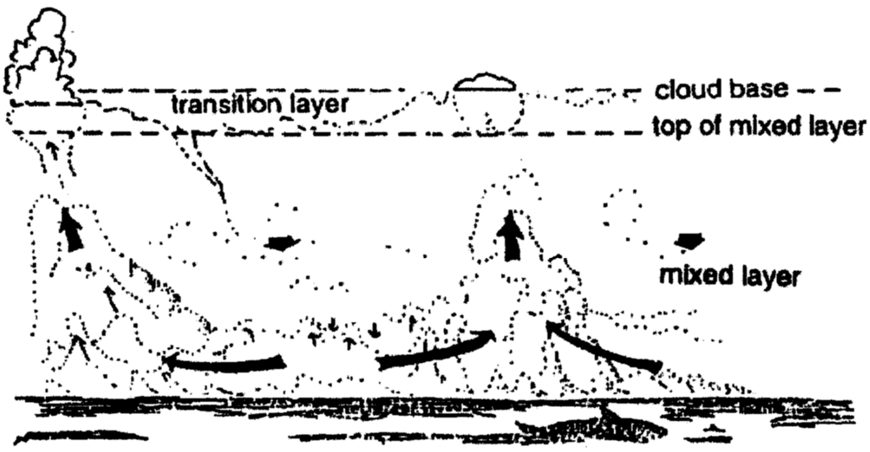

Figure 6. In conditions for which the wind effects dominate the mixing influence of surface-based buoyant eddies, the mean wind can organize structure in the convective boundary layer to form linear features that sometimes lead to cloud streets [17].

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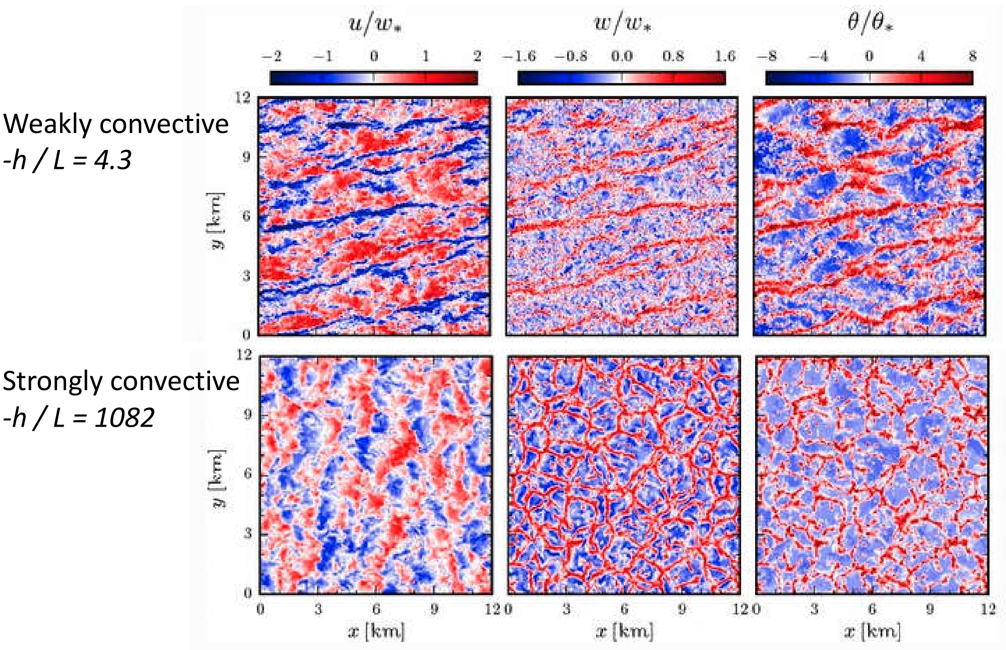

Figure 7. Instantaneous cross-sections of the perturbations of the streamwise velocity component u/w_* (left column), vertical velocity w/w_* (center column), and temperature θ/θ_* (*right column*) from large-eddy computer simulations, here plotted at a height 10% of the mixed layer thickness *h*. For *h* typically ≈1200 m for a midlatitude summer afternoon this is about 120 m above the surface. Winds are scaled by the convective velocity w_*, a scale determined by the surface sensible heat flux and *h*, typically ≈ 0.5-1.5 m s^{-1} under such conditions. As the importance of the horizontal wind shear relative to dry buoyant convection increases from *weakly convective*, denoted by *-h* /*L* = 4.3, top row to *strongly convective -h*/*L* = 1082, bottom row, where *L* is the Obukhov length), the 'habit' of motion changes from linear rolls to a cellular form. Updrafts exceeding 2.5 m/s are seen to be common in selected regions. (Adapted from [18]).

These and other simulations confirm Woodcock's work from 80 years earlier. It brings to mind an interaction from thirty years ago, a striking conversation in the literature between Woodcock and Deardorff, who had then just completed one of the first detailed computer simulations of the convective boundary layer. Deardorff [19] added his two CBL simulations as curves of *h*/*L* on Woodcock's gull soaring behavior chart (Figure 8). Note how the two stabilities Deardorff had simulated showed convective habits that neatly accorded with the distinction between circular and linear soaring in the Woodcock diagram, a particularly satisfying serendipitous result that also forecasts Salesky's results. Also relevant to our current interest in birds is an ancillary discussion these authors had, regarding the behavior of the gulls under the conditions indicated by the red arrow at the bottom of Figure 8. Why did the gulls soar under those conditions? Woodcock opined that perhaps some kind of 'collective gull action'—rising as a flock into the air, would stimulate sufficient updraft to carry the birds up to where the thermal would be strong enough to support their soaring. Deardorff noted two points indicated in Figure 8: "ΔT ≈ 4.3°C denote two of the several occasions when the gulls either took off suddenly from the sea surface and quickly produced their own thermal, or alternately, sensed the near approach of a thermal when on the sea surface and then took off and quickly found its center". Perhaps the birds could 'sense' the soon-to-arrive surface gust front, a possibility evident from Figure 1. Deardorff noted that, with their feet in the water, their heads in the air, feeling the wind and the temperature in both regions, the gulls had all of the 'information' plotted on Woodcock's diagram. This old story reminds us that as research on bird motion continues using geolocation sensors, additional *in situ* (or *intra avem*?) environmental measurements are needed to clarify the triggers for bird behavior.

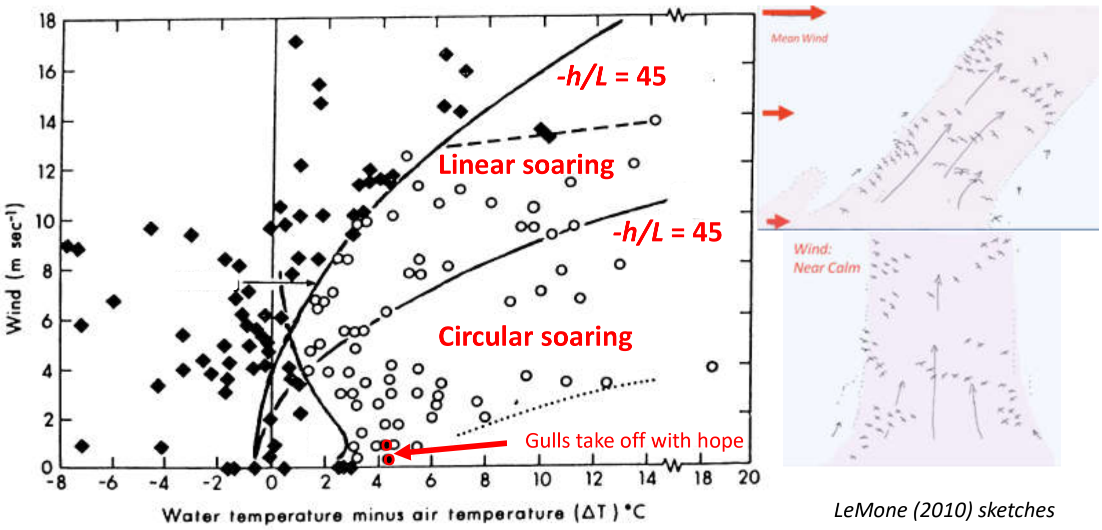

Figure 8. The culmination of the discussion between Woodcock and Deardorff regarding the observed herring gull soaring pattern and its connection to the boundary layer convective habit: Why should the gulls risk launching into flight for conditions illustrated by the red dots with the red arrow? Deardorff [19] drew on his work with one of the earliest large-eddy simulations of the convective boundary layer to include curves for boundary layer stability *-h/L* that delimit the change in soaring habit. At right are sketches by M. A. LeMone to illustrate how the gulls are soaring in the circular and linear fashions [20].

2.7. Geographic effects

Note that all of the computer simulations cited here represented homogenous surfaces. Many of the field campaigns examining the boundary layer were done in relatively featureless landscapes. The rich variety of vertical motions in the lower atmosphere shown earlier *could* be realized above such a homogeneous surface. However, birds (and glider pilots) know that there are regular updraft phenomena associated with the real-world surface texture, either through albedo or roughness variations or topographic changes. Such motions organized on the local or regional scale must surely be exploited by the flying animals.

2.8. Tropical river breeze circulation

Between August 24-28, 2016, a team launched nine altitude-controlled free balloons (controlled meteorological balloons, CMET; Voss, 2010) upwind of the Tapajós River in the east central Amazon Basin, Brazil. While the balloon trajectories do not emulate bird motion, they float freely with the wind. CMET, equipped with altitude control, satellite data communication, and aspirated sensors, allow examination of the interactions among convective boundary layer over land and water and the subsequent river breeze circulations near the great rivers in the region. Soundings established the thickness of interface between the easterly trade and westerly Tapajós breeze circulation. Under such conditions, a westerly river breeze acts against the steady easterly "Trade" wind, allowing the balloon to move alternately east and west depending on altitude even as the channeled flow advected it along the river channel in a 'corkscrew' manner. The strong gradient in surface-atmosphere temperature promotes a regular, geographically-anchored updraft, one that the vultures are seen regularly to appropriate.

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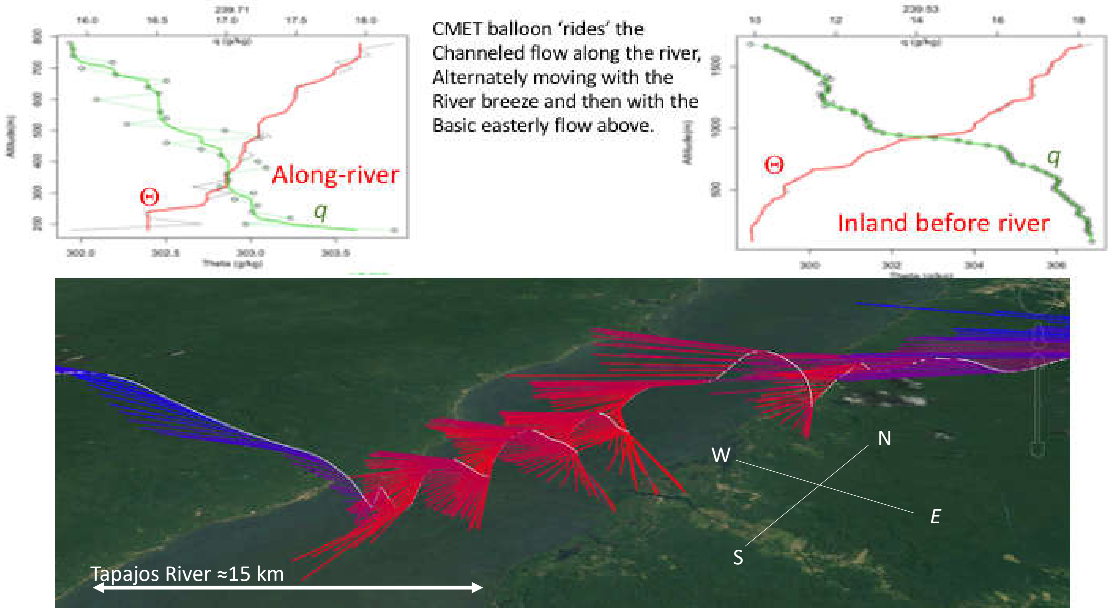

Figure 9. A striking example of how an edge in the landscape produces a regular diurnal wind interface: A controlled meteorological balloon (the Voss CMET [21]) encountered the wide Tapajós River in the Amazon Basin (4.05° S, 54.93° W). The upwind sounding ("Inland before river") is a conventional convective boundary layer. The "Along-river" sounding shows a shallow convective layer. Exercising the balloon by sending alternately to higher and lower altitude caused it to alternate between the easterly and westerly wind regimes. Under such conditions, a westerly river breeze acts against the steady easterly "Trade" Wind, allowing the balloon to move east-west, even as the channeled flow advected it to the south, along the river channel. This alternation caused the balloon to travel in a helical trajectory [22].

3. Discussion

During the day over land, and over large swaths of the ocean turbulent eddies are ubiquitous in the lower atmosphere. They are formed both by strong vertical changes in the winds speed and, as the surface heats the adjacent air, locally warmer spots spawn buoyant eddies—'thermals'. These accomplish mixing in lower layers, defining an important part of the avian habitat. Examples presented here illustrate that the properties of the mixed layer are common throughout the world. Also, it is evident that repeatable sequences of temperature and wind changes precede common upward motions at the edges the upward motions, perhaps offering an environmental clue to a bird in search of assistance in gaining altitude. In the deeper atmosphere such mixing at times may be in linear roll-like elements and at other times expresses cellular motions, depending on the relative importance of horizontal wind and the intensity of buoyant thermals.

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