Part II: Entities and elements of convection

Chapter 4

The buoyancy of lifted air parcels

How does buoyant air ascend through ambient air while satisfying the prime constraint of fluids, mass continuity? Messily, say time-lapse videos of cumulus clouds. We need massive complexity-reduction compromises like the concept of discrete *entities* to bring convection into the five-fingered grasp of human reason. Buoyant clouds are opaque like animals, even though they are actually less substantive than their invisible air environment. We must get what inspiration and information what we can from the observability of cloud 'skins', while recognizing the illusion of cloud identity and heft as both a cognitive hazard and a possibly useful tool. Sometimes they really *are* distinct and long-lived and impactful, deserving of names (hurricanes).

Our only rigorous basis so far for explaining an updraft is Newton's law for vertical acceleration (2.10d, 2.14d), whose b term is the ultimate driver of all fluid motion (problem 2.4.1). We must begin there.

4.1 Graphical analysis for moist thermo and probability

If a kilogram of air lifted to lower p could achieve positive buoyancy relative to its environment, convection is possible. There are two challenges to saying any more with the field equations of Part I. First is the unfinished business of predicting buoyancy with moisture folded in as a moist adiabatic process, leaving only the truly diabatic effects in (2.14e) as the necessary externalities of forcing and complications. Section 4.3 said only that $e_s(T)$ is monotonic and upward-curved, not how to reason with that fact, and a complicated formula doesn't actually help: a graphical way to express the curvature is clearest.

A second challenge to an entity-based viewpoint is how to express multiplicity, and bracket the various complexities that make it silly to take our little elements (like parcels and plumes) too literally. Dressing their depictions in probability garb (or graphical *spaghetti* of *ensembles* of distinct but equally-idealized realizations) helps keep the mind from fixating inappropriately. For instance, a one-dimensional sounding profile $T(p)$, $q(p)$ is usually taken as both the environment and the source of a lifted parcel's properties (from the lowest altitude, or the level of greatest h, or some mixture taken over some convection inflow layer). Data from point sensors on a balloon, released at some particular place and moment and rising slantwise through the sky over an hour, are an imperfect fit to those assumptions, so *representativeness error* sets a useful floor on how fussy to be about precision. The situationally-dependent processes of mixing and microphysics also add diversity to outcomes. Even for an air column from a gridded model, representing an instantaneous average profile, there's a problem with a literal interpretation of either the environment (for fine grids; because parcels don't rise vertically through their own pencil-narrow column sampled at one instant) or the parcel source (for coarse grids; because gravity naturally selects the *best* air for convection, not the average). In any of these cases, an ensemble of parcels rising and mixing and churning through an environment full of statistical fluctuations should be envisioned, and graphics can help cement this appropriate diversity in the viewer's mind.

Perhaps this can soften a culture of sometimes illy fixation on exact numerical values of extremely crude indices like convective available potential energy (CAPE), which can crowd out thinking if students respect thin lines on complicated aerological diagrams too much.

4.2 Conserved variables in lifted air

Our only rigorous basis so far for explaining an updraft is Newton's law for vertical acceleration (2.10d, 2.14d), with its b term as the ultimate driver of all fluid motion (problem 2.4.1). We therefore begin with a graphically supported understanding of the thermodynamics of b for rising parcels of air in a quasi-uniform unstable airmass, before turning to the mass-continuity problem of realizable ascending motions.

We can calculate air parcel density (or T_v) at any pressure using conserved variables, with an iterative solution of the nonlinear saturation condition if $q_t > q_{sat}(T,p)$. Conserved variables in the absence of surface contact, radiative heating, or precipitation, are total water q_t and moist static energy h (section 2.1.5). Figure 4.1 shows profiles of the specific static energies s, h, h_s for a Miami summertime sounding[a].

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[a] Created with the Python (pip) package mseplots-pkg, which rests on thermodynamic constants and functions of the MetPy package from Unidata. It has entropy and potential_temperature keywords, to show how little difference these approaches make.

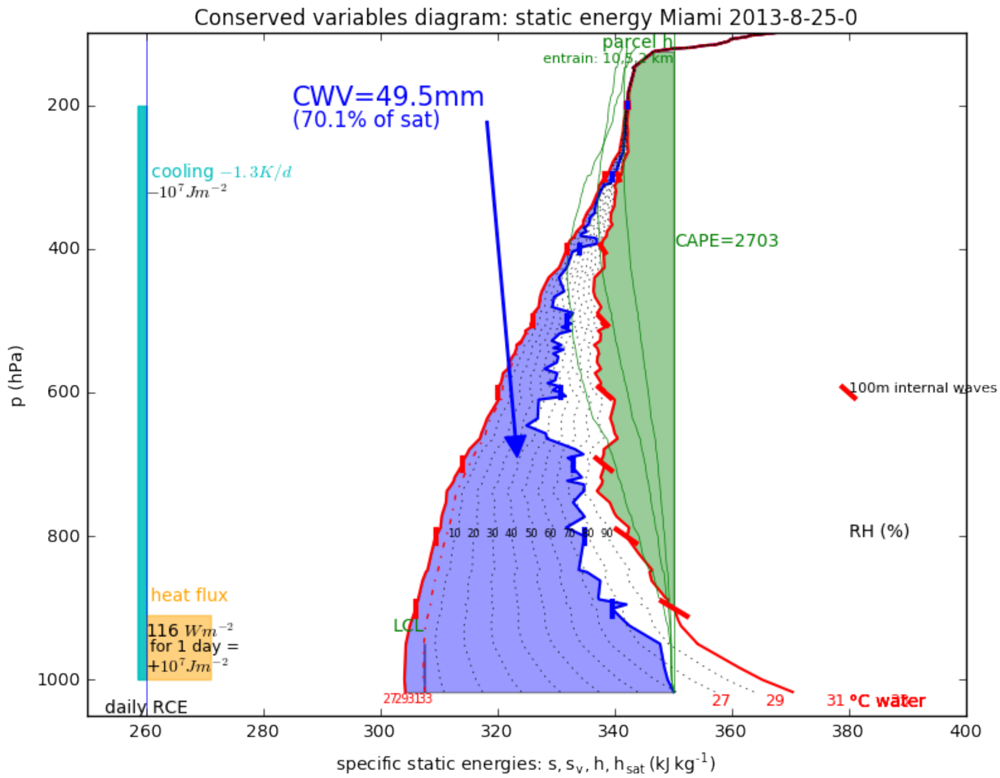

Fig. 4.1. Specific static energy profiles vs. pressure (mass). Static energies from left to right are: dry $s=C_pT+gZ$ (red solid), virtual s_v (red broken), moist $h=s+Lq_v$ (blue), and saturated $h_s=s+Lq_s(T,p)$ (rightmost red solid). Relative humidity RH in 10-90% are dotted (labeled at the 800 hPa level). Blue fill area is proportional to L times column water vapor. Below the lifted condensation level (LCL), buoyancy of a lifted parcel is assessed by the s_v curve. Above the LCL, its sign is indicated by the gap between h_s (red) and h_p for lifted near-surface air parcels (green curves, with entrainment rates of 0 (vertical) and 100% per (10 km,5 km,2 km), which act as the strengths of a linear pull of the rising parcel curve toward the h profile at each level. Thick stubs on *s, h,* h_{sat} profiles every 100 hPa show the effect of hypothetical +/- 100m adiabatic displacements in the air column, comparable to typical internal wave amplitudes, for envisioning their statistical effect on lifted-parcel buoyancy. Red number annotations at bottom show the *s* and h_{sat} of the molecular boundary layer over surface water with temperatures near the sounding's surface temperature, relevant for viewing surface fluxes as another distance-proportional mixing process. Annotations at left centered on 260 kJ/kg indicate typical daily diabatic increments for Earth-like radiative convective equilibrium (RCE), with cyan and orange areas representing 10^7 J m^{-2} of daily static energy changes by radiation (-1.3 K/d, compare Fig. 0.1) and surface flux (orange square, if distributed over a 100 hPa layer).

The reader should appreciate all these reasoning-relevant aspects of the diagram, as evaluated in the Problems and Exercises of section 4.5.

1. The vertical coordinate is hydrostatic pressure, so its increments are proportional to mass ($\Delta p_{hyd} = g\ \Delta m$).
2. The horizontal coordinate is specific energy (units: kJ/kg).
3. Because of 1 and 2, area on the diagram is proportional to energy.
4. Relative humidity RH (the hygrometer measurement) is proportional to the distance between the two indicators of the thermometer measurement (s *and* h_{sat}), as ruled by the dotted lines labeled 10-90%.
5. The filled blue area is proportional to latent energy, L times the column-integrated water vapor or *precipitable*[b] *water vapor.*
6. Unsaturated air conserves s and s_v during vertical displacements, so lifted parcel buoyancy below the lifting condensation level (LCL) and the static stability of unsaturated layers can be assessed by the slope of those leftmost red curves.
7. An undilute surface parcel lifted through the troposphere conserves h (thick vertical green line) even after condensation commences. The vertically integrated buoyancy of this parcel (assuming instant precipitation of condensate) is labeled CAPE. It is not strictly proportional to the green fill area (but nor to any aspect of a realistic convective process; avoid fixation).
8. Lifted parcel buoyancy of any *saturated* parcel (that is, above its LCL) is indicated by the horizontal distance between the green h_p and red h_{sat} curves, because at any given altitude $h_p - h_{sat} = C_p(T_p - T_{env}) + L[\ q_{sat}(T_p) - q_{sat}(T_{env})\ ]$ is monotonically (but not linearly) related to $T_p - T_{env}$, as expressed in section (2.3).
9. Horizontal mixing with the environment (entrainment) pulls any lifted parcel (green curves) toward the environmental h (blue curve) with a strength that is linearly related to diagram distance.
10. Surface flux can be viewed as a mixing process with the microlayer of air that is in thermodynamic equilibrium with the

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[b] This old term for condensed puddle depth in mm or kg m^{-2} (section 1.1) may have stemmed from rough coincidence of its typical values with typical rainstorm totals.

surface. Over water, that microlayer is saturated at the water temperature. If that water temperature is known, latent and sensible heat fluxes (respectively) are proportional to the respective distances between the sounding's lowest-level air values and the water temperature values (centered red number annotations at the bottom of the diagram).

11. The effect of small adiabatic vertical displacements in the environment (such as by buoyancy waves, section 2.2.3) is indicated by whiskers on the *s, h,* and h_{sat} curves. These are vertical on the s and h curves (both are conserved), but are sloped on the h_{sat} curve expressing nonlinear nature of the Clausius-Clapeyron relationship $e_{sat}(T)$.
12. A well-mixed unsaturated layer has a vertical s curve (like the *planetary boundary layer* PBL here), since absolute instability rapidly mixes a layer if *s* (strictly, s_v) decreases with height.
13. Energy added to the mixed-layer PBL by surface fluxes (area on the diagram, by point 3.) will be spread over a layer whose depth is defined by the area added and by the condition of verticality of s_v upward from the surface. Sensible heat flux SHF increases *s*, while SHF plus latent heat flux (LHF) moves the *h* curve to the right (adding *area* encompassed by the h curve). These principles are sufficient to distribute any given {SHF, LHF} energy input over a mixed-layer PBL from any initial sounding like a morning sounding on a summer day.

A few other points are worth noting:

- The relative smallness of water's virtual contribution to buoyancy, compared to its latent heating impact, can be appreciated graphically.
- There is no fundamental area relation for the distance that diabatic heating like SHF moves the h_s to the right. The h_s curve is the locus of the main nonlinearity, the Clausius-Clapeyron curvature of $e_s(T)$, and is the main reason we need a diagram instead of just equations.
- It is not possible to read the absolute temperature off the diagram; annotation along the s curve for the 0C level

would be a useful addition to respect the importance of ice.

4.3 Parcel diversity, dilution, and detrainment profiles

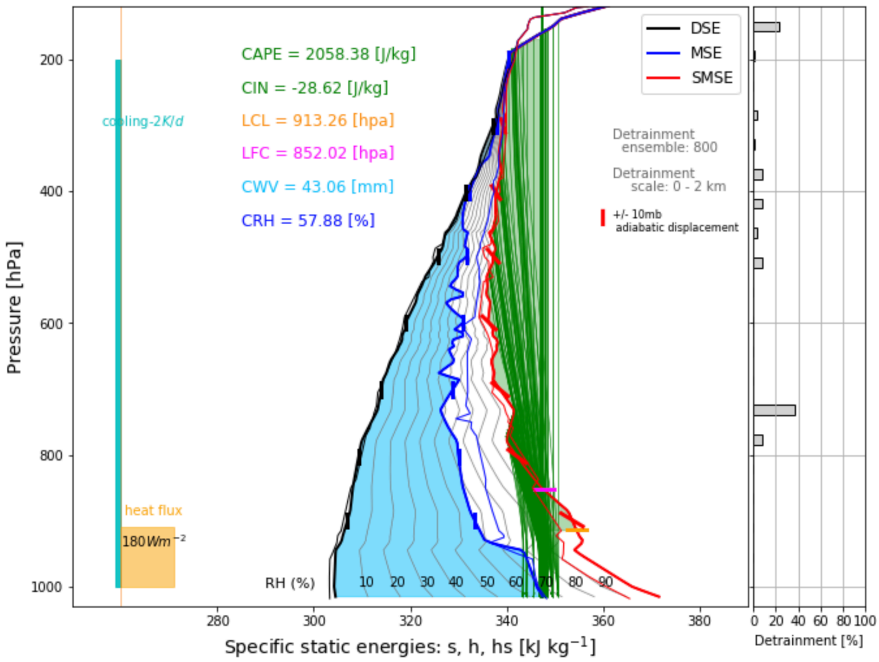

Fig. 4.2. As in Fig. 4.1, but for a different time and with some statistical features. Surface parcels are lifted from an assumed distribution of h values centered on the balloon data, each subject to a set of different entrainment rates. The bar plot at right shows the histogram of topmost $b>0$ altitudes for members of the ensemble, as an estimate of cloud top layers that might be produced by natural variability in the PBL and by the many mixtures created inside clouds. A second balloon sounding one day later is also overlaid, to illustrate the size of day to day variations.

Figure 4.2 shows a similar diagram with an ensemble of thermodynamically possible lifted parcels (green curves). These were created with two assumptions (adjustable as keywords in the Python call):

1. Parcel diversity. The balloon is assumed to have sampled the mean of a distribution of PBL h. Based on aircraft data at low

levels over a warm tropical ocean (Kingsmill and Houze 1993), 20 more samples are drawn randomly from a Normal distribution with a standard deviation of 2 kJ/kg[c].

2. Mixing diversity. For each parcel, a fixed *ad hoc* distribution of 5 entrainment rate coefficients is considered, ranging from the 1 km^{-1} value typical of shallow convection (chapter 6) to much smaller values that permit nearly-undilute ascent to great heights.

Together these give 100 parcels, whose altitudes of topmost positive buoyancy (summarized in the bar chart at right) are a crude estimate of the profile of likely detrainment altitudes in the sky. A photograph from the same day suggests some relevance to these computations, although feature altitude is hard to estimate visually (get a photo for Fig. 4.3, or remake for a multi-depth convection case with distinct detrainment levels; also use less silly significant digits on the numerical indices). A computer exercise invites you to explore this relationship for any place and time of your choosing where you might find a photograph near a sounding site, and share your results.

Layers where h_s increases rapidly tend to cap the ascent of relative more parcels in the distribution: in other words, from a broad distribution of h values in buoyant parcels, more will detrain preferentially into stable layers. This is a key mechanism forming a logical basis for a teleological interpretation of convection's job: adjusting the atmosphere toward a moist adiabat (Part III).

4.4 Problems and computer exercises

4.4.1 *Jupyter notebook of MSE plot*

View and obtain the MoistStaticEnergy.ipynb sounding plotting notebook at github.com/brianmapes/ShortCourse. Install Jupyter, and add the Siphon, MetPy, and mseplots-pkg Python packages (instructions

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[c] 1 kJ/kg in h is about 1K in their θ_e; likely a conservative estimate of PBL diversity.

in the notebook). Select a date, time, and location of interest from the Wyoming sounding archive, with interesting convection (maybe where you have an interesting sky photograph or time-lapse or satellite image).

Edit the notebook and execute it (in Jupyter) to display your sounding and interpret it. Are there any discernable differences between static energy plot (with all of the linear sum's clear properties listed above) vs. the entropy or potential-temperatures displays whose nonlinear formulas make those properties less obvious? Illustrate how features correspond to those in the skew-T display there. Discuss.

4.4.2 *Traditional sounding indices for convection*

Consider the many traditional sounding indices, for instance at https://www.spc.noaa.gov/exper/soundings/help/index.html or http://weather.uwyo.edu/upperair/indices.html.
How do the various measures fit into the matrix below?

Indicator of →	Likelihood of convection occurring	Expected (mean or typical) convective outcome or impact	Worst-case hazard the conditions might indicate as possible
Physically based (a crude model of some lifted-parcel scenario)			
Empirically based (calibrated with historical data)			

4.4.3 *IDV conserved-variable display*

Install the free IDV software from Unidata, version 5.6 or later (https://www.unidata.ucar.edu/downloads/idv/nightly/index.jsp). Under the Bundles menu, select Weather→Real Time Weather→Mapes Current Weather→CONUS-jet-vort-xsec-sounding. Wait while the data loads (you must be online). In the Dashboard window, under Field Selector, find the "Latest NCEP…" model data in the Data Sources area at left. In its Fields (3D→Derived), select Conserved Sounding and then click Create Display.

Drag the little squares around for the Sounding (a skew-T log-p plot) and the Probe for the Conserved Variables (a potential temperatures based version of Fig. 4.1). Examine current satellite imagery (on the Web, or in the IDV you can find these in the Data Choosers tab, Sat & Radar → Images area at left).

Move the probes to the same point, somewhere relevant to observed convection, and interpret these different depictions of the same vertical thermodynamic profiles. Which graphical features (distances between curves on the screen) correspond most informatively to distinctions you can see in the convection field? Discuss.