Chapter 0

Overview: our convecting atmosphere

Convection is a means for gravity to lower the center of mass of a fluid body, by bringing relatively denser air as low as possible under realizability constraints such as mass continuity. That statement is *teleological*, expressing the nature of convection by *the job it does.*

Convection is the motion that occurs when displaced parcels in a fluid experience a component of gravitational force that aligns with the displacement. Work is done (force times displacement), generating macroscopic kinetic energy (a coherent component to the motions of all the parcel's molecules), which is quickly redistributed by a pressure field that adjusts at the speed of sound to enforce mass continuity. That description is *mechanistic*, explaining convection by *how motion is imparted to air,* using a teleological account of pressure.

Which definition is truer, which "explanation" is better? Wrong questions: a deep appreciation must encompass both. Before diving in to this book's multi-threaded effort to convey such a tapestry of appreciation, the present chapter 0 summarizes a wide range of background facts and top-level statements. These serve to declare if not quite define[a] key terms (in *italics*) for later use, and to frame if not quite prove the book's account of the phenomenon of atmospheric convection, as argued in the three Parts and their chapters.

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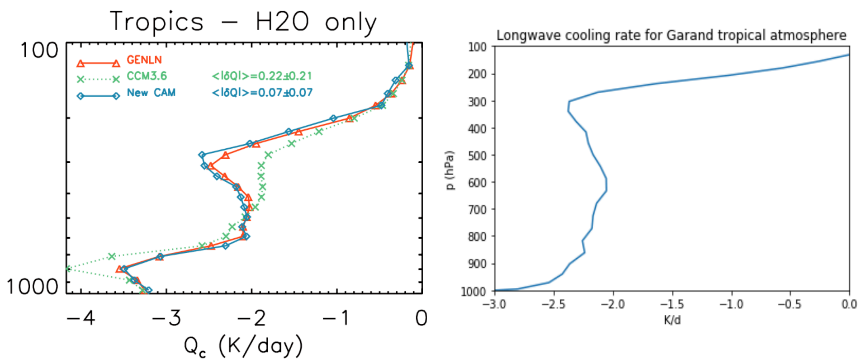
[a] A glossary is at the end of the book; I find vocabulary tests a necessary teaching tool.

A state of possibility for convection is called *gravitational instability*, although there is more than one kind (section 0.4). Earth's atmosphere is perpetually *convecting* because it is perpetually *destabilized* (section 0.1). Although ultimately radiatively driven, "instability" is redistributed by air motions (some of them "convective", by various definitions of that term), which change profiles of *potential density* (the density air *parcels* would have under a hypothetical vertical displacement to a reference altitude or pressure level). Our main interest is in *turbulent* vertical convection, although *laminar* synoptic-scale upglide and downglide of warmer and cooler airmasses in midlatitudes do comprise a *thermally direct* circulation deserving of the name *slantwise convection*[b].

0.1 Sun-heated surface, IR-cooled air, H_2O's 2 height scales

Sunlight reaches Earth's surface because air and water are nearly transparent in the visible part of the electromagnetic spectrum[c]. But without centuries of hard science, no observant person would know quite how air cools by emitting *longwave (infrared)* radiation (Fig 0.1).



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[b] Discussed nicely in the late parts of chapter 7 of Wallace and Hobbs (2006).

[c] This defines *visible*, since our eyes evolved to see through air and water. The spectral narrowness of (https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water) is so special that it bears on life's evolution: our watery Earth and 6000K Sun are very fortuitous, albeit unsurprising by the https://en.wikipedia.org/wiki/Anthropic_principle.

Fig. 0.1. Clear-sky radiative cooling profiles for averaged conditions in the tropical troposphere. Left: Radiative cooling rate change from Old (CCM3.6, green) to New (CAM, blue), an improvement toward the trusted reference (GENLN, red), adapted from Fig. 2 of Collins et al. (2004), which also interestingly explores some climate model impacts from the change. Right: the most up to date treatment (from calculations by Pincus et al. 2019 with input profiles not quite identical to those at left). Shortwave (solar) clear-air heating profiles are similar in shape, and nearly equal at noon, so the daily average or longitudinal average around the Earth is often about 70% of the longwave profiles shown (Mapes and Zuidema 1996).

Reasoning about radiation is possible, despite the complexities of the underlying physics. Purely radiative equilibrium, given air's composition, would feature upper-level temperatures (below the sun heated ozone layer) so cold that, if they existed, world-scouring convection would erupt. But convection has been doing its job for eons, so instead we should think of convection as *maintaining*[d] the troposphere[e] at a temperature far warmer than its radiative equilibrium value. This warmth is an *ultimate cause* account of why air cools radiatively. We can also consider the *proximate cause*[f]: what molecules are emitting the radiation that cools air? That cause is more useful for reasoning about varying concentrations of IR-active (polyatomic) gases like H_2O, which vary more dramatically than the always-large gap between actual temperature T and the useful fiction of a purely radiative equilibrium.

Clouds affect the troposphere's radiative cooling profile profoundly in any local column (illustrated below), and substantially on average (e.g. Kato et al. 2018), but the cooling of clear air and its peculiarly top-heavy profile remain key drivers of the *deep convection* of the entire troposphere. In the time averaged climate, convection (broadly construed) acts to supply energy equal to the emitted amount, level by

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[d] yet another teleological account of convection's "job"

[e] *Tropos* is from Greek, *overturning*. The Tropics are the sun's turning latitudes.

[f] https://en.wikipedia.org/wiki/Proximate_and_ultimate_causation

level, drawing energy from *sensible and latent heat flux* into air that touches the Earth's skin.

The strong infrared cooling near the 300 hPa *pressure level* in Fig. 0.1 is remarkable[g] because water vapor concentrations there (temperature about -35C, altitude about 10km) are only about 1% of surface values. This top-heaviness of infrared cooling requires deep convection to have a top-heavy heating profile on average, which cannot be achieved through the simple condensation of water: there is simply too little vapor mass available at cold upper-level temperatures. In order to do their job in the heat budget, then, deep convective updrafts must carry heat bodily, by being considerably warmer than their interstices. This in turn implies their rarity, in contrast to shallower convective motions that efficiently keep the lower-tropospheric temperature *lapse rate* nearly *neutral* (or *moist adiabatic)*. The foregoing is a stronger version of the inference of *hot towers* by Riehl and Malkus/Simpson (1958, 1979) from observed *moist-conserved variable* profiles -- inferences which, because of their blending of heat and moisture information, could also be satisfied by merely moist towers (implying a penetrative *eddy flux* of water).

Such warm updrafts are quite buoyant, making deep convection (on average) vigorous in the upper troposphere. Lightning and hail (*rimed ice*) are two consequences of upper level vigor, rooted partly in this rotation-band emission by the H_2O molecule. That upper-level cooling also has a litany of other consequences for tropical tropospheric dynamics on Earth (Mapes 2000). Representing this top-heavy cooling requires, at a minimum, a second *spectral band* in the infrared (e.g. Fig. 2 of Vallis et al. 2018) so its consequences for the atmosphere's *general circulation* and climate (merely glimpsed in Collins et al. 2004) are far less widely appreciated than the basic first-order bottom-up nature of tropospheric convection and climate.

[g] This intense *cooling to space* occurs in a distinctive rotation band of the H_2O molecule.

0.2 Top-down vs. bottom-up: w skew of drafts

Top-down convection is simplest to explain, because the displacement-parallel force doing work is gravity, preferentially drawing down air's denser parcels. In *bottom-up* convection, the mean gravity-balancing *hydrostatic* part of the broader-scale pressure field preferentially pushes warmer lighter parcels upward. These gravitational *buoyancy* forces are essentially symmetric, but the logic of upward buoyancy involves an extra logical step from heavy parcels descending. The real asymmetry between bottom-up and top-down depends on whether convection's vertically accelerating parcels are formed by the horizontal gathering of intensely warmed low-level air, or of intensely cooled air aloft. A convenient measure of this asymmetry, indicative of what is driving convection, is the mean cube of vertical velocity in the convecting layer, a statistic called *skew*. When up and down occur equally, the result is *symmetric* convective turbulence[h].

On Earth the thermal driving by radiation never stops, although periodic variations of solar heating offer us daily and seasonal signals we can repeatably observe in convection fields, and study for clues to mechanisms. Important but less *predictable* is the convection-contingent effect of clouds as a feedback on the radiative driving, producing coupled (rather than simply forced) phenomena that challenge our understanding at the frontier. The hope of predicting complex *unforced variability* pays the bills for all science in this area.

Cloud feedbacks on radiation are utterly dominant in the very challenging *open vs. closed cell* problem in cloud-topped boundary layers (Fig. 0.2), corresponding to bottom-up vs. top-down convection (respectively). The *albedo* of Earth, crucial for its energy budget and thus its mean temperature, hinges largely on low cloud fields like Fig. 0.2. The photo shows that local albedo depends on whether convection is top-down (whiter areas, *closed cells*) vs. bottom-up (*open cells*, where the

[h] Symmetric flow may also indicate *decaying* turbulence, perhaps generated by convection (work done) in the past, but now merely air's inertia playing itself out.

blue ocean shows through). But that in turn hinges on the clouds themselves (overcast vs. clearer skies, respectively). The convecting layer therefore exhibits a *hysteresis*, existing in either of two stable, long-lasting states, selected by accidents of history of each patch of air.

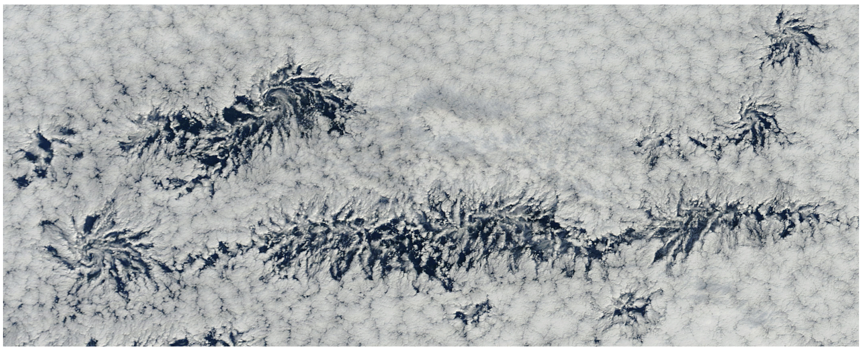

Fig. 0.2. Visible image of a stratocumulus cloud deck over ocean, with pockets of open cells (darker areas) where bottom-up convection prevails, amid closed cells (whiter areas) where convection is top-down. From http://worldview.nasa.gov.

The radiation driving top-down convection is intense cloud-top cooling, illustrated in the aircraft observations (Nicholls 1984) of Fig. 0.3 in and above a stratocumulus cloud deck. Cloudy radiation is complicated, so observations are emphasized here (dots and crosses), supported by calculations (solid curves). The net heating rate depends on radiant energy *flux convergence,* the negative of the vertical derivative of *net flux* (upward minus downward). The right panel shows longwave (IR) flux L, while the left panel shows midday shortwave S (which of course vanishes at night). Arrows denote upward vs. downward flux, measured on the belly and top of the aircraft respectively. The term $-d/dz(L\downarrow)$ is clearly the predominant effect: the absence of downwelling IR radiation is the important "to space" part of the *cooling to space* approximation.

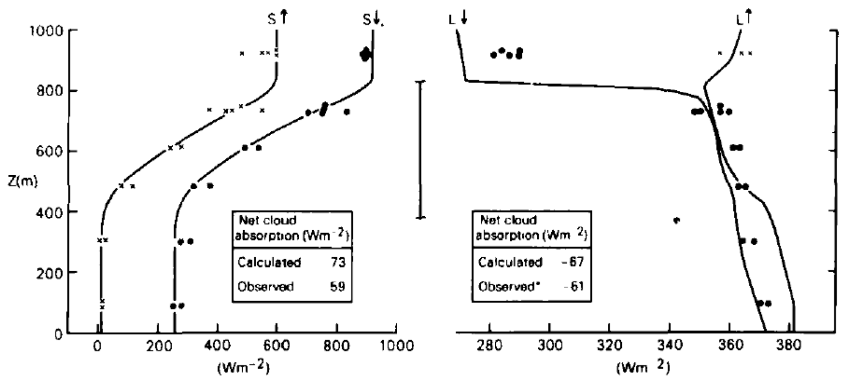

Fig. 0.3. Solar (S, left panel) and longwave (L, right panel) radiative fluxes, with upward and downward components (the *two-stream* approximation) indicated by arrows ↑↓, for a low-latitude stratocumulus cloud deck at midday. Curves are computed estimates, while symbols show aircraft observations. Figure 8 of Nicholls 1984.

0.3 More asymmetry: saturated drafts in stratification

In addition to top-down vs. bottom-up forcing, *moist (cloudy) convection* (see Stevens 2005 for an excellent broad survey) has other distinctive mechanisms that govern its up-down asymmetry (w skew).

1. Latent heat released by water condensation upon ascent contributes a displacement-proportional term to parcel warmth and thus the vertical buoyancy force. This term is partly compensated by *stratification* of the environment, but the latent heating term predominates in buoyant cumulus clouds by definition of buoyant. Besides saturated updrafts, the corresponding effect also occurs in downdrafts if condensed water is available to evaporate.

2. Mixtures of cloudy and clear air can be denser than either constituent. Specifically, the mixing fraction that yields exactly-saturated air has the greatest density of any mixture. This cooling upon mixing is called *buoyancy reversal*, and it can drive downdrafts whose close adjacency to cloudy updrafts can drive shear instability and thus momentum-forced turbulence, which itself feeds back into the mixing process. What scales of motion this effect drives is a little unclear: the mixing must occur at *molecular* scale, and the cloud water must then evaporate (fractions of a second later). Still, the gross density of moist air parcels at every larger scale is affected: when a 1 km turbulent ball of air with internal filaments of cloudy and unsaturated air finally truly mixes, its kilometer-scale bulk density changes!

3. Radiative impacts of cloud particles, especially in “window” spectral bands in which air is transparent, let moist convection

shape its own radiative driving and thus its profile. For instance, besides the intense infrared cooling of cloud tops in Fig. 0.3, cloud shading of land can dramatically weaken the surface heating that drives bottom-up convection.

Environmental stratification in fields of buoyant cumuli (effect 1 above) can be best understood teleologically: convection's job is to drive the unstable layer that spawns it toward *neutrality*. Its efficacy at that job drives the environmental density (by mechanisms clarified later) toward the updraft's profile, a *moist adiabatic* profile appropriate to the convection-governing buoyant draft[i].

Effects 1 and 2 -- buoyancy-releasing vertical drafts in stratified environments, with mixing-dependent negative buoyancy release -- cannot be replicated in any laboratory convection apparatus to date. Mixing-dependent chemical heating or bubble releases can be contrived, but not buoyancy releases that are pressure-dependent over the depth of laboratory tanks. Electrical heating grids driven by imaging can be done, but the finite resolution makes this more akin to numerical software modeling than true high Reynolds number laboratory work.

0.4 Conditionality of moist convective 'instability'

The word “stable” is ancient, from proto-Indo-European *to stand*. A (a ball on a hill is the standard trope of *instability*, the state of being not stable. Shear instability in fluids is often like this: the slightest perturbation will cause waves to grow, and eventually roll up into vortices. The *smaller-scale response to a larger-scale state of instability plus an initial perturbation* lacks a crisp name, unfortunately -- or perhaps not, since shorthand can confuse as much as clarify. Such a response has detailed characteristics (like a preferred wavelength), akin

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[i]Although real convection's fate is never governed by *undilute reversible* or *pseudoadiabatic* updrafts, these convenient lifted-parcel idealizations are often used to define approximate *moist adiabats* for common parlance.

to the hill having a steepest side, perhaps with a narrow chute where the ball is mostly likely to go down, or least likely to return from if it does.

A ball in a *dimple* on a hill (like in a volcano crater) expresses a *finite-amplitude instability,* like the explosive potential of gunpowder or a dry forest lacking only an ignition source. The *lifted-parcel instability* common to moist convection is like this, but asymmetric: only upward-displaced parcels reach saturation and unleash latent heat release effect 1 above. The common name *conditional instability* represents this situation, but ambiguously: there are myriad possible "conditions" (in the logical sense, "if only...") that can lead to runaway or spontaneous continuation of motion. Indeed, even a stable state lacks only some sequence of "if only..." processes to bring it to an unstable state, so utility (a clear functional meaning) is the only reliable guide to definitions.

Just as combustion requires all of fuel and oxygen and ignition, convection hinges on the combination of a conditionally unstable state (whose measure may be multivariate), and the meeting of the conditions. In Earth's atmosphere, the *ingredients*[j] of such actual, functional instability (that is, the condition whose response is actual convection) include moisture abundance and the *lapse rate* of temperature. Add in the probability of triggering disturbances, which we will meet again as the Ooyama (1971) *dispatcher function*, and there is no single mess or problem that moist convection's job is to clean up or "neutralize"! Unfortunately, terminology in our field is exasperatingly littered with historical cruft (Sherwood 2000, Schultz et al. 2000). For instance, the term *potential instability*[k] can be useful for predicting the turbulence of forcibly far-lifted cumulus updrafts, or explaining *mammatus* on descending *anvil cloud* bases. But its definition, used uncritically as a

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[j] This term is an example of a purposefully *vague* term of art (or jargon): search *ingredients-based forecasting* to find sometimes passionate debates around its use.

[k] Worse yet, equated as definition 2 to the enormously general terms "convective instability", "buoyant instability", and "thermal instability" in the authoritative http://glossary.ametsoc.org.

mindless formula, would suggest that dry air in midlevels is somehow 'good for convection', very wrongly.

In fluids, the ball-on-a-surface or parcel-minus-environment density difference versions of instability are far too crude to be quantitative: mass continuity (enforced by pressure, chapter 1) connects everything in realizable flows, complicatedly for large air displacement distances. The only hope of sensible meaning is for users of the word *instability* to carefully define it for your purpose, often a teleological one. Think well before you use terms, most especially familiar (long-overused) ones!

0.5 Unlikelihood, fitness, and the ecology of convection

When some patch of atmosphere exhibits a (multivariate) conditional instability, and fluctuations have produced exceedances of the conditional's conditions, then what? For realism of imagination, look at a summer sky or some satellite imagery[l] before reading on. Clearly an account of convection requires multi-scale descriptions, debatably called questions of convective *organization*[m]. Truly "organized" entities (a meaningful assembly of parts) are *unlikely* to form randomly and for no reason, but may be preferentially favored by *natural selection* if their structural details and peculiarities boost their energy efficiency or some other measure of the Darwinian concept of *fitness*.

With the word "unlikely", *probability* necessarily enters our discourse, our only hope of making any generalizable sense about convection's complicated form. The *distribution or density* of probability over a set of possible *situations*[n] is called *likelihood,* notated as *P(situation)*. But how to enumerate (and thus assign probability to) "situations"? This is an *epistemological opportunity*, a chance to align our feeble brains' thoughts with infinitely complex nature through a

[l] such as https://worldview.earthdata.nasa.gov/, https://rammb-slider.cira.colostate.edu

[m] from Greek *organon,* tool or instrument, implying a teleological function to the parts

[n] probability theory's *events* like the landing of coins or dice are combined in *situations*

human-friendly choice of description framework. Seeking such probabilistic *claims* and *narratives (accounts)* about nature puts us in the excellent company of other sciences, with access to their fruitful tool kits. The mathematical notation of probability is not as fussy as *reductionism's* calculus and algebra accountings of the specifics of fluid transport for instance (as marched through in Part I). Instead, the challenges are logical and conceptual, ultimately accessed via words and metaphors -- but those can have pitfalls. Careful thought is required.

Statistical mechanics thrillingly illuminated the droll *thermodynamics* of earlier centuries that brought us steam engines, albeit with a mental undertow for some of its practitioners[o]. Its re-interpretation of the thermodynamic *entropy* as the logarithm of the number of *indistinguishable microstates* of a *system* ("situations") is profound. Information theory (Shannon 1948) generalized this logarithmic form beyond the atomic and molecular realm where distinctions are literally unknowable by quantum mechanical *uncertainty principles*. In this broader view based on log-probability[p], the profundity of *informational entropy*[q] is as a quantification of our ignorance, or of our strategic refusal to distinguish, not as a new law of nature. Might principles from that fascinating field be brought to bear on the problem of convection's *patterns* in space-time? To some degree they already have, but again careful thought is required, and may offer new opportunities (Part III).

Perhaps convection's patterns can be viewed as *exploitation strategies of an energy resource* by *unlikely structures* (or patterns), echoing evolutionary biology, whose distinct plant or animal *individuals* our clouds and storms are sometimes likened to for merely cosmetic reasons. Its cousin discipline ecology, and social sciences like economics, are

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[o] Ludwig Boltzmann in 1886 wrote: "... natural science appears completely to lose ... the large and general questions; but all the more splendid is the success when, groping in the thicket of special questions, we suddenly find a small opening that allows a hitherto undreamt of outlook on the whole" (Annila 2019). He hanged himself in 1906.

[p] embodying the *frequentist interpretation* of probability as an enumeration

[q] best rendered verbally as *missing information,* as argued in Ben-Naim (2008)

rooted in similar ideas, but they wrangle more seriously with the framing issues around definition-dependent and overlapping multiple-scale (*micro and macro*) 'entities' and 'systems', as we must. Ecological and economic[r] principles like *succession* and *competition* and *survival* which rule our environmental worldviews and daily lives are at the very least a rich trove of metaphors we can draw on.

Information theory quantities like *mutual* and *transfer information* are becoming genuinely valuable in convection-adjacent fields (e.g. Ruddell and Kumar 2009). These are calculable from tractable, indeed even simple calculations, once the right strategic framings of *problems* and *systems* treating various types of entities as macro and micro, distinguished or interchangeable. All this may be viewed as a new flourishing in the somewhat orphan discipline of statistics, whose deeply problematic 19th - 20th century culture is fascinatingly reviewed at a popular science level in Pearl and McKenzie (2018). Their mission is to revitalize statistics' broken relationship to *causality,* another key weak linkage from statistics to the ultimate goals of science. We seek not mere measurement, even of "information", but robust methods of *predictive understanding*, somewhat beyond this book's goal of deep appreciation.

Back to convection. Competition between neighboring air *parcels* (on many overlapping scales of definition of "parcels") is the central process of cumuliform convection. Pressure is one major weapon in this competition, favoring the narrow; but mixing is another, which favors the broad (Part II). Natural selection by gravity relentlessly favors the fittest, but the resource consists in more than one ingredient (moisture as well as geopotential energy for instance), and 'fitness' is continually redefined locally by the whole ecosystem, as in biology. Does selection apply strictly to individual "entities" (however defined), or to whole groups of them plus their "environments", in the *situations* nomenclature above?

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[r] both from the Greek root *oikos* "house, dwelling place, habitation"

Unlike biology, where selection operates over the vast time scales of DNA's memory for morphological possibilities (Dawkins 1989), convective cloud fields develop anew and naively each time instability becomes available to exploit. We observe (and would like to measure usefully) how complex multi-cellular storm entities gradually rise to predominance, through a succession-like process -- whether viewed as competitive, cooperative, or exploitative. The resulting wild beauty of storms can inspire curiosity for a lifetime, even as maturity teaches the salience of probability and averages and asymptotes and integral constraints whose precise enforcement mechanisms may be a fool's errand to try to detail.

If neighboring parcels feel the same displacement-reinforcing force, motions driven by gravity ("convective" motions in a broad sense) can be broad and persistent enough to engage the flywheel of horizontally rotational momentum on our spinning planet: this is *synoptic-scale* convection. If neighboring parcels feel differential force, it generates shear, whose momentum instabilities (another class of problem, beyond our titular scope) drives sub-parcel-scale turbulence. Together all these processes fulfil gravity's grand mission, subject to the realizability constraints of the laws of motion (such as mass continuity), trading off ease of assembly of structures against energy efficiency, culminating in the structures we observe. Part III will revisit the prospects of *extremal principles* as a handle on this beautiful mess, but first we must unpack that innocuous phrase "we observe".

0.6 Observability, cognitive biases, and scope selection

In addition to natural selection as a force in nature, *cognitive selection* shapes all discourse and even thought, and so necessarily shaped this book. What underlies this moment of my writing, or your reading?

Is Earth's wondrously life-sustaining climate, with atmospheric convection bringing water to its lands, an 'unlikely' coincidence of factors? No, it is an *inevitable* coincidence of those factors, because the entire question is asked downstream of the condition that we are here to observe the situation. This is cosmology's *anthropic principle* (footnoted above), brought down to Earth. More mundane versions of this same cognitive pitfall (with facets that could be variously called *pre-screening bias*, *unarticulated conditional sampling*, *survivor bias*, *confirmation bias*) cast shadows throughout our corpus of knowledge about the world (as evoked in the Preface). An area of great advances in contemporary thought, long known but exposed so starkly by the large number of enumerated instances made easy in the data age, is the naming and thus spotlighting of these cognitive biases and distortions themselves. Everyone who has discussed politics at a family meal knows that nonunique or even wildly divergent worldviews can develop, even in perfectly-rational *Bayesian learners*, when fed on differently pre-screened *information diets*. These are now the classic paradoxes of *artificial intellegence safety*, one of humanity's direst new concerns.

In convection science, one major observation bias is that condensed water reflects electromagnetic radiation (light, radar waves, etc.). It doesn't help that our brains are built to *identify* (literally: assign identity to) contiguous opaque entities in the air we inhabit, assigning them a sense of longevity (only sometimes valid for cloud systems) and *heft*. It is worth recalling that a buoyant cloud is actually a relative void of mass compared to the invisible air around it, by definition of buoyant. If these feel like obvious truths you feel intuitively when looking at the sky or radar data, you have a better mind than mine. What are the consequences for our science?

This field has matured from case-study description to generalized knowledge over about 2-3 generations. But an account of "convection" focusing mainly on its opaque parts is incomplete, no matter how many instances are accumulated. For instance, airplane-window views have a visibility bias against overcast areas 100s of km in size, arguably underpinning simplistic early views of the *cumulus parameterization problem* that my PhD advisor and his generational cohort made a career of contrasting (e.g. Houze and Betts 1981) with the new data gushers of radars and satellites. Today the discourse may almost have overcompensated, as the acronym MCS (for *mesoscale convective system*) is sometimes taken with excessive specificity – it is a mere umbrella term, slightly less vague than its predecessor term "cloud clusters" but still based largely on blob size in satellite or radar imagery. Without functional measures of the importance of mesoscale contiguity or structural patterns (Mapes 2019), might cosmetic categorizations and labels like "scale" and "organization" be of little or even negative utility scientifically?

Internal structure of convective storms sampled by aircraft also has biases, toward some combination of interest (justifying the expense and effort) and safe flying conditions, as thoughtfully discussed in Ludlam and Scorer (1953) for instance. Aircraft sampling was consciously partitoned by quartiles of size of satellite-observed deep cloud blobs in one large field campaign (Lukas and Webster 1992, Mapes and Houze 1992), although in practice the logistics of aircraft targeting are challenging, and such a blob-size measure may be more of a convenient metric than a profoundly important one.

0.7 The pull of interests: extremes vs. large scales

The biggest divide in the science of atmospheric convection is between the mission of improved prediction and warning against hazardous local storms (Brooks et al. 2018), and the mission of larger-scale weather and climate prediction and projection, which involves the *moist dynamics* of *convecting flows* on larger scales.

In the first kind of science, the importance filter for what gets studied is a cost function based on life and property damage. That function is extremely steep with respect to storm characteristics like local intensity and stationarity or coverage of areas especially on land. In that version of convective meteorology, it is perfectly rational to focus on tails of the tails of the distribution *P(situation)*, without dragging along a whole science of gentler instances. In the second kind of science, the expected mean value of latent heat release and eddy fluxes by convection are an integral over *P(situation)* dominated by its middle, emphasizing typical or likely phenomenology.

With this book's mission of imparting "appreciation", extremes are not the main focus, but are noticed where their dynamics are truly distinctive, like in *supercells*. But there I have nothing new to add to the many passionate treatises on those exciting phenomena (e.g. Doswell 2001, the lavishly well illustrated Markowski and Richardson 2010, Bluestein 2013, Trapp 2013). Students and many researchers tend to be excited more by storms than statistics, but this book leans more to the latter.

A major driver of the multiscale study of convecting flow is *cumulus parameterization,* an engineering effort with underlying genuine science (as reviewed in Arakawa 2004). The aim is to devise a computationally fast, simple *surrogate model* that can deliver unbiased horizontal averages of the heat, moisture, and momentum tendencies produced by the whole ensemble of convective entities in larger-scale grid boxes, as a function of the gridbox-averaged[s] conditions. This enterprise could hardly be more different from storm interests, yet this book must touch on both, and the governing equations (Part I) and basic elements of reasoning ("cells", Part II) do overlap considerably. Again this book cannot begin to compete with the great tomes on that topic (e.g. Plant and Yano 2015), and will seek merely to impart an appreciation of principles (in Part III).

[s] and perhaps of other moments of a statistical treatment of sub-gridbox scale fluctuations