Part III: Envelopes and larger-scale interactions

Chapter 7

Dispatch and survival in multi-cellular entities

The PDE sets of Part I like (2.15) comprise a very general knowledge about the dynamics of fluids, and Earth's moist air in particular, but that was only one level of appreciation. There we saw how *teleology* can express the essential, truest understanding of the nature of something: in that case, pressure. The micro-macro distinction (molecules vs. continuum) also gave us a clean paradigm for the more general concept of *scale separation* or *filtering* (chapter 3). Software PDE solvers (atmosphere models) are glorious tools, both at high resolution where they comprise a new source of data on convection's structure, and at low resolution as a demanding test of our understanding its function. But they are not quite understanding itself. The conceptual *entities* of Part II added something new.

Entities align with our mind's limitations, such as narrow discrete focus and finger-related limits on number appreciation. But they also activate its strengths, such as hierarchical reasoning with logarithms (a glorious flip-side of the apparent weakness of limited enumeration), and attentive attraction to extended dramas among characters (if not taken too literally). To get further, we need principles of entity *interactions*. Because our entity depictions are crude caricatures, compounding them in simple heaps will not sum up to right answers: our only hope is to seek *emergent principles of interaction*, perhaps drawing on other fields of scholarship, which all bear the same problems with *scale*.

7.1 Introduction: systems of cells of bubbles

Even shallow moist convection is observed to be frequently non-random in its spatial patterns (Zhu et al. 1992). Large-scale structures resembling flowers or fish skeletons (Rasp et al. 2019) develop especially when multi-bubble convective cells get deep enough to precipitate, and that process becomes overwhelmingly salient for deep convection. Still-larger scale structure is evident, but for the moment let us focus on contiguous *cloud systems.*

Let us label any multi-cellular entity governed by a positive feedback loop, with new cells spawned preferentially adjacent to prior cells, as a *system*. In the case of deep convection, a popular umbrella term is *mesoscale convective system* (MCS, Houze 2004). The adjective *mesoscale* typically refers to horizontal cloud or rain area contiguity larger than 100 km. Everything mesoscale is undeniably multi-cellular, and even cumulonimbus *cells* are multi-bubble entities as seen in Part II.

Like *thermal*, a descriptive term that motivated specific entity models which went on to title themselves after it, *MCS* is a catch-all that invites the *category error* of equating it with specific dynamical paradigms for its best-studied instances (like a *squall line*). One appropriately general and agnostic conceptual model of such entities is the *particle fountain* of Yuter and Houze (1995), firmly grounded in the electromagnetic observability (chapter 0.6) behind empirical descriptions, the first step to scientific appreciation of every phenomenon.

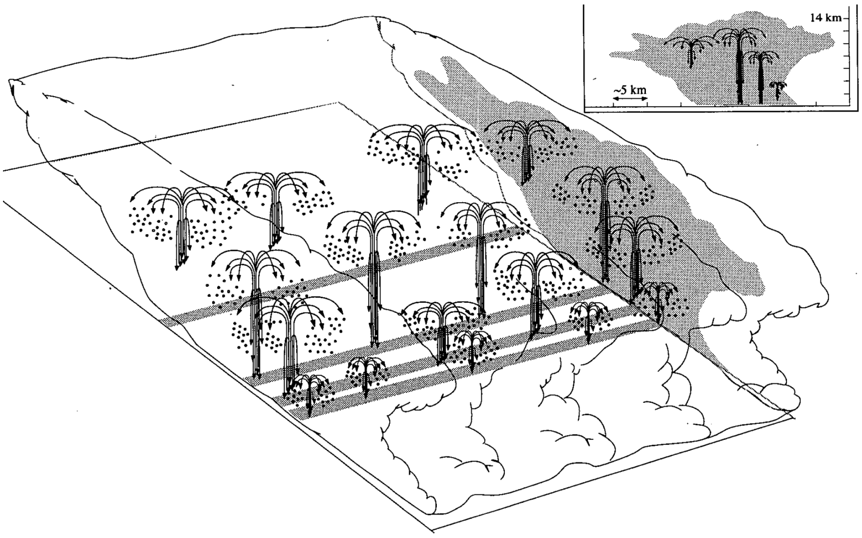

Fig. 7.1. Particle fountain model of the observed phenomenon of MCSs. Convective cells that are abundantly dispatched within a region, *for whatever reason,* expel ice crystals at high altitudes which merge into a contiguous area of cloud and falling hydrometeors. Adapted from Yuter and Houze (1995), who call this "an extension of bubble-based conceptual models".

A sizable cottage industry is devoted to further sub-categorizations of MCSs, in case studies and in conditionally sampled statistics of large samples from today's amazing global data sources like "spaceborne" (orbiting) meteorological radars. Many excellent sources focus on mesoscale processes and their impactful if arbitrary characterization distinctions (for instance, the titular scope of Trapp 2013). Here we only lightly survey such mechanisms for elementary appreciation, before steering discussion toward a combinatoric reasoning, which in this book is finally aimed more at expecting the typical than at explaining extremes (as admitted in section 0.7).

7.2 Dispatch probability, survival, and reproduction

Once discrete entities are defined, a counting scheme can be set up to keep track of them. A memorable formulation of this idea is the "dispatcher function" in section 4 of Ooyama (1971)[a]:

> If…the environment of all the bubbles is the same, … the properties of a bubble with any set of initial conditions [**s**] can be calculated by the [bubble] model … independent of similar calculations for other bubbles. … At a given time-step and at a given horizontal grid-point of the large-scale model, [the number distribution of] a statistical ensemble of bubbles with various initial states **s** … is denoted by N(**s**). To be precise, N(**s**) d**s** is defined as the number of bubbles, per unit time and per unit area, starting from initial states between **s** and **s**+d**s**, that is, between [starting altitude] p* and p*+dp*, [mass] m* and m*+dm*, etc. It seems appropriate to call N(s) a "dispatcher" function.

The assumed *independence* of dispatched entities here is an initial expression of agnosticism, not a strongly valid claim about nature. One aspect of a meaningful definition of *organization* will find expression in its modification.

The independence assumption envisions convective bubbles of different sizes as *competing* for a *common resource* (instability, measured in energy terms), in the form of an identical shared environment. Such an unconditioned competition tends to favor the largest (most undilute) bubbles that are permitted to exist, the most buoyant green curves on Fig. 4.2. A straightforward consequence and illustration is the longstanding syndrome in global models with parameterized deep convection that scheme-produced rainfall occurs too easily and thus too frequently. We will return to such *game theory* like considerations in chapter 9.

Two main altitude layers are involved in the interactions and feedbacks that shape multi-cellular entities like MCSs: the *planetary boundary layer* (PBL), where effects tend to be quite local or tied to merely advectively moving airmasses, and the lower reaches of the

[a] in a "special issue" whose now-eliminated access difficulty may have limited readership

overlying *free troposphere* where nonlocal wave propagation can also be important. Although upper-tropospheric dynamics often reaches down to *force* or at least *disinhibit* these convective events, especially on synoptic scales, the bottom-up nature of deep convection and the vertical confinement of water availability (Mapes 2001) make those upper-level influences arguably secondary in many cases, as asserted in chapter 0.

7.3 Near-field dispatch effects: impacts of the convected air

The dispatcher function's basic resource is conditionally unstable PBL air. Its mechanism of constructing larger (and thus more successful) bubbles is often the *gust front*, a sharp thermal gradient and gravitationally driven updraft above convergent surface flow at the edges of divergent *downdraft outflows*. These effects are often pooled in the term *cold pools*, because outflow air is comprised of cool air, chilled by the evaporation of precipitation. The production of precipitation particles, their fall and evaporation, and the descent of the chilled air cause a tens-of-minutes time lag of the effect of one convective cell on the next dispatch event.

So long as old downdraft outflow air can be spatially segregated from the source of rising air, for instance by simple horizontal offset in a squall translating with time, convection can thrive on the *nonuniformity* of its PBL, even if the large-scale *mean* PBL in the broad area containing the system becomes neutralized or stable. But a final end to runaway-dispatcher positive feedbacks (both gust front and disinhibition) must come when the entire PBL of an unstable airmass has been lofted in convective drafts, replaced with downdraft outflow that eliminates all instability. At that point, post-convective PBL air must gradually 'recover' its instability (in the form of h) via surface fluxes.

Over warm ocean where flux is proportional to wind speed, recovery has a characteristic distance scale of about 500 km. There the spatial possibilities for this ceaseless game of outflow, lifting, and recovery on such a spatial scale are endless, even in the merely horizontal 2D domain. Convective cloud fields over warm oceans are almost never free of the long chains of history, so mesoscale structure is omnipresent, perhaps 'saturated' or equilibrated with its sources and damping in the spatially spectral language of chapter 3. Over land, in contrast, dispatcher-scale causality can be reset overnight, so that the cloud field must begins from more homogeneous initial conditions the next day. This daily reset makes warm lands often a more informative laboratory for defining and testing ideas about *organization,* although the particularity of geography often makes process inferences from land study less generalizable than from the arbitrary spot of a ship at sea.

7.4 Mid-distance interactions: waves of low-level T'

In contrast to PBL-rooted dispatch, the lower free tropospheric layer often plays more of a screening role, culling survivorship of entities, at least in situations less organized than the slab jumps and squalls of section 5.4. This claim is supported for instance by a sign reversal near 900 hPa of the sensitivity of deep convection to domain-averaged T perturbations in an isotropic cyclic cloud-permitting model (CCPM), as shown in Fig. 7.2a.

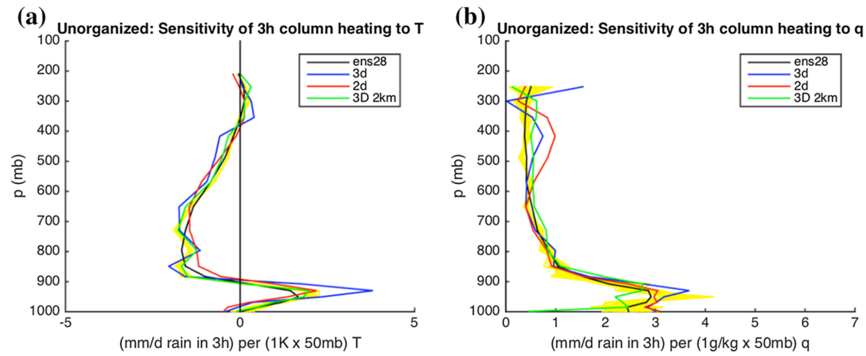

Fig. 7.2. Sensitivity (horizontal axis) of simulated rainfall over 3 subsequent hours to instantaneous perturbations of T and q at each indicated altitude (on vertical axis). The results pertain to a cyclic convection-permitting model (CCPM) of about 2km horizontal mesh size, in a convecting state of statistical equilibrium with prescribed radiation-like

cooling about the strength of Fig. 0.1 over surface water at 28C. Adapted from Fig. 5 of Mapes et al. 2017.

Since the sensitivity of such CCPM convection is nearly linear (Tulich and Mapes 2010), a clever matrix inversion technique (Kuang 2010) can be used to summarize it in the form of a time-independent data object, a *linear response function* matrix, of which Fig. 7.2 is an integrated (functional) summary. That result was derived from long simulations of isotropic, unsheared convection of quite modest intensity, in small domains containing only isolated or even intermittent cumulonimbus clouds -- arguably the closest we can bring model-realized convection to the ideal of randomly dispatched entities.

Strong positive sensitivity to PBL T and to q in Fig. 7.2 can be understood in terms of simple parcel buoyancy (Fig. 4.1). Above-PBL moisture sensitivity is also positive but smaller, with a nearly-uniform profile that implies the functional or *effective entrainment* in the CCPM's realized convective entities, although that information content is not easily extracted into a coefficient for a mixing scheme.

Negative sensitivity to lower free tropospheric T is consistent with the notion of *convective inhibition*, and its removal *disinhibition,* but is a far bigger and deeper-layer effect than the integrated negative buoyancy of an *undilute* lifted parcel (the traditional and rather trivial *CIN* definition lamented in chapter 4) can explain. Reasons for that negative sensitivity are further explored in Tian and Kuang (2019).

This negative sensitivity is thought to be crucial to the dynamics of convectively-coupled waves in the tropical atmosphere (Kiladis 2009) through mechanisms elucidated in Mapes (2000) and elaborated in Kuang (2008). It is also important in the near-field problem of MCSs, in combination with the more obvious gust front effects of the previous chapter (e.g. Fovell and Tan 1998), although the tens-of-minutes time lags among multiple effects, some of them transparent air, makes causality tricky to infer clearly in such disturbed and transient settings.

Stable stratification in the unsaturated air around moist convection makes inflows and outflows obey the dispersion relation of the *internal wave* (aka gravity or bouyancy wave) flow solutions considered in section 2.2.2. These effects are mathematically first-order but quite unintuitive, so my own road to belief and understanding was importantly supported by laboratory tank experiments (Fig. 1 of Mapes 1993, partially reproduced below). The invisibility and transience of internal waves remain an observational challenge to their outdoor appreciation, although their crests do create visible cloud features -- most famously high-amplitude and quasi-stationary lee *mountain waves,* but quite ubiquitous to the observant.

Vertically pointing water vapor LiDAR data offer a compelling new way to see the vertical displacements in the stratigraphy of the atmosphere, as shown in Fig. 7.3 from Barbados Cloud Observatory (Stevens et al. 2016). In addition to secular trends (in which low-frequency 'waves' are hard to distinguish from the advection sloping features), more periodic laminar features can be discerned, for instance with periods near 1 hour, and near the shortest possible period for internal waves, $2\pi/N$ (about 10 minutes in a moist adiabatic stratification, although shorter in a more stable inversion layer). Amplitudes are commonly about 100m (justifying the adiabatic displacement whiskers on Fig. 4.1), and vertical coherence of features can exceed 1 km.

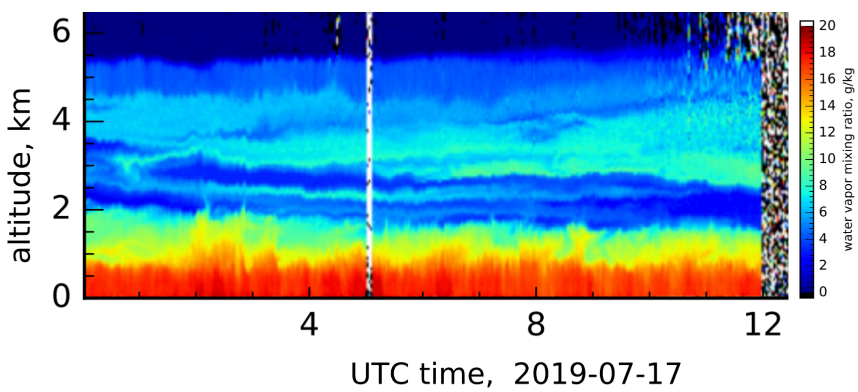

Fig. 7.3. Water vapor mixing ratio as detected by a clear-air Raman LiDAR system on Barbados on July 17, 2019. Adapted from quick-look imagery file

http://bcoweb.mpimet.mpg.de/quicklooks/lidarql/RamanLidar-CORAL/lowResolution/co2019/co1907/coral_190717_0002_0000.pdf. A satellite view of the cloud field setting on that day may be perused at https://go.nasa.gov/2yihy1Z.

Only shallow convection was present in the area of Fig. 7.3, as evident from the low water vapor mixing ratio just above 2km as well as from the satellite imagery link in the caption. Deep convection can excite, and couple, internal waves that are much larger in terms of both scale (vertical and horizontal and temporal) and amplitude, sometimes so large that linearity is inadequate and the waves are called *undular bores* (e.g. Haghi et al. 2019).

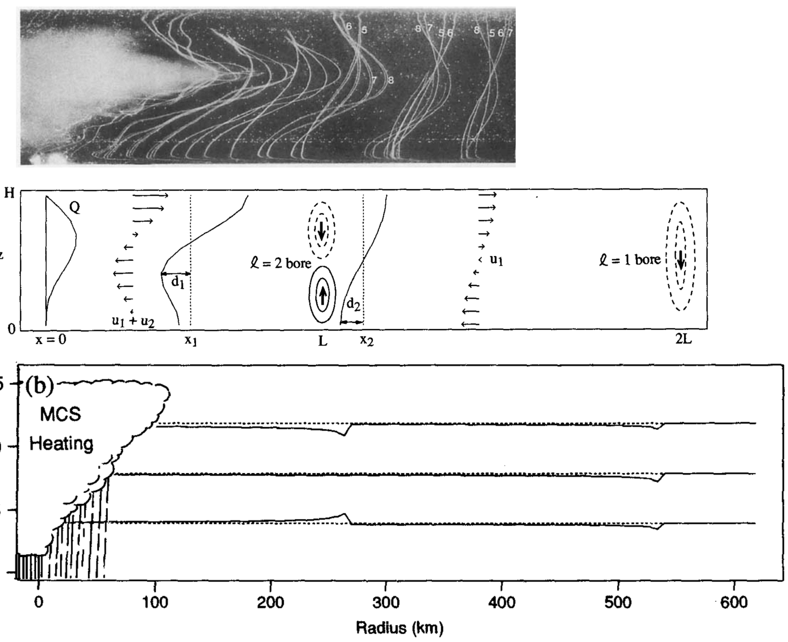

Fig. 7.4. Stratified environment flow and displacement responses to a localized convective entity (from Mapes 1993). The top panel (Fig. 1 there) is a photograph of dye lines in an almost two-dimensional (2D) tank, strobe lit at 5-8 buoyancy oscillation periods (5-8 x $2\pi/N$) after sudden release of dyed buoyant fluid at left. The spooky smoothness of far-field flow profiles is clear, as vertical wavenumbers separate themselves out horizontally. The middle panel is a schematic solution in slab 2D (x-z plane) geometry for a buoyancy source of specified top-heavy shape that is maintained after sudden switch-on (Fig. 3 there). Horizontal displacements (d1 and d2) are the time

integral of horizontal winds (arrows) whose pattern at any point evolves with the passage of the "bore" or wavefront features propagating to the right. The bottom panel (Fig. 4b of Mapes 1993) is for a similar buoyancy source in cylindrical (3D) geometry, and shows vertical displacements (solid) of initially horizontal (dotted lines) material surfaces.

A concentrated local heating like latent heat release in a MCS, forces adiabatic wave-like motions in its environment which spread the warmth horizontally by downward displacement of the stratification (bottom panel of Fig. 7.4), as part of a wave[b] response that travels at a speed proportional to vertical wavelength (section 2.2.2). Despite the multiple heating processes involved (phase changes, radiation, small-scale eddy heat fluxes), the far-field wave response really does respond to the decomposition of that total heating by vertical wavenumber, a dispersive *chromatography* effect that is spooky like any "spectral" phenomenon.

Although the deep-layer mean warming has been exported to a very broad area (over 500 km in 3 hours), Fig. 7.4 illustrates how a vertical dipole (wavenumber-1) component, expressing the difference between the top-heavy heating and the deep-layer "mode" of the wave solution, travels half as fast and thus has its effects confined to a smaller area in which they are therefore more intense.

Upward displacement and environmental cooling at low levels can occur (bottom panel) even though the imposed heating Q>0 at all levels. The resulting disinhibition contributes another near-field (or mid-distance) positive feedback to the enhanced dispatch effects from the previous section, acting to make convection locally gregarious (Mapes 1993) or to organize it into convectively coupled waves (Raymond 1983, Kiladis et al. 2009).

However, the inflow wind profile driven by top-heavy heating also has an unfavorable implication (near-field arrows in middle panel of Fig. 7.4). The inflow of low-*h* midlevel air is a mesoscale form of *dynamic entrainment* into the MCS-scale net updraft, like we encountered in convective-scale entities of chapter 5. While this inflowing air will not

[b] The irreversible down-only wave front was called a *buoyancy bore by* Mapes (1993).

necessarily be mixed into updrafts right away to reduce their buoyancy, its low *h* must somehow have an impact on longer time scales, as a *gross moist stability*[c], conceptually a brake on the instability of the runaway dispatcher-plus-survivorship complex that governs system success.

Still-higher vertical wavenumbers in a buoyancy release (heating) event remain even nearer to their source, as wiggles in the density profile. In an area of repeated cell dispatch, the lifted-parcel buoyancy of subsequent convective updrafts is affected, just like the wiggles in h_{sat} in Fig. 4.2 that cap the buoyancy of members of the ensemble of green updraft curves causing spikes in the 'detrainment' histogram there. As discussed in section 4.3, this detrainment or *buoyancy sorting* mechanism makes such subsequent convective heating act to smooth out the wiggles, adjusting[d] the *T* profile in convection's near field toward that convection's effective moist adiabat. In other words, high vertical wavenumbers of convective heating are specifically damped by prior cell - subsequent cell interactions in these multicellular systems.

The exception that proves the rule of high-wavenumber damping in MCSs is the systematic thin (high vertical wavenumber) dipole T forcing by shallow melting at the 0C level plus the associated latent heat of freezing that occurs a little higher, at whatever altitude the nucleation of freezing places it on average (Mapes and Houze 1995). Dispersion by vertical wavenumber also shapes the temperature structure of sharp radiative cooling layers, making a warm layer at the base of dry layers. That warmth reduces the relative buoyancy of updrafts, and may specifically aid the longevity of such layers, by protecting them from penetration and moistening by convection from below (Mapes and Zuidema 1996).

One final illustration of the reality of spectral chromatography is shown in Fig. 7.5. In addition to wavenumbers ½ and 1 (monopole and dipole heating profiles) from Fig. 7.4, the next-lowest wavenumber of

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[c] a term adding to section 0.4's lament about "stability" words; e.g. Raymond et al. (2009)

[d] Bretherton and Smolarkiewicz (1989), Bretherton (1993), Mapes and Houze (1995)

the troposphere (3/2) can sometimes escape the event horizon of the high wavenumber damping in these multicellular MCS events. Again we see the spookily (spectrally) smooth wavelike shape that seems closer to mathematical dynamics solutions than to the turbulent mess of individual convective cells, as in the top photograph of Fig. 7.4.

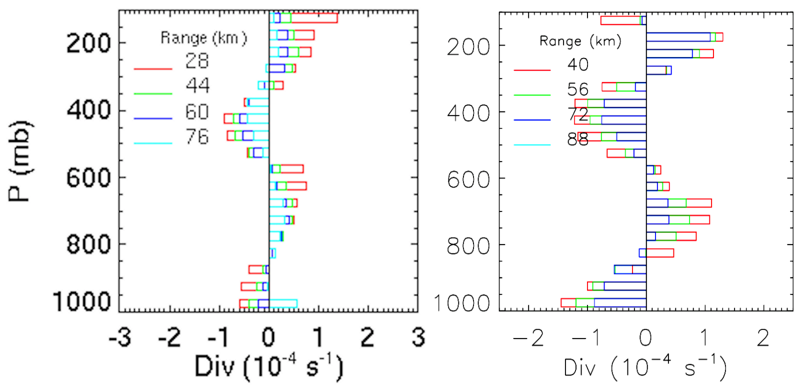

Fig. 7.5. Unusual wavenumber 3/2 profiles of horizontal wind divergence profiles in MCSs, measured by shipborne Doppler radars (as in Mapes and Lin 2005), averaged over 1 hour and over cylinders of air of the indicated radii (Range legends). Left: 1997-08-18, 22 UTC on the TEPPS campaign (Zuidema et al. 2006). Right: 1999-05-22, 16 UTC on the JASMINE campaign (more data in Fig. 3 of Zuidema and Mapes 2008).

Summarizing, the foregoing showed how the intimate interaction of updrafts with their predecessors' legacy (cold pools in the PBL, vertical displacements in the stratigraphy of the lower tropopshere) can lead to a very nonrandom dispatcher function and survival screening. These positive feedback mechanisms lead to multicellular “MCS” meta-entities that are at least two named scales bigger than the air “bubbles” that make up “cells”, although we begin to realize that a continuum view of scale would be closer to nature.

Do such meta-entities of convection still play the same simple teleological roles like *adjustment,* albeit perhaps toward a different target state or effective “moist adiabat”? Or do their additional realizability constraints, such as the significant inertia implied in horizontal flow branches, start to perform a whole different "job"? Might they even create new jobs that smaller-scale processes must perform, for instance by disrupting pre-existing balances?

7.5 Shear's help: focus, 2-dimensionality, supercell lift

The horizontal geometry of convecting flow exists on a continuum extending from circular 2D (waves, cold pools, etc) to the 1D lines, the infinitely-long sum of circles (https://en.wikipedia.org/wiki/Huygens–Fresnel_principle). In the middle ground of "one and a half dimensional" flow, arcs and line segments compete against the pure ideals of isotropic thermals and squall lines (section 5.4). How do such competitions play out?

Convection in shear tends to become arranged in more two-dimensional configurations, either across the PBL shear vector or along the midlevel shear (Robe and Emanuel 2001). Some near-field advantages of this concentration of updrafts into lines may include "mutual protection"[e] of clouds from exposure to the dry environment (Randall and Huffman 1980), and boosting of the dispatcher function's preferential production of larger updraft entities (Khairoutdinov and Randall 2006). Individual thermals are also affected directly by shear, for instance through dynamic pressure effects (Peters et al. 2019).

Convection simulated in CCPMs responds differently to its large-scale environment according to its place along the circular-to-linear shape continuum. Experiments measuring a CCPM's interaction with a larger-scale wave, varying convection's geometry through the periodic domain's aspect ratio or through imposed shear (Riley 2010), reveal an intrigueing internal optimum. Relatedly, but in a different kind of large-scale interaction harness, Anber et al. (2014) also found a nonmonotonic dependence on imposed shear: "For weak wind shear, time-averaged rainfall decreases with shear and convection remains disorganized. For larger wind shear, rainfall increases with shear, as convection becomes

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[e] a *behavioral* analogy to herd animals, but one honed through survivorship in past time

organized into linear mesoscale systems". The linear response function (sensitivity profiles) of Fig. 7.2 are also vastly different for long narrow domains that enforce squall-line geometry on the convection (see the other panels of Fig. 5 of Mapes et al. 2017), although the interpretive cautions there must be noted: the vapor climate of such squall-only atmospheres is drastically drier, so "sensitivity" is relative to that base state.

7.6 Mid-distance interactions II: mesovortex effects

The mid-distance *T* effects on convective dispatch and survival discussed around waves in section 7.4 have direct analogs in balanced vortex flows (Raymond and Jiang 1990). Spectral dispersion are again involved, because different vertical wavenumbers have different *deformation radii*. Tropical cyclone development stands as an important application and arguably a more tractable laboratory for discerning some of these effects, and a basis for defining "organization" in extremely meaningful ways. But cyclones also have additional dynamical complexities, such as different horizontal transports of moisture and frictionally controlled wind convergence in the PBL. A thorough discussion of these phenomena in the present framing is beyond the present scope, but that discussion's absence required this mention.

7.7 Problems and solutions

7.7.1