What might be wrong with convection in the grey-zone?

Has anyone developed an experimental fix?
Yes
No
Sort of

- **Missing processes:**
  - Triggering / maintenance of convection by cold-pool uplift. (5,10,13,16)
  - Mixing-driven downdrafts. (7,13)
  - Convective overshoot and subsequent fall-back. (13)
  - Sensitivity to wind-sheer (downdrafts / organisation). (10,13)
  - Microphysical processes in updrafts. (4)

- **Missing interactions** between parameterised and resolved processes:
  - Forcing of grid-mean vertical velocity by sub-grid updrafts & downdrafts. (8,9,18)
  - Forcing of sub-grid updrafts & downdraft by resolved T, q, p gradients. (12,14)

- **Invalid assumptions**:
  - Convective quasi-equilibrium (assume convection is entirely diagnostic). (3,4,5,13,17)
  - Statistical Equilibrium (average over many "features" per grid-box). (15)
  - Segmentally-constant / homogeneous / "top-hat" updrafts & downdrafts. (11,12,15)
  - Instantaneous ascent. (20)
  - Small updraft area fraction. (1,2,6,19)
  - Local compensating subsidence (6,8,9)

- **Lack of "scale-awareness";** as resolution increases:
  - Sub-grid mass-flux should reduce (more is resolved). (1,2,6,13,19)
  - Sub-grid perturbation of plume properties should reduce (more is resolved).
  - Fractional mixing rates for sub-grid plumes should increase (smaller features). (13)

Missing Processes

Triggering / maintenance of convection by cold-pool uplift.

- **Grandpeix & Lafore (2010)** developed a prognostic cold-pool scheme, fed by the parameterised convective downdraft, which forces the deep convective triggering and closure. Their scheme dramatically improves the diurnal cycle, as shown in **Rio et al (2013).**
- **Park (2014)** developed a similar prognostic cold-pool as part of the UNICON scheme; the cold-pool forces various elements of the convection via a parameter representing the degree of organisation of the convection.
- **Kuell & Bott (2011)** included a Cellular Automaton type component in their HYMACS scheme, in which convective downdrafts in one grid-cell can force the triggering of convection in neighbouring grid-cells.

Mixing-driven downdrafts

- The **Park (2014)** UNICON scheme extended the mixing buoyancy-sorting method for calculating entrainment / detrainment (**Kain & Fritsch 1990**) so that when mixtures of cloudy and environmental air are strongly negatively buoyant (due to evaporation of cloud condensate), they are transferred to a downdraft scheme, rather than being detrained to the environment.

Missing Processes

Convective overshoot and subsequent fall-back

• Many convection schemes use a vertical velocity equation in the cloud-model to predict the cloud-top height based on where the updraft KE runs out, some height above the LNB. However, most of them simply detrain the updraft air at this height, which is unrealistic, since it is negatively buoyant (in reality, most of the detrained air should fall back to its LNB, but may entrain environmental air on its way back down). **Park (2014)** represents this process in the UNICON scheme, by transferring the overshooting cloud-top plume wholesale into a downdraft scheme.

Sensitivity to wind-sheer (downdrafts / organisation)

• **Park (2014)** made the evaporation of convective precipitation depend on the sheer (i.e. when the updraft is tilted, more precip falls into the dry environment). This feeds the downdraft, which feeds their cold-pool model, which in-turn forces a "convective organisation" parameter affecting entrainment and triggering. But precip evaporation in the environment is only one of several mechanisms by-which sheer affects convective organisation.

• **Kuell & Bott (2011)** made the triggering of convection by downdrafts sensitive to the low-level sheer (triggering is promoted maximally where the cold-pool spreading velocity matches the sheer vector over the boundary-layer depth). But again, convection is sensitive to sheer in other ways too.

Missing Processes

Microphysical processes in updrafts

Many convective parameterisations include some representation of microphysical processes in the updraft, but this is always vastly simplistic compared to the microphysical schemes applied to the resolved cloud variables (often, updraft condensate is assumed to instantaneously rain out where it exceeds a tuneable threshold mixing ratio, and the frozen fraction is a diagnostic function of temperature).

Gerard (2007) avoided this inconsistency by making the convection scheme detrain all condensate to the environment, so that precipitation formation is handled entirely by the grid-scale microphysics. However, these processes are probably highly sensitive to the very strong sub-grid inhomogeneity present in qv, qcl, qcf in and around deep convective clouds, so the grid-scale treatment maybe inaccurate (e.g. qcl+qcf will be much higher in the updraft core than it is in the detrained anvil cloud).

Missing interactions between parameterised and resolved processes

Forcing of grid-mean vertical velocity by sub-grid updrafts & downdrafts.

Most convective parameterisations induce grid-scale ascent, because the convective heating applied to the grid-column makes it buoyant relative to neighbouring columns, leading the model dynamics to accelerate it upwards over subsequent timesteps. In reality, the ascent within convective updrafts aliases directly onto resolved scales (since local compensating subsidence is usually minimal for deep convection). Is the resolved dynamical response to an imposed grid-mean heating profile sufficient to represent this? Or does the parameterisation need to directly force the resolved w in order to get the transient dynamical response to sub-grid convection right?

- **Shutts (2015)** stochastically samples the uncertainty in this physics-dynamics coupling issue by adding random perturbations to the horizontal divergence field where convective detrainment occurs. This shows promising results in the probabilistic scores in the ECMWF IFS ensemble.
- See also the discussion about compensating subsidence under "Invalid assumptions" (later slide); this is basically the same issue.

Missing interactions between parameterised and resolved processes

Forcing of sub-grid updrafts & downdrafts by resolved T, q, p gradients.

Convective parameterisations generally assume the convection responds to a horizontally stationary profile, and its ascent is influenced only by internally generated buoyancy, mixing and drag. In reality, sub-grid convection may interact with resolved-scale gradients (e.g. along fronts and squall-lines), vertical pressure forces, gravity waves, etc.

• A number of schemes include a dependence on the grid-scale w (or grid-scale moisture convergence). There is strong observational evidence for a correlation between large-scale convergence and deep convection (e.g. **Peters et al. 2013**). However, does the convergence force the convection, or is the convergence simply part of the convection?

• **Moeng (2014)** formulated a parameterisation for the sub-grid vertical fluxes exclusively as a function of the resolved horizontal gradients in w and the transported scalars. This approach appears nicely applicable in CRMs, but it relies on at least some of the convective dynamics being explicitly resolved (it does not model sub-grid plumes, but represents the vertical fluxes due to sub-grid inhomogeneities in poorly resolved explicit updrafts and downdrafts).

Invalid assumptions

Convective quasi-equilibrium (assume convection is entirely diagnostic)

The ensemble of convective clouds within a grid-box is assumed to stay in a diagnosable equilibrium with the grid-mean profiles and/or fluxes. How the equilibrium cloud-state is determined varies between schemes; in many it is assumed to be that which removes moist conditional instability over a fixed timescale (CAPE closure), or yields zero net change in vertically integrated water vapour below cloud-base (moisture convergence closure). Observationally, convective clouds do not conform to any diagnosable equilibrium; they have considerable internal timescales and inertia of their own.

- **Scinocca & McFarlane (2004)** used a prognostic CAPE closure which relates the rate of change of mass-flux (rather than its instantaneous value) to the CAPE. This improved the variability of convective rainfall in the tropics.
- **Gerard & Geleyn (2005), Gerard (2007)** formulated a scheme in which the convective vertical velocity and updraft area fraction are prognostic variables. W has a prognostic vertical momentum budget, the updraft area closure has a storage term for the heat contained in the updraft; so the scheme has internal timescales associated with the present volume & vertical inertia of the updrafts.
- **Grandpeix & Lafore (2010), Park (2014)** developed schemes which account for the memory associated with convective cold-pools.
- See also discussion about stochastic convection schemes (next slide).
- But none of these represent the major source of memory in the slowly developing updraft radius / degree of organisation of the convection.

Invalid assumptions

Statistical Equilibrium (average over many "features" per grid-box)

Aside from convective memory / internal timescales, departures from quasi-equilibrium also occur due to the grid-box containing a small "sample size" of individual updrafts. The actual sub-grid mass-flux / number of updrafts in a grid area depends on sub-grid variations in T, q etc which the model cannot "know", so they are effectively random. The implied uncertainty / variability in grid-scale convective tendencies increases with decreasing grid-size.

- **Plant & Craig (2008)** developed a multi-plume convection scheme which stochastically samples the sub-grid uncertainty in the number and size of plumes in the grid area, leading to a stochastically varying convective tendency.

Segmentally-constant / homogeneous / "top-hat" updrafts & downdrafts

Bulk mass-flux convection schemes all make this assumption. Multi-plume "spectral" convection schemes (e.g. **Plant & Craig 2008**) relax this assumption by simulating multiple updrafts with different properties, but each updraft is still assumed to be homogeneous.

- **Moeng et al (2010) , Moeng (2014)** developed a formulation which accounts for the inhomogeneity in the vertical velocity and transported scalars in the vertical transport by poorly resolved explicit convection in CRMs. This has the potential to improve scale-adaptivity at convection permitting resolutions.
- To my knowledge, no one has yet represented intra-plume inhomogeneity in a sub-grid convection scheme.

Invalid assumptions

Instantaneous ascent

Generally, convective parameterisations rely on the assumption that the whole updraft / overturning cycle is represented within one timestep (this is closely related to the Quasi-Equilibrium assumption, where each grid area contains an ensemble of clouds covering all stages of the life-cycle). However, even the schemes that incorporate significant non-equilibrium behaviour retain this assumption. In reality, the time taken for a deep convective ascent may last multiple GCM timesteps, and could have a significant effect during the development and onset of convection. Unfortunately, addressing this requires including a prognostic representation of the convective updraft mass and its properties, rather than diagnosing these using a plume calculation as is traditional.

• **Yano et al (2010)** developed a Segmentally Constant Approximation decomposition of the grid-box into multiple segments (each containing the full set of prognostic variables) which represent updrafts and downdrafts. This approach is still very much under development; it remains to be seen how it will perform in a host model, and whether the advantages will outweigh the computational expense of all the added prognostic segments. However, SCA can be thought of as a bridge between a convective parameterisation and a CRM; compared to the CRMs embedded in each grid-cell in the Multi-scale Modelling Framework / Super-parameterisation approach, SCA has a huge computational advantage.

Invalid assumptions

Small updraft area fraction

Most mass-flux schemes make this assumption, often in order to equate the properties of the environment with those of the grid-mean profiles.

• **Arakawa et al (2011)** reformulated the basic mass-flux equations so-as to drop this assumption. They showed that an alternative assumption about how the mass-flux changes as a function of updraft area fraction yielded good agreement with an LES deep convection simulation. As resolution increases towards fully resolving the convection, the updraft area fraction becomes increasingly binary in each grid-box, and their formulation smoothly turns the parameterised convection off in this limit, yielding good scale-adaptivity.

• **Arakawa & Wu (2013), Wu & Arakawa (2014)** further developed the same approach.

• **Grell & Freitas (2014)** implemented the Arakawa updraft-area dependence using the Grell convection scheme in WRF, and showed promising results for the scale-adaptivity of the scheme when running at differing horizontal resolutions for a LAM domain covering South America.

Invalid assumptions

Local compensating subsidence

Most convection schemes assume "what goes up must come down" locally; if the scheme doesn't directly force w or the continuity budget, it must assume compensating subsidence within the grid-box in order to conserve mass. Observationally, convection directly forces widespread horizontal low-level convergence and upper-level divergence instead. Traditional mass-flux schemes do have this effect, because the grid-mean heating they produce makes convectively active columns buoyant, so that the dynamics responds by creating resolved ascent. But we have no reason to assume that the transient response to this grid-mean heating is the same as the true forced divergence, and it may lead to unrealistic dynamical responses to parameterised convection.

- **Kuell et al (2007), Kuell & Bott (2008)** developed an alternative in their HYMACS scheme; the host model's mass-budget is directly perturbed instead of assuming local subsidence; this creates pressure-gradients which force consistent and realistic large-scale horizontal convergence and divergence to and from the convection.
- **Grell and Freitas (2014)** also tested a version of their parameterisation in WRF which distributes the subsidence heating term over the grid-points immediately neighbouring the one where the convection occurs.

Lack of "scale-awareness"; as resolution increases:

Sub-grid mass-flux should reduce (more is resolved)

- **Arakawa et al (2011)** and subsequent papers (see earlier slide on updraft area fraction). As resolution increases, the updraft area fraction increasingly tends to either 0 or 1 in each grid-box, and the Arakawa scheme smoothly and consistently becomes inactive in this limit. The success of this approach is crucially dependent on the closure used to determine the updraft area fraction.
- **Park (2014)** discusses shutting down the convection with increasing resolution by making the mixing entrainment and detrainment rates increase, so that the sub-grid convective plumes homogenize immediately with their environment and do nothing in the limit of very high resolution.

Sub-grid perturbation of plume properties should reduce (more is resolved).

Convective triggering in parameterisations is highly sensitive to the initial perturbation applied in the parcel initiation. This perturbation represents the likely deviation in buoyancy of the initiating parcel from its environment due to sub-grid variability. As such, it should reduce as resolution is increased, as more of the buoyancy variations become resolved. This would aid the scale-adaptivity of convection schemes, but isn't done.

Lack of "scale-awareness"; as resolution increases:

Fractional mixing rates for sub-grid plumes should increase (smaller features).

Many convection parameterisations include shallow and deep versions of the scheme, where the shallow scheme has higher mixing entrainment and detrainment rates consistent with smaller updraft radii. Scale-awareness is usually bluntly enforced by simply switching the deep convection scheme off in high resolution LAMs, but retaining the shallow scheme.

- **Park (2014),** as mentioned on the previous slide, discuss forcing the parameterised updraft radii to be smaller at higher resolution so-as to adapt the mixing entrainment / detrainment with scale. It is not clear from the paper whether this feature is actually included in their scheme though.

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