

Convection waves: significant large-scale weather with medium range predictability (if subgrid parameterizations work right)

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Abstract

Convection waves (such as the moist Kelvin wave) are predictable significant weather events with both scientific and practical interest. Theoretical models exist, but real-world observations have limited ability to incisively validate their idealized assumptions. An NWP framework could help, but requires full-physics models that simulate the basic phenomenon well enough to permit data assimilation and initialized forecast studies. One efficient way of improving model physics for this purpose is a linear-wave parameterization of the rest of the atmosphere (Kuang 2008a), used as a test harness in which to tune single-column model (SCM) schemes to interact with larger scales more like a periodic patch of cloud resolving model (CRM) does.

1. Phenomenology

This paper highlights convection waves, or (quoting the lecture's title) "divergent manifold weather," as a wonderfully direct and strong challenge to subgrid parameterization schemes and their interactions with dynamics. Convection waves are especially prominent in the tropics (see review by Kiladis et al. 2009), but propagating envelopes of convection are also seen in middle latitudes (Carbone et al. 2002). Here we focus on the equator, where weak Coriolis constraints produce a broad extended waveguide hosting large-scale waves with good scale separation from their embedded convection, and where weak background winds minimize Doppler-shifting ambiguity in detecting propagation. For purposes of process clarity, the intraseasonal (or Madden-Julian) oscillation (MJO) is set aside here. While powerful and important, the MJO is an especially difficult phenomenon. At such a low frequency, many small time tendencies (processes) can be invoked as important, so definitive explanation is elusive. The equatorial moist Kelvin wave is arguably the cleanest case of a scale-separated convection wave.

A grand Kelvin wave example is shown in Figure 1, from early 1998 (see Straub et al. 2006 for more on this case). The 1997-1998 warm event in the Pacific permitted this wave of deep convection to circle the entire globe (slanted purple streak) over the course of a month, triggering South China Sea monsoon onset as well as the final termination of the aging El Nino event itself. Satellite images show the wave in the east-central Atlantic (Fig. 1a) and central Pacific (Fig. 1b). In the latter case, cloud bands suggest that the wave made important connections to higher-latitude weather. This case dramatizes the fact that real medium-range predictability about significant weather is potentially at stake, if models can accurately capture wave-convection interaction processes.

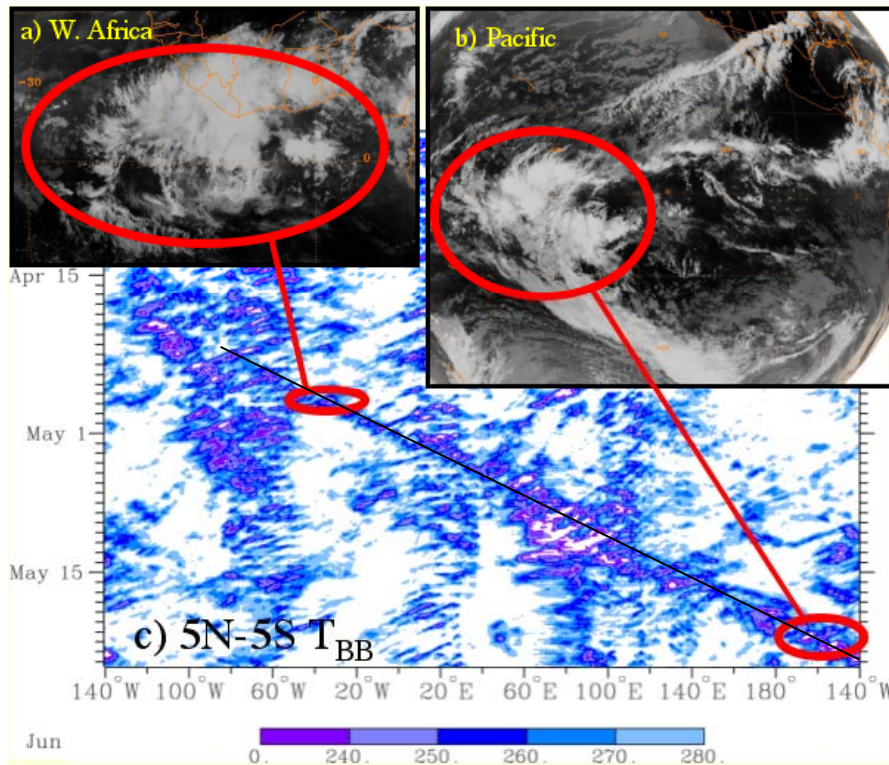


Figure 1 A moist Kelvin wave in April-May 1998 (studied by Straub et al. 2006). Panels a and b show infrared images roughly at the places and times indicated on the time-longitude brightness temperature section c. (panel c courtesy of G. Kiladis). The black slanted reference line has a slope of 10 degrees per day, or 13 m/s. IR imagery animations of this case may be viewed at <http://metofis.rsmas.miami.edu/~bmapes/Kelvincase.html>

2. Predictability

To formalize these claims of potential model-based medium-range predictability, Figure 2 illustrates the predictability of equatorial waves in aqua-planet simulations using a global explicit-convective model

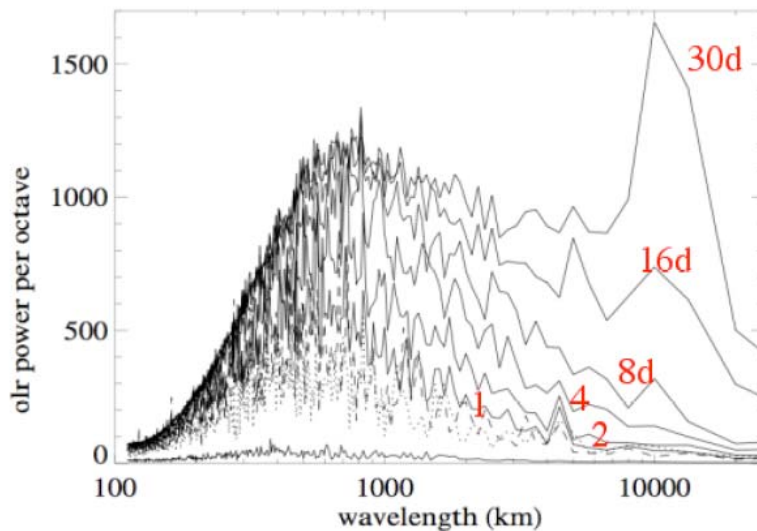


Figure 2: Error growth curves indicating the scale spectrum of predictability of tropical cloudiness variations in NICAM global explicit convection simulations (Mapes et al. 2008). Squared errors of outgoing longwave radiation (OLR) are proportional to area under the curves. Labels indicate averaging times, not snapshots at the indicated lead times, for diagram clarity. The prominent wave-4 (10,000 km) Kelvin wave in these aqua-planet runs exhibits predictability well into the medium range, even as short wavelength errors saturate within a couple of days.

(Mapes et al. 2008). The rising sequence of curves shows error growth with time after grid spacing is halved from 14 to 7km. (Both resolutions exhibit similar wave climatology, so we interpret this error growth as a not-quite-perfect-model predictability study, not a resolution dependence issue.) The prominent wave-4 (10,000 km wavelength) Kelvin wave retains its predictability well into the medium range, even as ~1000 km wavelength features are scrambled in a day or two. The vertical progression of error growth, and the spectral notch near 5000km, fit poorly with textbook turbulence predictability notions of error growing “upscale” in a literal sense, as a “cascade” (a sequence of local-in-scale interactions).

It is unfortunate, and seems absurd at a philosophical level, that such fine global grids are needed to simulate 10,000 km structures. Our ability to experiment with such expensive computations is severely limited. But until subgrid parameterizations can be shown to act like explicit convection for large-scale wave purposes, in some definitive way (e.g. as advocated in section 6 below), explicit convection approaches remain arguably our closest thing to ground truth in this area, even with such compromised resolutions.

3. Ingredients: cloud types

The basic ingredients of wave-modulated tropical convection are familiar: shallow, medium, and deep convective cloud towers; and stratiform layer (or anvil) clouds and precipitation. These basic cloud types often occur within coherent deep convective cloud *systems* (which go by the generic name mesoscale convective systems, MCSs; often just lumped as “convection” in large-scale meteorology parlance). MCSs remain mysterious entities, but may in fact be a special case of convection waves, as discussed in Mapes et al. (2006). The almost contiguous nature of MCS cloudiness and outflow airmasses may make a wave viewpoint seem strange to some readers, but there is evidence. For example, scrutiny of 2D cloud model simulations shows a clear distinction between the old familiar MCS-organizing mechanism of spreading gravity currents (cold surface air outflows) and ‘gust front mode’ gravity waves (Fig. 9 of Tulich and Mapes 2008).

These elementary “cloud types” of tropical weather can now be catalogued quantitatively using data from the CloudSat cloud profiling radar (described in G. Stephens, this volume). Figure 3 shows the joint distribution of cloud cover for 20N-20S by echo base vs. top (from Riley and Mapes, manuscript in preparation). Distinct modes in the probability density continuum are seen to justify the discrete language used above (tower vs.

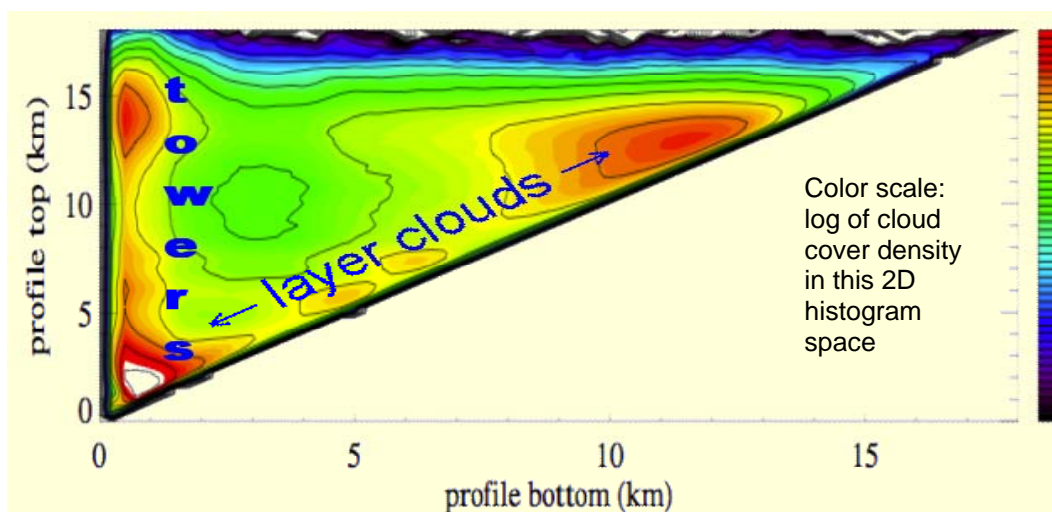


Figure 3: Joint histogram of base vs. top for all cloud profiles (echo-containing segments along vertically incident radar beams), as seen by CloudSat in 20S-20N in its first year or so of operation. Low-based vs. thin echoes straddling the central frequency minimum are denoted ‘towers’ vs. ‘layer clouds,’ respectively.

layer; shallow, medium, deep). Close inspection shows twin modes in middle troposphere clouds, a statistically robust phenomenon whose physical basis we do not fully understand yet. Of course, clear air must be remembered as another, complementary ingredient of wave structure, and unsaturated humidity variations across a wave can often involve more water substance than do the cloud variations.

These modes in the probability distribution (cloud types) broadly support discrete treatments of cloud populations for theoretical models (e.g. Khouider and Majda 2006, 2008 and antecedents). Still, simply having the right ingredients does not guarantee the dish (waves within waves on multiple scales).

4. Combining ingredients

Convection waves depend not on cloud morphology *per se*, but on relationships among the underlying *processes* (tendencies in the model equations) – wave-scale advective tendencies of course, but also sub-wave-scale processes: condensation before wave-scale air saturation is reached, unresolved transports by penetrative and turbulent drafts, particle sedimentation, etc. In the face of this suite of processes, our pre-selection of phenomenon – variations whose spectral power is concentrated along dispersion curves of linear shallow-water waves – simplifies analysis and empowers deduction.

These wavy propagation characteristics suggest a wave model: an interaction between density gradients and the resulting gravity-induced air motions, which in turn feed back to maintain and evolve the density field through advection and wave-induced heatings. To the extent that linearity holds, wave-scale advection may further be simplified as *vertical* advection of *background or basic-state* vertical gradients by the wave's perturbation vertical motions. Evidence for linearity includes lack of amplitude dependence: for example other lighter streaks in Fig. 1c propagating at the same speed as the main featured Kelvin wave, or counter propagating waves passing through each other.

5. A mechanistic focus question: the role of T vs. q variations

This section highlights a single process-level question in convection waves: *what is the relative importance of stability (T) and moisture (q) fields in determining how wave motions shape the density field to yield propagation and growth?*

5.1. Clues in simple theories and models

It is obvious by the name, and well demonstrated by many lines of work (e.g. Derbyshire et al. 2004), that moisture is an important variable governing moist convection. Yet so-called “dry” wave models, with convective heating dependent only on some aspect of vertical stability, have had some success while invoking only dry entropy advection ($w_{wave} \partial\theta/\partial z$). One example is Mapes (2000), where a formal q dependence factor $f(q)$ was simply set to unity. The assumption implicit in such a formulation is not that $w_{wave} \partial q/\partial z$ (a.k.a. moisture convergence) is zero, but rather that it acts to maintain a constant background humidity in the presence of stability-governed waves in the precipitation and latent heating fields. This implicitly constant q field is expressed in the assumption that the (certainly large) humidity dependence of convection contributes nothing to its phase dependence.

Moisture dependence in similar models has been added by subsequent authors (e.g. Khouider and Majda 2006, 2008 and antecedent references), and was elevated to a titular conceptual model element in Kuang (2008b). This was based partially on a finding (Kuang 2008a, Fig. 16) that wave instability (in a modeling system described in section 6 below) disappears when vertical humidity advection (moisture convergence) is disabled altogether. In light of the discussion above, this seems like an exaggeration of the actual working hypothesis embodied in a ‘dry’ model. Still, the technique of Kuang (2008a) is flexible and powerful enough for more refined experiments. For example, one could ask whether deviations in the vertical gradient of

moisture are important, as a nonlinear effect involving the advection of perturbation vertical gradients by perturbation vertical velocity in the wave.

Returning to our main question, Kuang (pers. comm.) has also used his modeling system to test the more realistic experimental analog of a dry model -- relaxing wave-scale q fields toward a constant background profile. He comes to the same qualitative conclusion as a similar experiment in the explicit model of Grabowski and Moncrieff (2004): *that the humidity field is a crucial variable in convection wave dynamics*. This conclusion was also based in part (Kuang 2008b, section 3d) on the similarity of wave tilt across waves of many spatial scales. The argument, in the time domain, is that this period dependence of the lag between modes (of wave motion and of shallow-deep-stratiform cloudiness) requires a prognostic variable with long wave-timescale memory (like moisture storage).

The process-level implications of accepting the centrality of moisture are subtle. The net moistening and drying tendencies that cause q to vary across a wave are small imbalances between large terms: mainly advection vs. condensation/precipitation, but also evaporation. It might therefore seem that many individual processes -- from microphysics and precipitation efficiency as a function of cumulus height, to details of the profiles of q and w , to lateral advection -- could be important. A vertically-integrated moist static energy viewpoint on humidity variations is sometimes taken, to evade the large condensation term. But again, small residuals between large canceling terms govern the tendency -- in this case in the vertical, hinging on details of profile shape. These blank mathematical fears may be overblown: physically, it is easy to make ascending regions moisten before they precipitate, by making deep convection (or convection's depth) sensitive to dry air (e.g. Bechtold et al. 2008). Still, improving model moisture process balances *quantitatively*, through confrontation with observations, has broader benefits such as data assimilation effectiveness (Andersson et al. 2005), so dedicated NWP work on tropical convection waves might pay off at multiple levels.

Might the delicacy of moisture effects constitute a prediction of frailty (i.e., that waves should differ regionally and seasonally due to all sorts of background state effects, and perhaps be highly nonlinear)? If so, does the first-order observations of robust wave existence, with nearly constant and amplitude-independent propagation speed indicative of quasi-linear density-field waves, constitute indirect but potentially powerful evidence against a theory invoking fickle moisture in addition to trusty density? More thought and evidence are needed to advance this argument with any real force.

5.2. Clues from explicit models and observations

Conditioned by the ideas above, let us briefly examine the relative *magnitude* of T and q fluctuations in convection waves. For more discussion, the reader is referred to section 8 of Mapes et al. (2006). As a reference point, Figure 4 shows composite T and q anomalies in a time section through wave-triggered second-generation convective storms in a 2D cloud model during spinup (Fig. 13 of Tulich and Mapes 2008). Consider the convective development stage (negative lags with respect to rainfall). Cool ambient temperatures along the rising cloud top level dominate the density anomaly, and thus are the structural signature of the wave, but q anomalies are also large in this growing cloud wedge.

Viewed as a forcing, the cooling at negative lags acts to enhance cumulus buoyancy and 'lift the cap' off deepening convection. But enhanced humidity within the cloud layer surely boosts development too, and is also (at least partly) wave-induced, by advection. Yet both T and q perturbations also include important feedbacks from the developing convection itself. The dependence of this feedback on, say, microphysics can seem counterintuitive: shallow convection may moisten the lower troposphere *more* by precipitating, to the extent that the net latent heat release drives ascending motion (moisture convergence) in the low levels and time scales are being considered. Such paths of linear reasoning (forcing and feedback) lead in circles, so

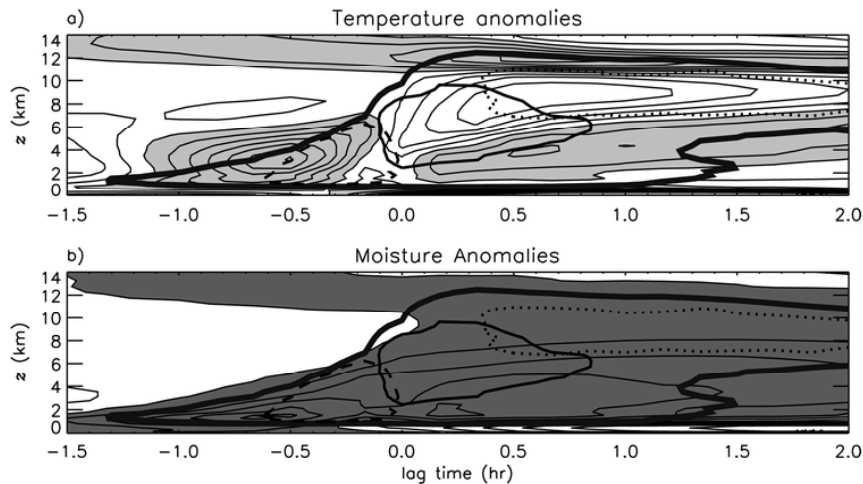


Figure 4: Rain-centered composite T and q anomalies during early stages of convection wave development in a 2D cloud model (second-generation cloud clusters, Fig. 13 of Tulich and Mapes 2008). Heavy outline is a cloud water contour (identical in both cases). Lightest contours show T and q , in units 0.1 K and 0.1 g/kg , shaded negative in (a) and positive in (b) respectively. Medium contours show heating rate, subdivided into shallow convective (dash), deep convective (solid) and stratiform (dotted).

where moist static energy h decreases with height. This extent (net heating \rightarrow w link) depends on what space in the end they must be packaged into closed quantitative wave models whose predictions can be tested against observations.

The relative magnitude of q' relative to T' in Fig. 4 is about 1 to 1 (g/kg to K). In this proportion, T' is dominant in terms of air density (virtual temperature), while q' is the dominant contribution to h (so that air in the wedge has enhanced $h' > 0$, despite being cooler). A third basis for interpretation of relative magnitudes makes reference to the background vertical gradients. Since h decreases with height in the lower troposphere, a vertical displacement causes more moistening than cooling, so the roughly 1 to 1 ratio here is consistent in sign with a wave vertical displacement. The 1:1 ratio (g/kg per K) in Fig. 1 is about the smallest moisture amplitude seen in convection waves, and may be artificially limited by the 2D geometry, so T -dominated interpretations in these model studies may not generalize to all waves.

For lower and lower frequency convection variations, observed amplitudes of composite q' moistening in the wet phase become larger and larger (see Mapes et al. 2006), relative to both rainfall (its Fig. 7) and T' (its Fig. 14). Alternately, one could speak of more drying through the suppressed phase. Does this frequency dependence of moisture storage, in light of broad similarities among waves of at various scales, argue against its central importance, by the argument suggested at the end of section 5a? Looking closer, Kuang (2008a) showed that his “simulated wave structures are found to change systematically with horizontal wavelength.” Perhaps we need to seek these differences, and not just gross commonalities, in more refined observational analyses – but then this strains comparability with a simplified model, as nature has background flows, geographical structure, stochastic forcing of stable modes, etc.

To make scientific progress, more work is needed both with idealized explicit (cloud resolving) models and with hypothesized-mechanism (conceptual and mathematical toy) models, as well as more refined observational analysis. But reconciliation of findings across these methodological and model-observation gaps may not be definitively possible. It would be a huge boost if NWP modeling tools could be brought to bear. We have already argued that there may be real, valuable predictability payoff to be harvested through NWP involvement. The final section outlines a strategy for such an effort.

6. A suggested way forward

Theoretical models with oscillations that arguably resemble observed waves can only take us so far. Besides the wish for deeper scientific understanding, ways to improve realistic models are also desired, short of the brute force approach of 1. run long 3D simulations, 2. characterize the statistics of the variability produced, 3. adjust model and repeat. Only in a realistic NWP model with a decent simulation of convection waves can the next steps be taken confidently: learning to accurately assimilate and initialize divergent motions and moist processes, and attempting forecasts for cases like Fig. 1.

Consider this 3-step strategy:

1. Complete the development and verification of a portable convection-wave ‘test harness’ for 1D models. Kuang (2008a) is my prototype here: in his method, an atmospheric column – be it a periodic cloud resolving model (CRM, 2D or 3D) or a single column model (SCM) – is solved subject to a parameterization of the Rest Of the Atmosphere (ROA). The ROA consists of two parts: 1. steady destabilization (based on radiation and/or mean ascent profiles); and 2. a wave medium for a thermally forced linear plane gravity wave of specified horizontal wavelength, whose other columns are solved by the column model itself in different phases of its time-varying (oscillating) simulation. By running the system for a suite of wavelengths, a spectrum of convection waves can be explored. Note that only *horizontal* wavelength is specified; the model is free to determine whatever vertical structure and frequency (speed) of waves the CRM convection (or SCM) cares to couple to. To verify this method, the results of a small periodic CRM with ROA parameterization should be shown to correspond to the spectrum of waves the same CRM produces when run freely in a large domain.
2. Put a SCM in this harness, and adjust it to act like a trusted CRM. With the rapidity of test-harness runs, a wide range of knobs could be adjusted, starting with the usual suspects (entrainment in convection, downdrafts, etc.) For example, at ECMWF, an enhancement of humidity sensitivity of the convection scheme by means of a dryness-dependent entrainment rate (Bechtold et al. 2008) was found to greatly increase (improve) wave variability. A much wider space of parameters and their values could be explored in a SCM-ROA framework than in full 3D runs.
3. With the SCM tuned thusly, the usual battery of NWP testing could commence: 3D simulation characterization and further tuning if needed, data assimilation, and forecasting. Analysis increments from the assimilation system should be composited by wave phase and the model tuned to reduce them. Initial and systematic forecast errors should be examined for the same purpose. Here observations and a model could fully confront one another in a realistic setting, yielding both improved scientific understanding (interpretation) of the former in the conceptual space of process parameterizations, and enhanced forecast skill for the latter.

Some of these ideas and efforts are in progress (Kuang, pers. comm.). We hope to run a GCSS working group intercomparison activity, and pursue our own attempts, in the realm of a climate model as a matter of convenience of research access. Actually, some of the power of NWP tools is becoming available to climate models, through DART, CAPT, and MERRA replay capabilities (google acronyms for details).

Summarizing, we have argued that convection waves are an important, predictable phenomenon with scientific as well as practical interest. Linear mechanism reasoning leads in circles, so closed models of cyclic waves are a necessary component of understanding, but require incisive forms of validation and testing. Observations have finite reach into the assumption space of simple models, so truly rich model-observation collaborations might best take place in an NWP framework. However, parameterized-convection

models need to be tuned to have the phenomenon at all before this can take place. Making a SCM act like a CRM in a test harness with a wave-medium parameterization of the Rest of Atmosphere (ROA) seems a useful step in that direction. Convection waves provide a wealth of opportunities for both basic science and improved forecasts of significant weather events, but there is much work to do.

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