An extended single column approach for modeling wave-convection interactions

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Summary

Motivation

1. Wave-convection coupling is a well observed, very important, yet relatively simple form of large-scale organization of convection
2. This coupling cannot be studied under the traditional single column framework

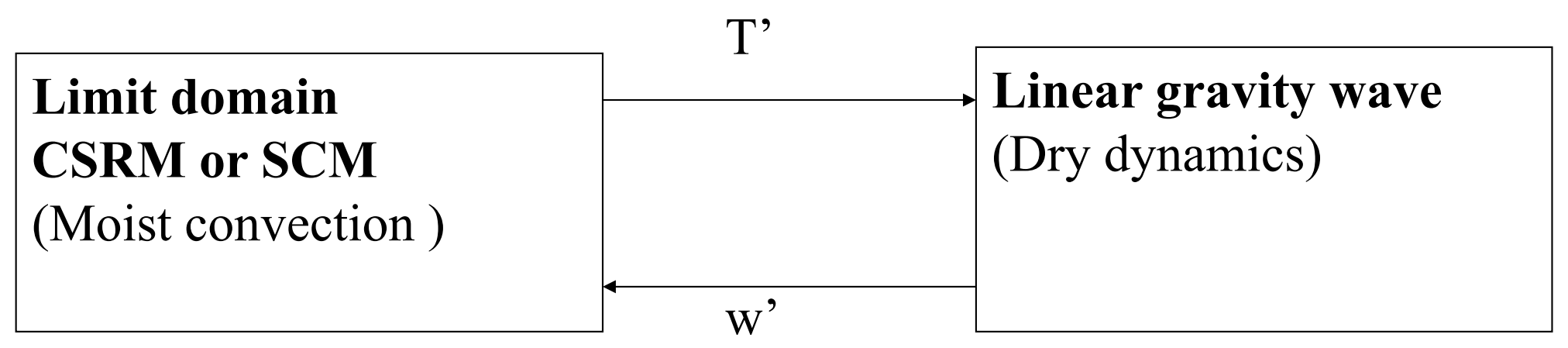
Basic idea

1. Consider the simplest case of 2D linear gravity waves
2. Treat one horizontal wavenumber at a time (inspired by the apparent linearity in observed waves)
3. Couple through a vertical line in the wave, which is modeled with a limited-domain cloud system resolving model (CSRM) or a single column model (SCM)

Goals and current results

1. Capture the essence in a minimal setting
2. Use as a test harness to evaluate and improve cumulus parameterizations
3. Applications to CSRMs and the Relaxed Arakawa-Schubert and the Emanuel schemes are presented

How the coupling works



Limit domain
CSRM or SCM
(Moist convection)

Linear gravity wave
(Dry dynamics)

Linear gravity wave component:

Takes (virtual) temperature anomaly profile, considers the gravity wave adjustment, and updates the wave vertical velocity profile

For 2D linear gravity waves

$$\begin{aligned}\bar{\rho}u'_t &= -p'_x - \varepsilon\bar{\rho}u' \\ (\bar{\rho}u')_x + (\bar{\rho}w')_z &= 0\end{aligned} \longrightarrow \left(\frac{\partial}{\partial t}+\varepsilon\right)(\bar{\rho}w')_z = -k^2 p'$$

$$\longrightarrow \left\{\left(\frac{\partial}{\partial t}+\varepsilon\right)[\bar{\rho}w'(x_0,z,t)]_z\right\}_z = -k^2\frac{\bar{\rho}g}{\bar{T}}T'(x_0,z,t).$$

The last step uses hydrostatic balance; k is horizontal wavenumber; ε is momentum damping; an anelastic system was assumed, but not required

Single column component

Takes the wave vertical velocity profile, models moist convection, and updates the temperature anomaly profile

$$T'_t + \boxed{w'\left(\frac{d\bar{T}}{dz}+\frac{g}{c_p}\right)} = S'_T$$

$$q'_t + \boxed{w'\frac{d\bar{q}}{dz}} = S'_q$$

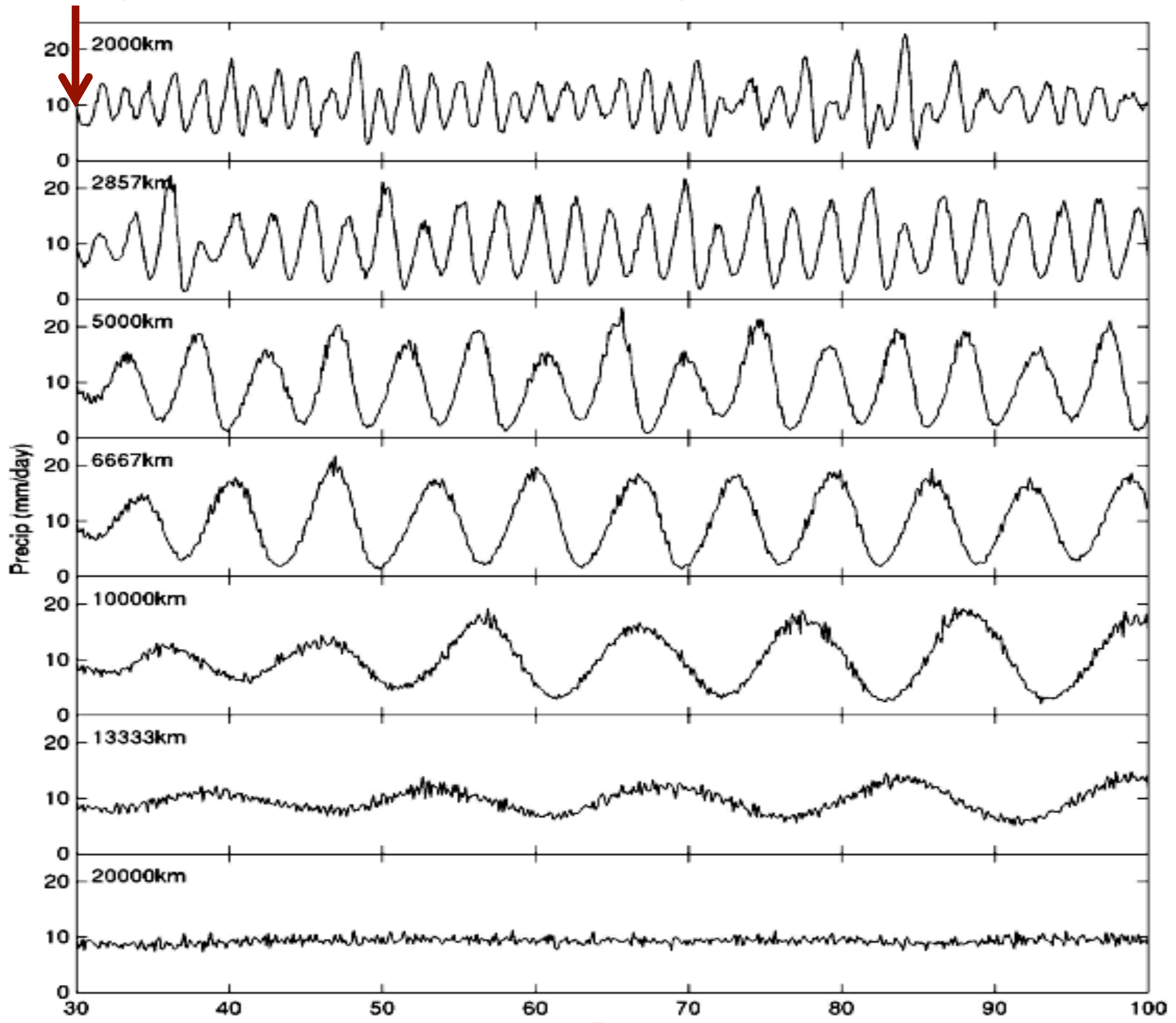
Wave influence on convection (vertical advection due to large-scale wave motion)

Results with a CSRM

Spontaneous development of coupled waves

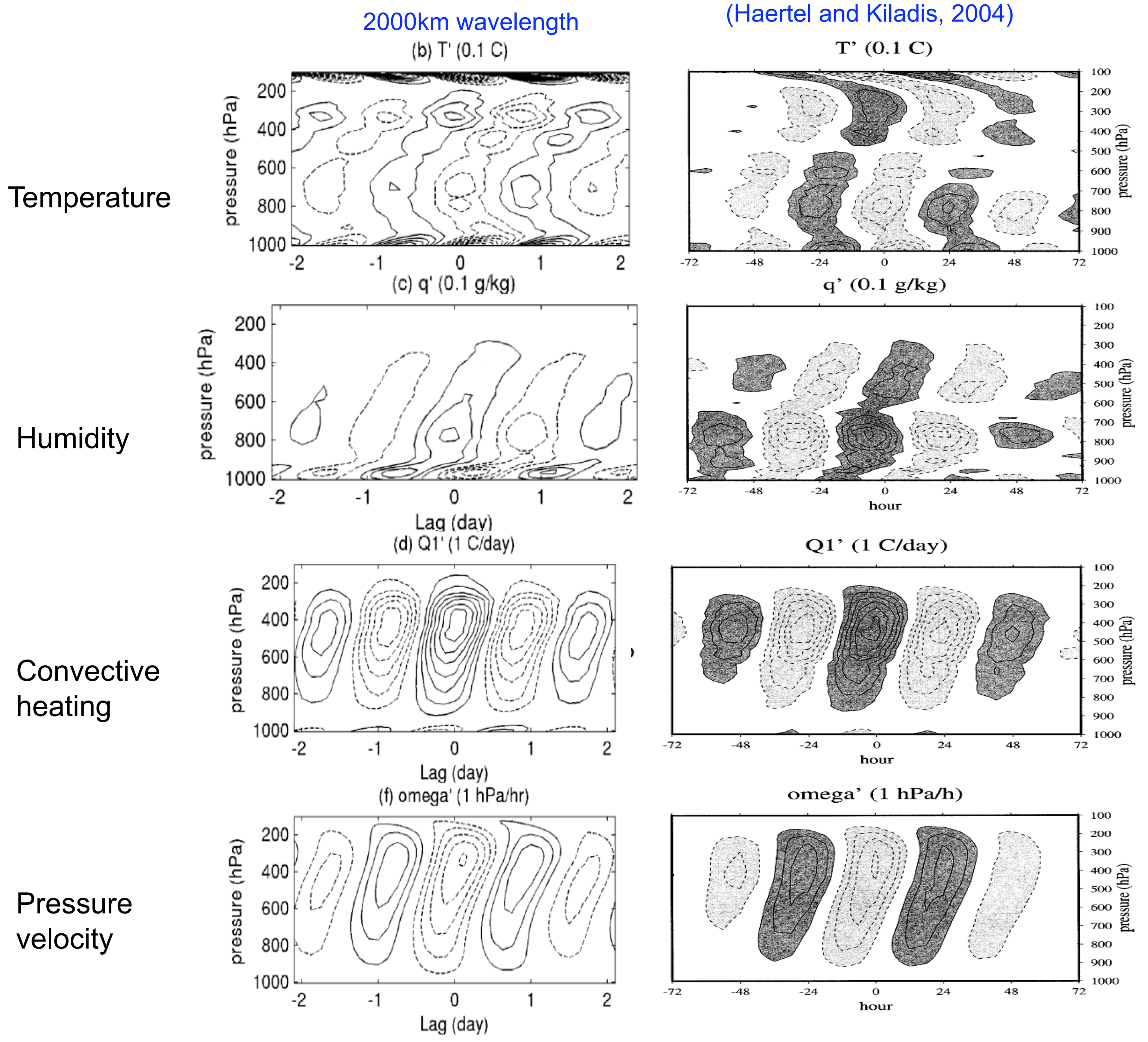
Precipitation v.s. time for a range of horizontal wavelengths

Coupling to wave starts here. Without coupling, the standard deviation is 0.6mm/day



Some details: the above assumes a mean vertical advection observed during TOGA-COARE (hence the mean precipitation of ~9mm/day). The System for Atmospheric Model (SAM) (courtesy of Marat Khairoutdinov) was used. When the Weather Research Forecast model (WRF) is used, results are qualitatively similar.

Composite structures



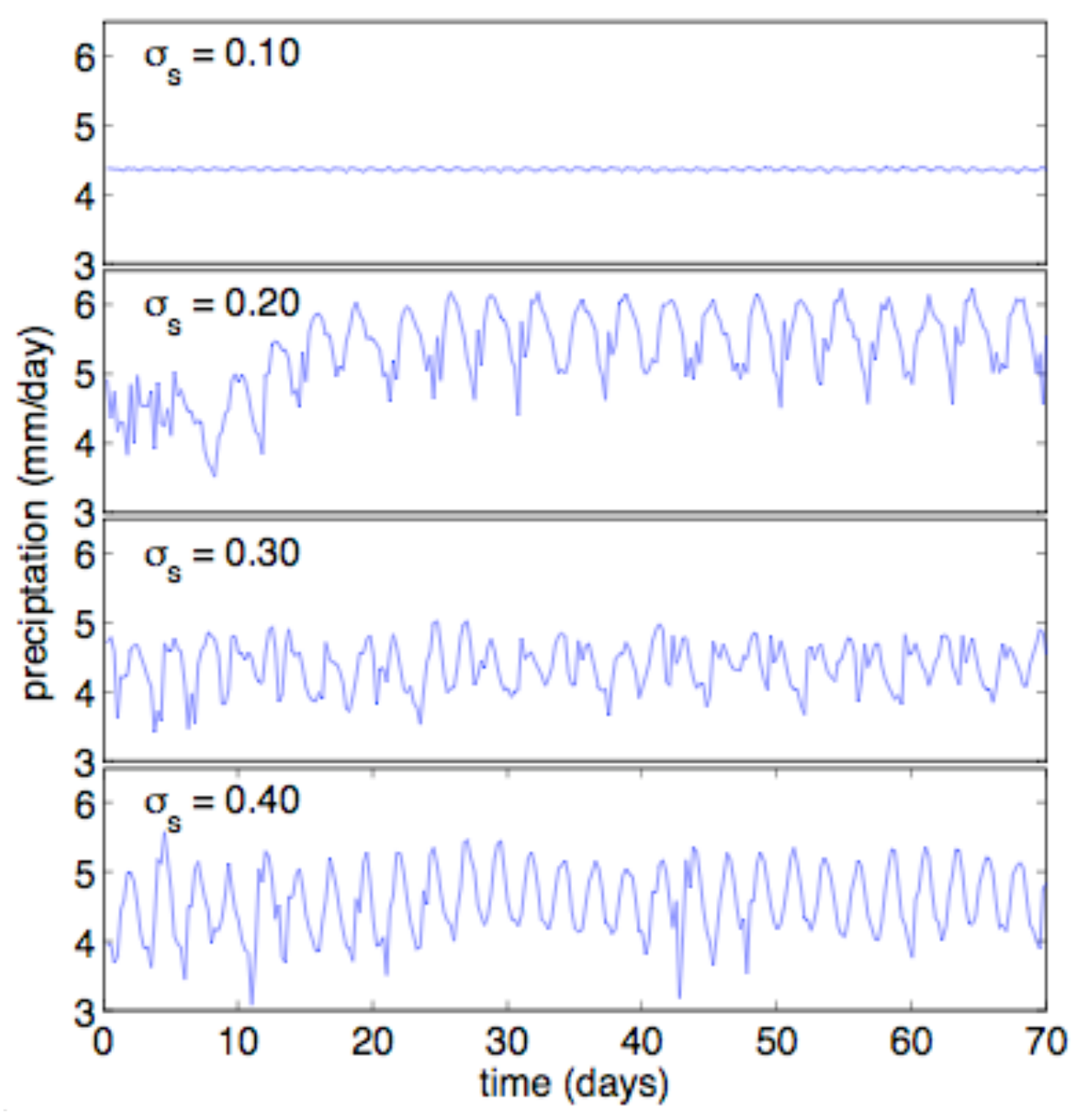
1. Reasonable agreement, but note the comparison is only qualitative because of the idealized nature of the simulations.
2. A 16000km long quasi-3D run confirmed the spontaneous development of coupled waves, with the fastest growing wavelength of ~5500km.

Results with parameterizations

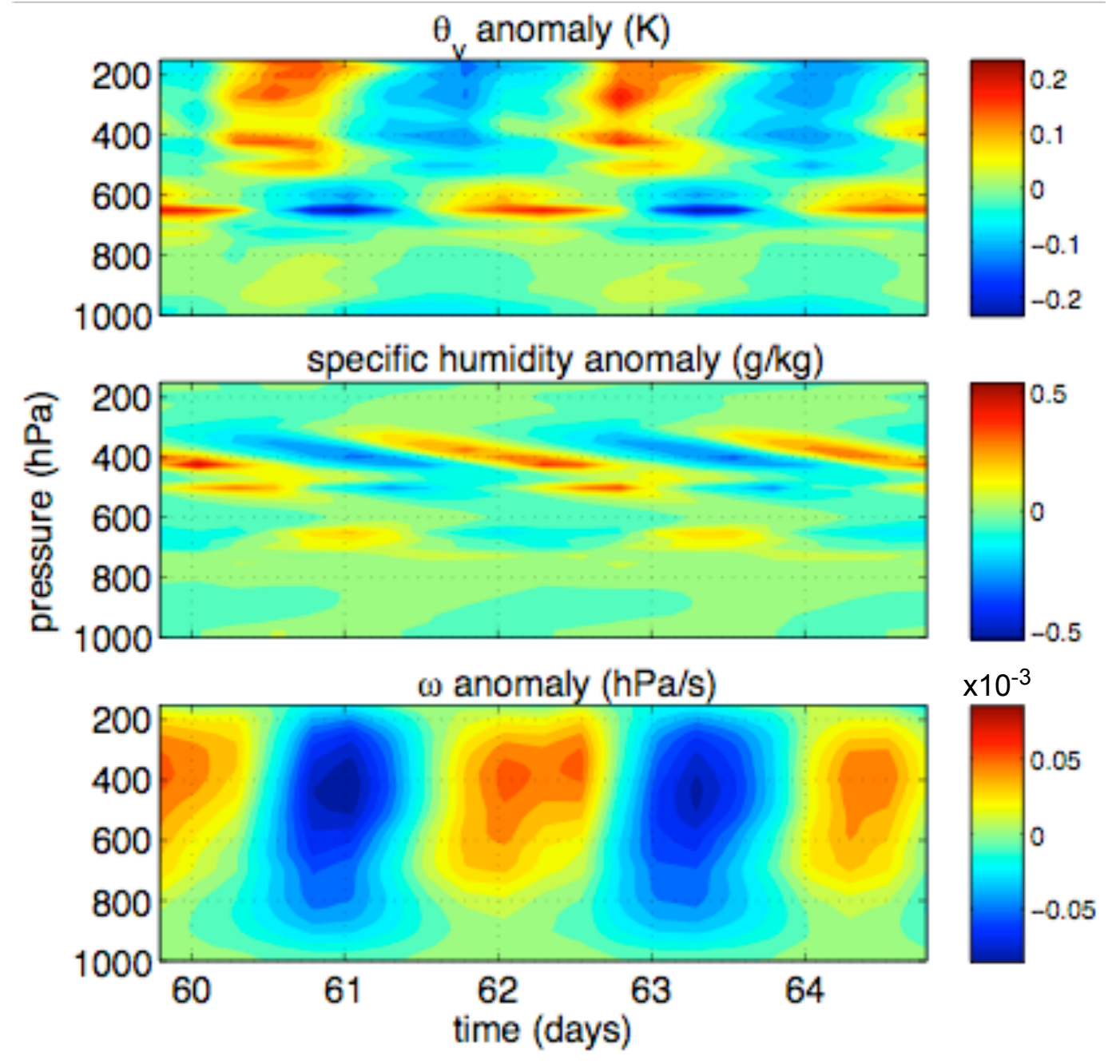
As in the CSRM experiments, runs below are with fixed radiation and simple bulk formula for surface fluxes (no enhancement from downdrafts induced gustiness). A mean vertical advection however is not imposed.

Emanuel Scheme

As the fraction of precipitation that falls outside of clouds (σ_s) is increased from its default value, following Grabowski and Moncrieff (2004), there is more variance in precip.



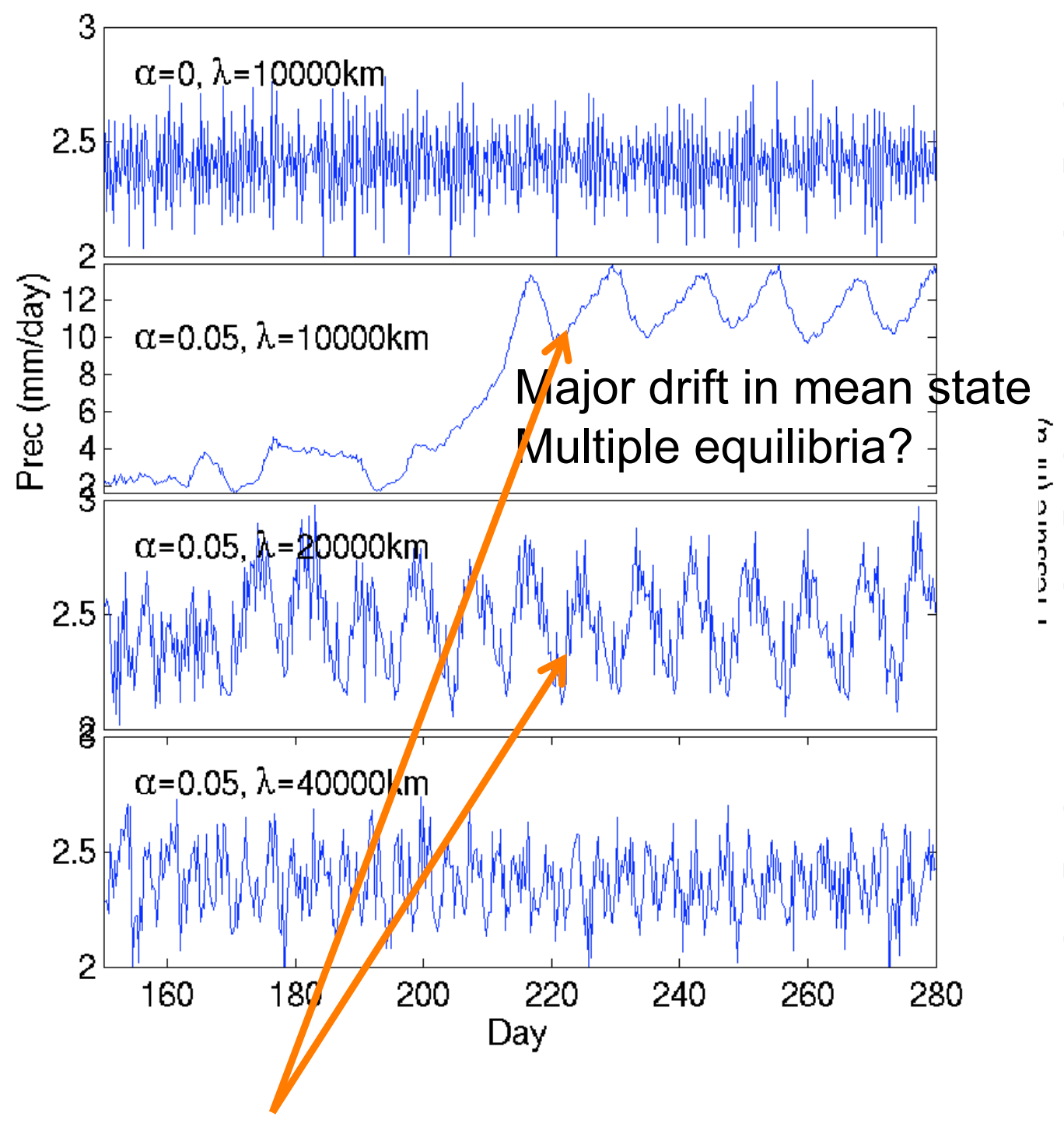
But the wave structures are very different from observations and CSRM results.



A wavelength of ~7000km is used here. The period didn't change with the horizontal wavelength, inconsistent with the CSRM results

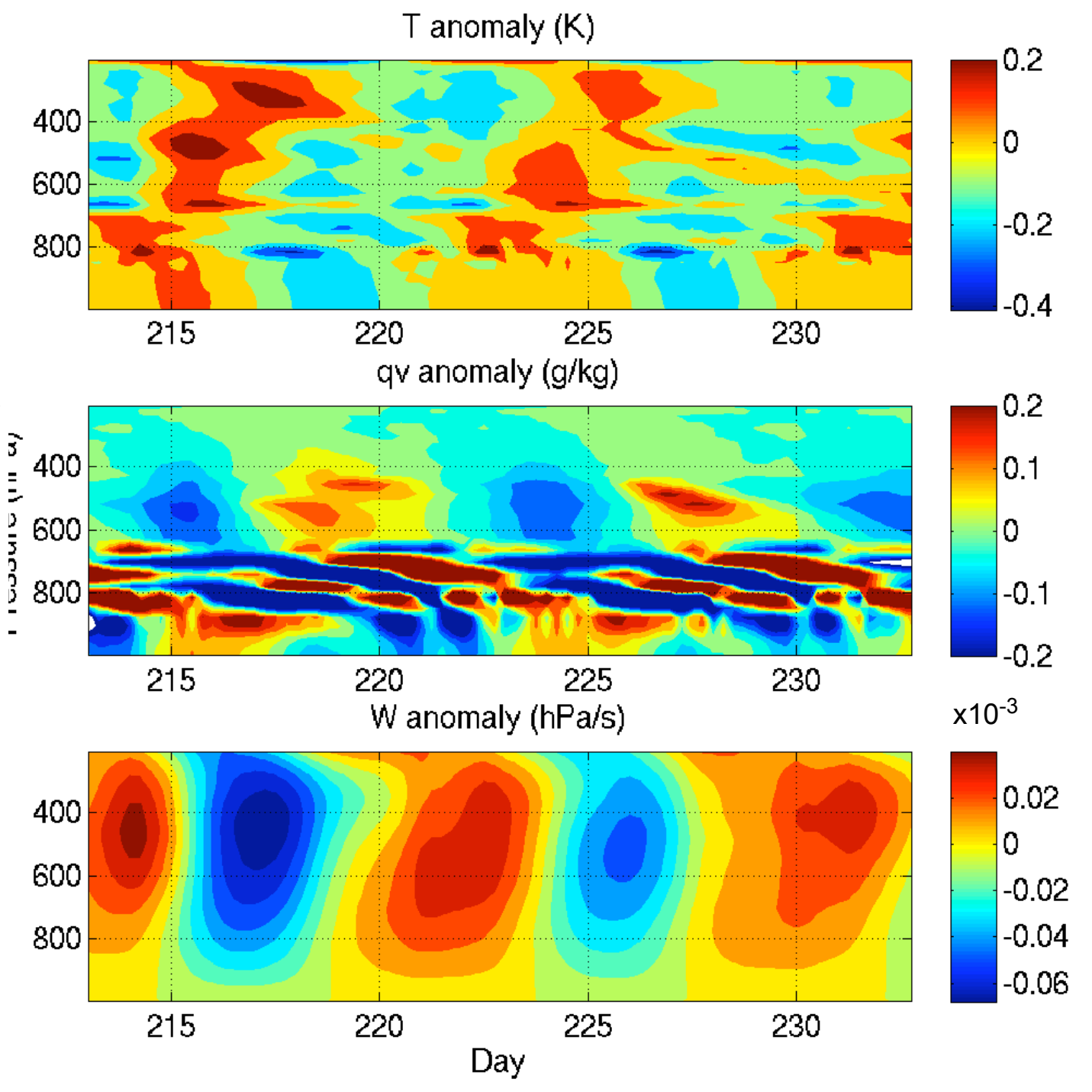
Relaxed Arakawa-Schubert Scheme (GFDL AM2 version)

Confirms that when the Tokioka parameter α is increased, there is more coupling and more variance, **but**, there are a number of issues



Major drift in mean state
Multiple equilibria?

Wave structure for the third case on the left
There seems to be some tilted structure in temperature and some signal in moisture, **but**, what's happening between 900hPa and 600hPa?



Different wavelengths but similar periods, thus different phase speeds

Remarks

1. Neither the default RAS scheme nor the Emanuel scheme produced coupled waves, consistent with results from full GCM experiments.
2. Repeating previous tuning produced more variance but no necessarily the right structure, and there are a number of inconsistencies between the parameterizations and the CSRM in terms of the coupling.
3. High-resolution LES experiments with a purity tracer shows the presence of undilute air parcels are much lower than assumed by the Emanuel scheme, and virtually non-existent in the mid-upper troposphere

References

Grabowski and Moncrieff, 2004, Q. J. R. Meteorol. Soc., pg3081.
Haertel and Kiladis, 2004, J. Atmos. Sci., pg2707.
Tokioka et al, 1988, J. Meteor. Soc. Japan, pg883