The impact of vertical motion structure on the amplification of tropical convection

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Vertical motion structures vary in space and time in the ITCZ

- Top-heavy
  - High GMS
  - Affects moist static energy budgets, gross moist stability (GMS)
  - Omega (dp/dz)
  - Large-scale dynamics

- Bottom-heavy
  - Low GMS
  - e.g. Back and Bretherton 2006, Handlos and Back 2014, Inoue and Back 2015a&b, many others
Geographic variability in mean vertical motion profiles due to effects of SST-gradients, relative SST,
Temporal variability of vertical motion profiles:

- During tropical deep convection, often observe bottom-heavy vertical motion profiles transitioning to top-heavy vertical motion profiles

- Thought to occur for range of timescales of variability
- Does this play a role in amplification/decay?
- What is appropriate value for comparing with theory?
Objectives:

• Investigate mechanisms of convective amplification and decay by analyzing the gross moist stability (GMS)

\[ \Gamma \equiv \frac{\nabla \cdot \langle h\bar{v} \rangle}{\nabla \cdot \langle s\bar{v} \rangle} \]

– Sometimes convection “self-amplifies” via low GMS associated with bottom-heavy vertical motion profiles

– Climatological GMS related to feedbacks between convection & radiation, evaporation
Normalize MSE budget terms by intensity → Gross Moist Stability (GMS)

\[-\left( \frac{\partial h}{\partial t} \right) = \left( -u \frac{\partial h}{\partial x} - v \frac{\partial h}{\partial y} \right) + \left( -\omega \frac{\partial h}{\partial p} \right) - \Gamma_{\text{c}} \]

\[\nabla \cdot (s\vec{v}) = \Gamma_{h} + \Gamma_{v} - \Gamma_{c}\]

GMS describes efficiency of h export by horizontal, vertical motion
Effective GMS is \( \Gamma - \Gamma_{c} \)

Examine relationship to convective growth/decay during lifecycles

- Growth?
- Decay?

-\( \Omega \) (Pa/s)
Can “predict” **Amplifying** and **Decaying** phases of event lifecycle using:

a) small temperature tendency

b) rain increases with column moisture

![Diagram showing MSE and its interactions](image)

- **MSE Import > Export, Effective GMS < 0**

\[ \Gamma < \Gamma_c \]

**Amplification**

\[ \frac{\partial P}{\partial t} > 0 \]

Similarly, **decay** for **positive effective GMS**
Test idea using Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE)

• November 1992 through February 1993 (Intensive Observation Period)
• Domain: Intensive Flux Array (IFA)
• Data set constructed by Minghua Zhang (Zhang and Lin, 1997)

• Filter data to remove diurnal cycle (so T tendency small)
• Bin by an effective GMS (drying efficiency) $\Gamma - \Gamma_c$ (for cases with denominator $> 10$ $\text{W/m}^2$)
• Examine frequency of precipitation increases, amount of precipitation increase
Amplifying phase

\[ \Gamma < \Gamma_c \]

Decaying phase

\[ \Gamma < \Gamma_c \]

(a) \( \delta \) Prec vs \( \Gamma - \Gamma_c \)

(b) Probability of Increase in Prec vs \( \Gamma - \Gamma_c \)

(c) Prec vs \( \Gamma - \Gamma_c \)

Low GMS associated with precipitation growth, high GMS associated with precipitation decay

GMS near-critical associated with high precip

Inoue and Back, 2015
Critical GMS (associated with diabatic terms) relatively constant

\[ \frac{\partial h}{\partial t} \cdot (s\bar{v}) = \Gamma_v + \Gamma_h - \Gamma_c \]

- Critical GMS is relatively constant in both amp/decay phases (no a priori reason to expect)
- Radiation plus surface fluxes always tend to destabilize the convection by supplying MSE source
- Diabatic sources don’t seem to regulate transition from growth to decay (timescale dependent?)

\[ \Gamma - \Gamma_c \]
Vertical GMS explains variability in amplifying phase

\[
\frac{\partial h}{\partial t} - \nabla \cdot (s \bar{v}) = \Gamma_v + \Gamma_h - \Gamma_c = \Gamma - \Gamma_c
\]

In the amplifying phase, vertical GMS explains most of the variability of effective GMS

(a) Omega [Pa/s] vs \(\Gamma - \Gamma_c\)

Pressure (hPa)

Inoue and Back, 2015

\(\Gamma - \Gamma_C, \Gamma_H, \Gamma_V, \Gamma_C vs \Gamma - \Gamma_C\)
Vertical advection (& GMS) variations related to vertical motion profile shape

(b) Omega [Pa/s] vs \( \Gamma_V \) \((\nabla \cdot <sv> > 0)\)

MSE *imported* by vertical motion

MSE *exported* by vertical motion
Horizontal GMS explains the variability in decaying phase

\[ \frac{\partial h}{\partial t} \cdot (s\vec{v}) = \Gamma_v + \Gamma_h - \Gamma_c \]

\[ = \Gamma - \Gamma_c \]

In the decaying phase, horizontal GMS explains most of the variability of effective GMS.

Indicates decaying is due to the horizontal advection (plus vertical advection)
Constant critical GMS associated with regression of radiative cooling plus evaporation on precipitation

• This is a better fit than assuming constant gross moist stability

\[ F \approx \gamma \nabla \cdot \langle s\bar{v} \rangle, \quad \Gamma_C \equiv \frac{F}{\nabla \cdot \langle s\bar{v} \rangle} \approx \gamma. \]
Interpretation:

- Gross moist stability fluctuates around a critical (characteristic) value which is determined by relationship between convection and surface fluxes, radiative cooling

\[
F \simeq \gamma \nabla \cdot \langle sv \rangle, \quad \Gamma_C \equiv \frac{F}{\nabla \cdot \langle sv \rangle} \simeq \gamma.
\]

\[
\Gamma - \gamma < 0 \quad \text{Amplifying phase}
\]

\[
\Gamma - \gamma > 0. \quad \text{Decaying phase}
\]

- Feedbacks (radiative-convection and convergence) determine threshold

- Characteristic GMS the one important for MJO, ITCZ-scale dynamics?
Gross moist stability fluctuations around a characteristic value?

**Case I: Greater Characteristic GMS**

Like ITCZ regions without strong SST gradients?

**Case II: Smaller Characteristic GMS**

Like ITCZ regions driven by strong SST gradients?
Variations in relationship between convection and radiative cooling, surface fluxes consistent with this

Radiative cooling reductions per unit precip depend on cloud height
Precipitation and surface fluxes correlated throughout ITCZ

Back and Bretherton, 2005
Why geographic variability in vertical motion profiles, feedbacks?

- Back and Bretherton 2009a showed that Lindzen and Nigam 1987-type mechanism drives most surface convergence patterns,
- Back and Bretherton 2009b showed that depth convection associated w/surface convergence reaches modulated by local SST
- Deeper convection is associated with greater reductions in radiative cooling when convection happens

Free troposphere T influenced by warm pool
Conclusions

• Substantial geographic and temporal variability in vertical motion profiles

• Sometimes convection “self-amplifies” by importing moisture, leading to more convection, when GMS is below threshold value
  • Threshold value related to feedbacks between diabatic terms and convection

• Geographic variability in characteristic GMS can be explained by differences in feedbacks