Diurnal Timescale Feedbacks in the Tropical Cumulus Regime

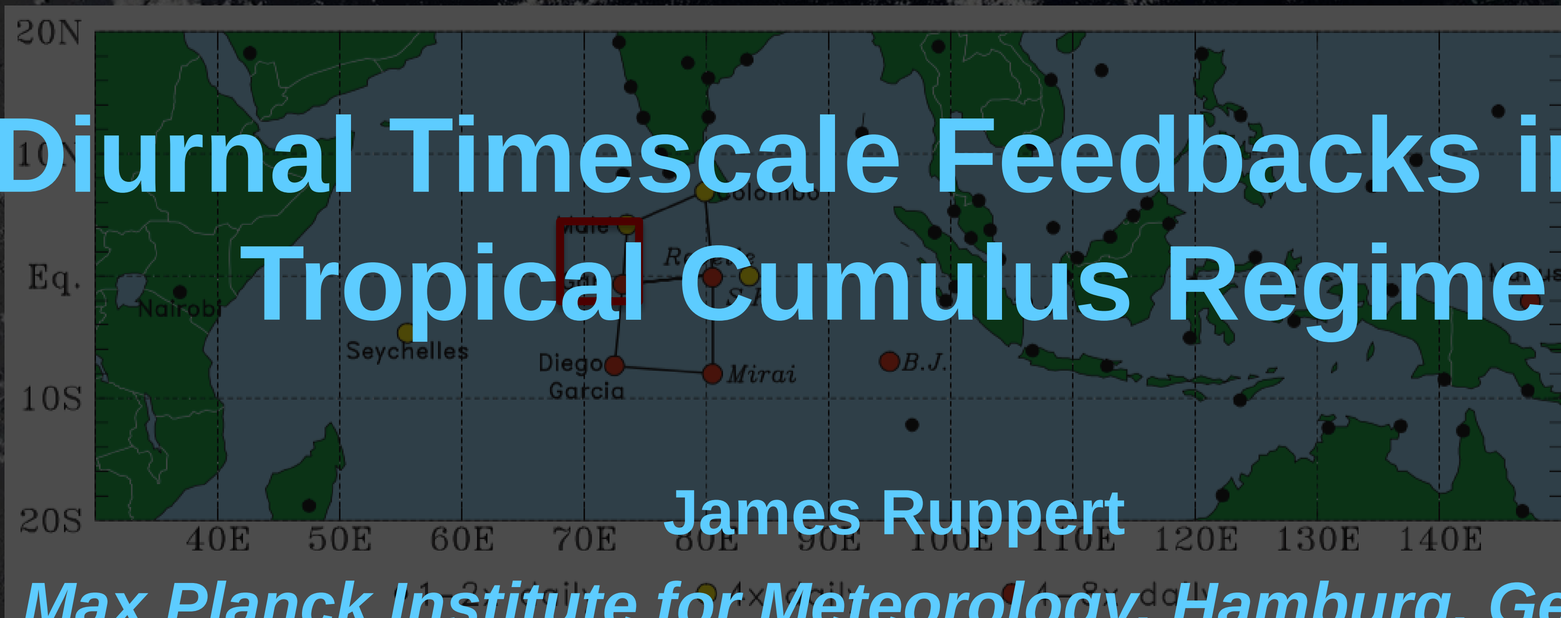
James Ruppert

Max Planck Institute for Meteorology, Hamburg, Germany

GEWEX CPCM, Tropical Climate Part 1

8 September 2016

DYNAMO Sounding Array



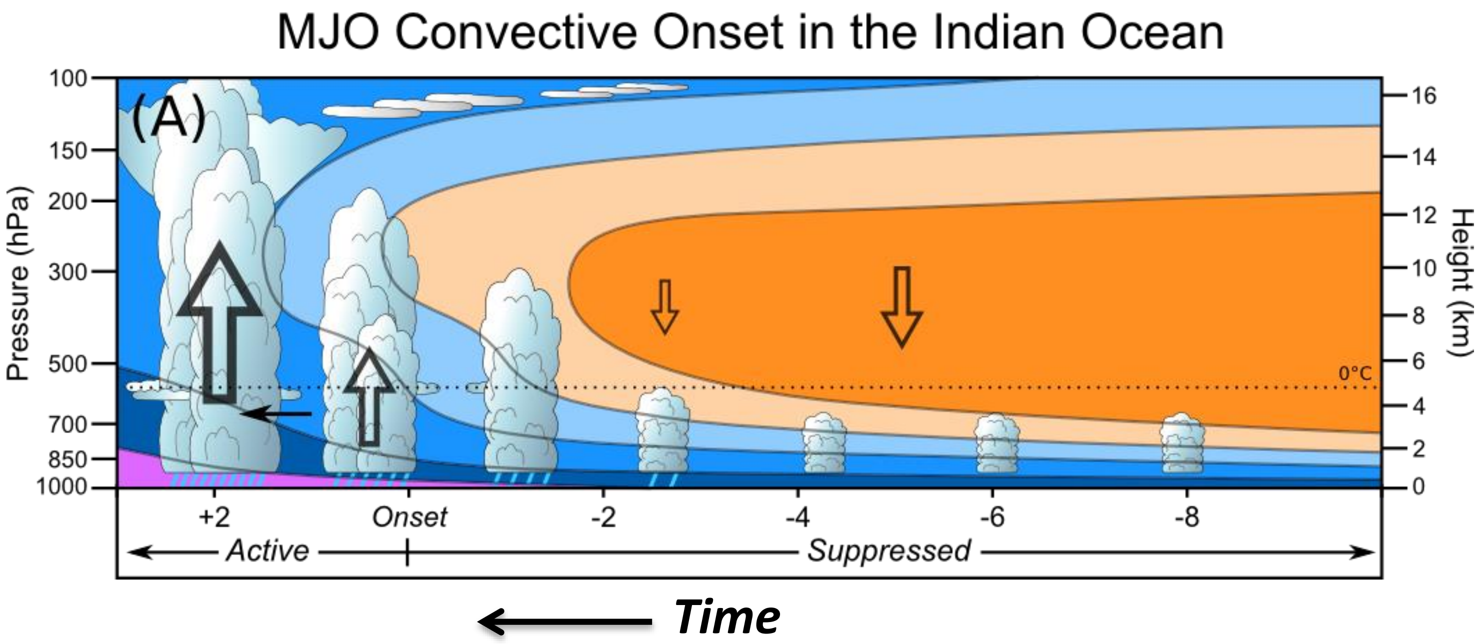
Gan Island

Acknowledgements

- Richard Johnson, Sue van den Heever, Eric Maloney, Dave Randall, Cathy Hohenegger
- George Bryan for providing CM1, including assistance

Alexander von Humboldt
Stiftung/Foundation

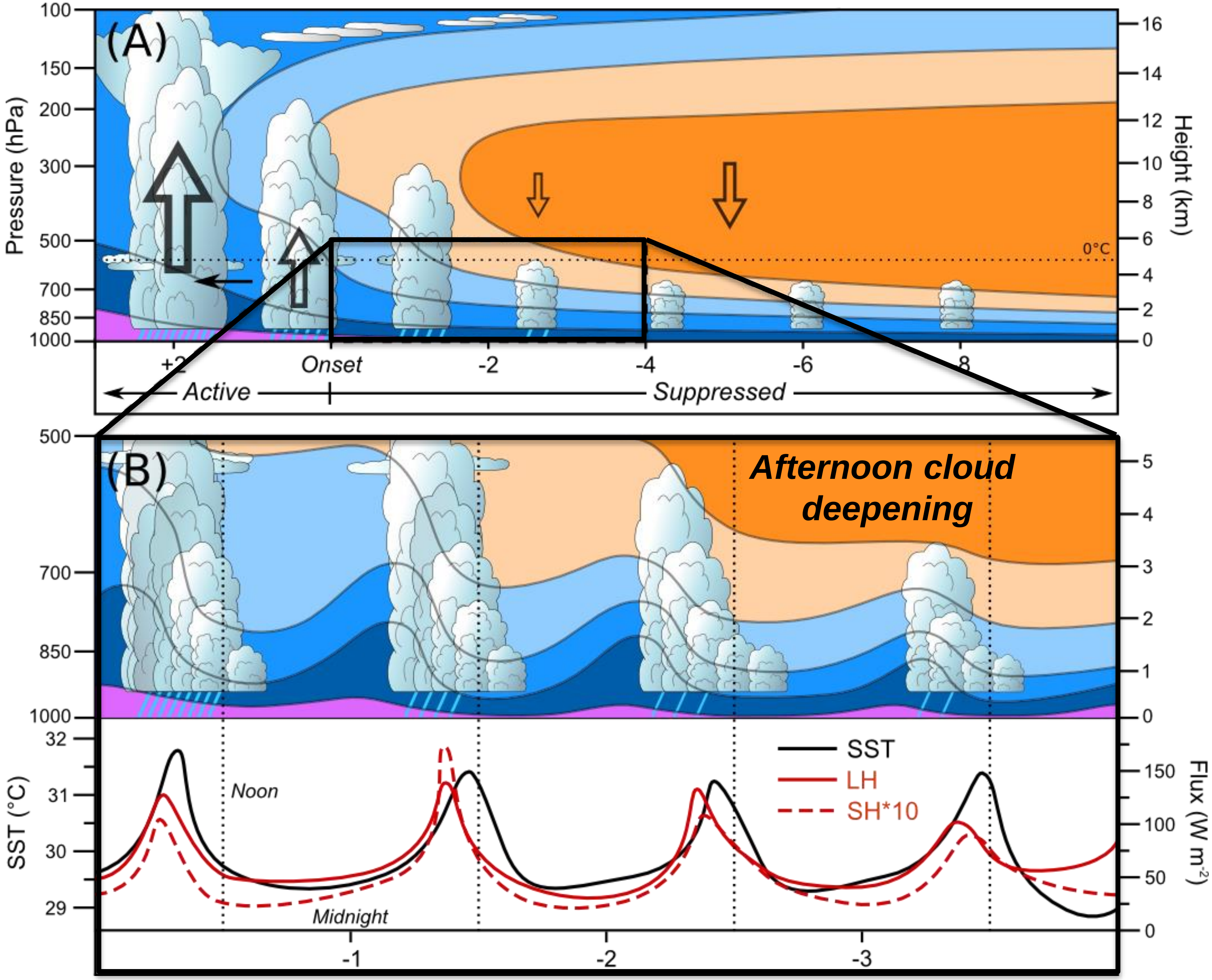
NSF



- Madden–Julian oscillation (MJO) "onset"
- Dynamics of the MJO (DYNAMO; 2011–12)

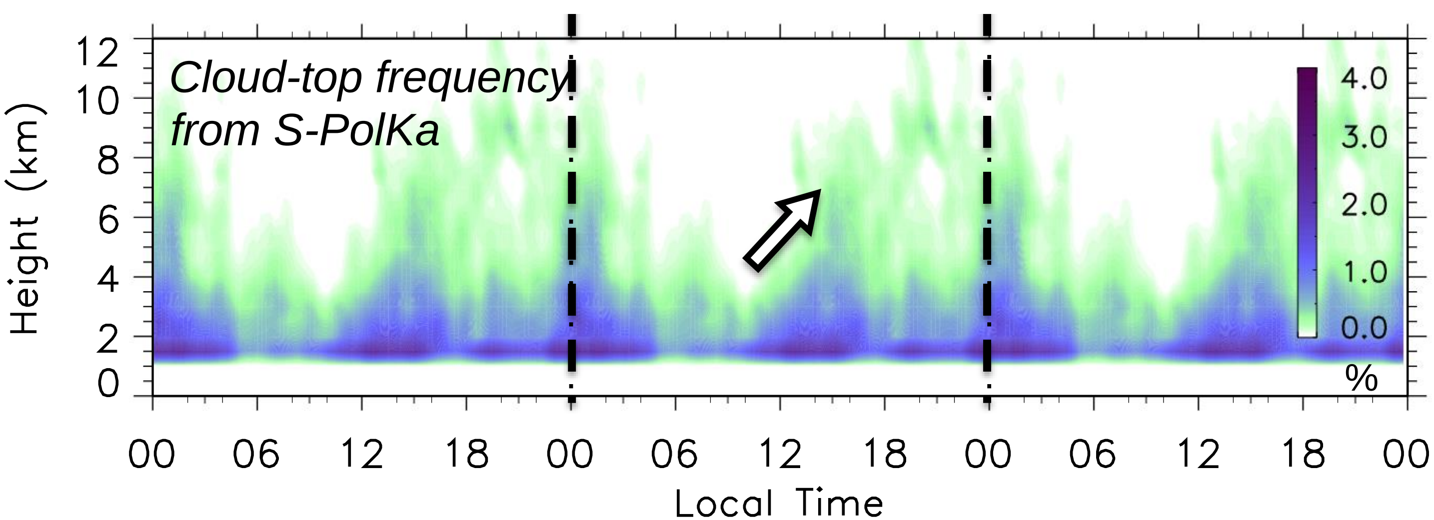
Ruppert and Johnson (2015, JAS)

MJO Convective Onset in the Indian Ocean



Ruppert and Johnson (2015, JAS)

Diurnal Composites (repeated 3x)



Study Objective

Does the diurnal cycle of moist convection rectify* onto longer timescales?

- Simulate the cumulus diurnal cycle in a suppressed regime, isolate nonlinear (daily-mean) forcing
- ****Rectification:*** intraseasonal upper ocean warming (Webster et al. 1996; Bernie et al. 2005; Shinoda 2005)

Model Framework

- CM1 (Cloud Model 1; Bryan and Fritsch 2002) initialized from mean suppressed phase sounding
- Physics:
  - Morrison 2-moment microphysics
  - Deardorff TKE
  - ***Goddard LW, SW radiation***
  - Surface:
    - ***Prescribed SST, diurnal cycle (2^{o}C range)***
    - ***Fixed exchange coefficients***
- Model Domain:
  - O(100 km) in x,y, 22 km in z
  - $\Delta x,y$ = 200 m, 50 m < Δz < 350 m

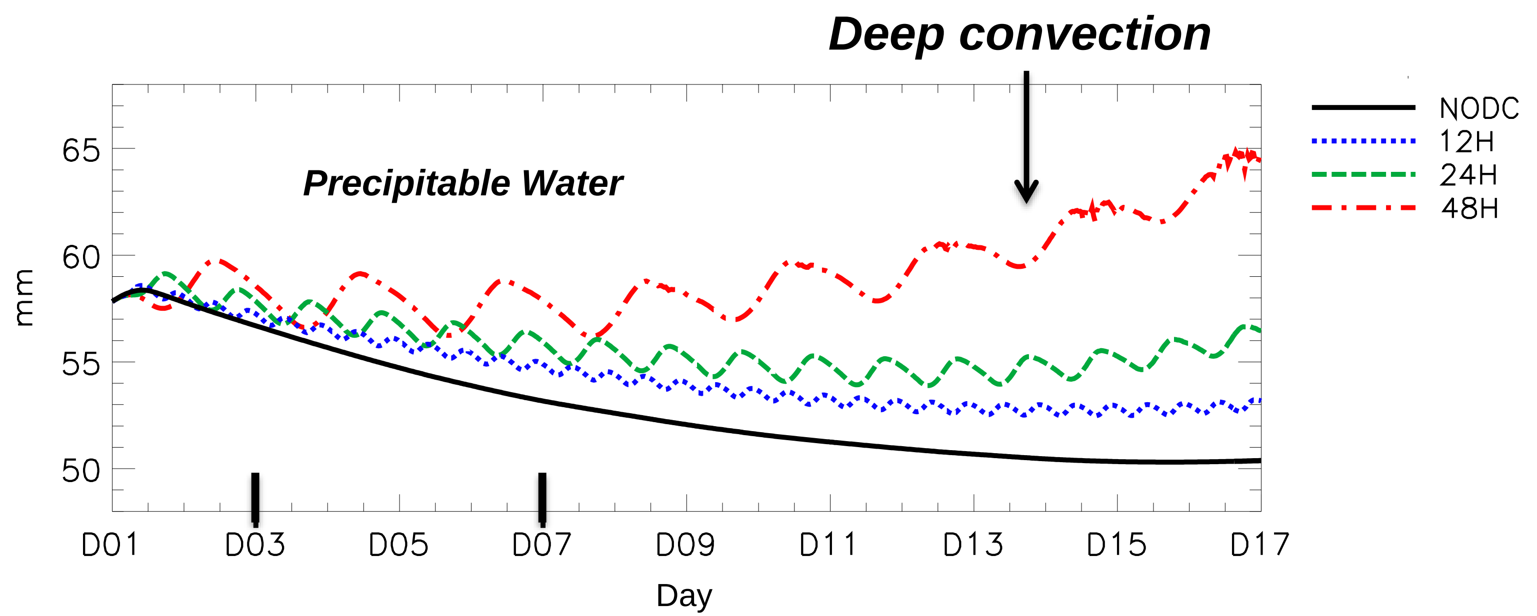
Model Framework

- Large scale must be parameterized: “Weak Temperature Gradient” (WTG) balance:
  - Diabatic sources offset by large-scale adiabatic motion → $\boldsymbol{w_{wtg}}$
  - $\boldsymbol{w_{wtg}}$ diagnosed during runtime, used to advect $\boldsymbol{\theta}$ and $\boldsymbol{q}$
  - Spectral WTG relaxation: θ-anomalies endure as an inverse function of depth (Herman and Raymond 2014)
- Diurnal cycle in $\boldsymbol{w_{wtg}}$

Experiment Rationale

- Stretch the diurnal cycle to scale nonlinearity:
  - **NODC**: diurnal forcing (shortwave, SST) fixed to daily means
  - **12H**: diurnal cycle scaled to 12 h
  - **24H**: … to 24 h
  - **48H**: … to 48 h

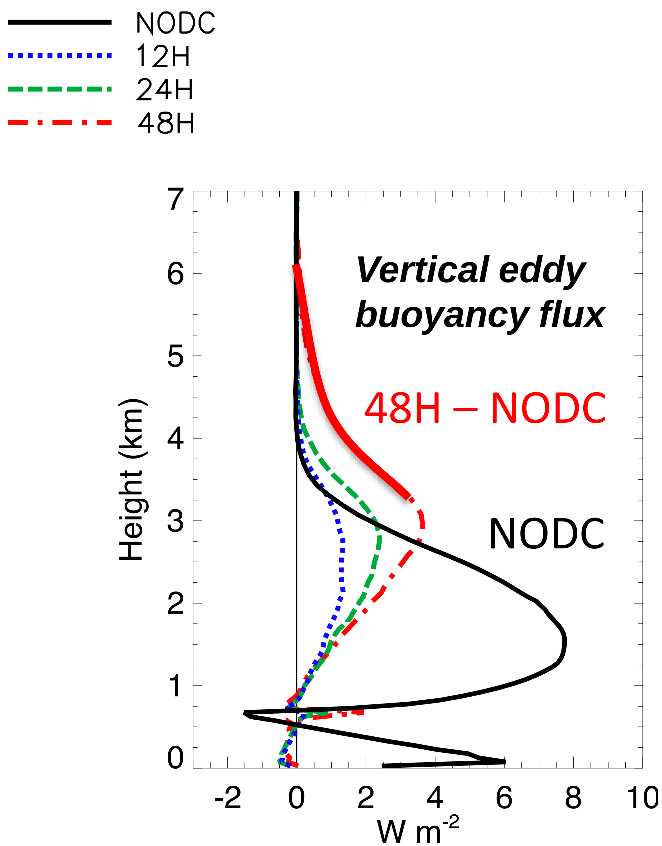
Day-to-day Evolution



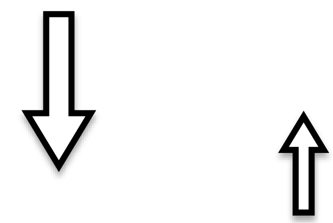
Drying wanes, moistening takes over

Moistening accelerated for longer diurnal period → indicative of diurnal timescale feedback

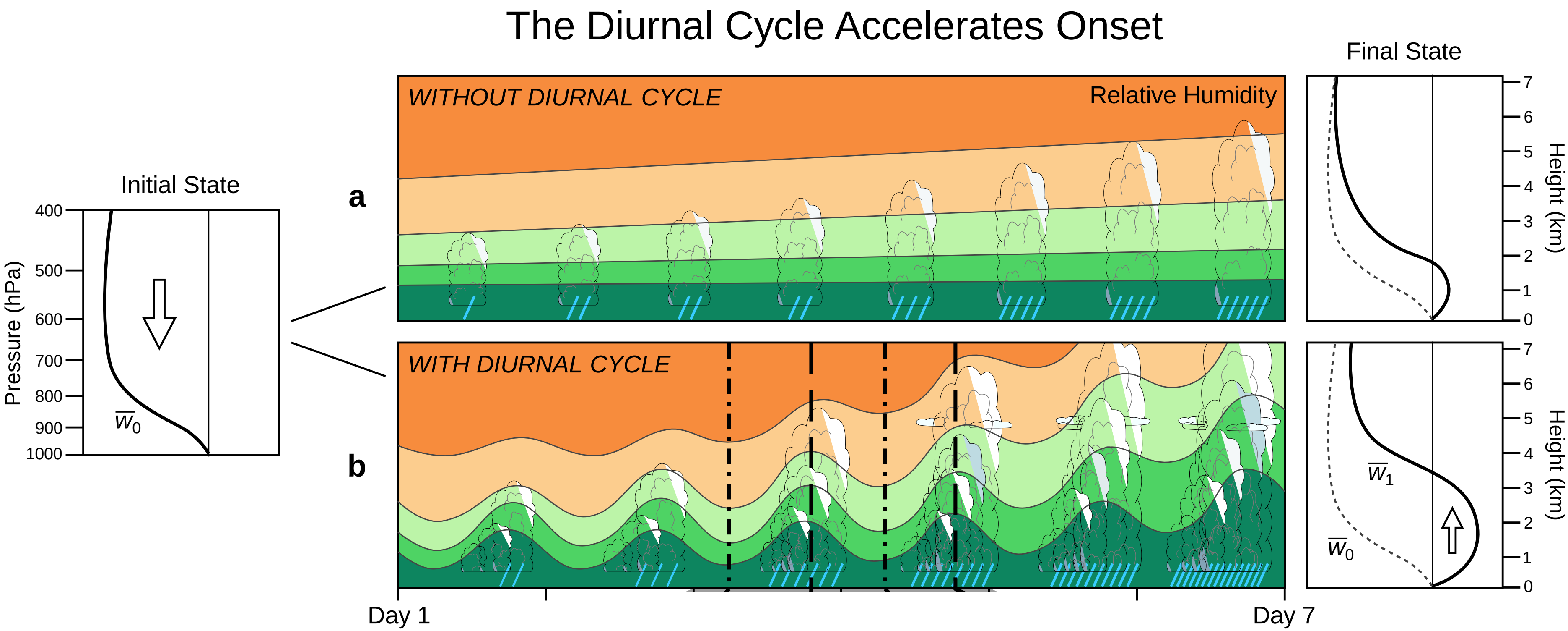
Mean Differences



Greater convective-cloud activity

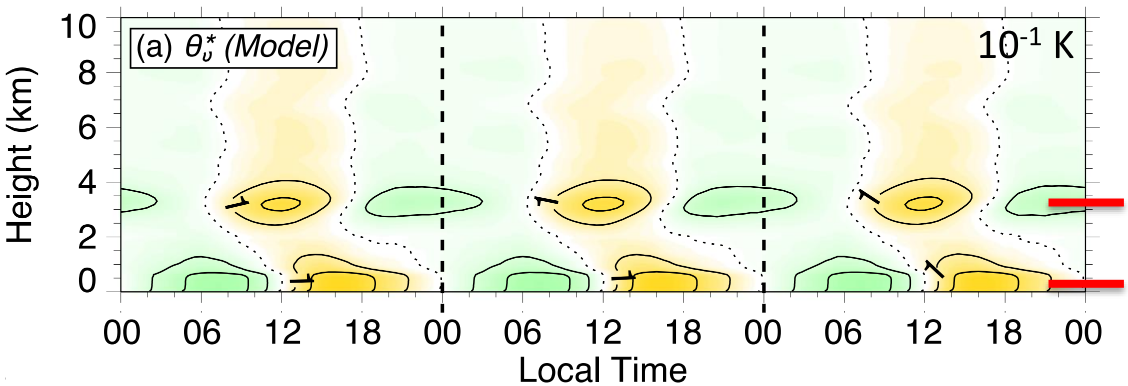


Reduced large-scale subsidence



The Diurnal Cycle Accelerates Onset
Initial State
Pressure (hPa)
400
500
600
700
800
900
1000
$\overline{w}_0$
a
b
WITHOUT DIURNAL CYCLE
Relative Humidity
WITH DIURNAL CYCLE
Day 1
Day 7
Final State
Height (km)
0
1
2
3
4
5
6
7
$\overline{w}_1$
$\overline{w}_0$

Diurnal Cycle of θ_v

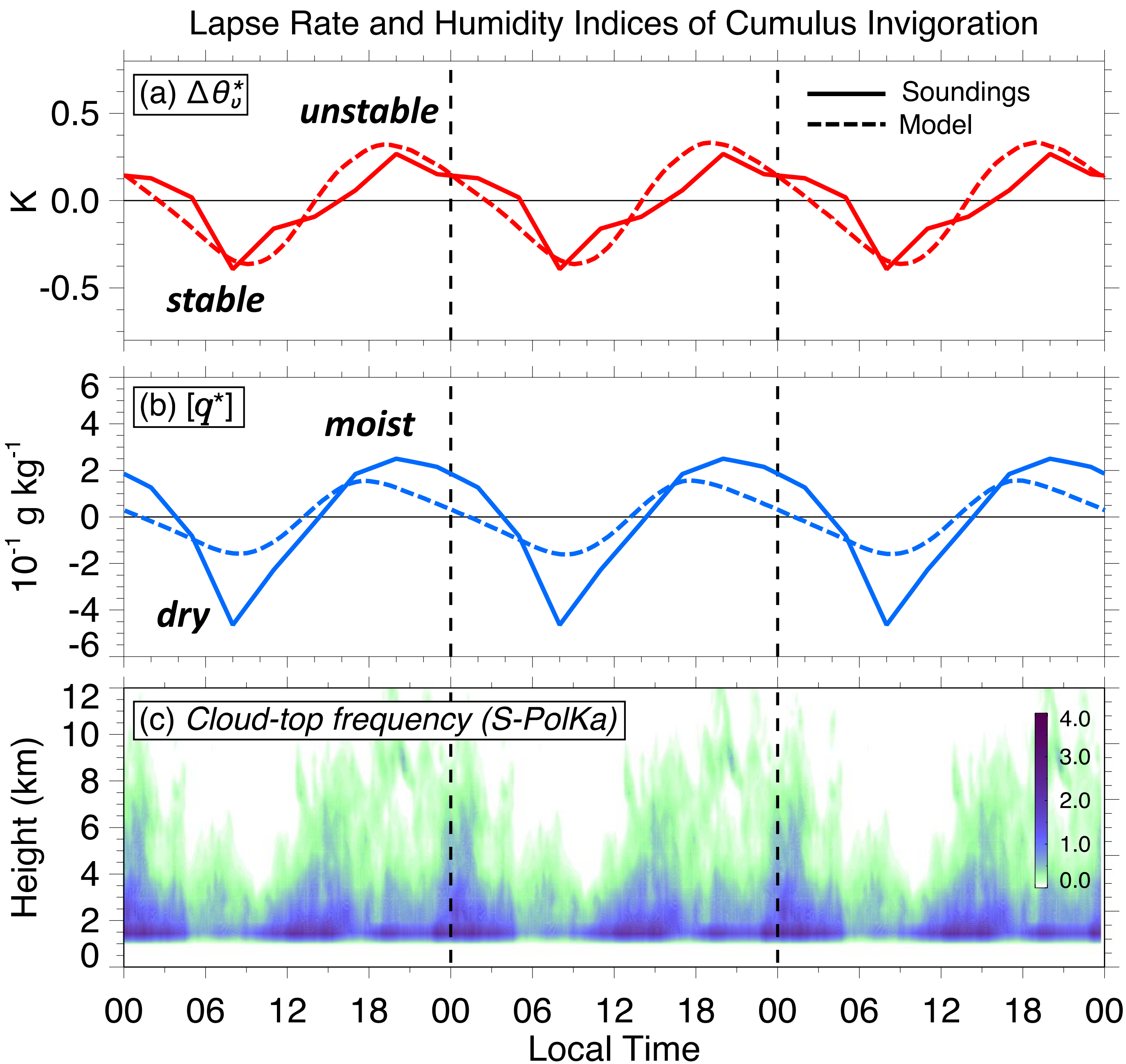


- PBL warmest in the afternoon
- Aloft, signal shifted earlier due to $\boldsymbol{w_{wtg}}$

Revelle soundings

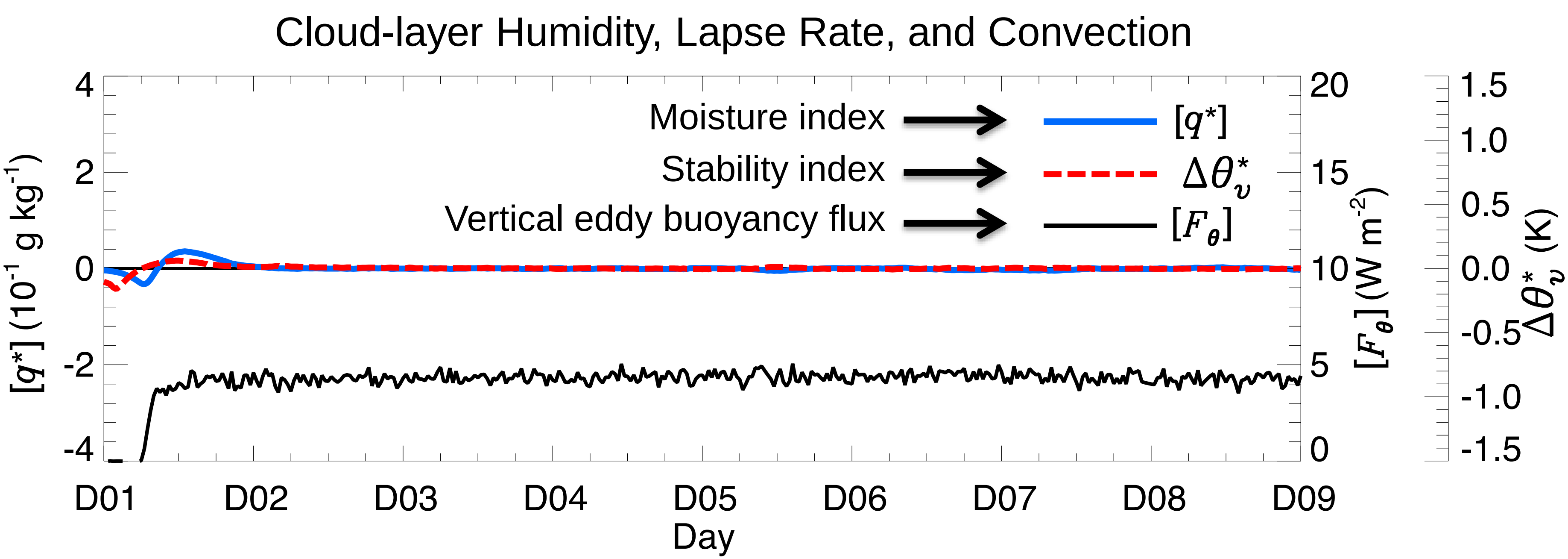
- Much greater θ_v* amplitude

00 06 12 18 00 06 12 18 00 06 12 18 00
Local Time



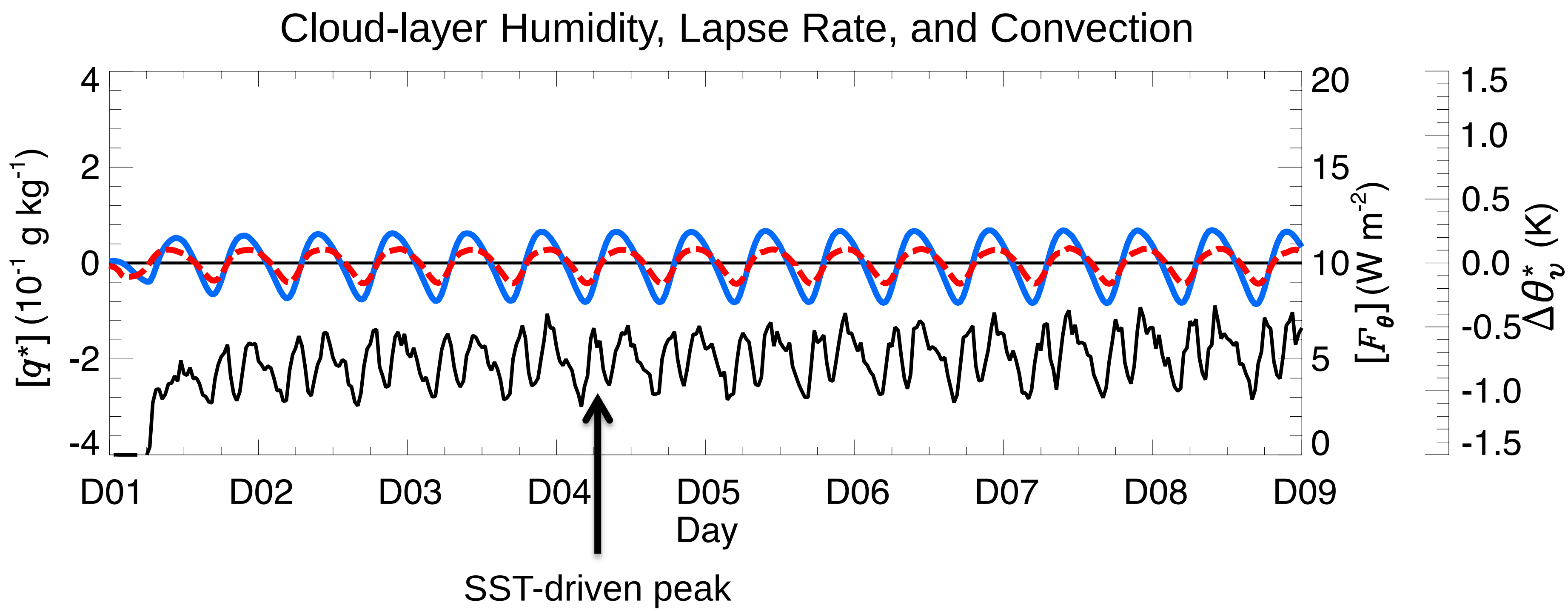
Lapse Rate and Humidity Indices of Cumulus Invigoration
(a) $\Delta\theta_v^*$
unstable
stable
Soundings
Model
K
0.5
0.0
-0.5
(b) $[q^*]$
moist
dry
10^{-1} g kg^{-1}
6
4
2
0
-2
-4
-6
(c) Cloud-top frequency (S-PolKa)
Height (km)
12
10
8
6
4
2
0
4.0
3.0
2.0
1.0
0.0
00
06
12
18
00
06
12
18
00
06
12
18
00
Local Time

NODC



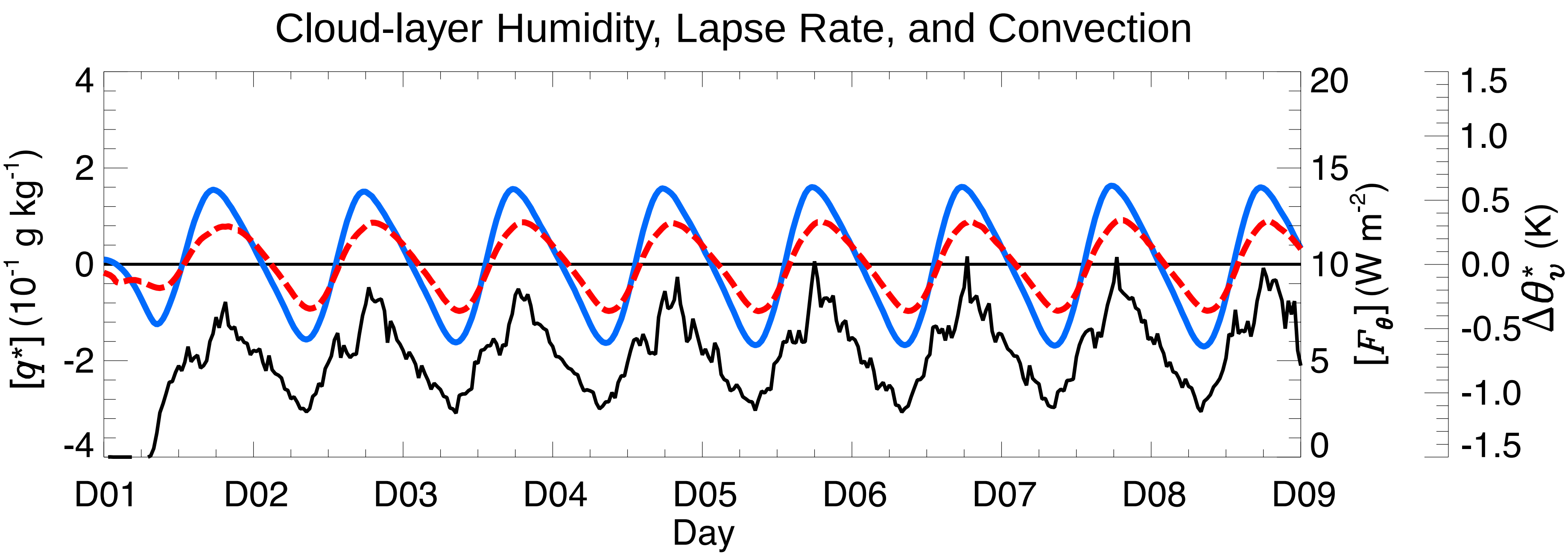
Cloud-layer Humidity, Lapse Rate, and Convection
Moisture index
Stability index
Vertical eddy buoyancy flux
[q*]
Δθ*_v
[F_θ]
[q*] (10^-1 g kg^-1)
[F_θ] (W m^-2)
Δθ*_v (K)
4
2
0
-2
-4
20
15
10
5
0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
D01
D02
D03
D04
D05
D06
D07
D08
D09
Day

12H



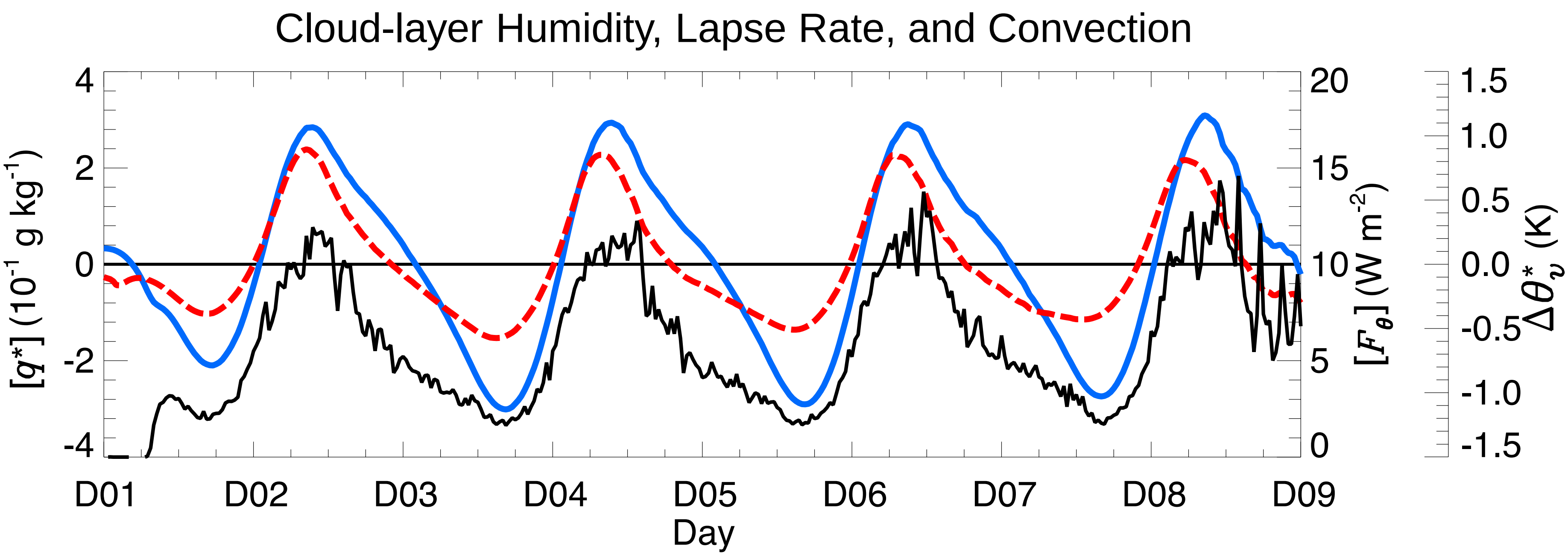
Cloud-layer Humidity, Lapse Rate, and Convection
4
2
0
-2
-4
$[q^*]$ (10^{-1} g kg^{-1})
20
15
10
5
0
$[F_\theta]$ (W m^{-2})
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
$\Delta\theta_v^*$ (K)
D01
D02
D03
D04
D05
D06
D07
D08
D09
Day
SST-driven peak

24H

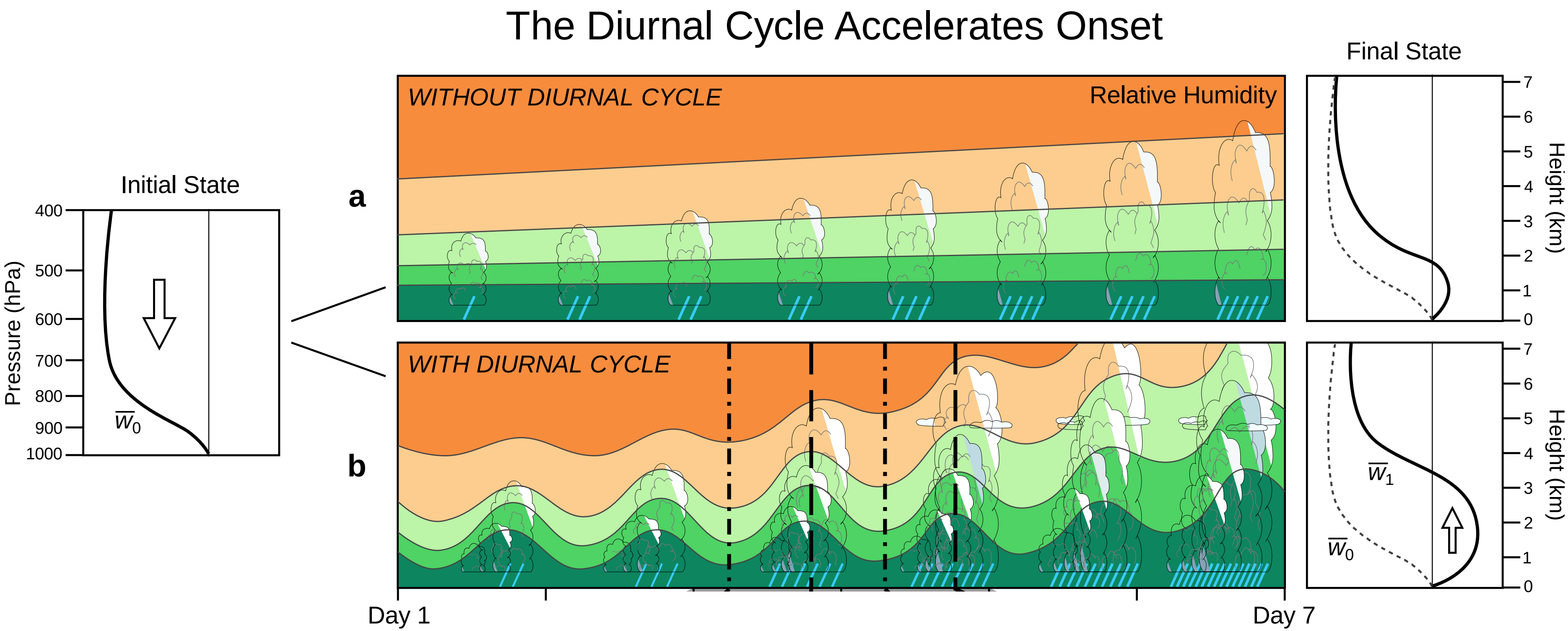


Cloud-layer Humidity, Lapse Rate, and Convection
4
2
0
-2
-4
[q*] (10^-1 g kg^-1)
20
15
10
5
0
[F_θ] (W m^-2)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Δθ*_v (K)
D01
D02
D03
D04
D05
D06
D07
D08
D09
Day

48H



Diurnal forcing agents—moisture and stability—amplify with diurnal period



The Diurnal Cycle Accelerates Onset
Initial State
Pressure (hPa)
400
500
600
700
800
900
1000
$\overline{w}_0$
a
b
WITHOUT DIURNAL CYCLE
Relative Humidity
WITH DIURNAL CYCLE
Day 1
Day 7
Final State
Height (km)
0
1
2
3
4
5
6
7
$\overline{w}_1$
$\overline{w}_0$

Conclusions

- Co-varying diurnal cycles of lapse rate and humidity increase daily-mean convective heating (a nonlinear timescale feedback)
- This timescale feedback accelerates the onset of deep convection, assuming WTG balance

Open Questions

- A more complete treatment of large-scale dynamical coupling is required
  - Large-scale *w* is crudely represented here → substantial amplitude bias in θ, w_{wtg}
- Do / how do diurnal timescale feedbacks manifest in other climate regimes?
  - Over land, where the diurnal heating cycle is much stronger
  - Over the Maritime Continent (land–sea contrast)

References

Bernie, D. J., S. J. Woolnough, J. M. Slingo, and E. Guilyardi, 2005: Modeling diurnal and intraseasonal variability of the ocean mixed layer. *J. Clim.*, **18**, 1190–1202.

Bryan, G. H., and J. M. Fritsch, 2002: A benchmark simulation for moist nonhydrostatic numerical models. *Mon. Wea. Rev.,* **130,** 2917–2928.

Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution Requirements for the Simulation of Deep Moist Convection. *Mon. Wea. Rev.*, **131**, 2394–2416.

Herman, M. J., and D. J. Raymond, 2014: WTG cloud modeling with spectral decomposition of heating. *J. Adv. Model. Earth Sys.*, **6**, 1121–1140.

Madden, R., and P. Julian,1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702–708.

Ruppert, J. H., Jr., and R. H. Johnson, 2015: Diurnally modulated cumulus moistening in the pre-onset stage of the Madden–Julian oscillation during DYNAMO. *J. Atmos. Sci.,* **72,** 1622–1647.

Ruppert, J. H., Jr., and R. H. Johnson, 2016: On the cumulus diurnal cycle over the tropical warm pool. *J. Adv. Model. Earth Syst.,* **8,** 669–690.

Ruppert, J. H., Jr., 2016: Diurnal timescale feedbacks in the tropical cumulus regime. *J. Adv. Model. Earth Syst.*, accepted pending minor revisions.

Shinoda, T., 2005: Impact of the Diurnal Cycle of Solar Radiation on Intraseasonal SST Variability in the Western Equatorial Pacific. *J. Climate,* **18,** 2628–2636.

Webster, P. J., C. A. Clayson, and J. A. Curry, 1996: Clouds, Radiation, and the Diurnal Cycle of Sea Surface Temperature in the Tropical Western Pacific. *J. Climate*, **9**, 1712–1730.

Zhang, C., J. Gottschalck, E. D. Maloney, M. W. Moncrieff, F. Vitart, D. E. Waliser, B. Wang, and M. C. Wheeler, 2013: Cracking the MJO nut. *Geophys. Res. Lett.*, **40**, 1223–1230.