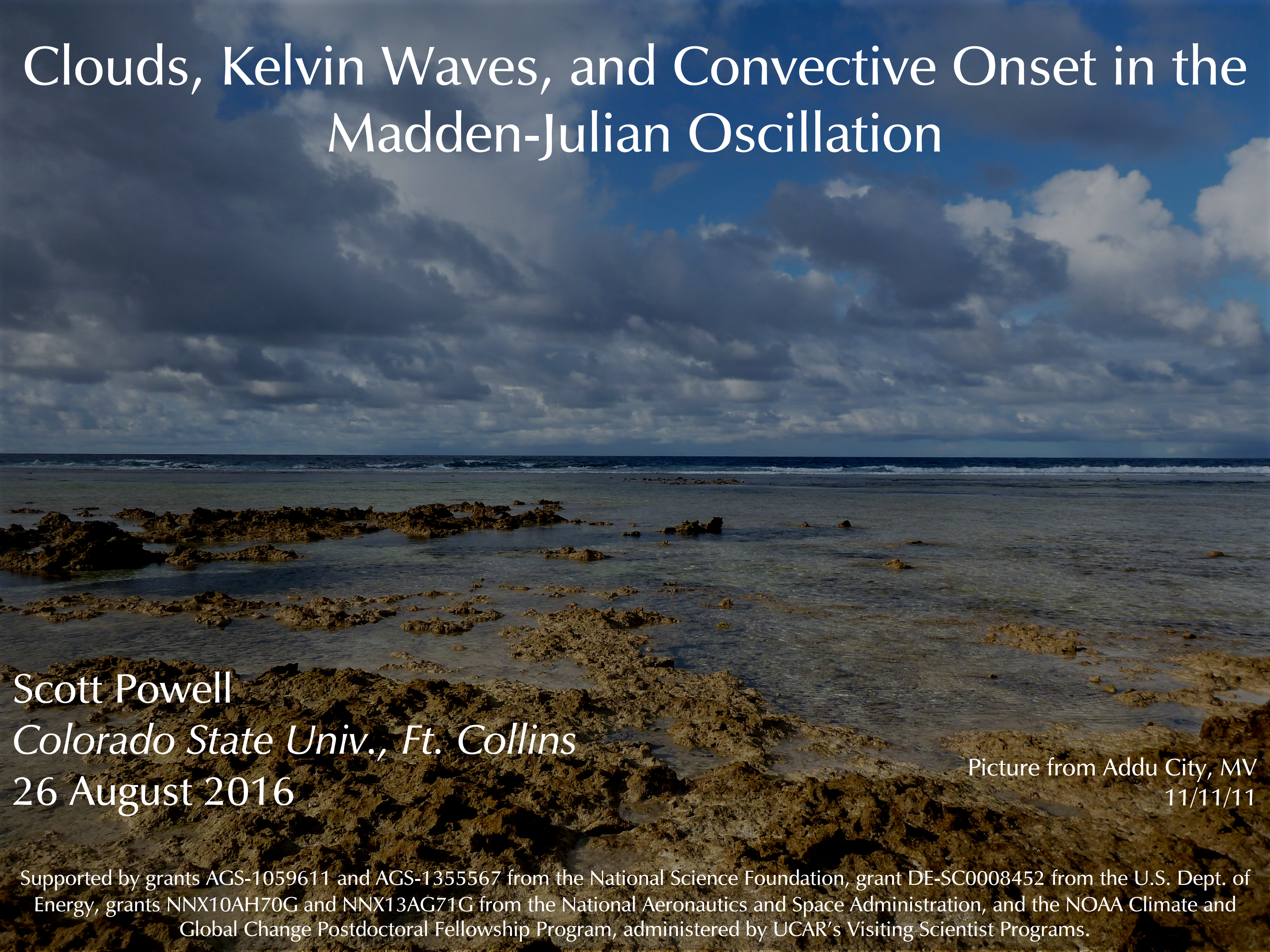
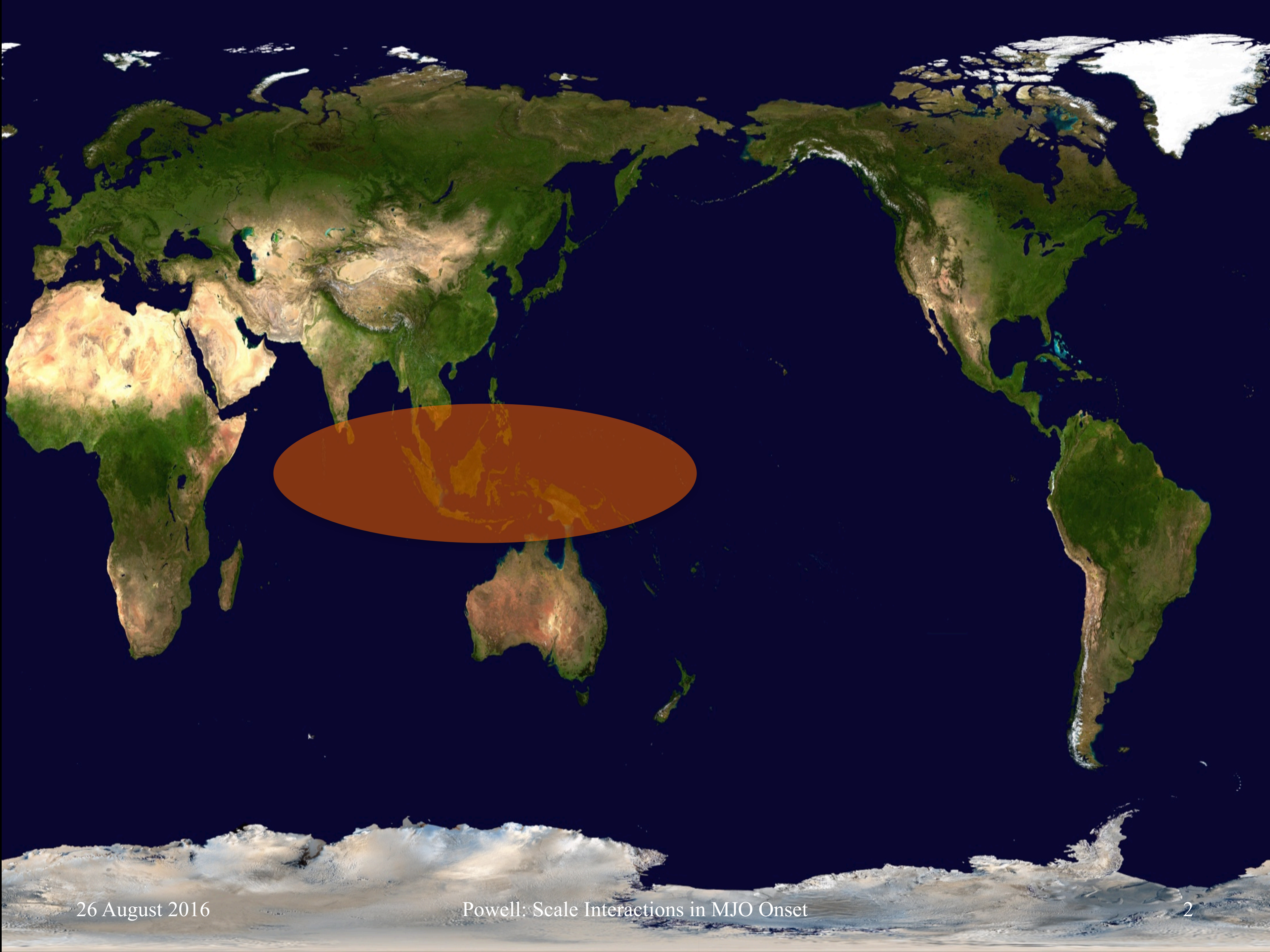


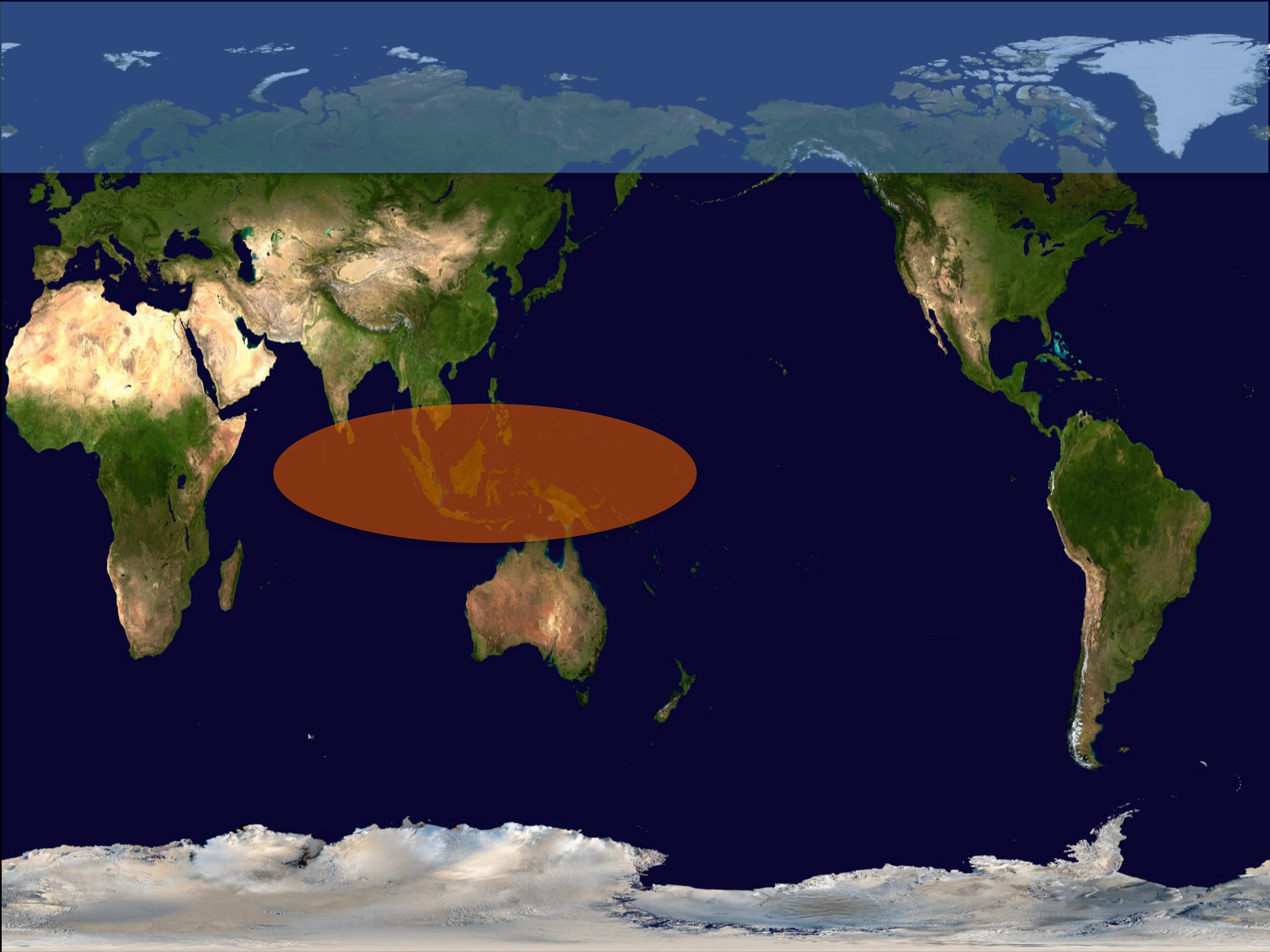
Clouds, Kelvin Waves, and Convective Onset in the Madden-Julian Oscillation

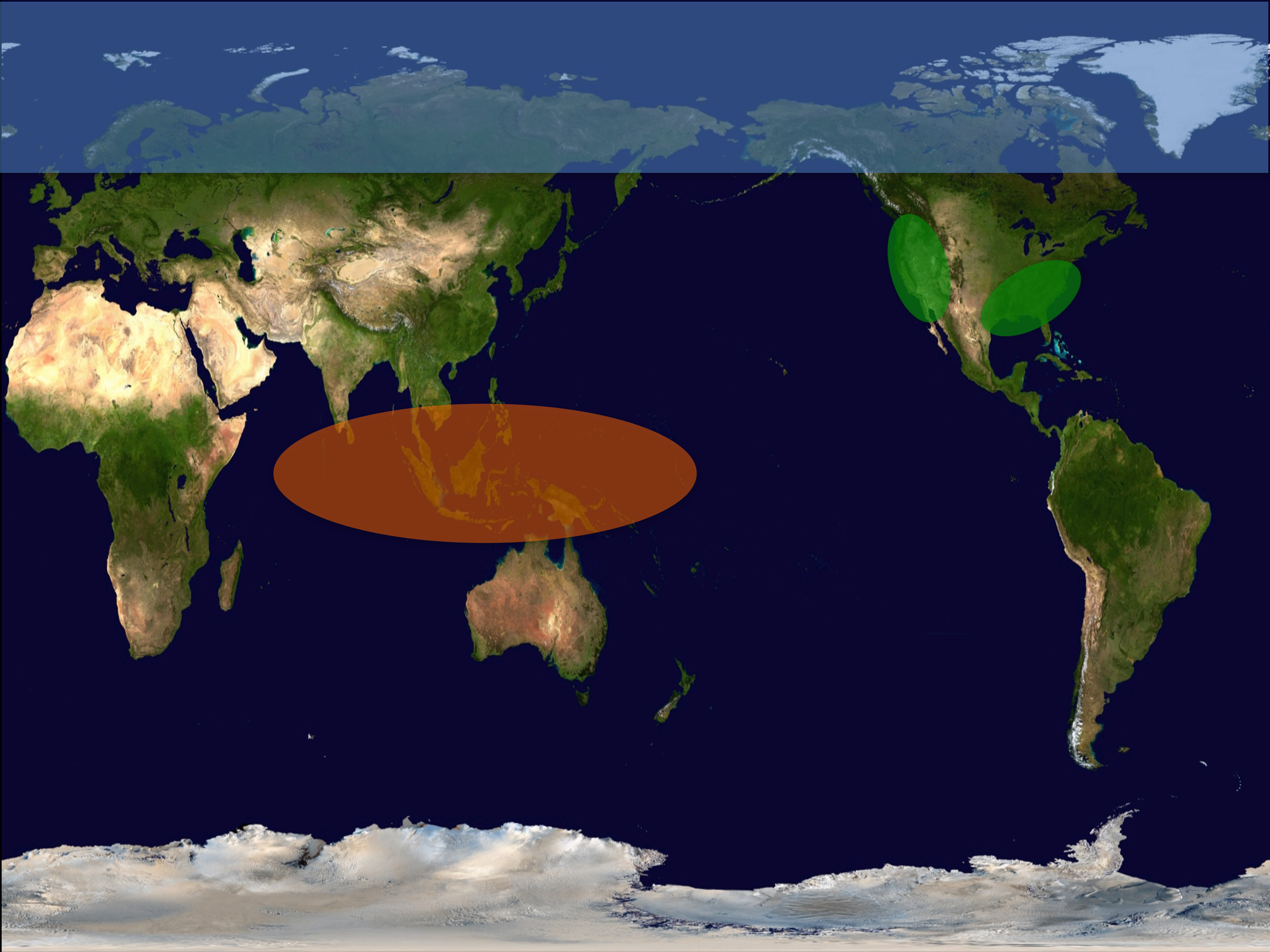
Scott Powell
Colorado State Univ., Ft. Collins
26 August 2016

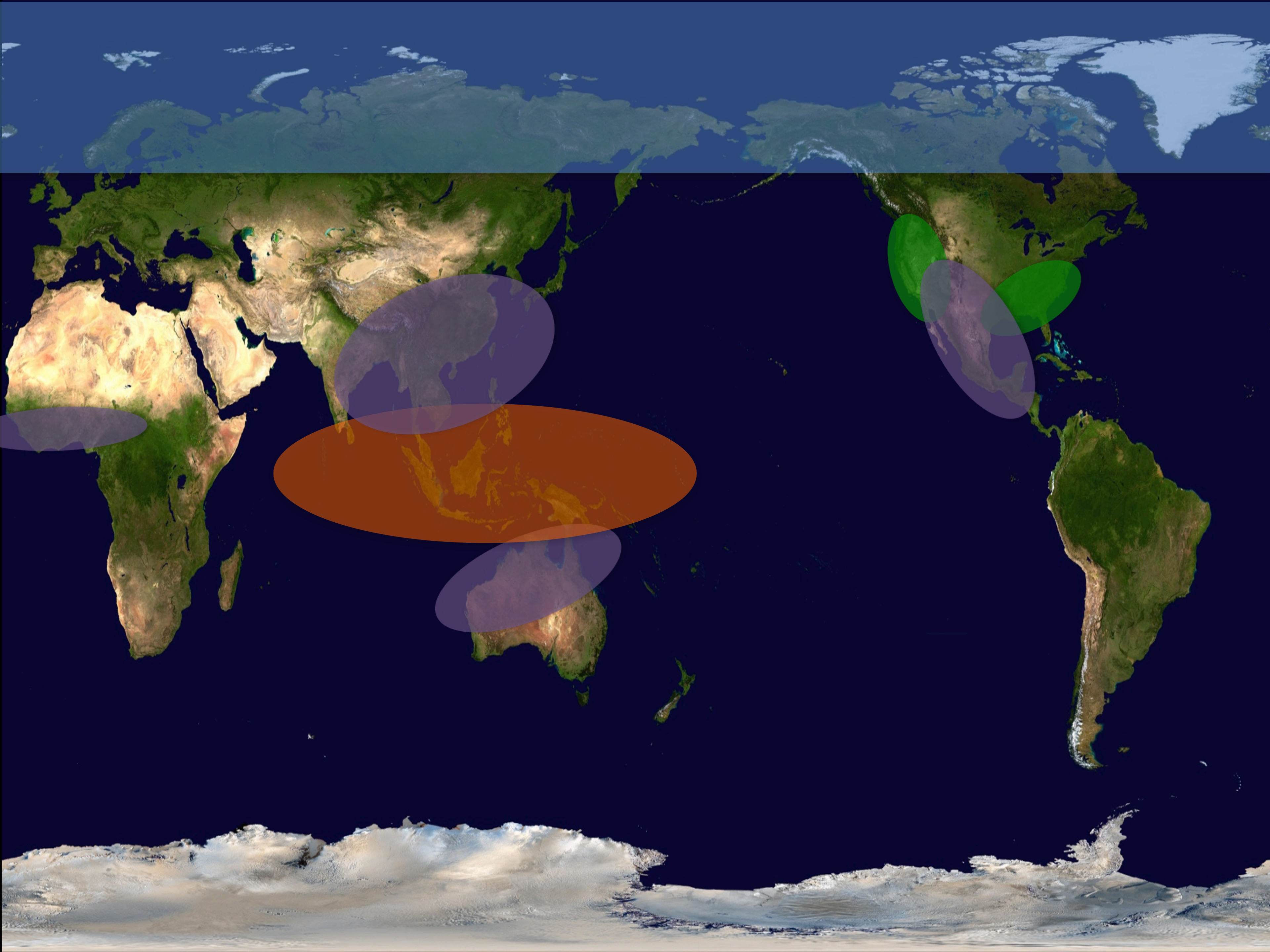
Picture from Addu City, MV
11/11/11

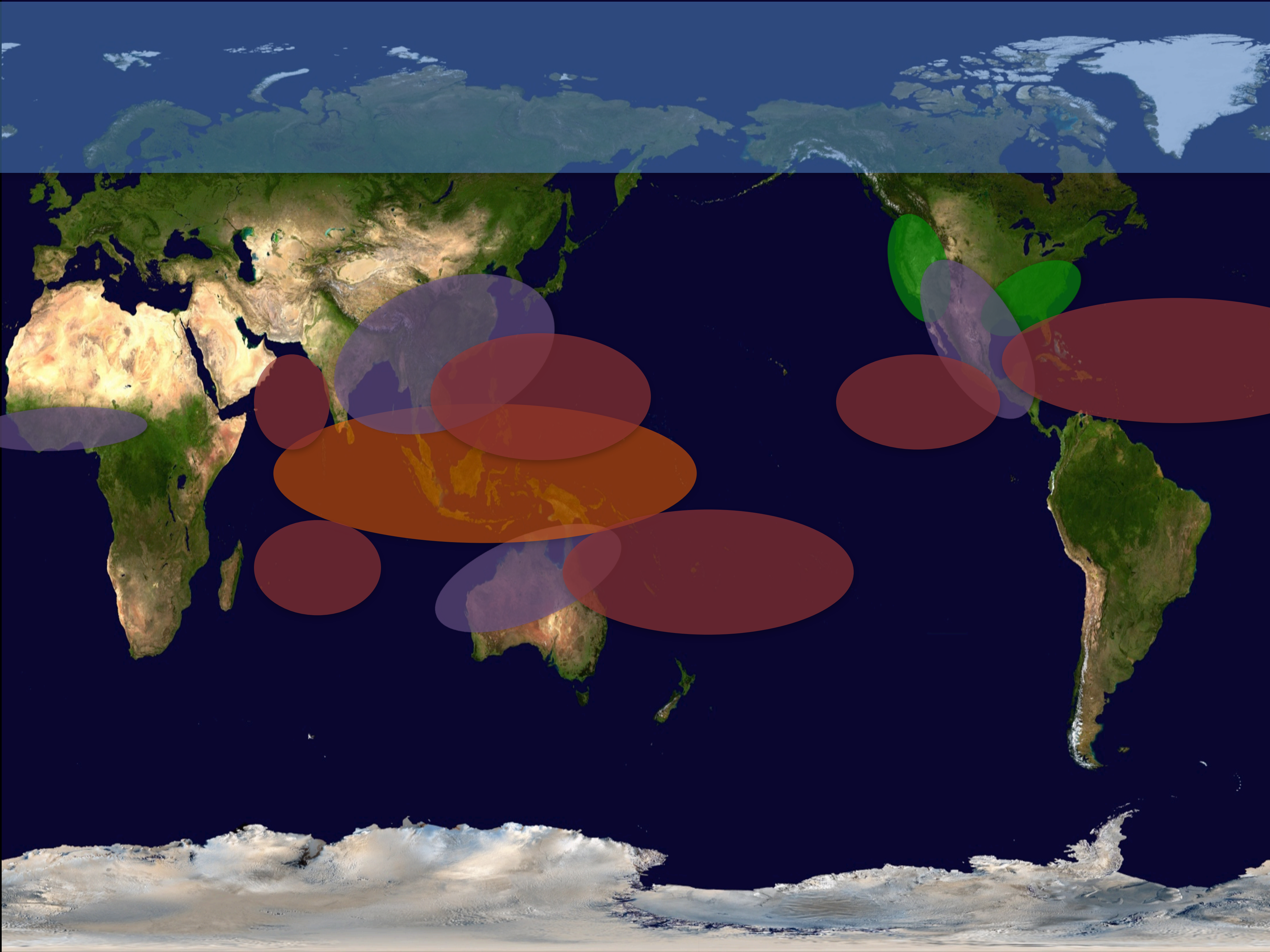
Supported by grants AGS-1059611 and AGS-1355567 from the National Science Foundation, grant DE-SC0008452 from the U.S. Dept. of Energy, grants NNX10AH70G and NNX13AG71G from the National Aeronautics and Space Administration, and the NOAA Climate and Global Change Postdoctoral Fellowship Program, administered by UCAR's Visiting Scientist Programs.

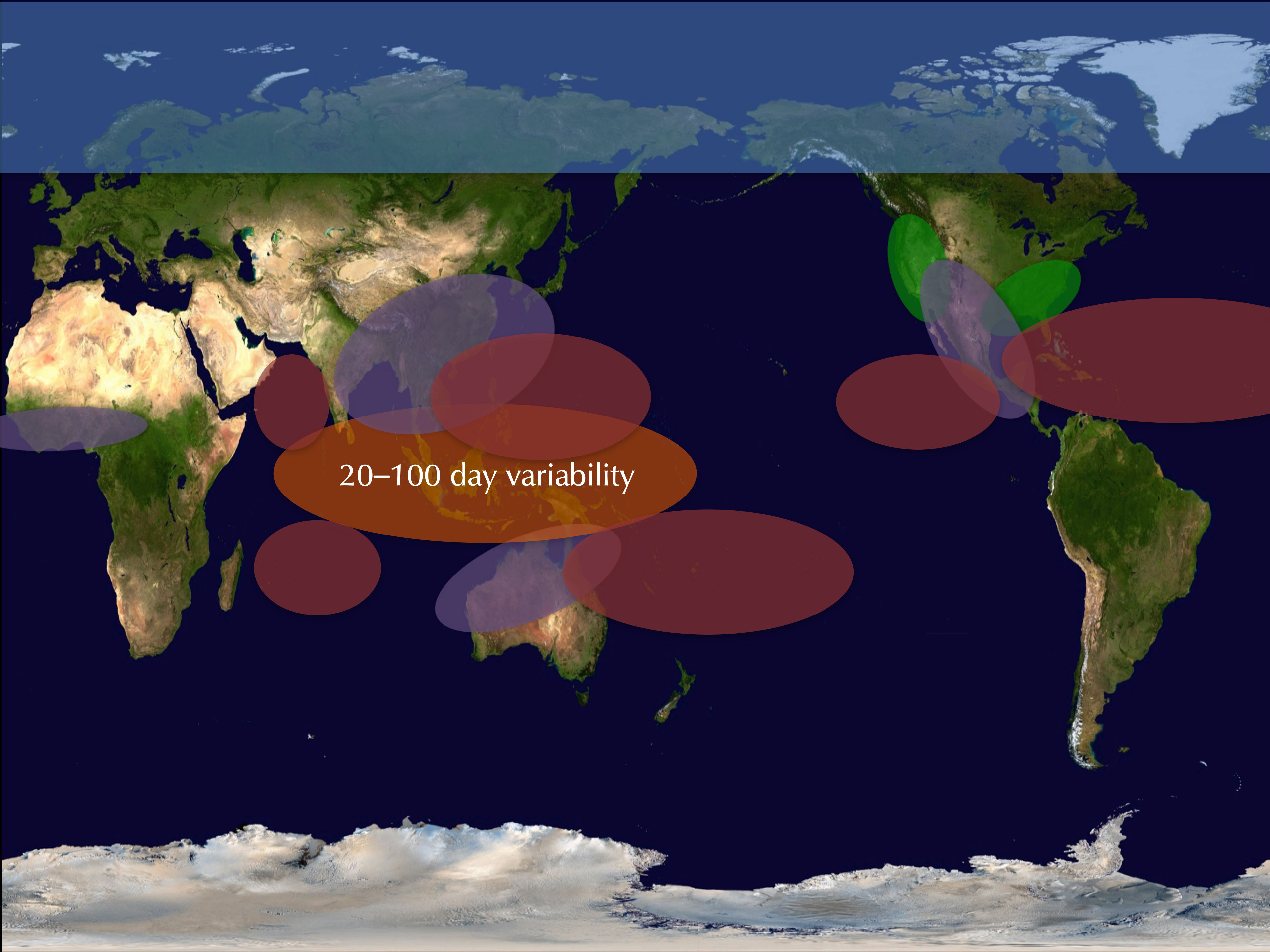


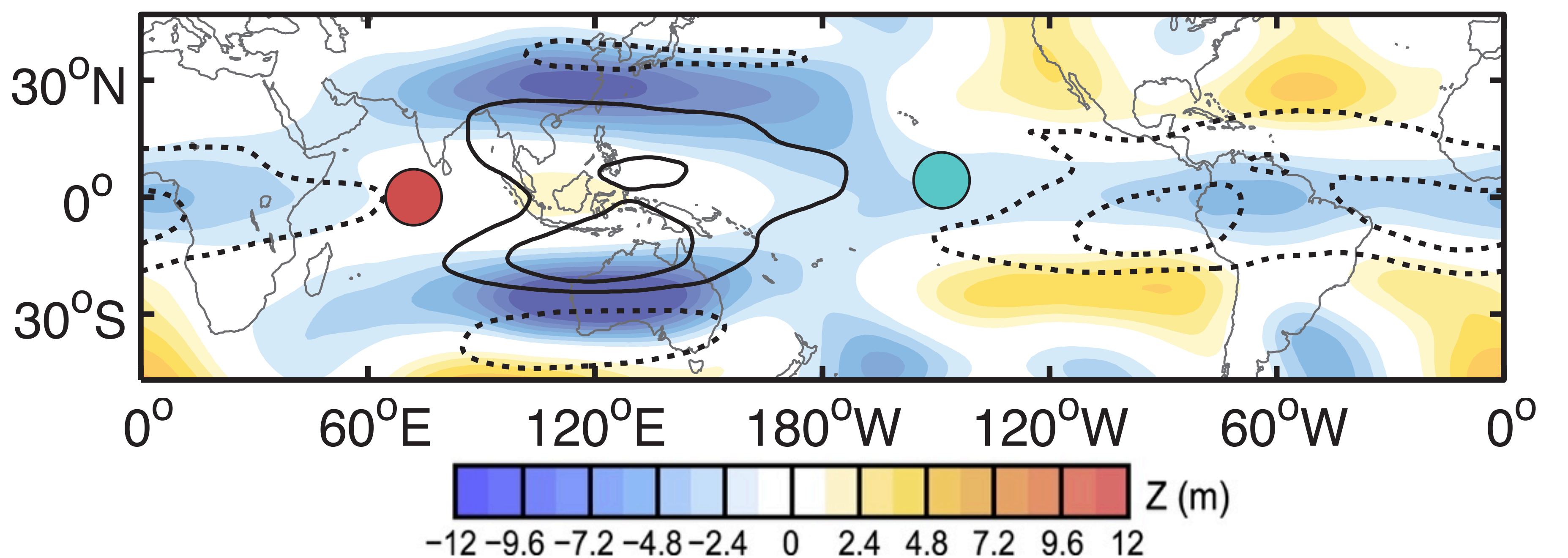




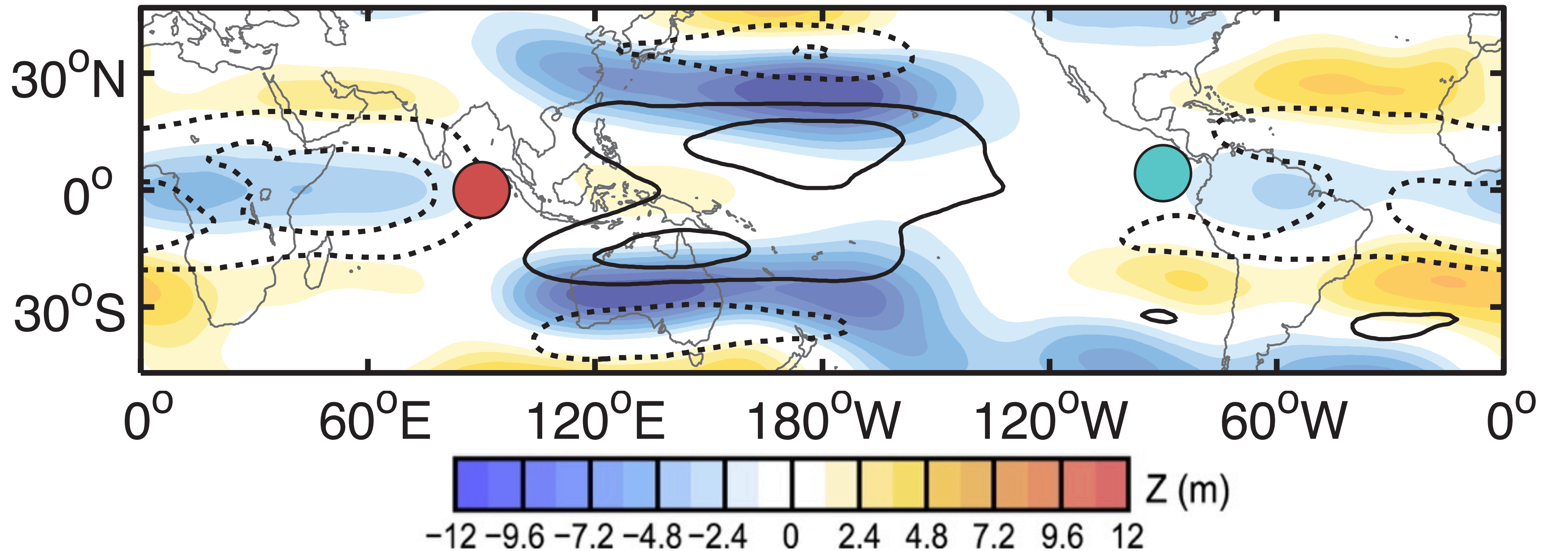




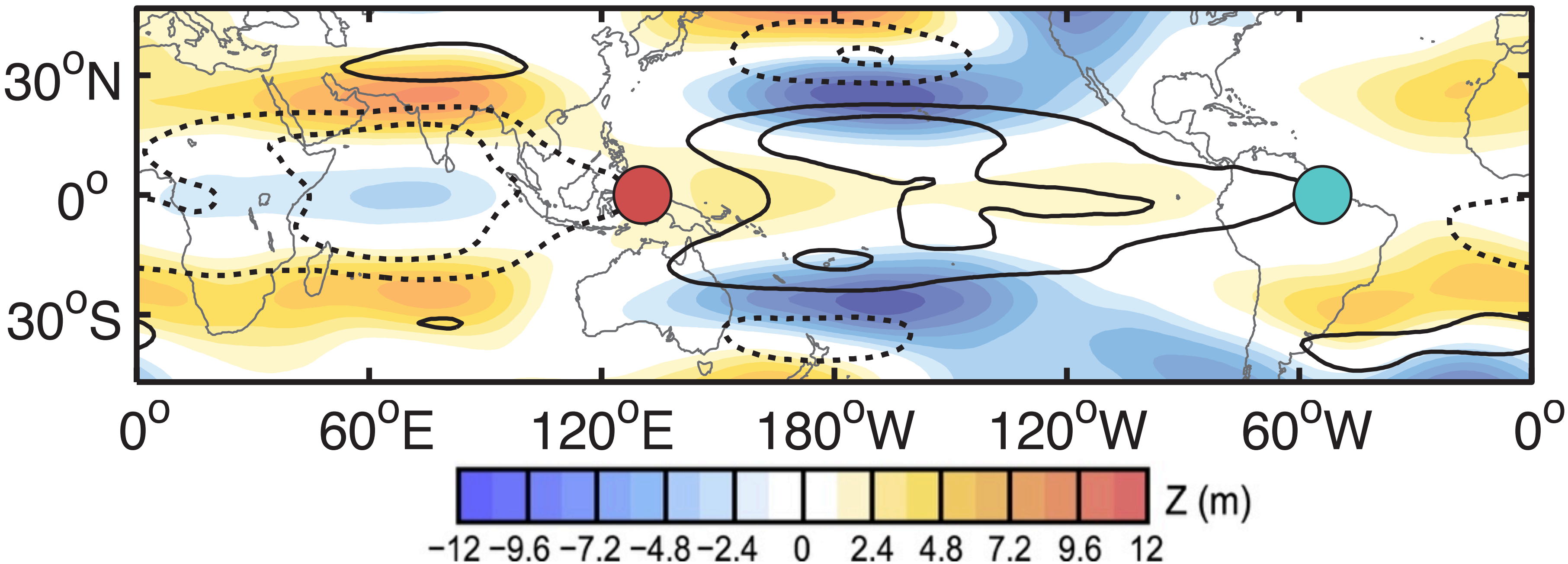

20–100 day variability


30°N
0°
30°S
0°
60°E
120°E
180°W
120°W
60°W
0°
Z (m)
−12 −9.6 −7.2 −4.8 −2.4 0 2.4 4.8 7.2 9.6 12

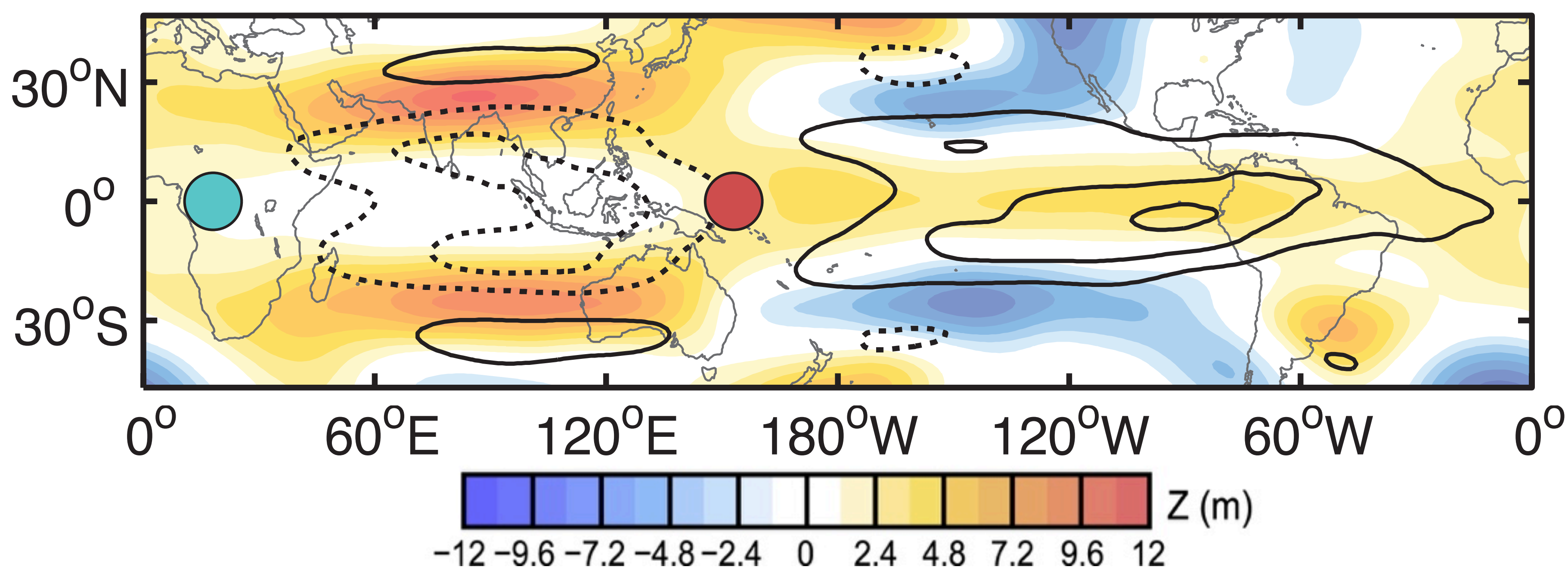
Adames and Wallace (2014)



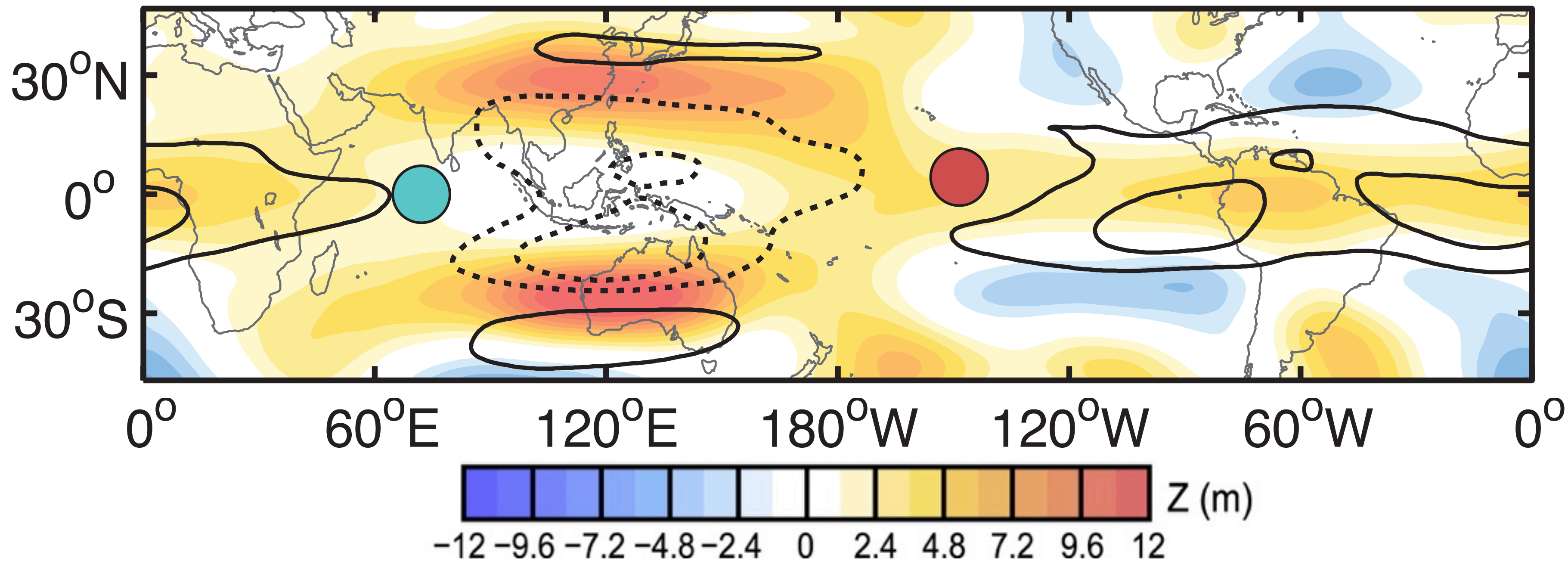
Adames and Wallace (2014)

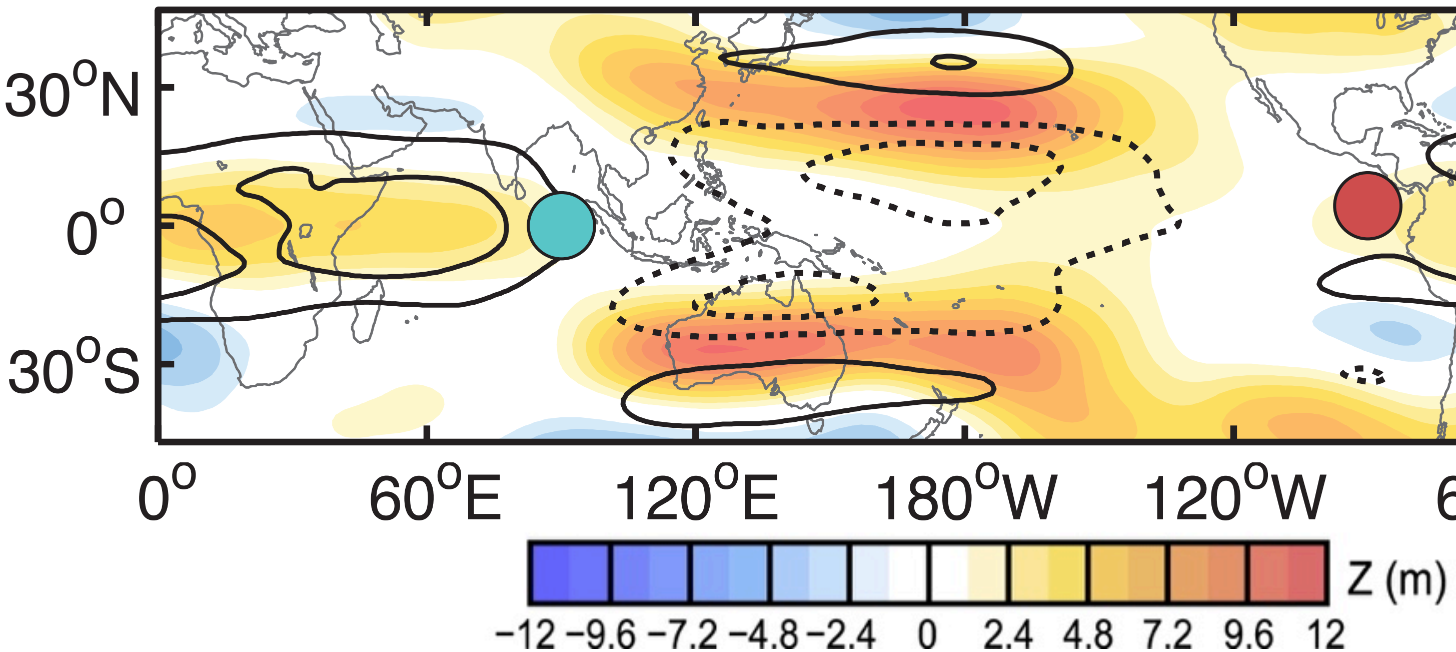


Adames and Wallace (2014)

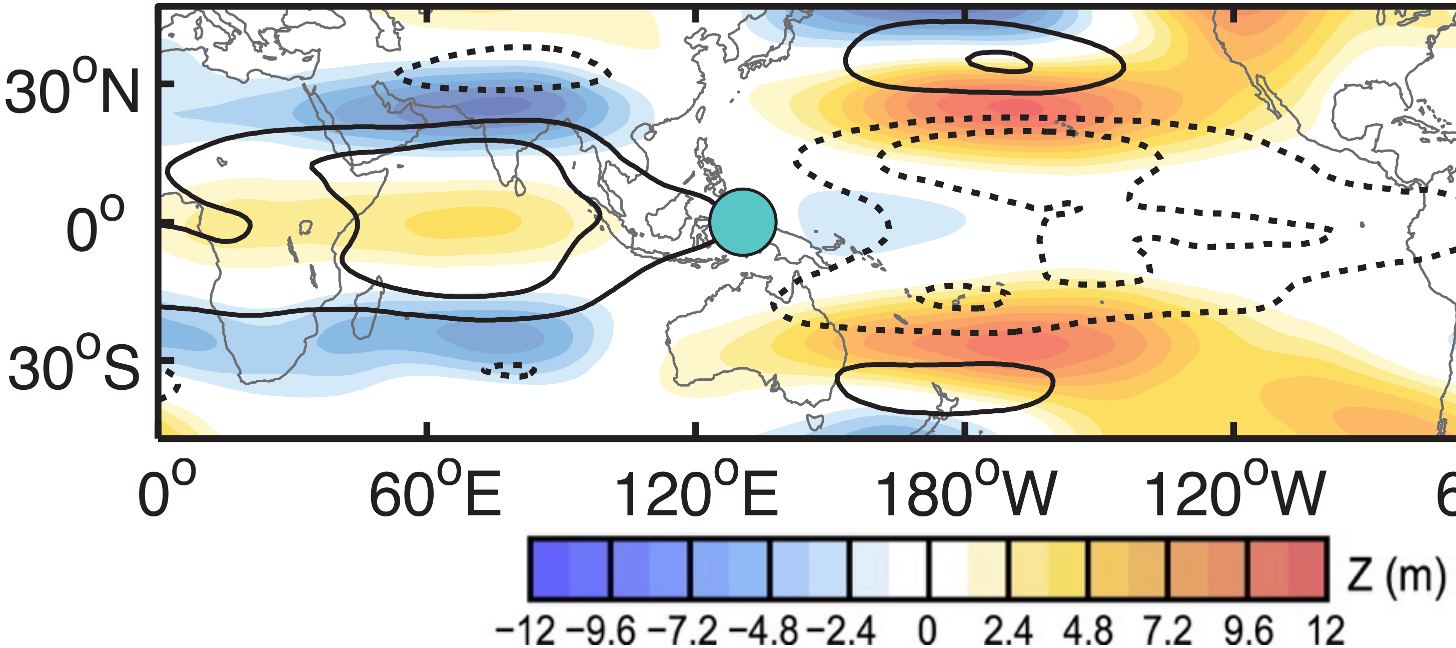


Adames and Wallace (2014)

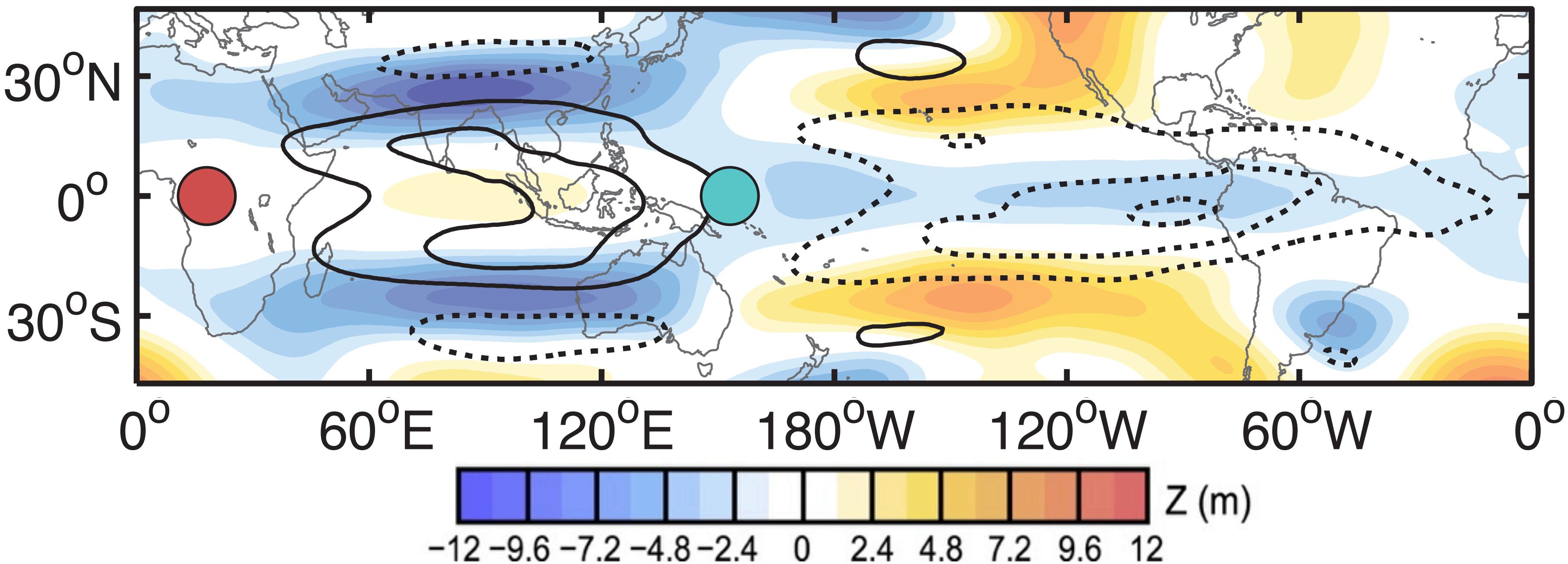


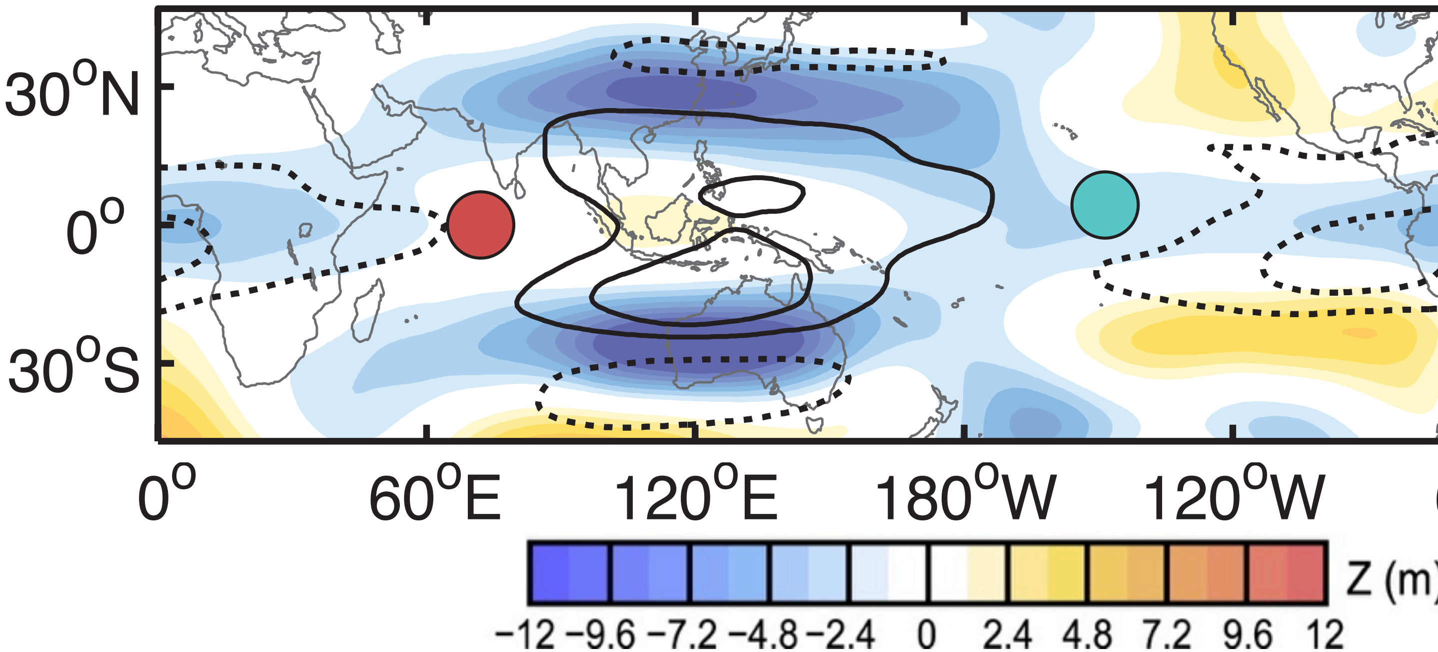

30°N
0°
30°S
0°
60°E
120°E
180°W
120°W
60°W
0°
Z (m)
−12 −9.6 −7.2 −4.8 −2.4 0 2.4 4.8 7.2 9.6 12

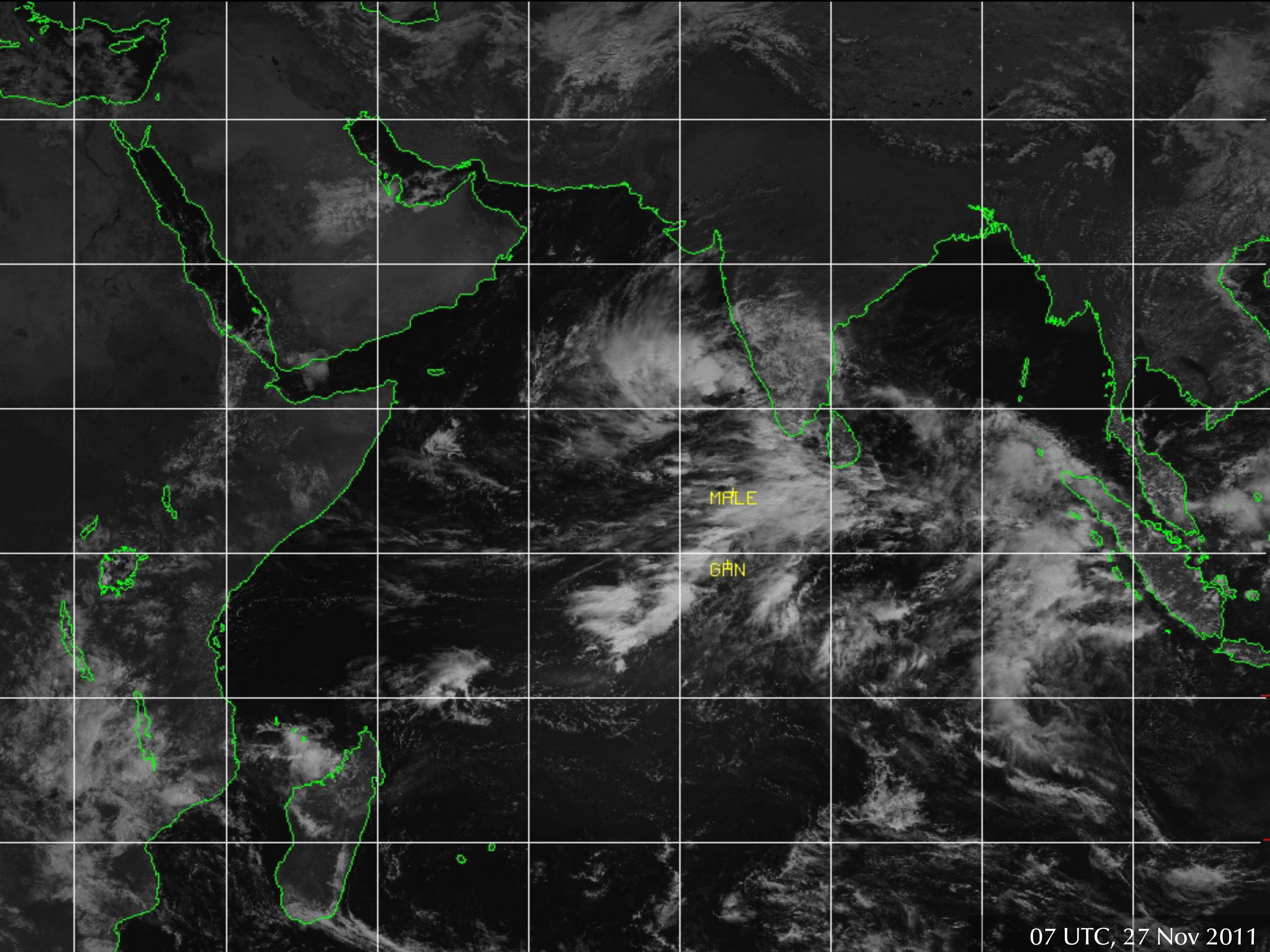
Adames and Wallace (2014)

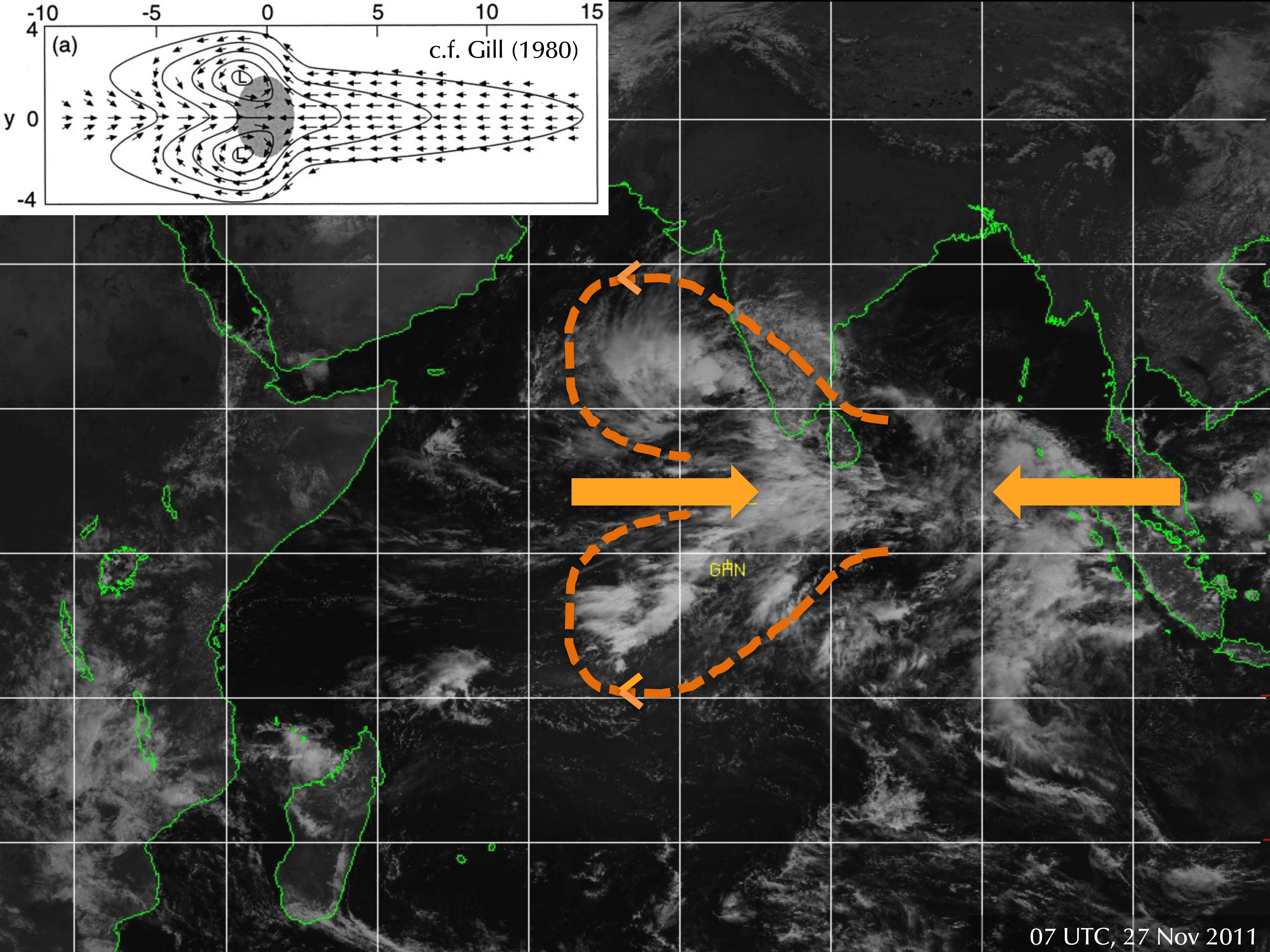


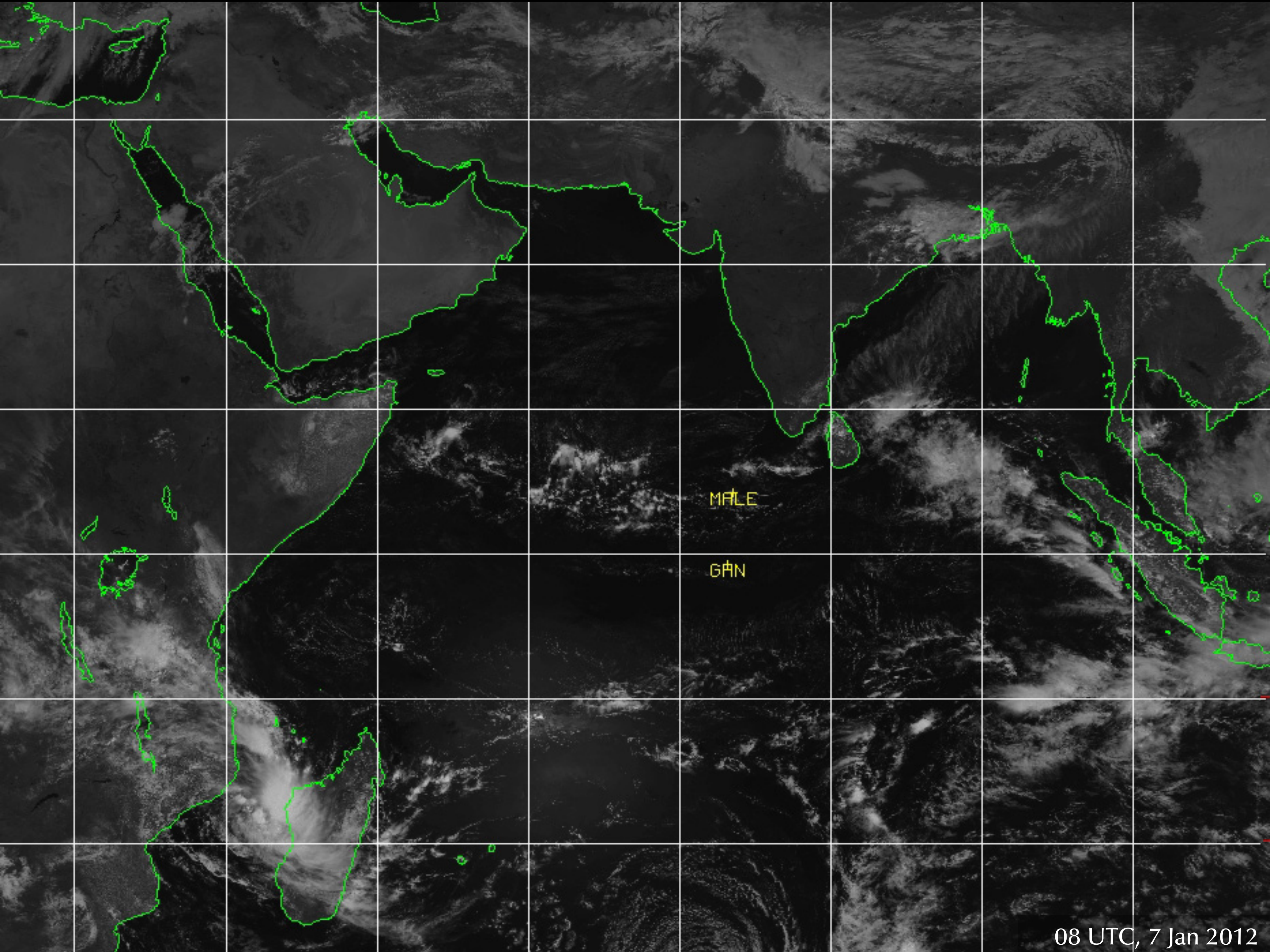
Adames and Wallace (2014)

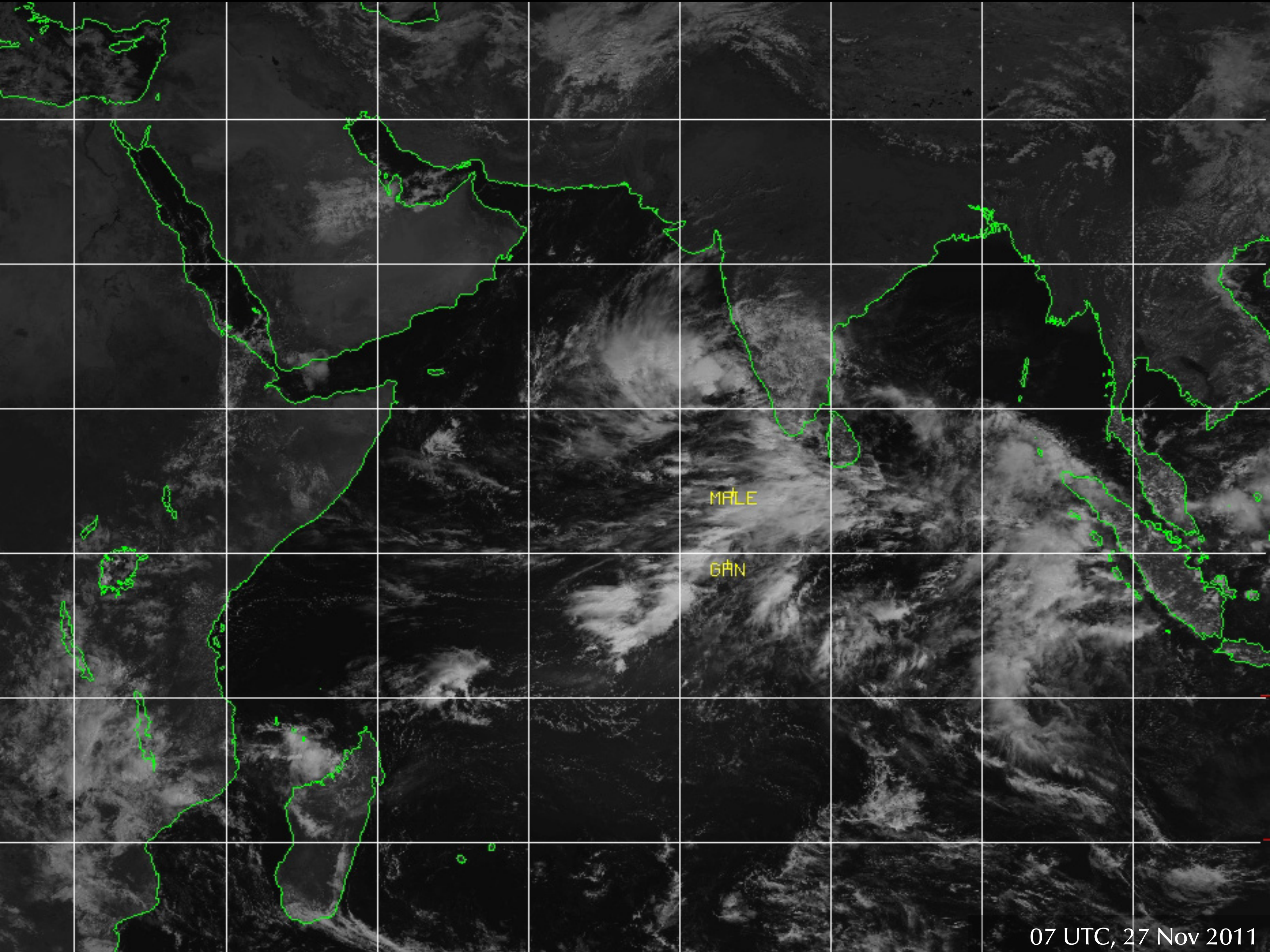



30°N
0°
30°S
0°
60°E
120°E
180°W
120°W
60°W
0°
Z (m)
−12 −9.6 −7.2 −4.8 −2.4 0 2.4 4.8 7.2 9.6 12

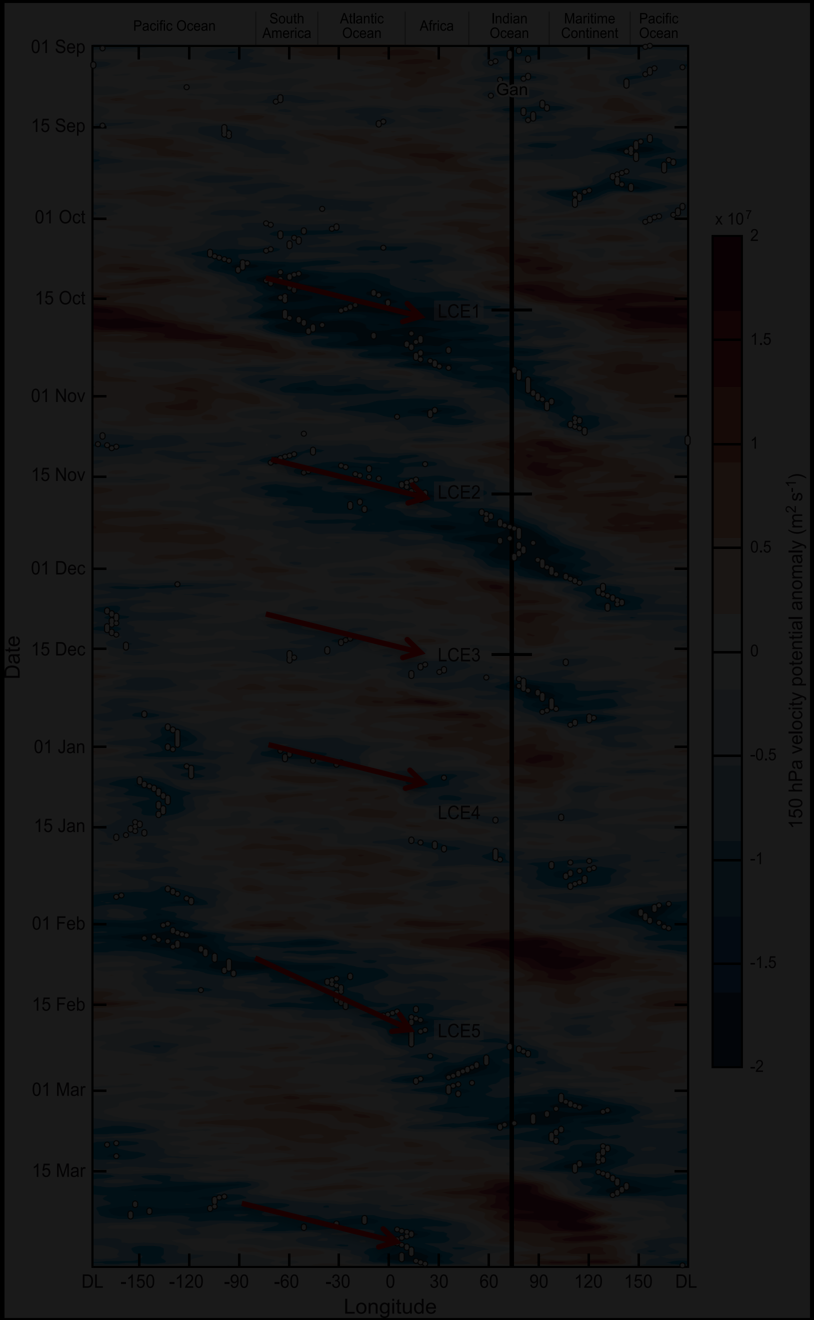

MALE
GAN
07 UTC, 27 Nov 2011


-10
-5
0
5
10
15
4
0
-4
y
(a)
c.f. Gill (1980)
L
L
GAN
07 UTC, 27 Nov 2011


MALE
GAN
08 UTC, 7 Jan 2012


MALE
GAN
07 UTC, 27 Nov 2011

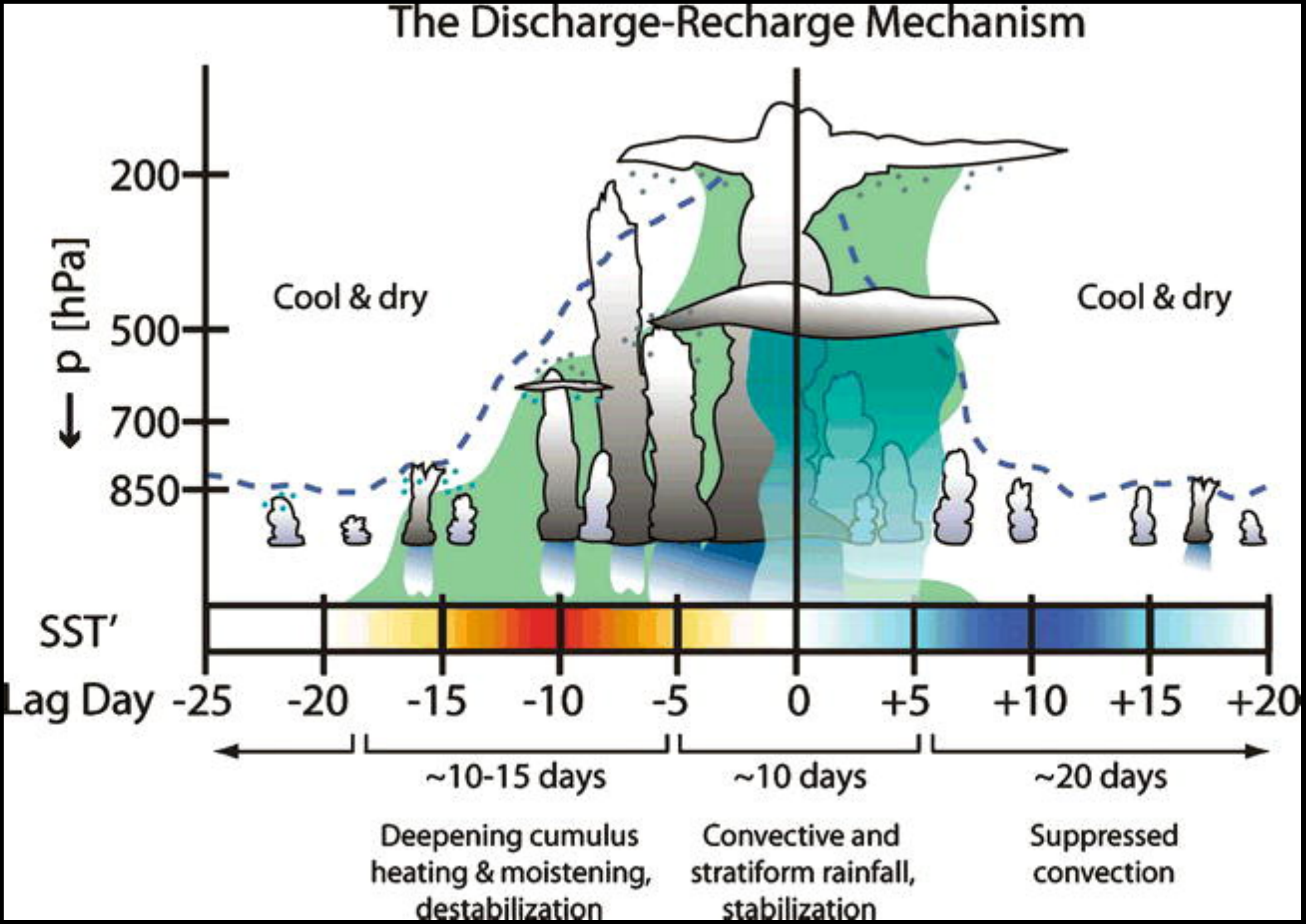
Hypothesis: Convection passively responds to changes in the large-scale environment.



Originally: Knutson and Weickmann (1987)

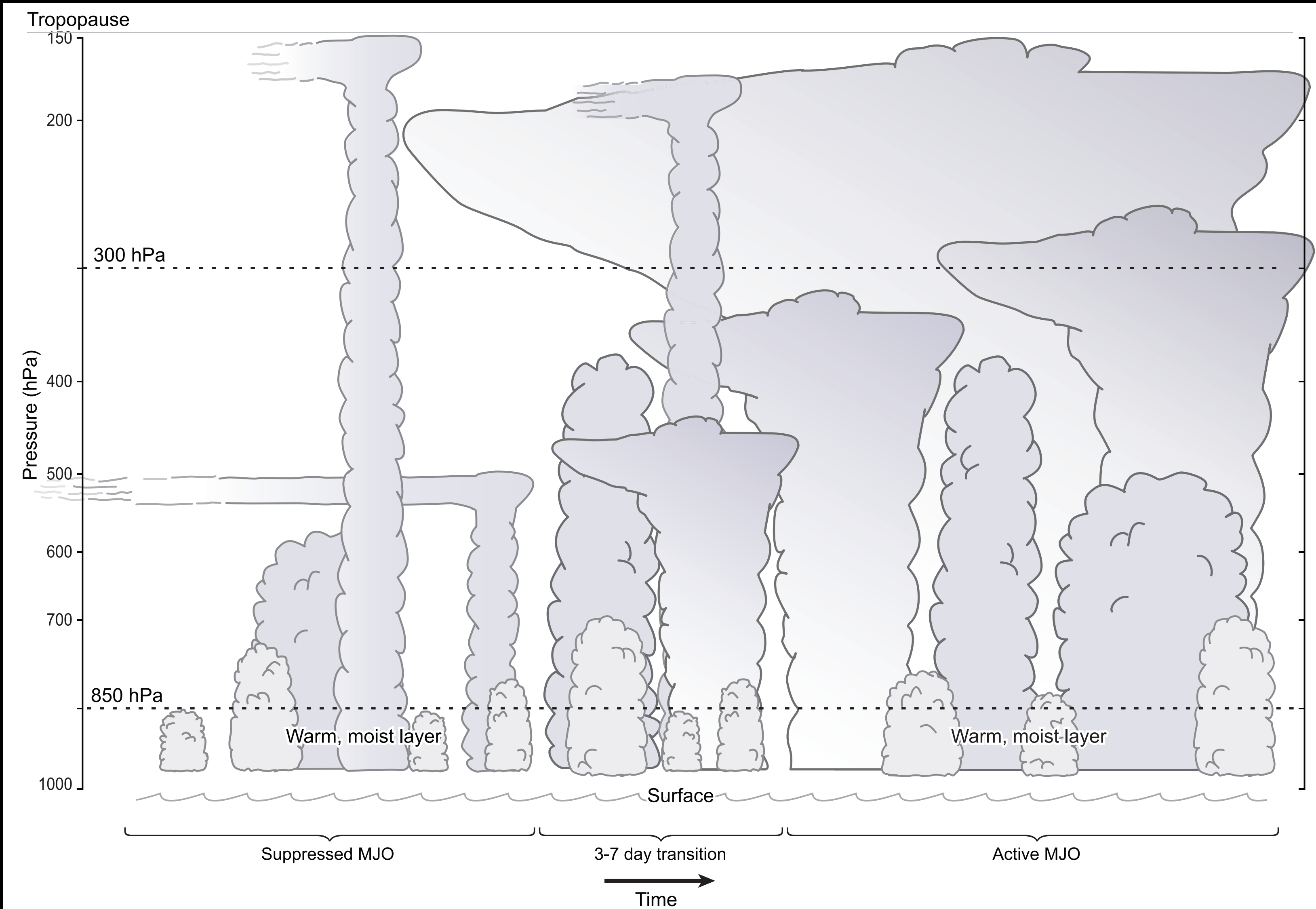
Figure: Powell and Houze (2015b)

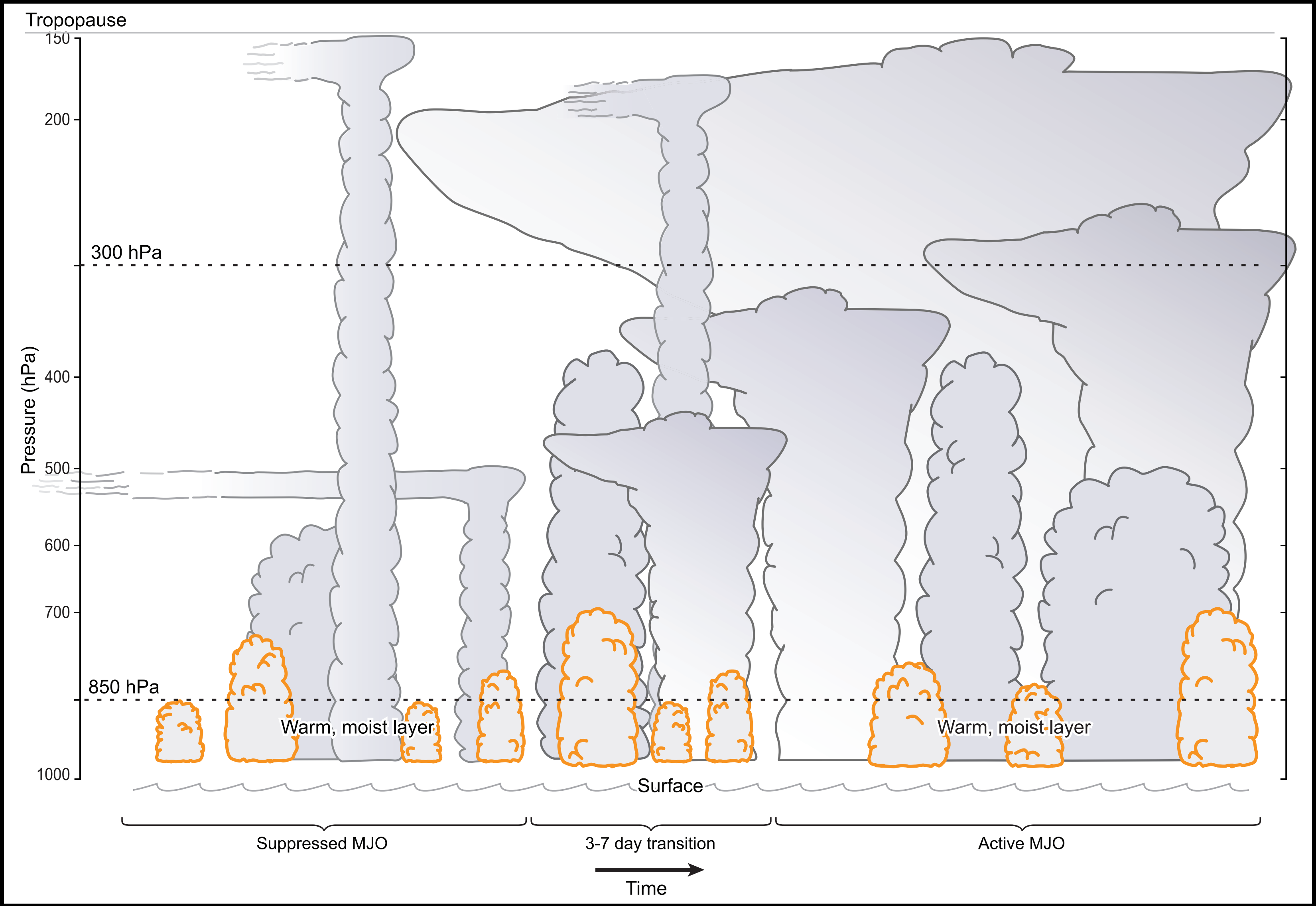
Hypothesis: Clouds are actively involved in "preconditioning" environment for MJO.



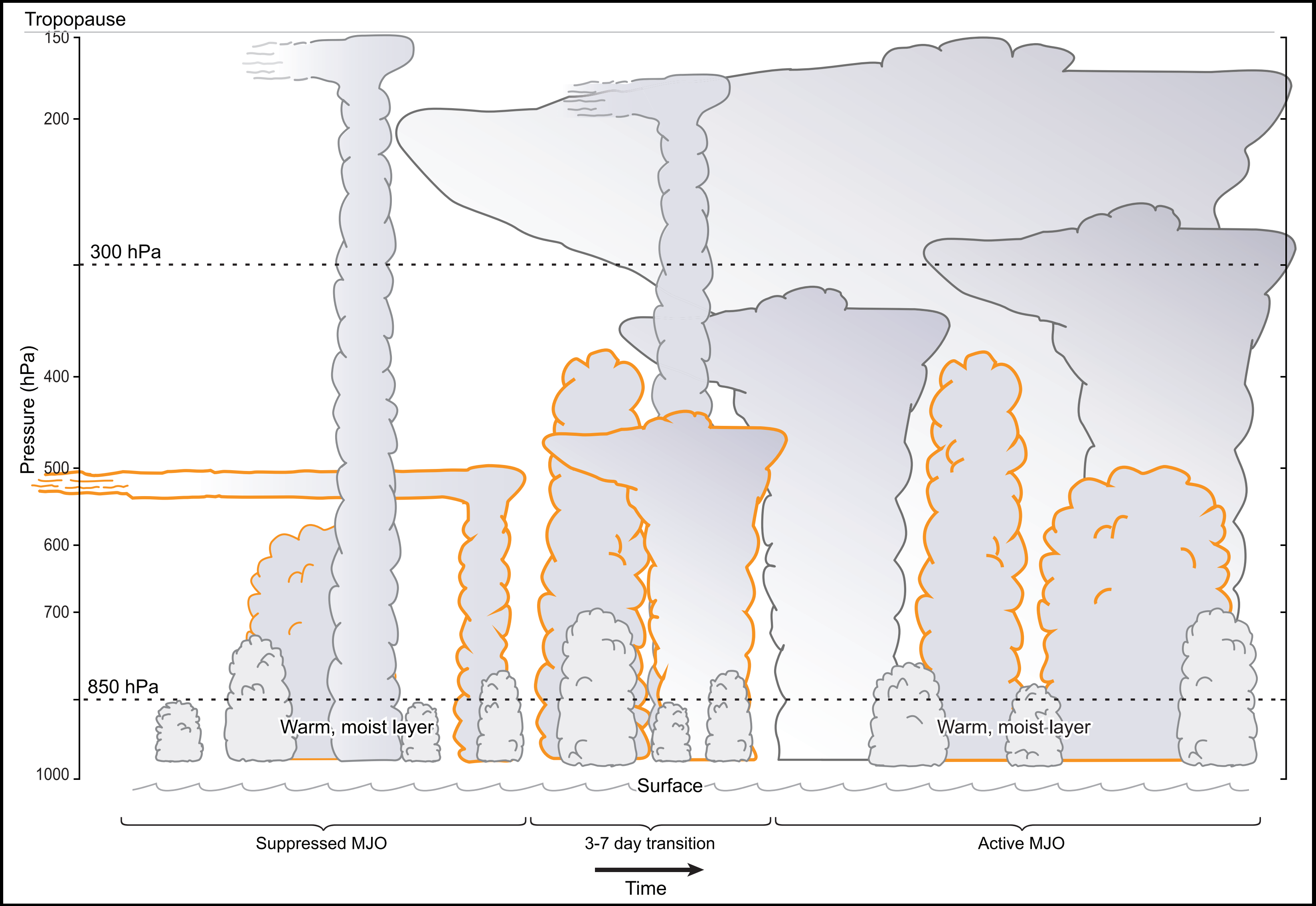
Benedict and Randall (2007), following Bladé and Hartmann (1993) and Kemball-Cook and Weare (2001)

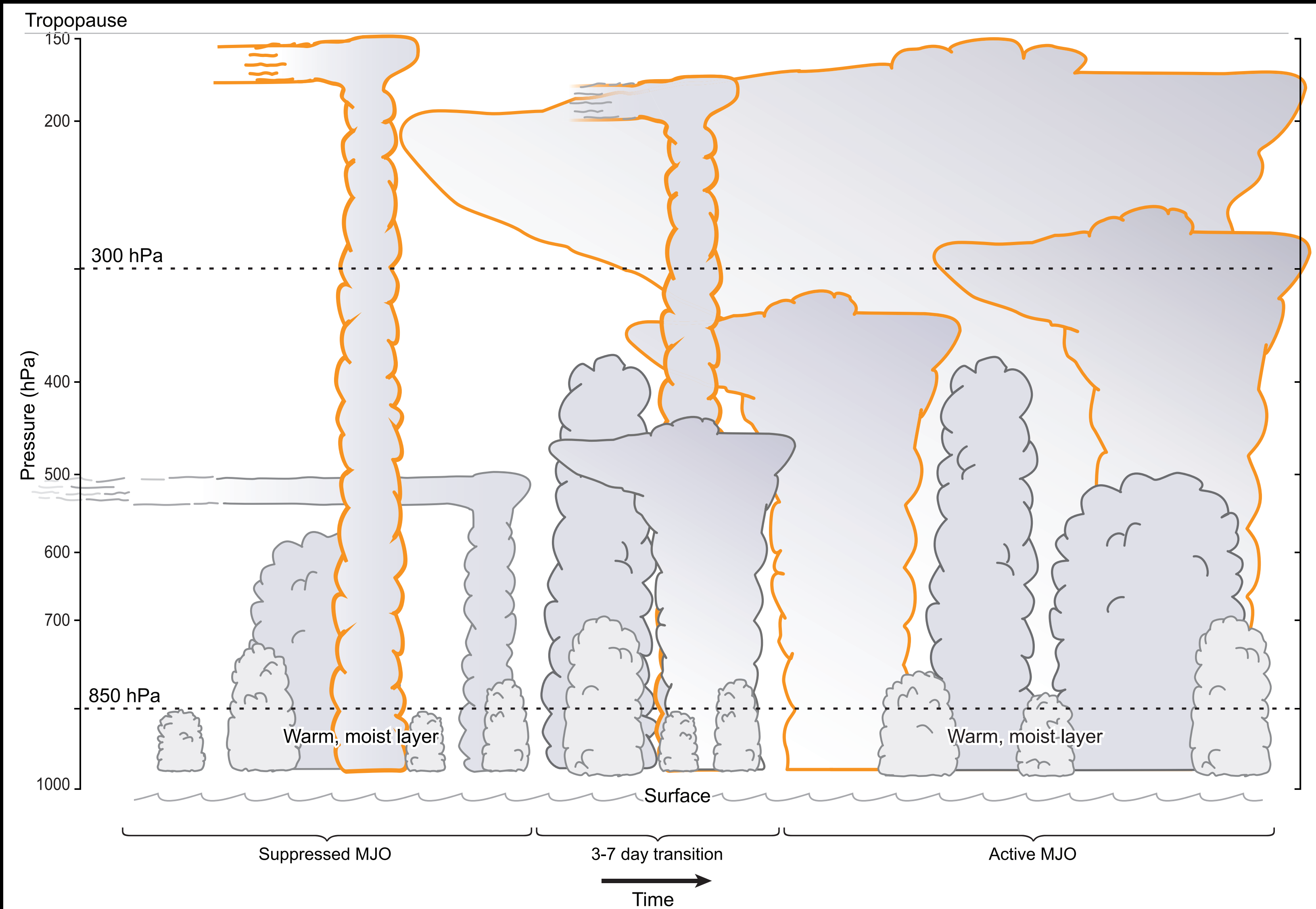
DYNAMO Field Experiment (October 2011 – March 2012)


Tropopause
150
200
300 hPa
400
500
600
700
850 hPa
1000
Pressure (hPa)
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time

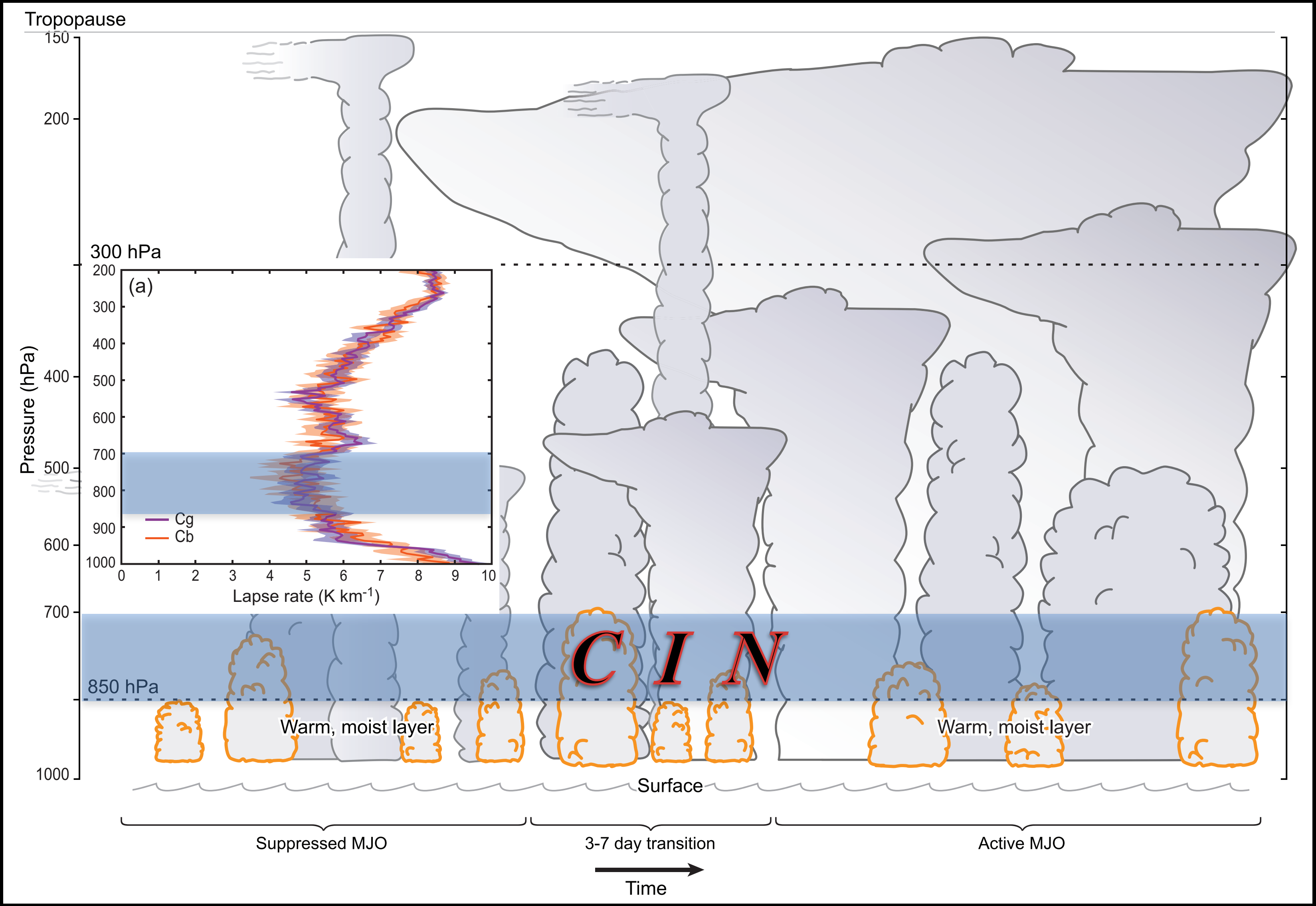


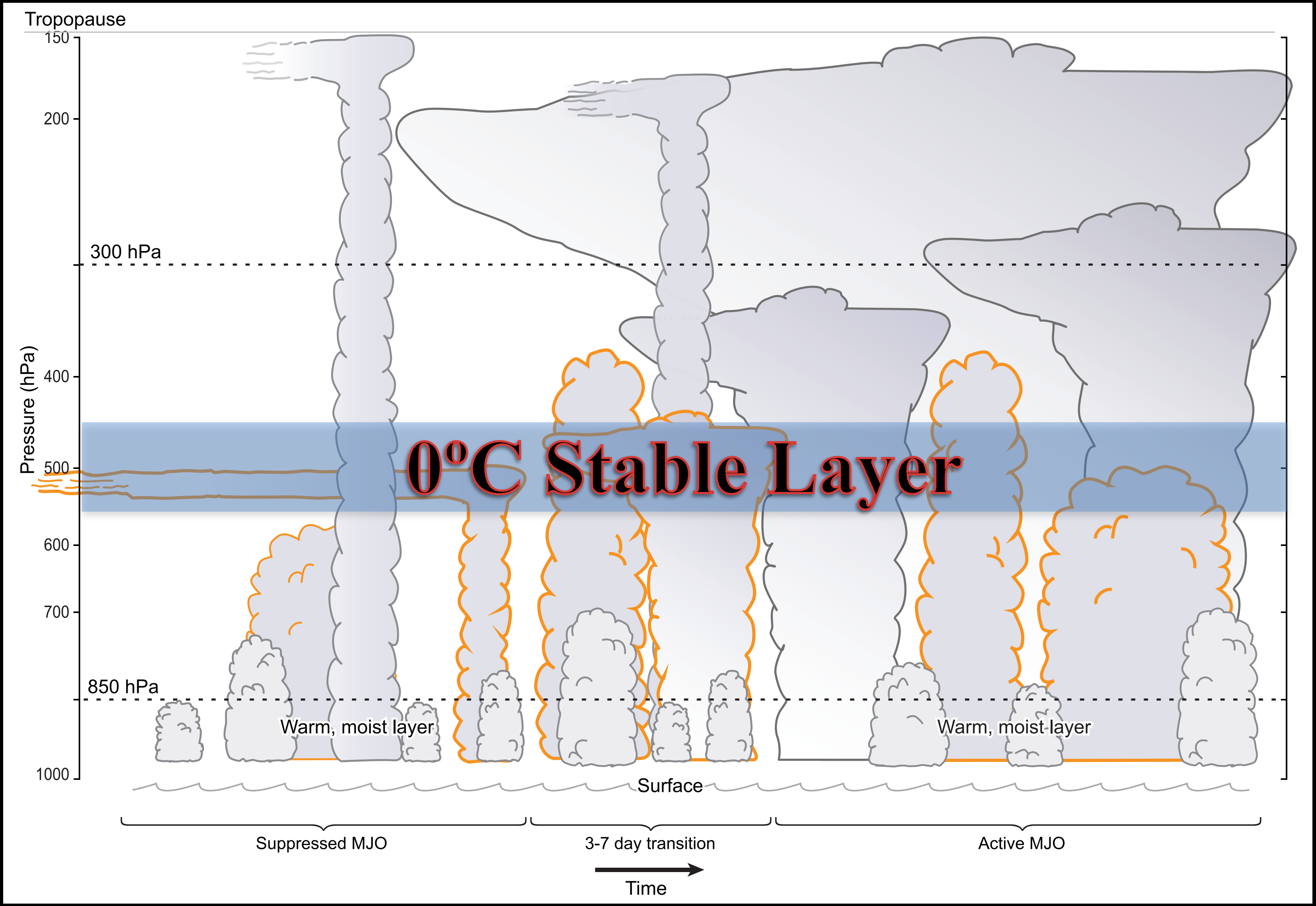
Tropopause
150
200
300 hPa
400
500
600
700
850 hPa
1000
Pressure (hPa)
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time

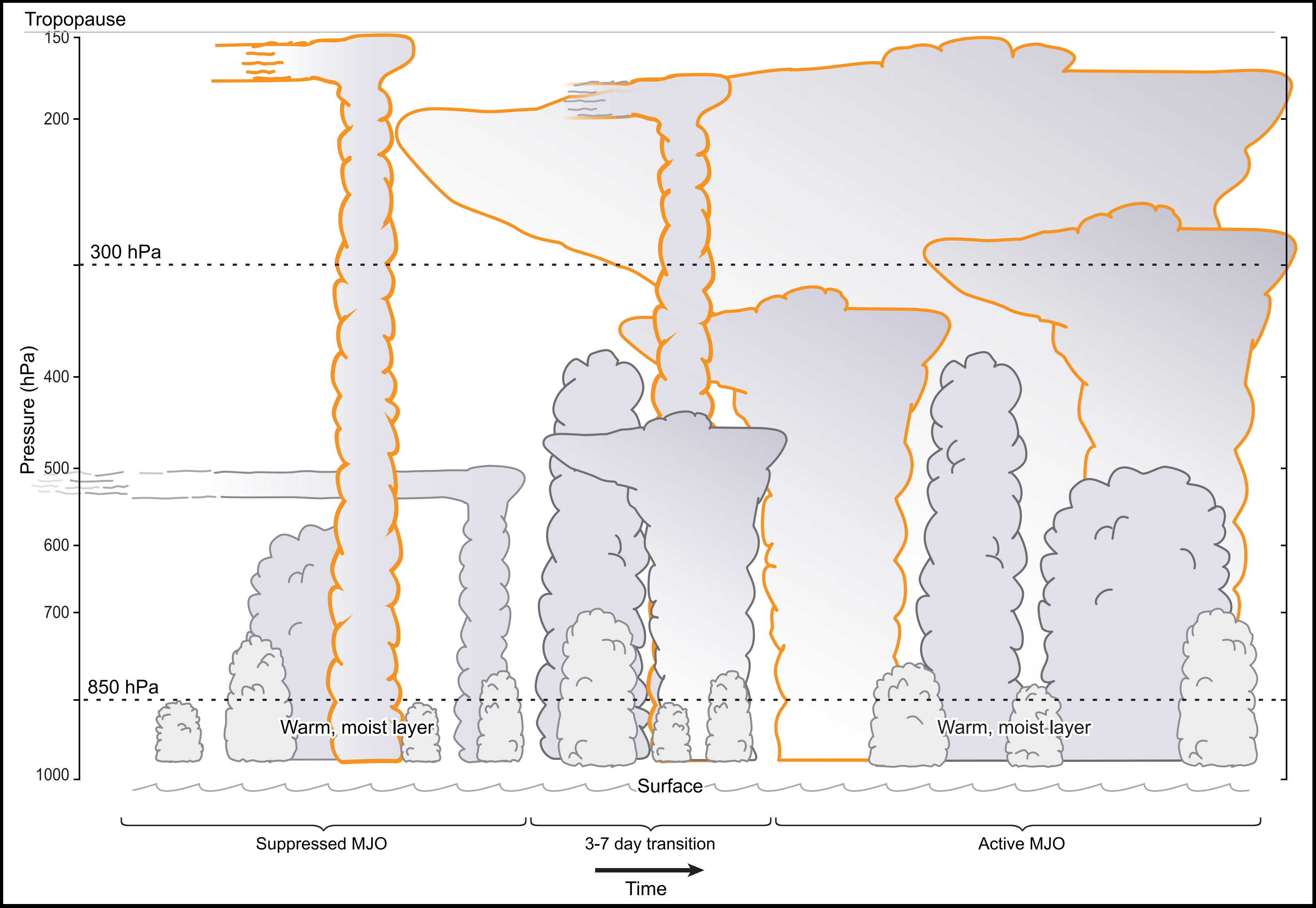

Tropopause
150
200
300 hPa
Pressure (hPa)
400
500
600
700
850 hPa
1000
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time

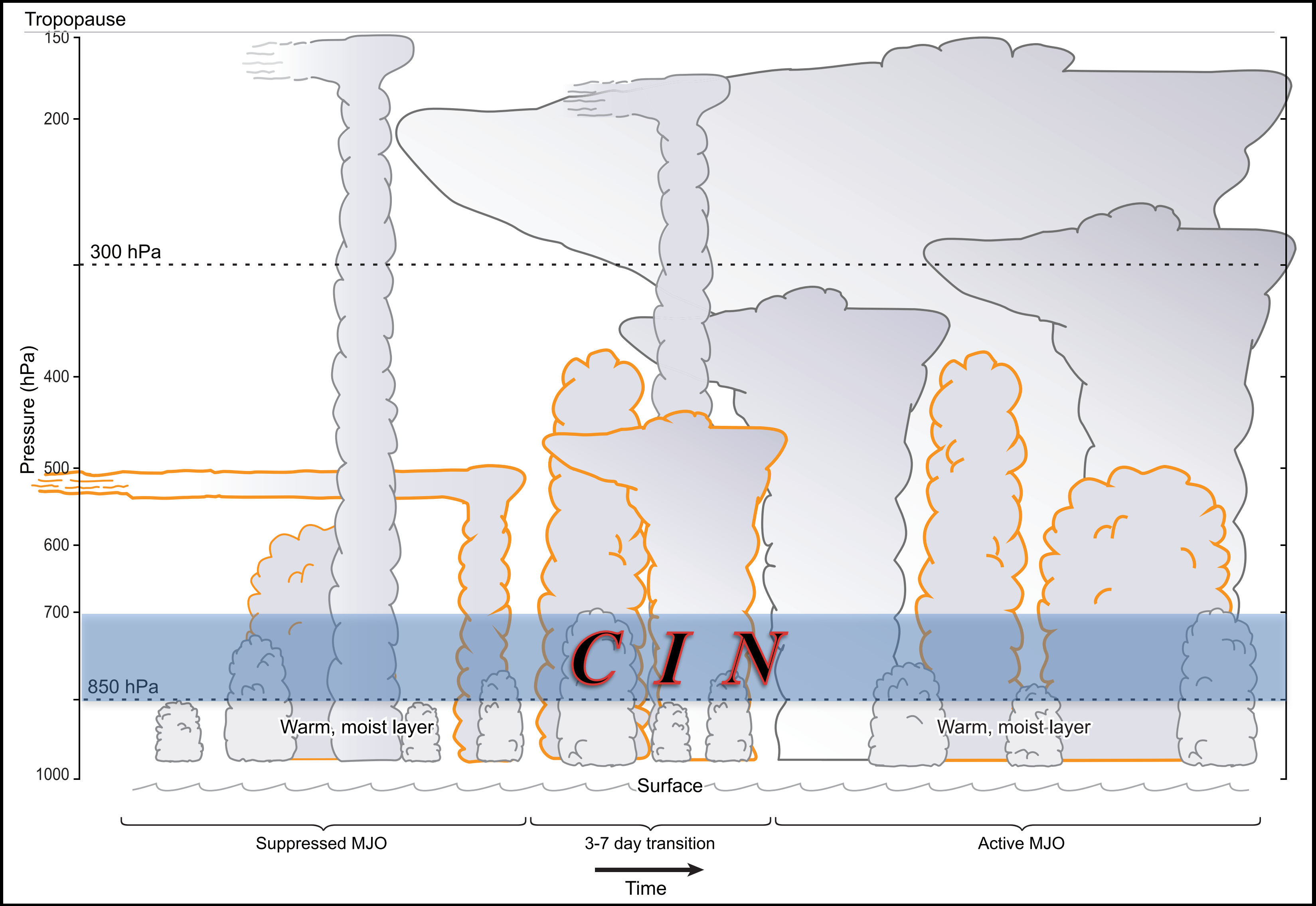


Tropopause
150
200
300 hPa
400
500
600
700
850 hPa
1000
Pressure (hPa)
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time


Tropopause
150
200
300 hPa
400
500
600
700
850 hPa
1000
Pressure (hPa)
(a)
200
300
400
500
600
700
800
900
1000
Cg
Cb
0 1 2 3 4 5 6 7 8 9 10
Lapse rate (K km-1)
CIN
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time


Tropopause
150
200
300 hPa
Pressure (hPa)
400
500
600
700
850 hPa
1000
0°C Stable Layer
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time


Tropopause
150
200
300 hPa
400
500
600
700
850 hPa
1000
Pressure (hPa)
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time


Tropopause
150
200
300 hPa
400
500
600
700
850 hPa
1000
Pressure (hPa)
C I N
Warm, moist layer
Warm, moist layer
Surface
Suppressed MJO
3-7 day transition
Active MJO
Time

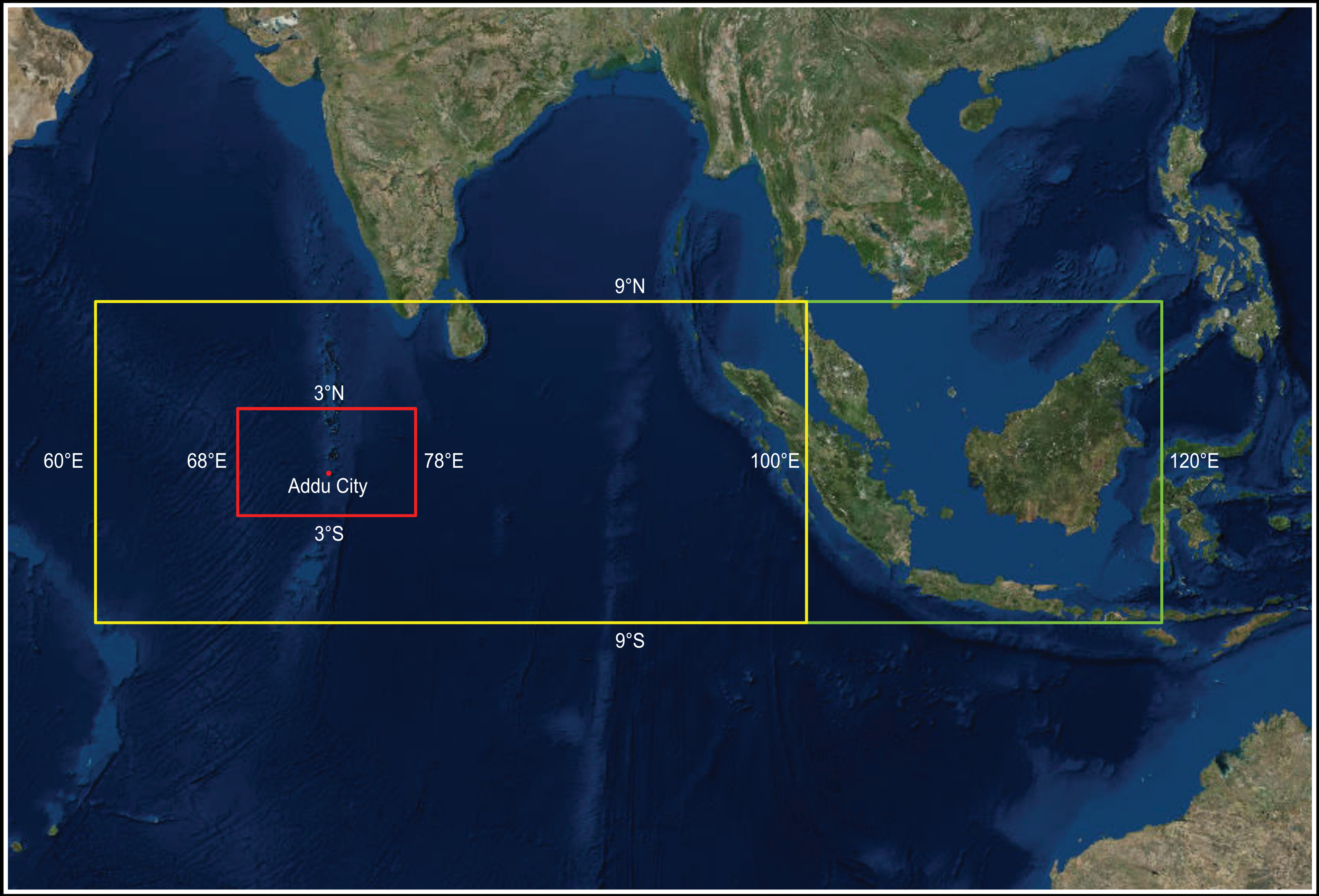
Objectives

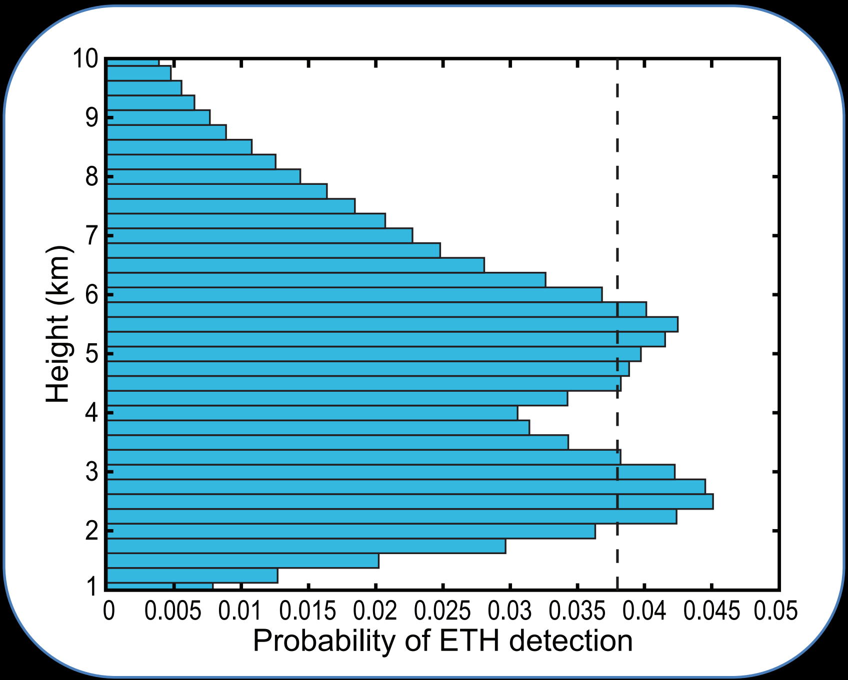
1. Do clouds moisten environment or does something else, allowing for cloud development?

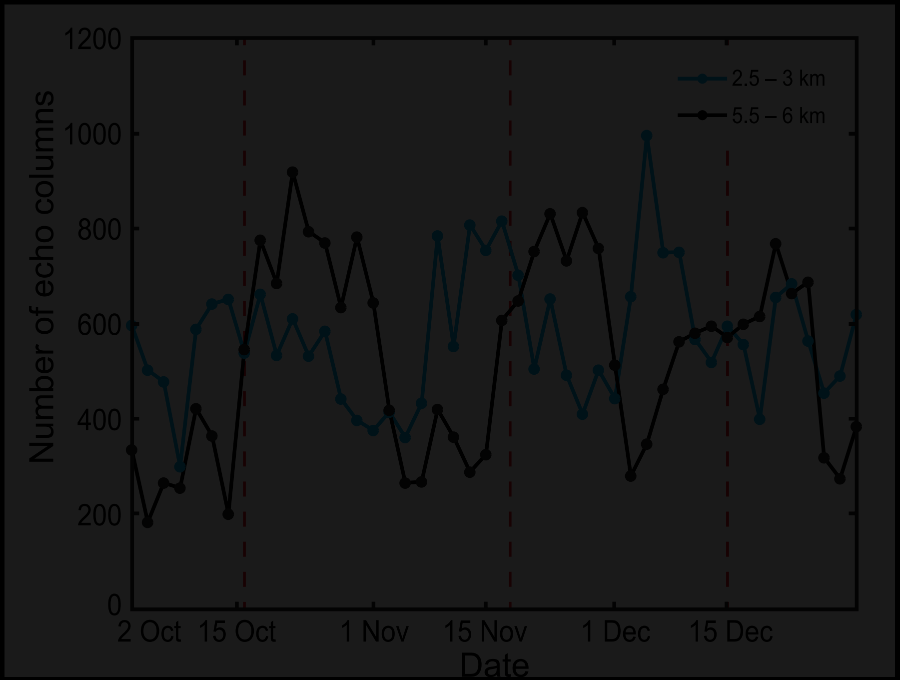
2. Role of global circulation anomalies in cloud growth

Moistening by Cumulonimbi

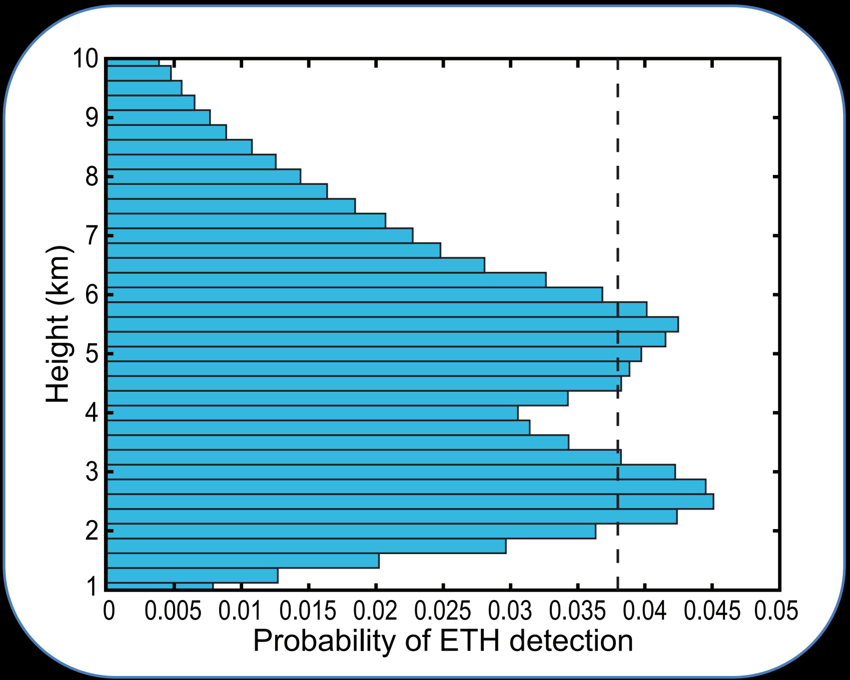
Do moderately deep clouds moisten the troposphere during transition periods, or does moistening permit observed cloud deepening?

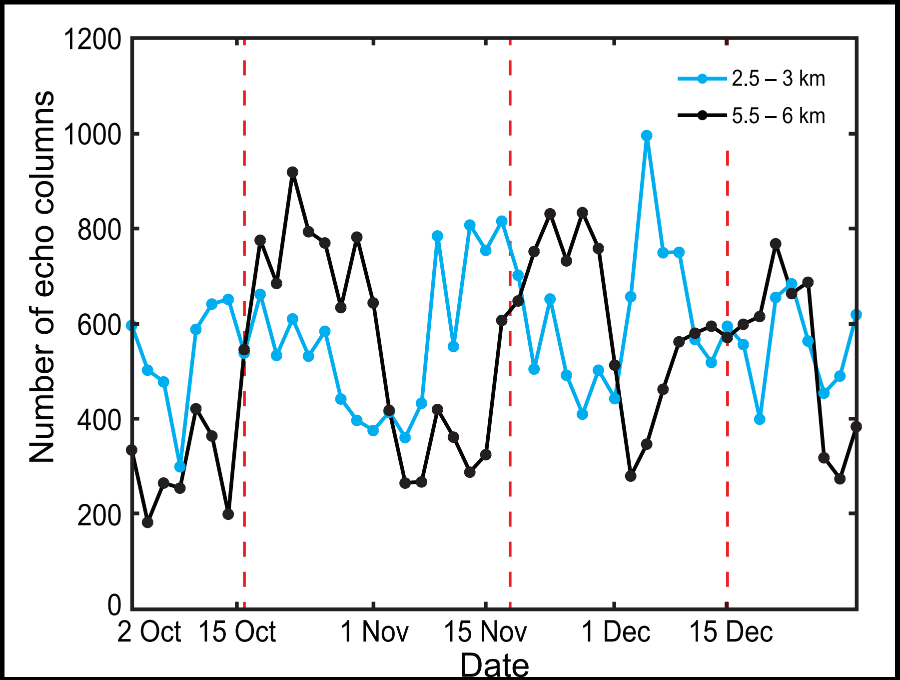

9°N
3°N
60°E
68°E
78°E
100°E
120°E
Addu City
3°S
9°S



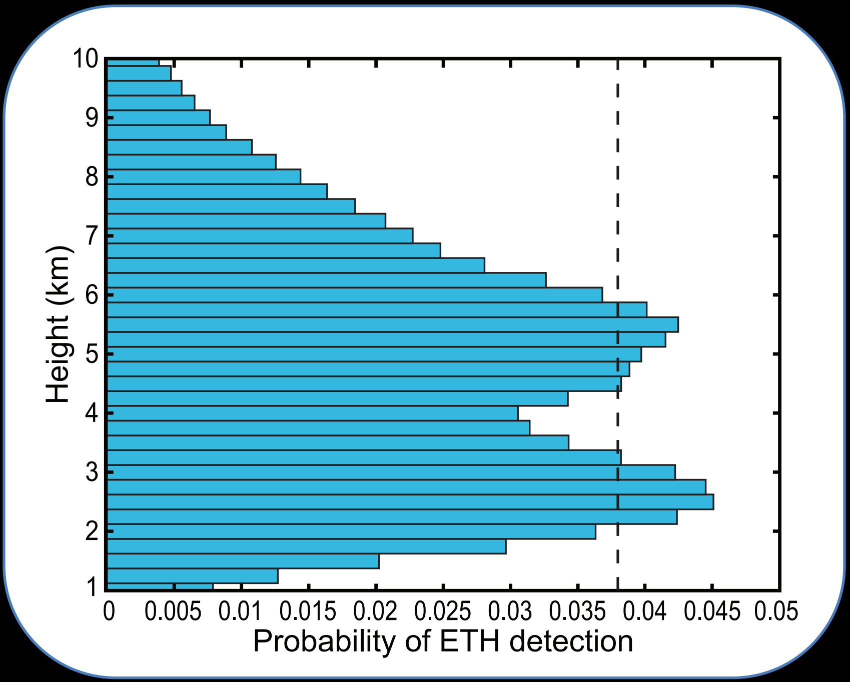


TRMM 20dBZ echo tops: 9N–9S; 60–100E

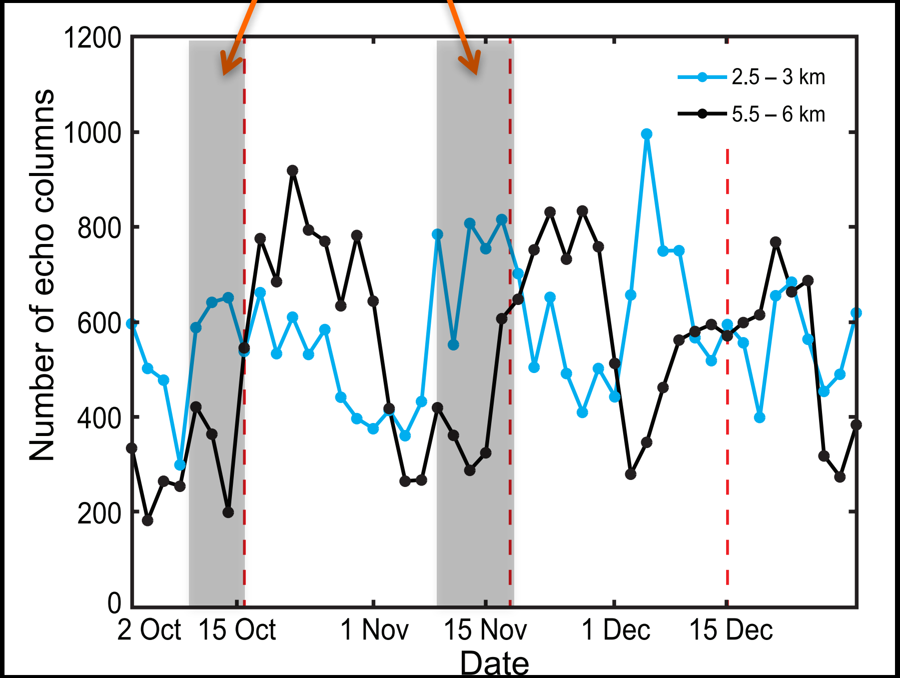




TRMM 20dBZ echo tops: 9N–9S; 60–100E

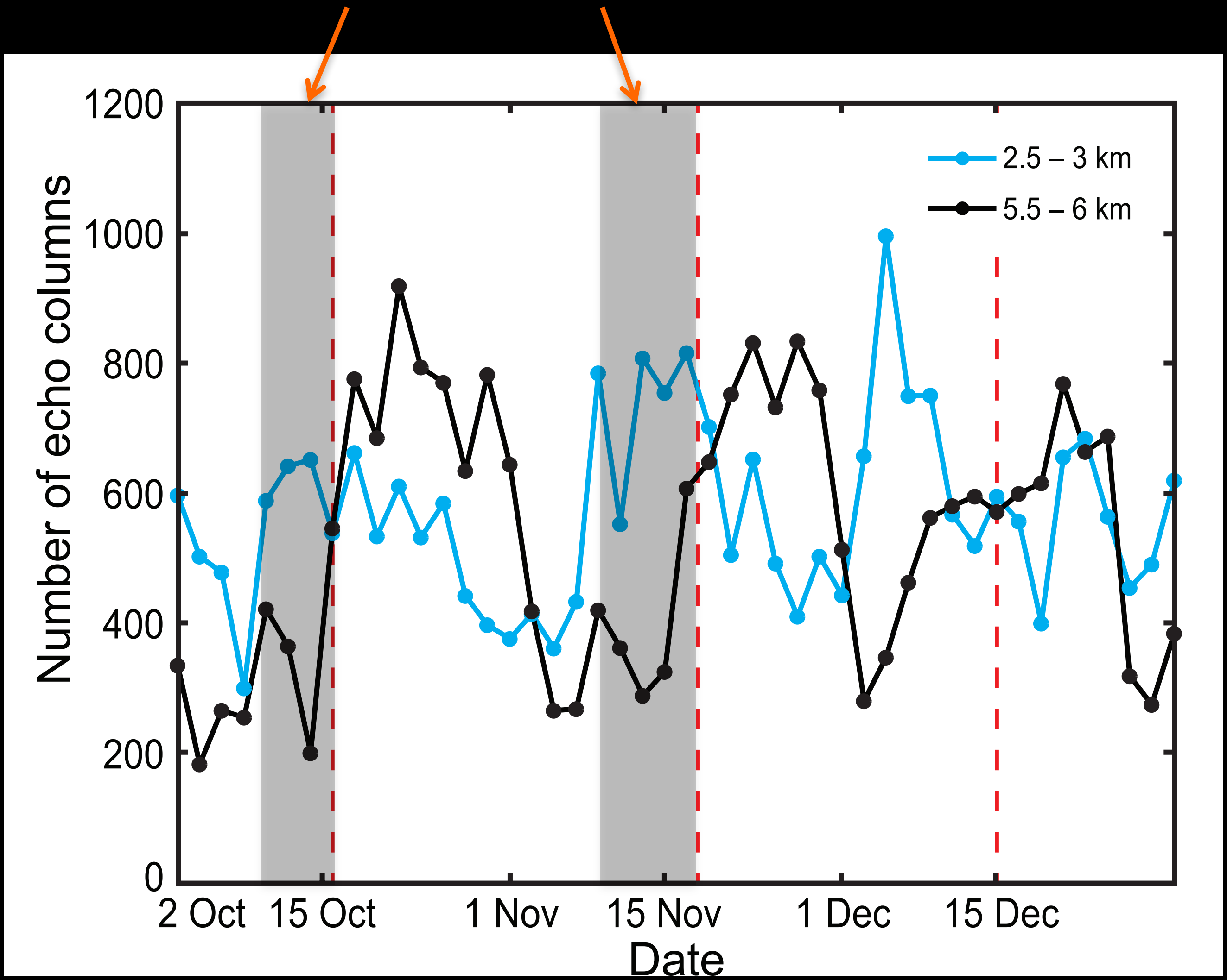


Transition periods



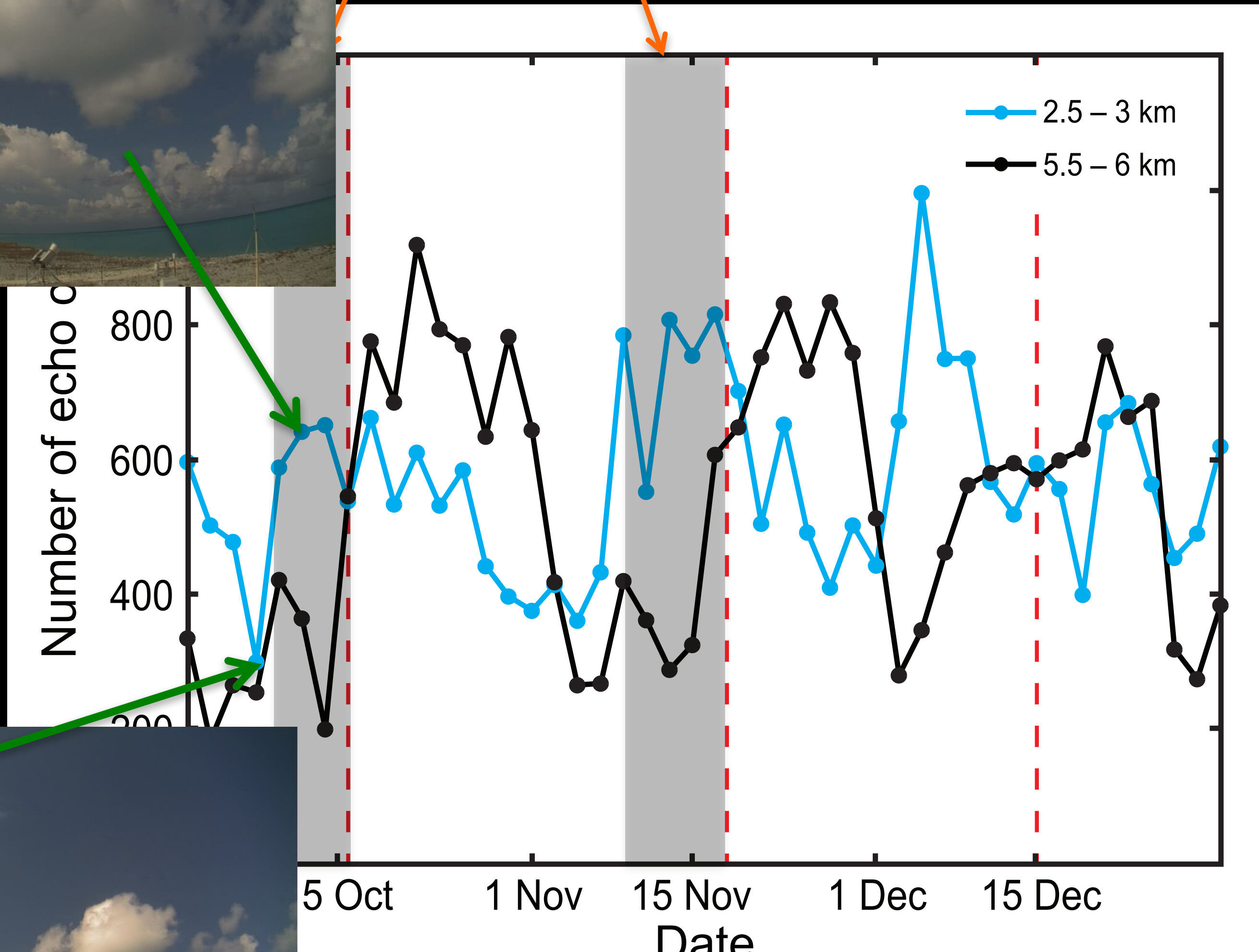
TRMM 20dBZ echo tops: 9N–9S; 60–100E

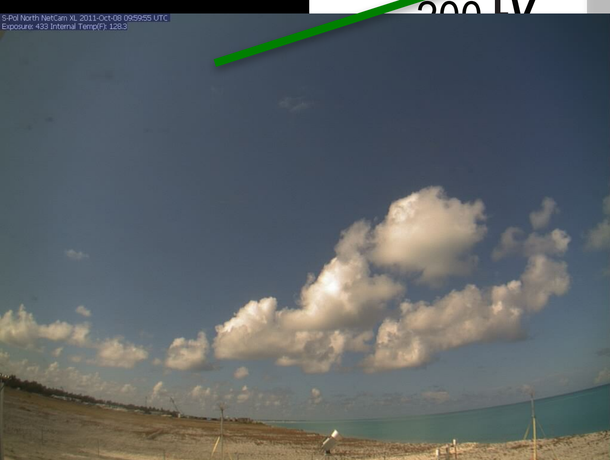
Transition periods



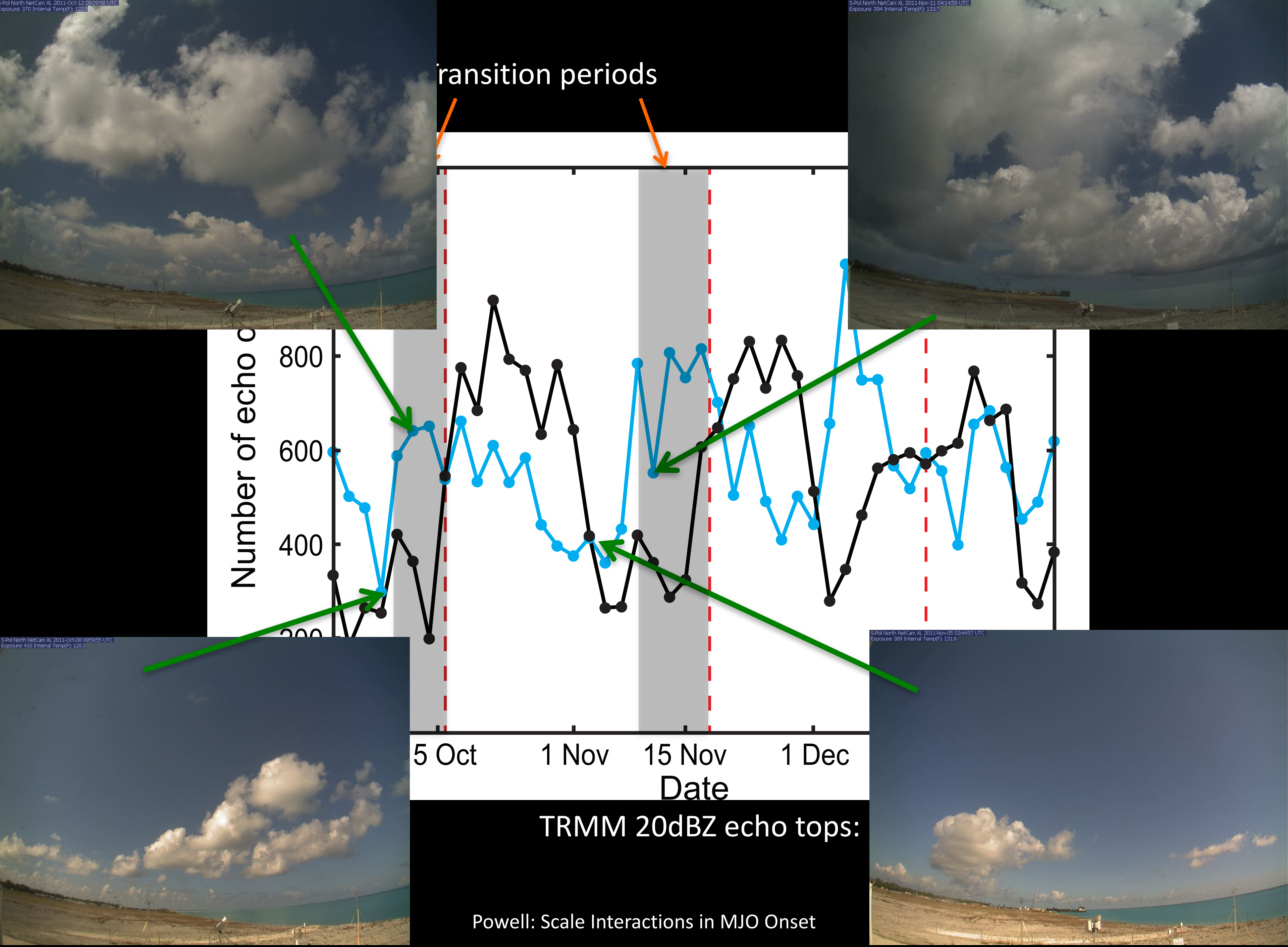
TRMM 20dBZ echo tops: 9N–9S; 60–100E

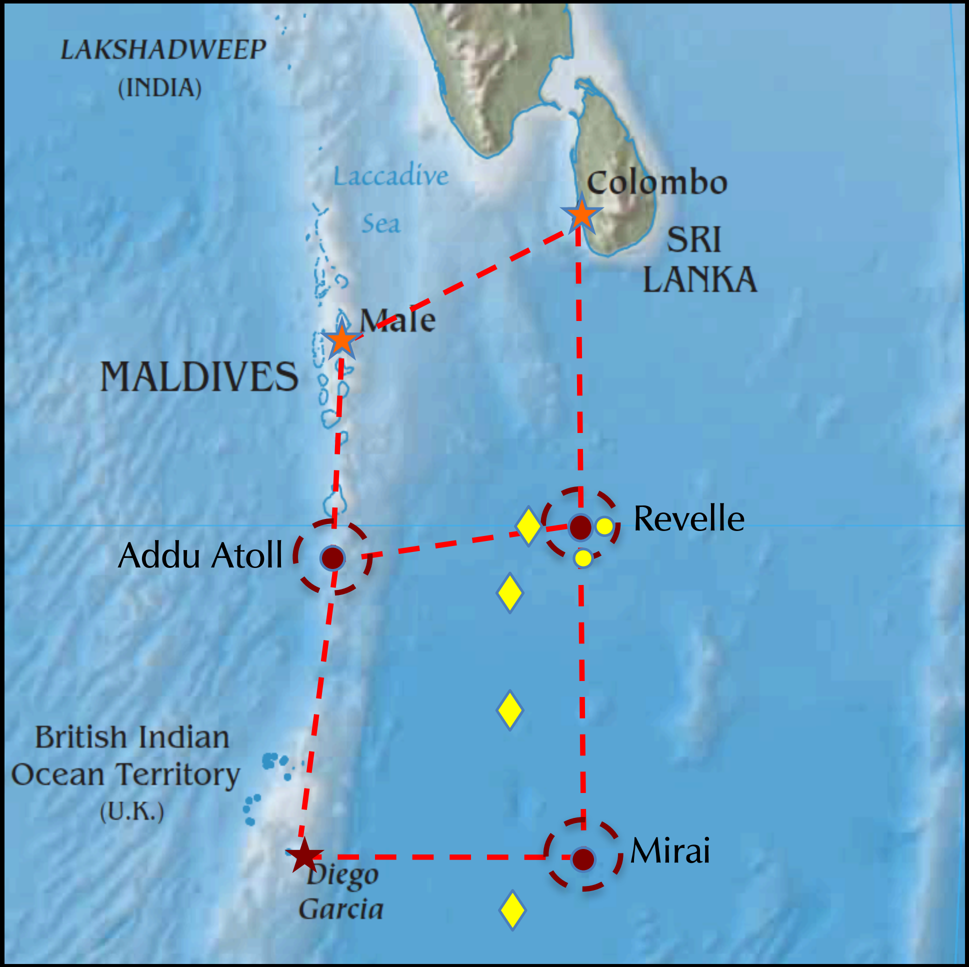
ransition periods

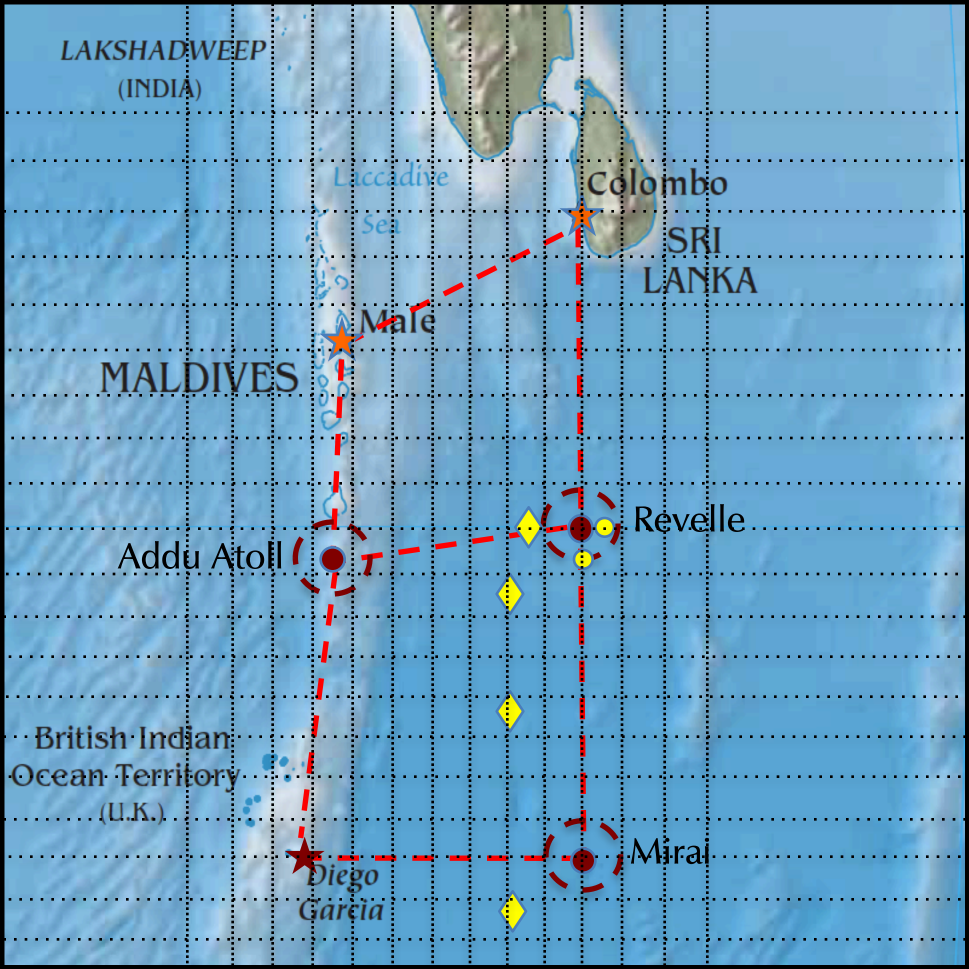




TRMM 20dBZ echo tops: 9N–9S; 60–100E


ransition periods
Number of echo o
800
600
400
5 Oct
1 Nov
15 Nov
1 Dec
Date
TRMM 20dBZ echo tops:

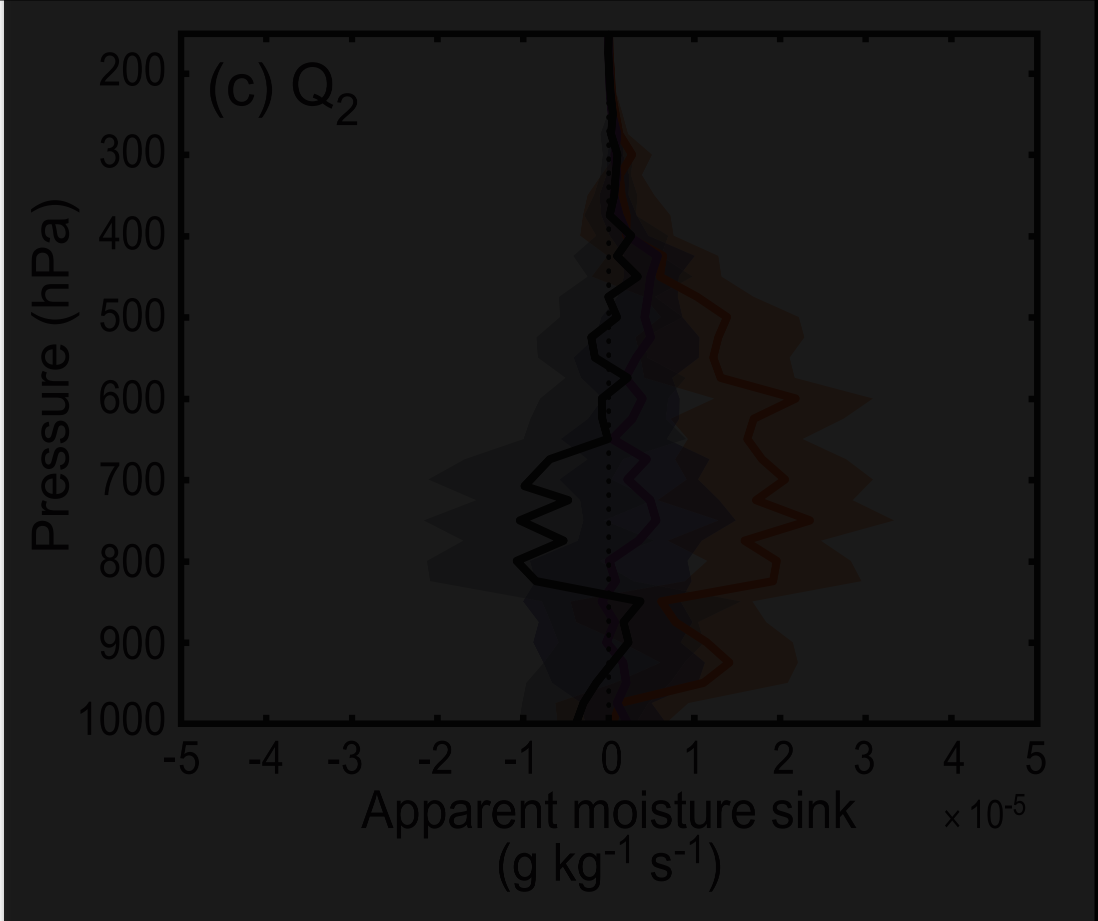

LAKSHADWEEP
(INDIA)
Laccadive
Sea
Colombo
SRI
LANKA
Male
MALDIVES
Revelle
Addu Atoll
British Indian
Ocean Territory
(U.K.)
Mirai
Diego
Garcia



LAKSHADWEEP
(INDIA)
Laccadive
Sea
Colombo
SRI
LANKA
Male
MALDIVES
Revelle
Addu Atoll
British Indian
Ocean Territory
(U.K.)
Mirai
Diego
Garcia

$$\frac{\partial q}{\partial t} = -\mathbf{v}_h \cdot \nabla q - \omega \frac{\partial q}{\partial p} - Q_2$$

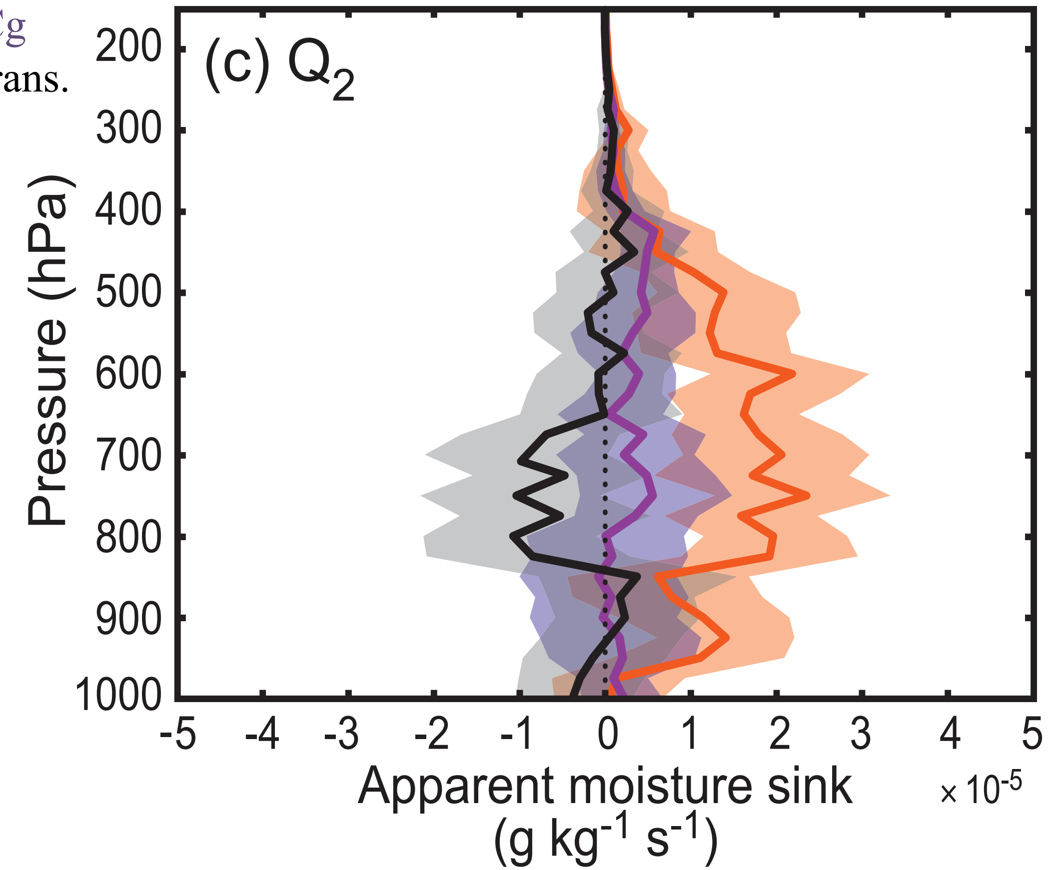
$$Q_2 = \left(\overline{c} - \overline{e}\right) + \frac{\partial}{\partial p}\left(\overline{\omega' q'}\right)$$



Purple = Cg
Black = Trans.
Red = Cb

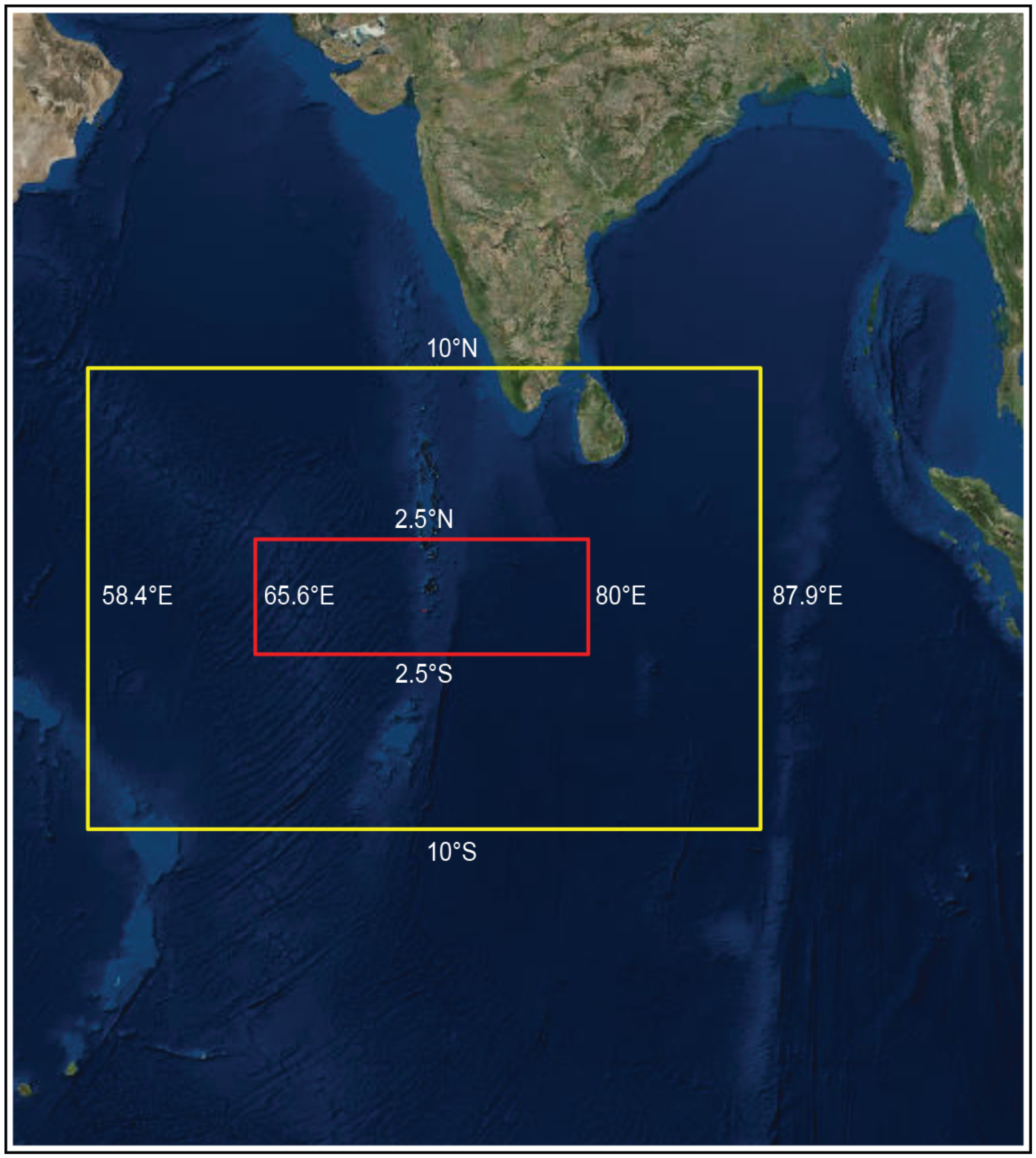
$$\frac{\partial q}{\partial t} = -\mathbf{v}_h \cdot \nabla q - \omega \frac{\partial q}{\partial p} - Q_2$$

$$Q_2 = \left(\overline{c} - \overline{e}\right) + \frac{\partial}{\partial p}\left(\overline{\omega' q'}\right)$$



WRF V3.5.1

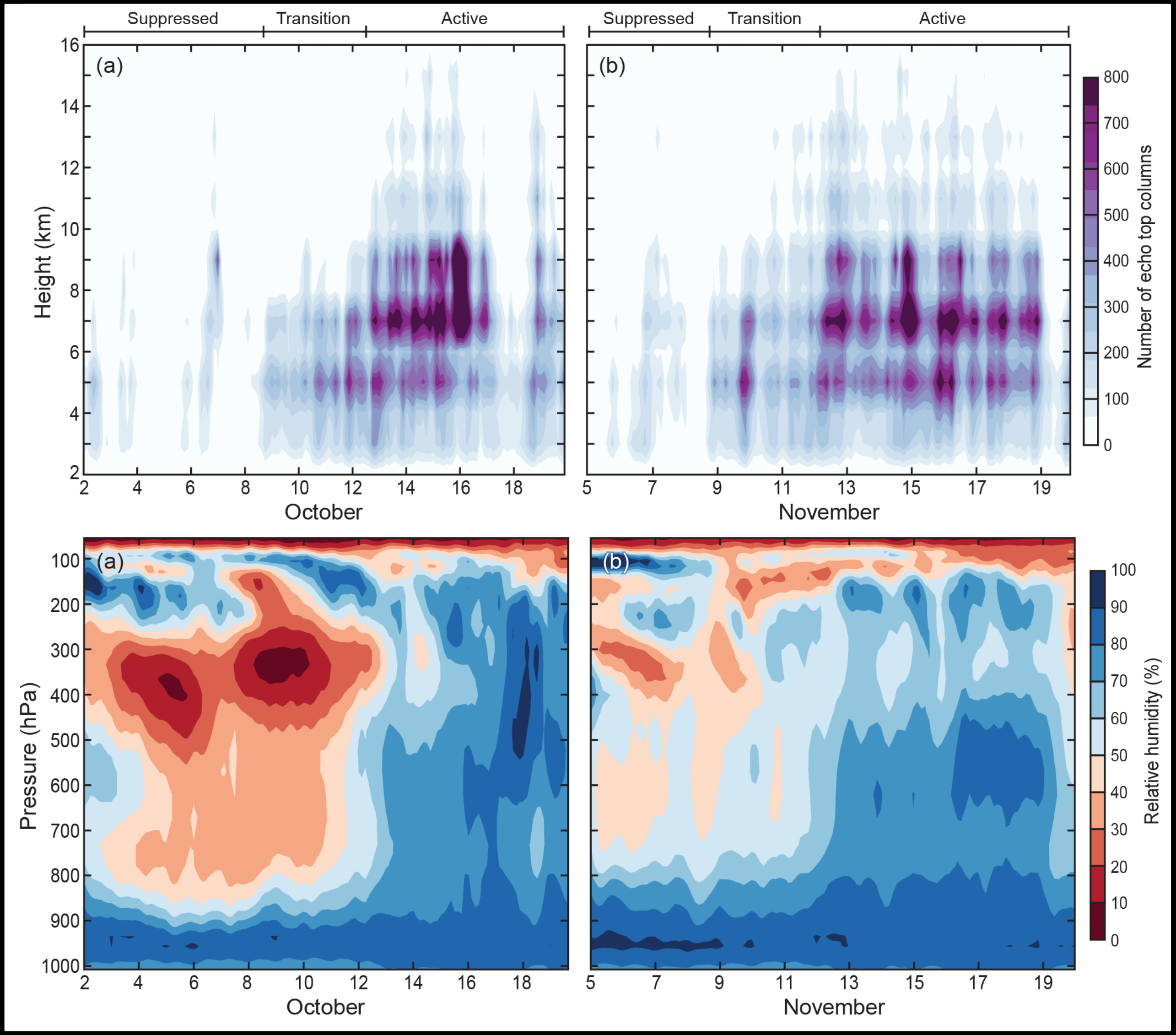
- 2 km grid spacing
- Thompson microphysics (following, e.g., Powell et al. 2012)
- MYJ PBL scheme
- Forced with ERA-I every 6 hours and NOAA RTG for sea surface temperature
- 1–20 October and 4–20 November 2011



Powell (2016)
Rain-type classification following
Powell et al. (2016)

20 dBZ echo top height frequency

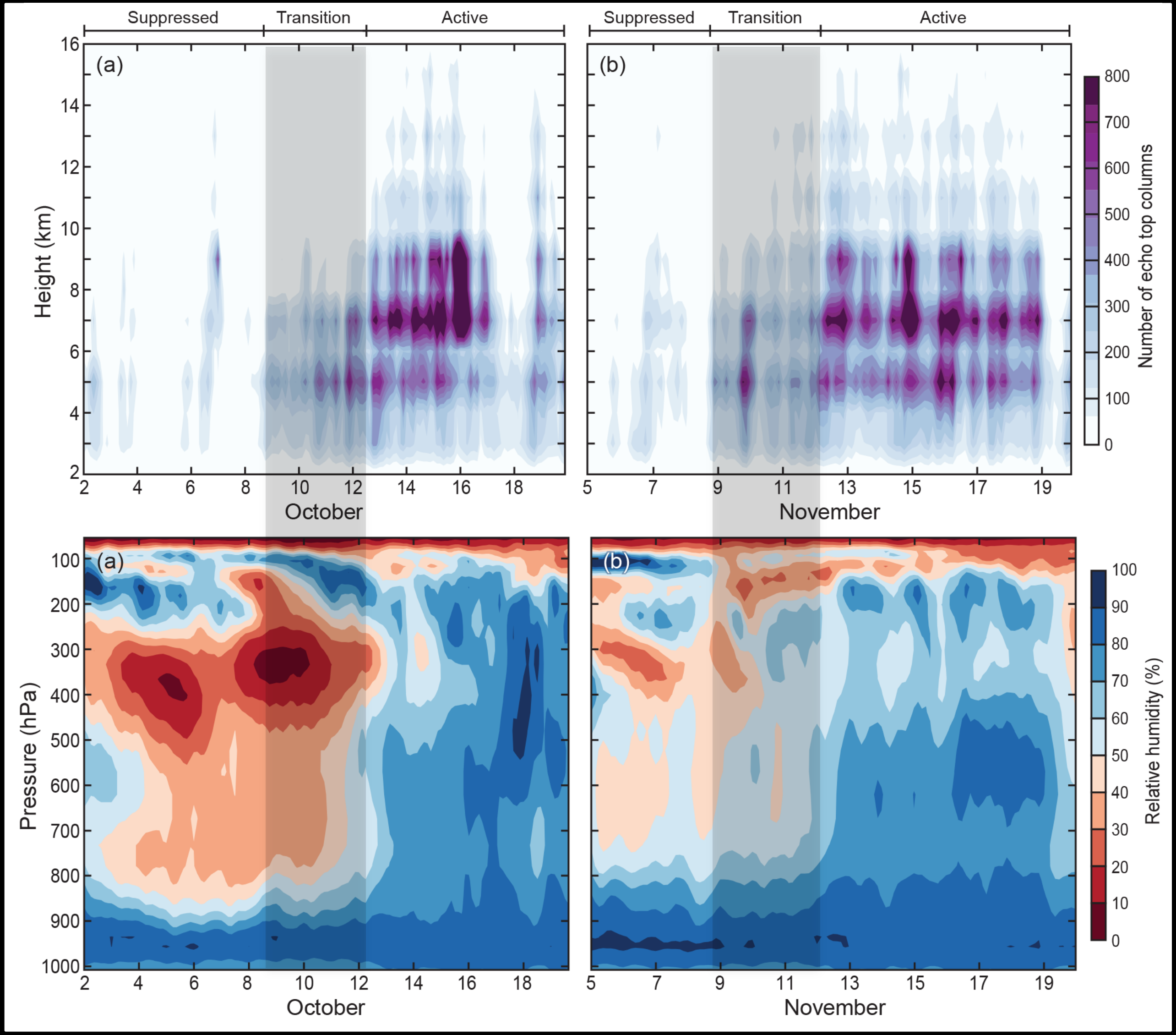
Relative Humidity

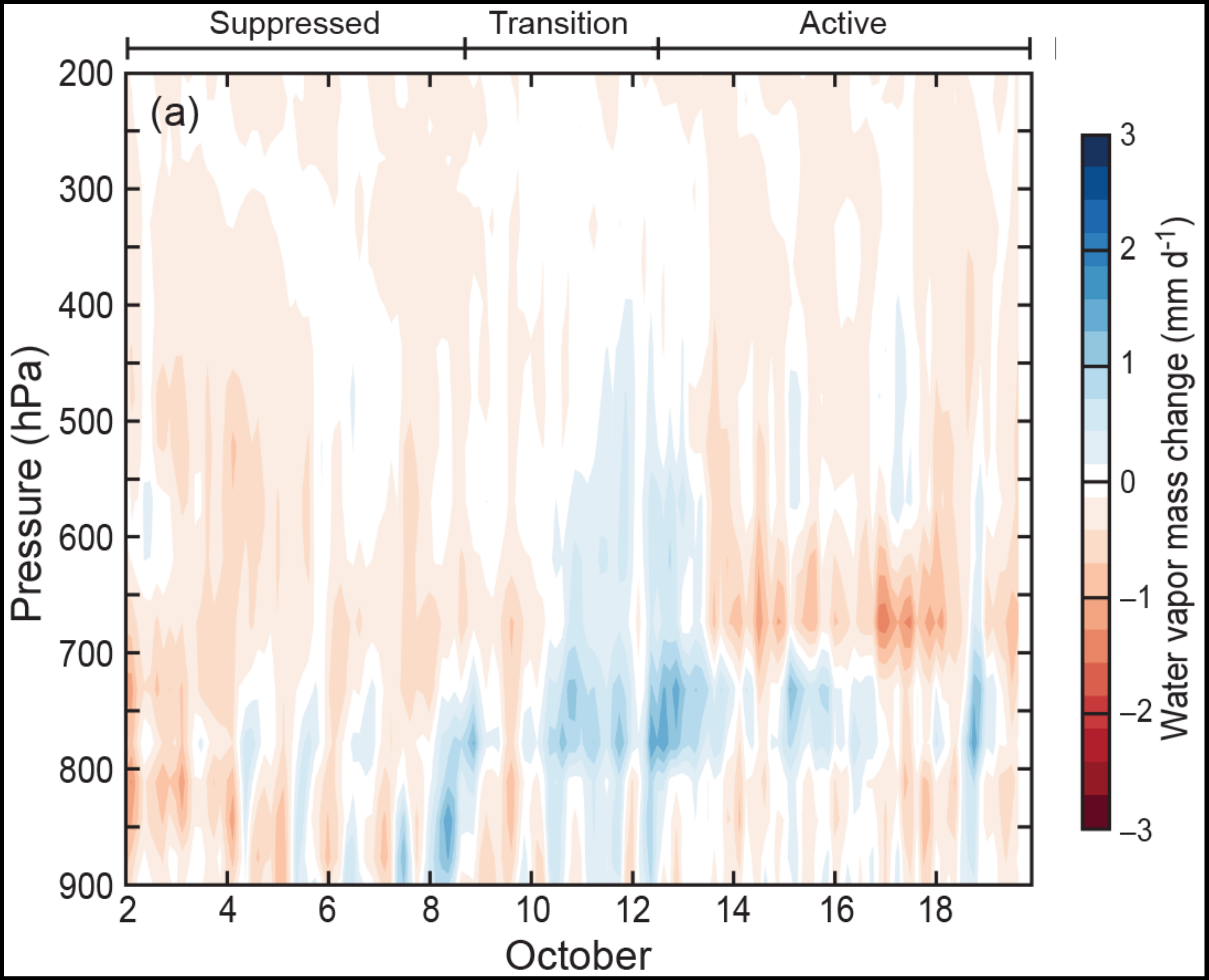


Powell (2016)
Rain-type classification following
Powell et al. (2016)

20 dBZ echo top height frequency

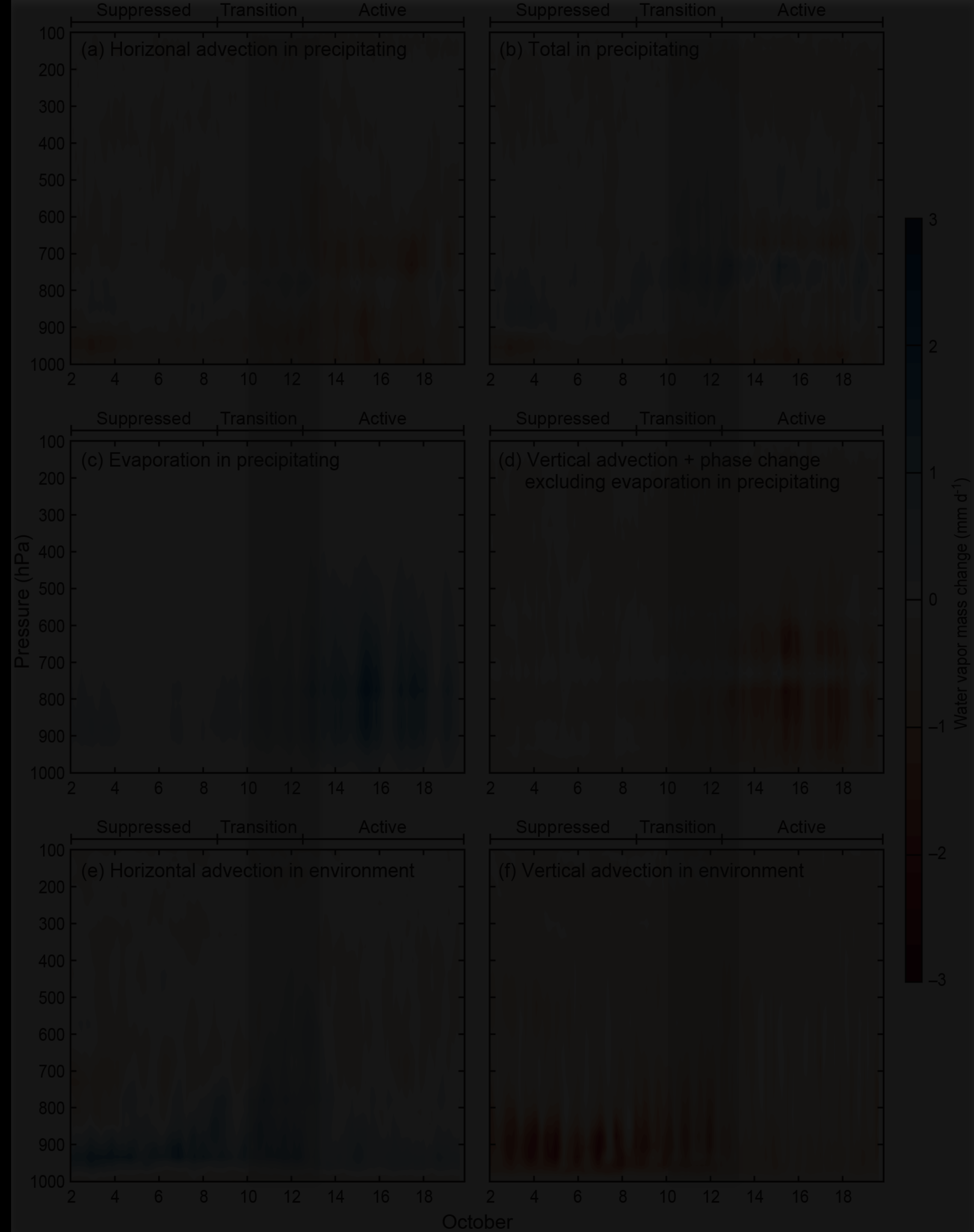
Relative Humidity




Suppressed
Transition
Active
(a)
Pressure (hPa)
200
300
400
500
600
700
800
900
2
4
6
8
10
12
14
16
18
October
Water vapor mass change (mm d-1)
3
2
1
0
–1
–2
–3

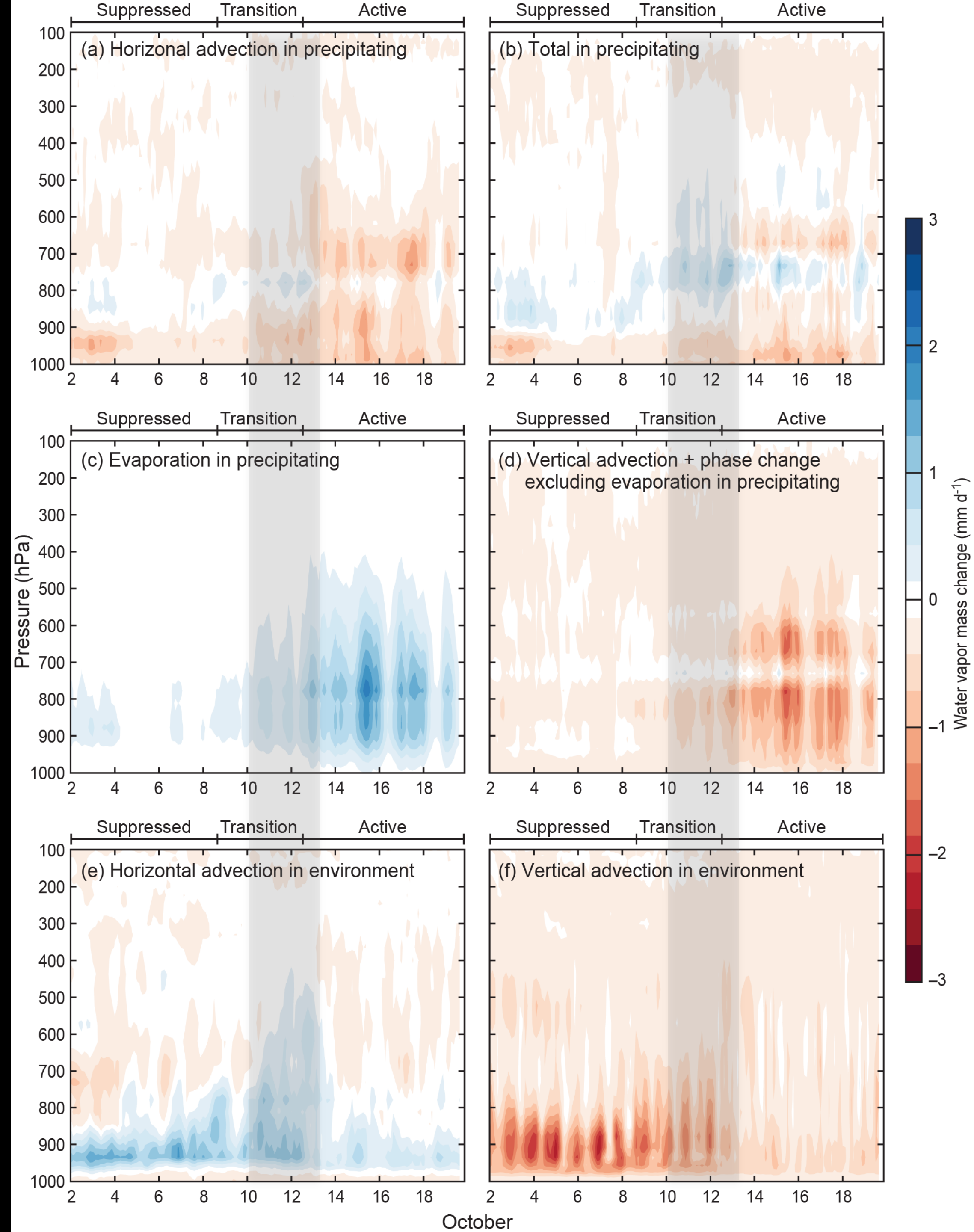
$$\frac{\partial m_{grid}}{\partial t} = -\frac{dP}{g} dx^2 (\mathbf{u} \cdot \nabla q) + M$$

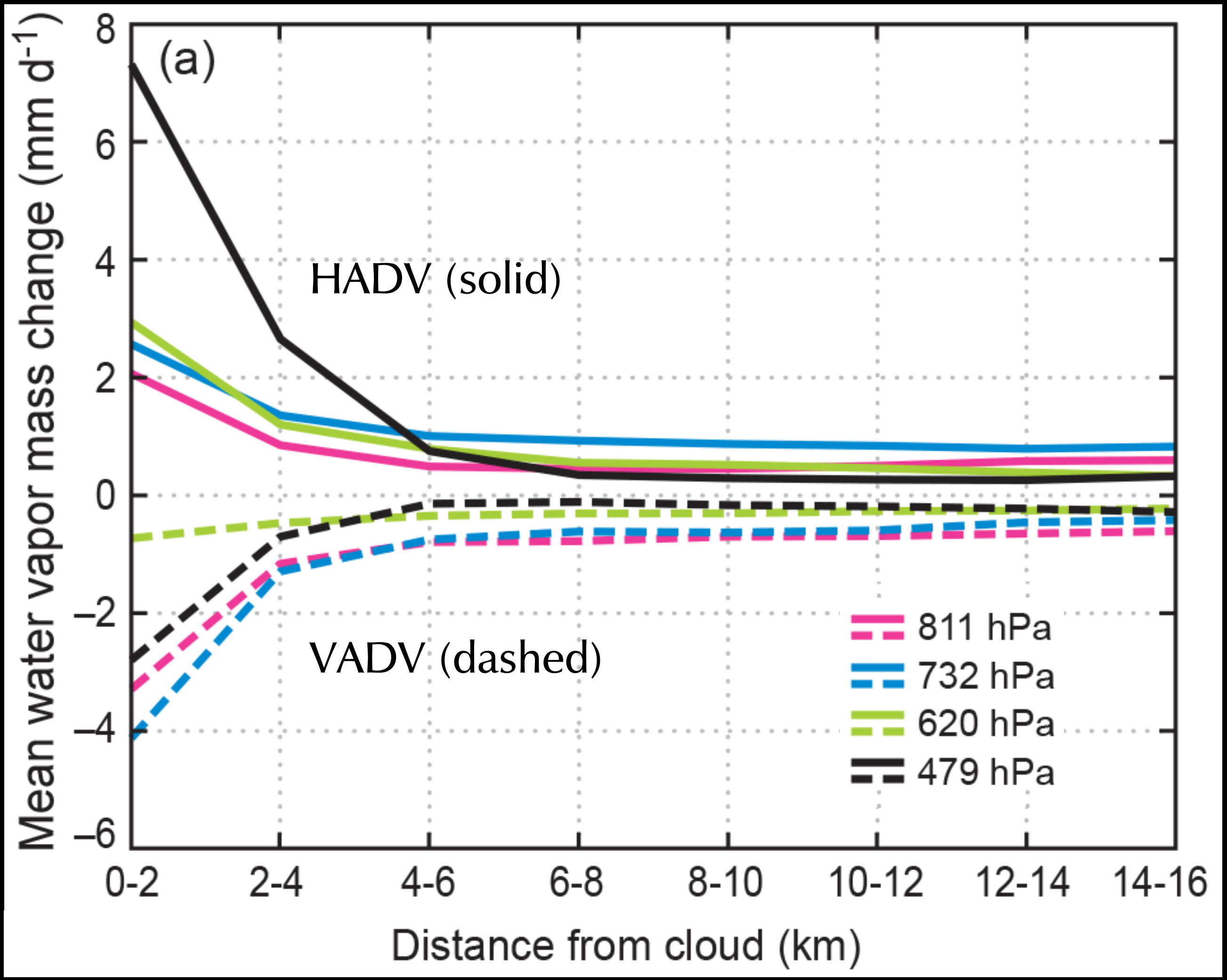
- HADV in precipitating clouds
- VADV in precipitating clouds
- Net phase change in precipitating clouds
- HADV in clear-air environment
- VADV in clear-air environment



$$\frac{\partial m_{grid}}{\partial t} = -\frac{dP}{g} dx^2 (\mathbf{u} \cdot \nabla q) + M$$

- HADV in precipitating clouds
- VADV in precipitating clouds
- Net phase change in precipitating clouds
- HADV in clear-air environment
- VADV in clear-air environment

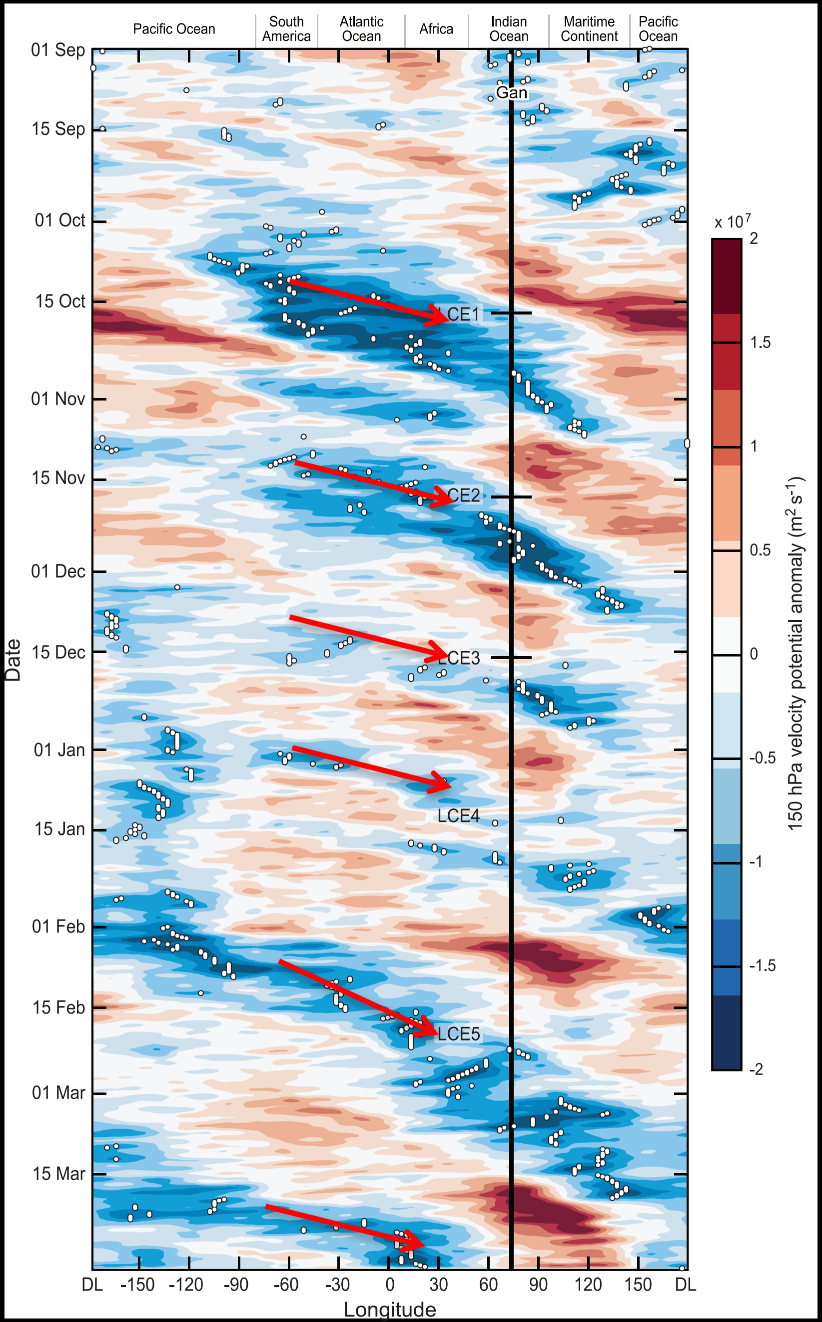



Mean water vapor mass change (mm d^{-1})
8
6
4
2
0
−2
−4
−6
(a)
HADV (solid)
VADV (dashed)
811 hPa
732 hPa
620 hPa
479 hPa
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
Distance from cloud (km)

The Circumnavigating Kelvin Wave

How does LS upper-tropospheric divergence relate to convection rooted in a warm, moist boundary layer?

Hypothesis: Convection passively responds to changes in the large-scale environment.



Originally: Knutson and Weickmann (1987)

Figure: Powell and Houze (2015b)

Large-scale vertical velocity anomalies are in phase with velocity potential anomalies.

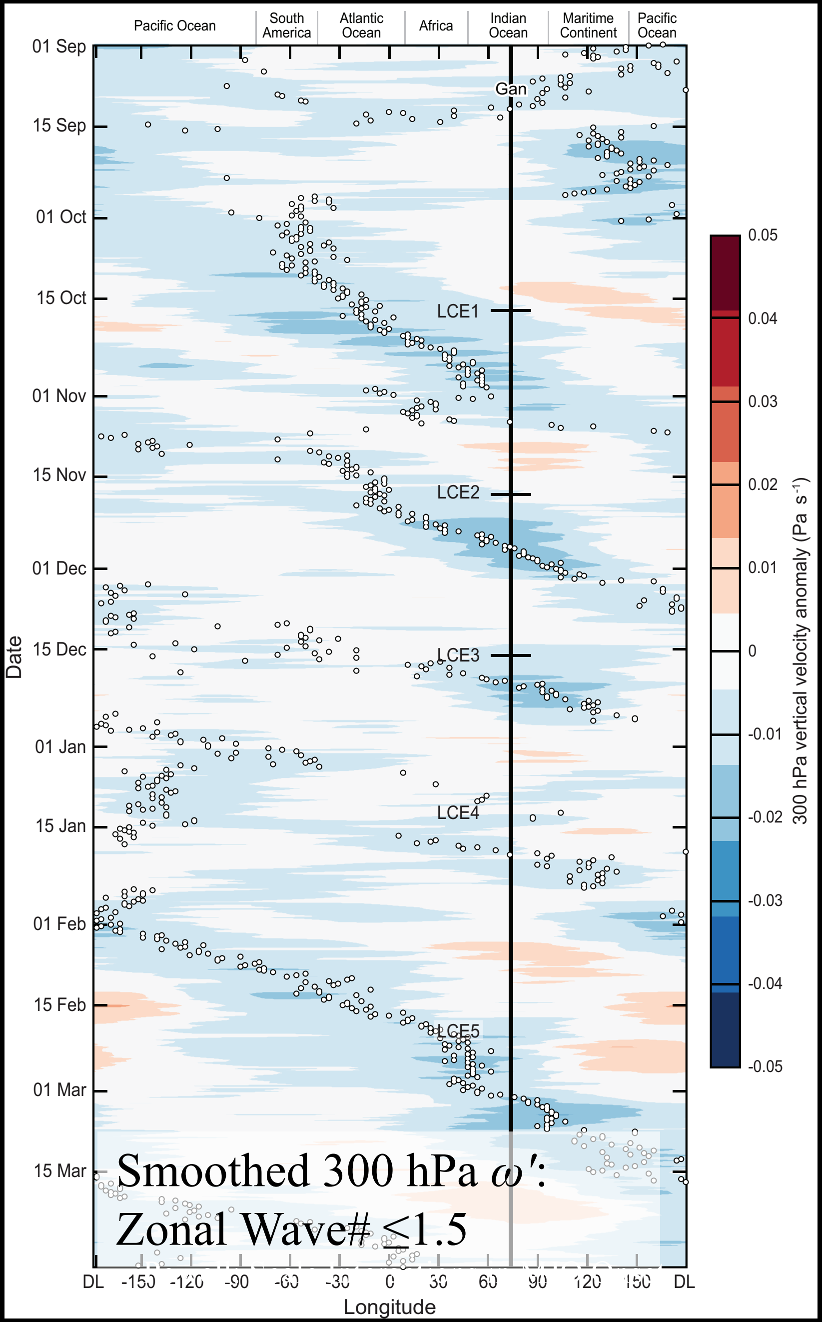
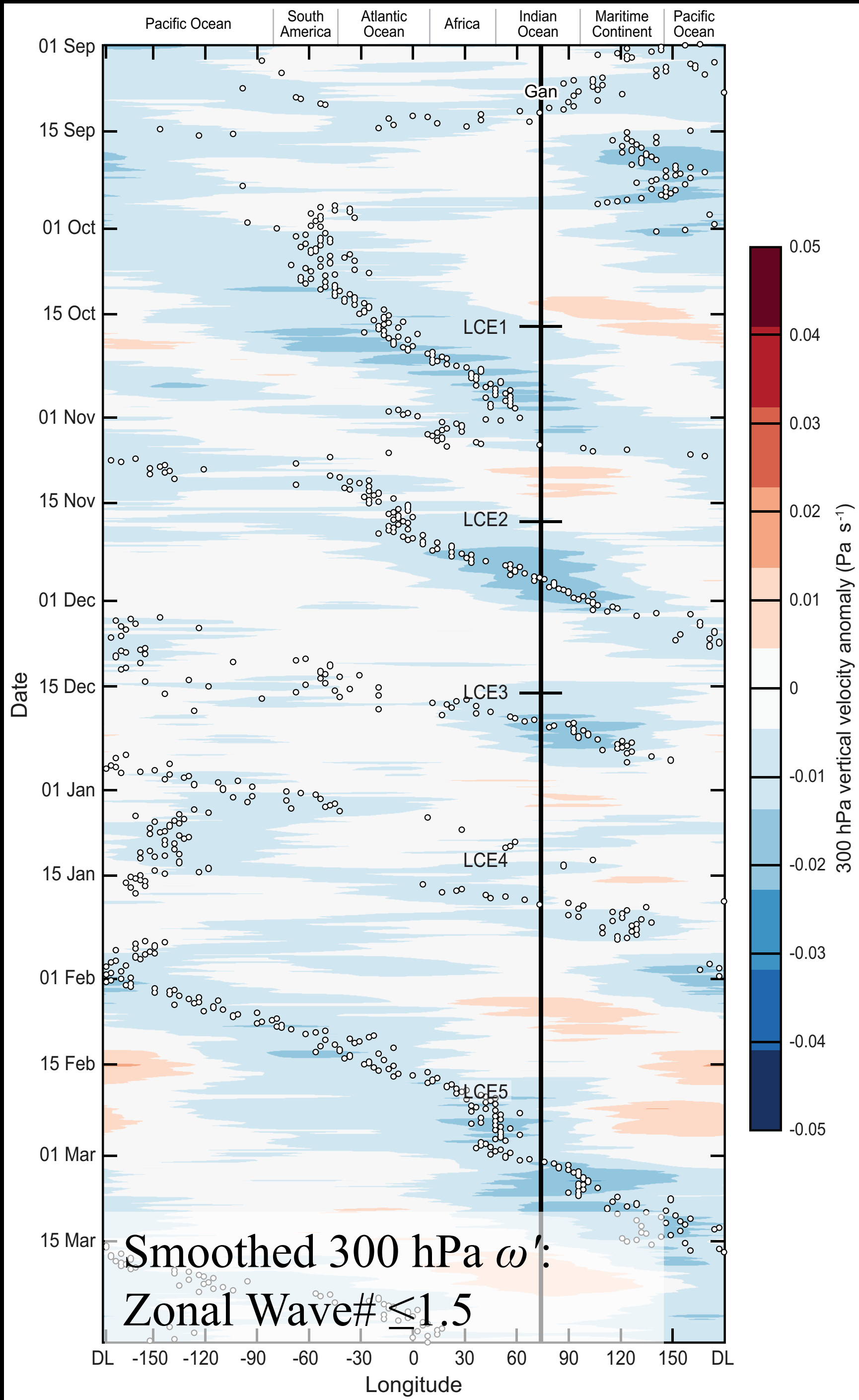
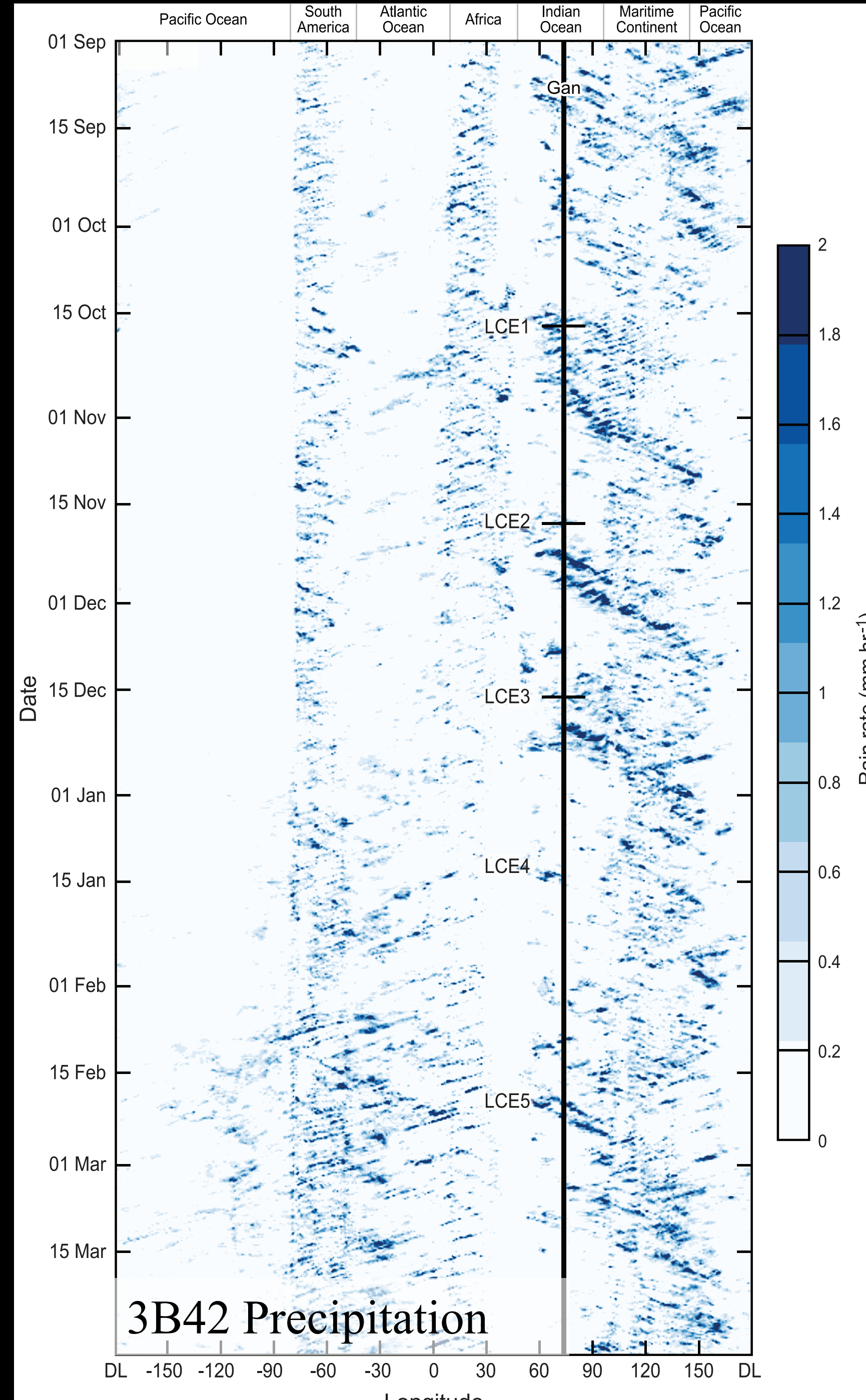
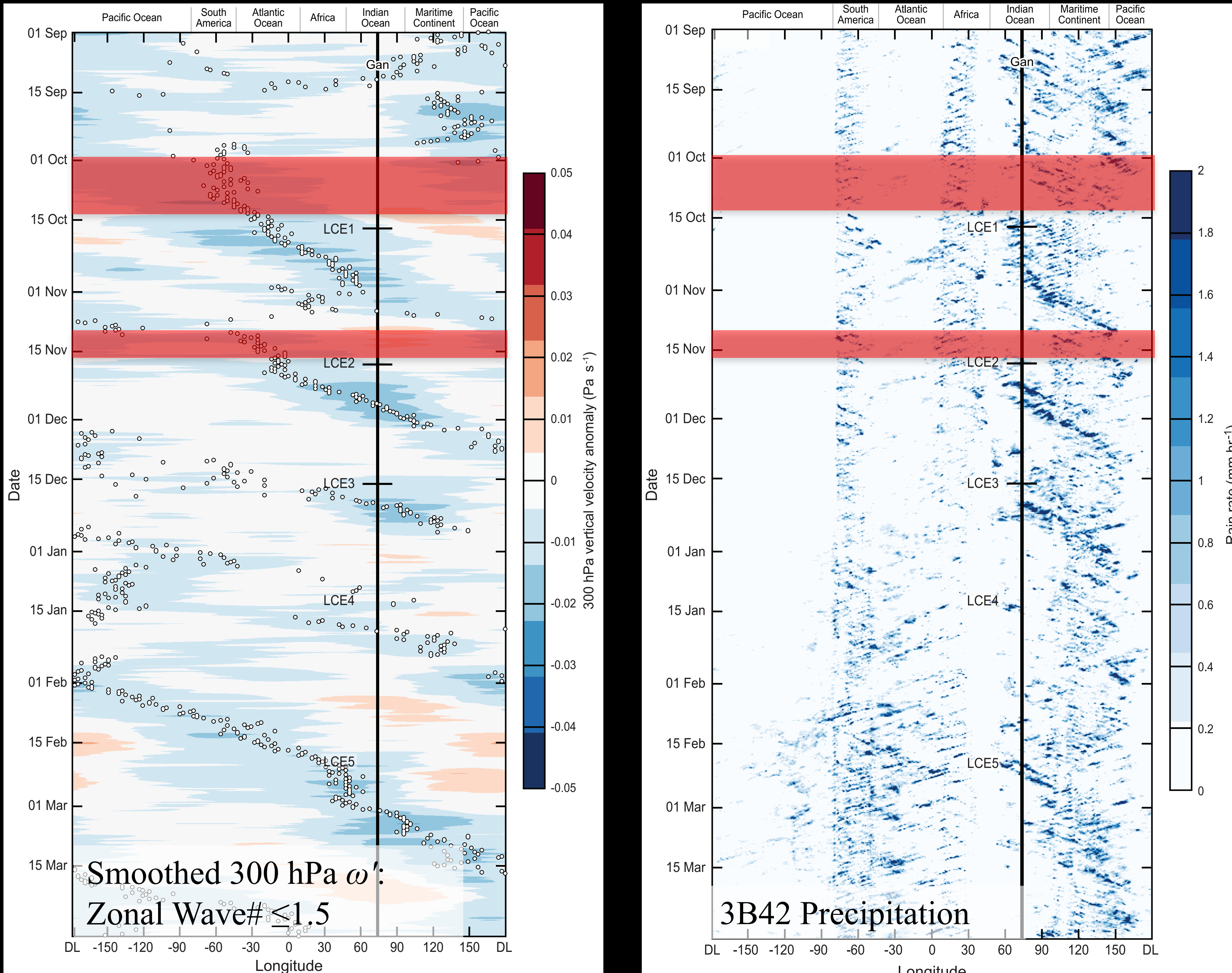


Figure: Powell and Houze (2015b)

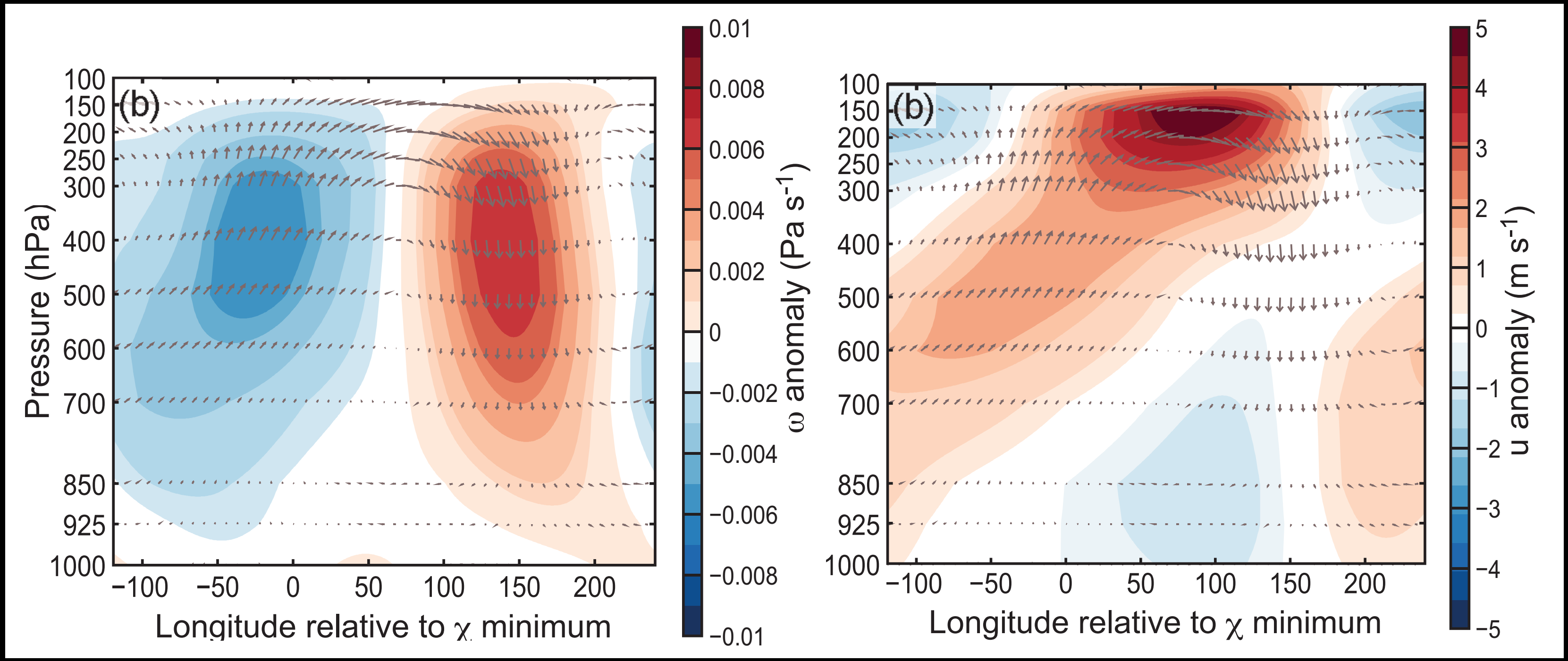

Pacific Ocean
South America
Atlantic Ocean
Africa
Indian Ocean
Maritime Continent
Pacific Ocean
01 Sep
15 Sep
01 Oct
15 Oct
01 Nov
15 Nov
01 Dec
15 Dec
01 Jan
15 Jan
01 Feb
15 Feb
01 Mar
15 Mar
Date
Gan
LCE1
LCE2
LCE3
LCE4
LCE5
DL -150 -120 -90 -60 -30 0 30 60 90 120 150 DL
Longitude
0.05 0.04 0.03 0.02 0.01 0 -0.01 -0.02 -0.03 -0.04 -0.05
300 hPa vertical velocity anomaly (Pa s-1)
Smoothed 300 hPa ω':
Zonal Wave# ≤1.5

Pacific Ocean
South America
Atlantic Ocean
Africa
Indian Ocean
Maritime Continent
Pacific Ocean
01 Sep
15 Sep
01 Oct
15 Oct
01 Nov
15 Nov
01 Dec
15 Dec
01 Jan
15 Jan
01 Feb
15 Feb
01 Mar
15 Mar
Date
Gan
LCE1
LCE2
LCE3
LCE4
LCE5
DL -150 -120 -90 -60 -30 0 30 60 90 120 150 DL
Longitude
2 1.8 1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 0
Rain rate (mm hr-1)
3B42 Precipitation

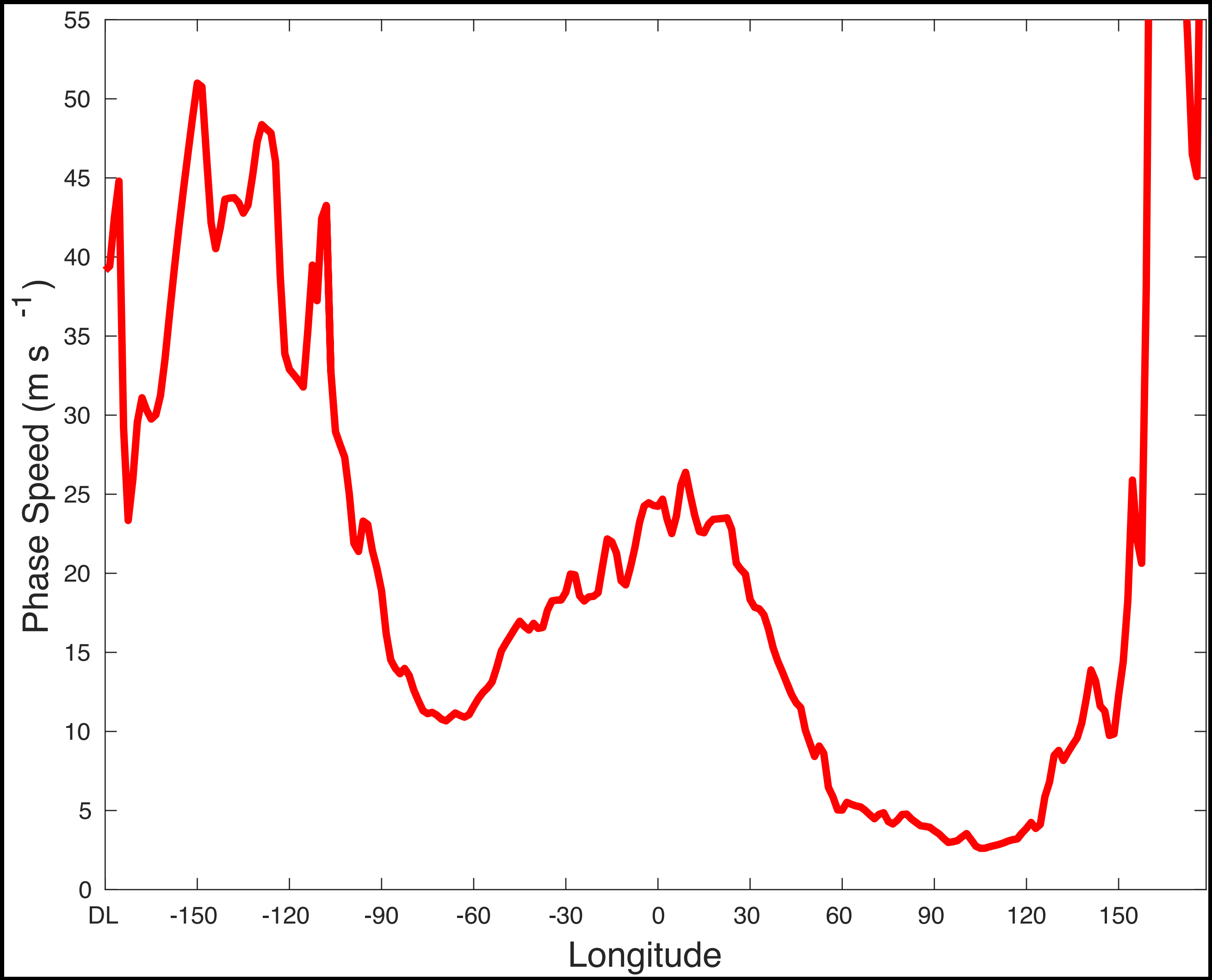


Pacific Ocean
South America
Atlantic Ocean
Africa
Indian Ocean
Maritime Continent
Pacific Ocean
01 Sep
15 Sep
01 Oct
15 Oct
01 Nov
15 Nov
01 Dec
15 Dec
01 Jan
15 Jan
01 Feb
15 Feb
01 Mar
15 Mar
Date
Gan
LCE1
LCE2
LCE3
LCE4
LCE5
Smoothed 300 hPa ω':
Zonal Wave# ≤1.5
DL -150 -120 -90 -60 -30 0 30 60 90 120 150 DL
Longitude
300 hPa vertical velocity anomaly (Pa s-1)
0.05 0.04 0.03 0.02 0.01 0 -0.01 -0.02 -0.03 -0.04 -0.05
3B42 Precipitation
Rain rate (mm hr-1)
2 1.8 1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 0

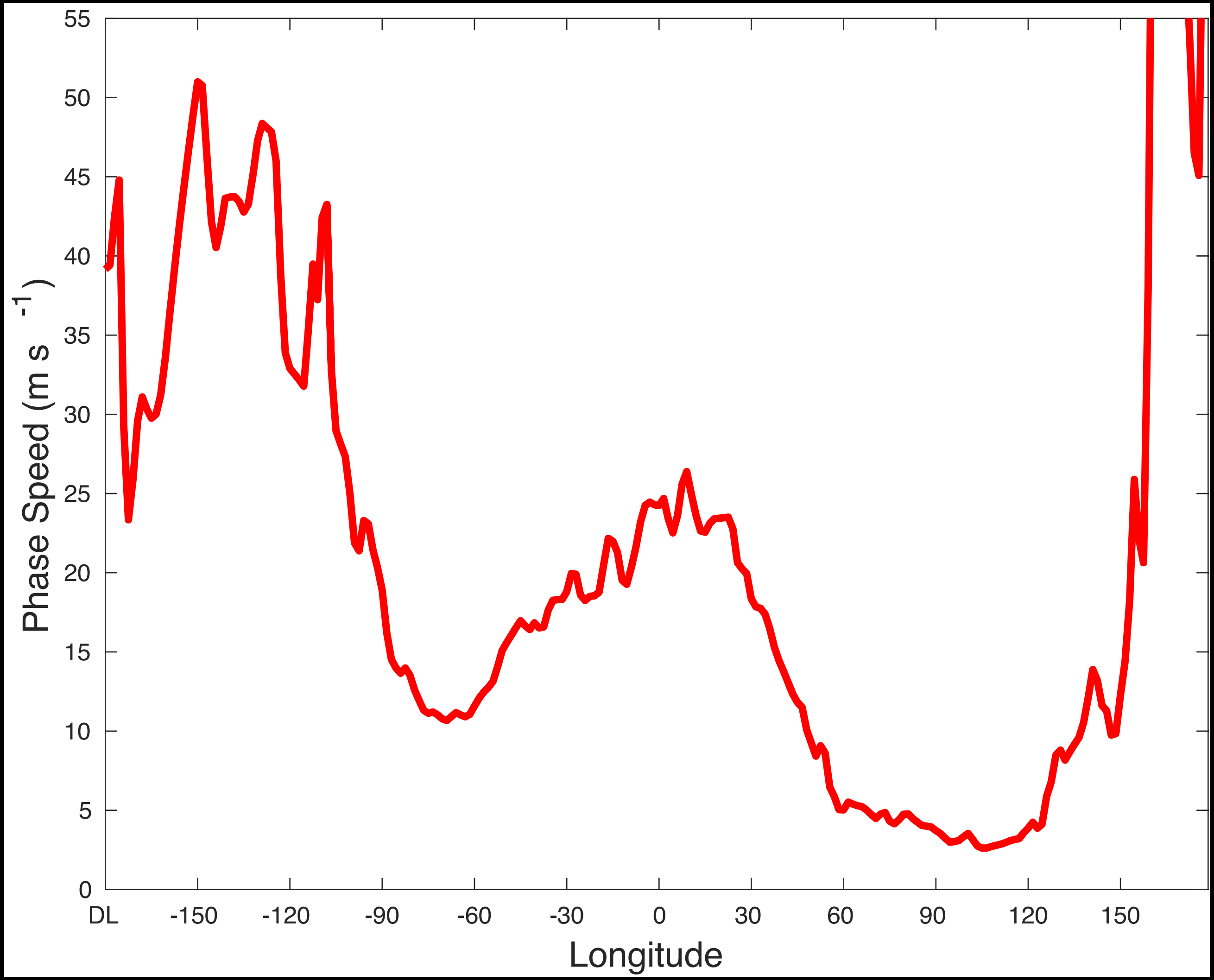
ω′ *u′*

Wave # ≤ 1.5

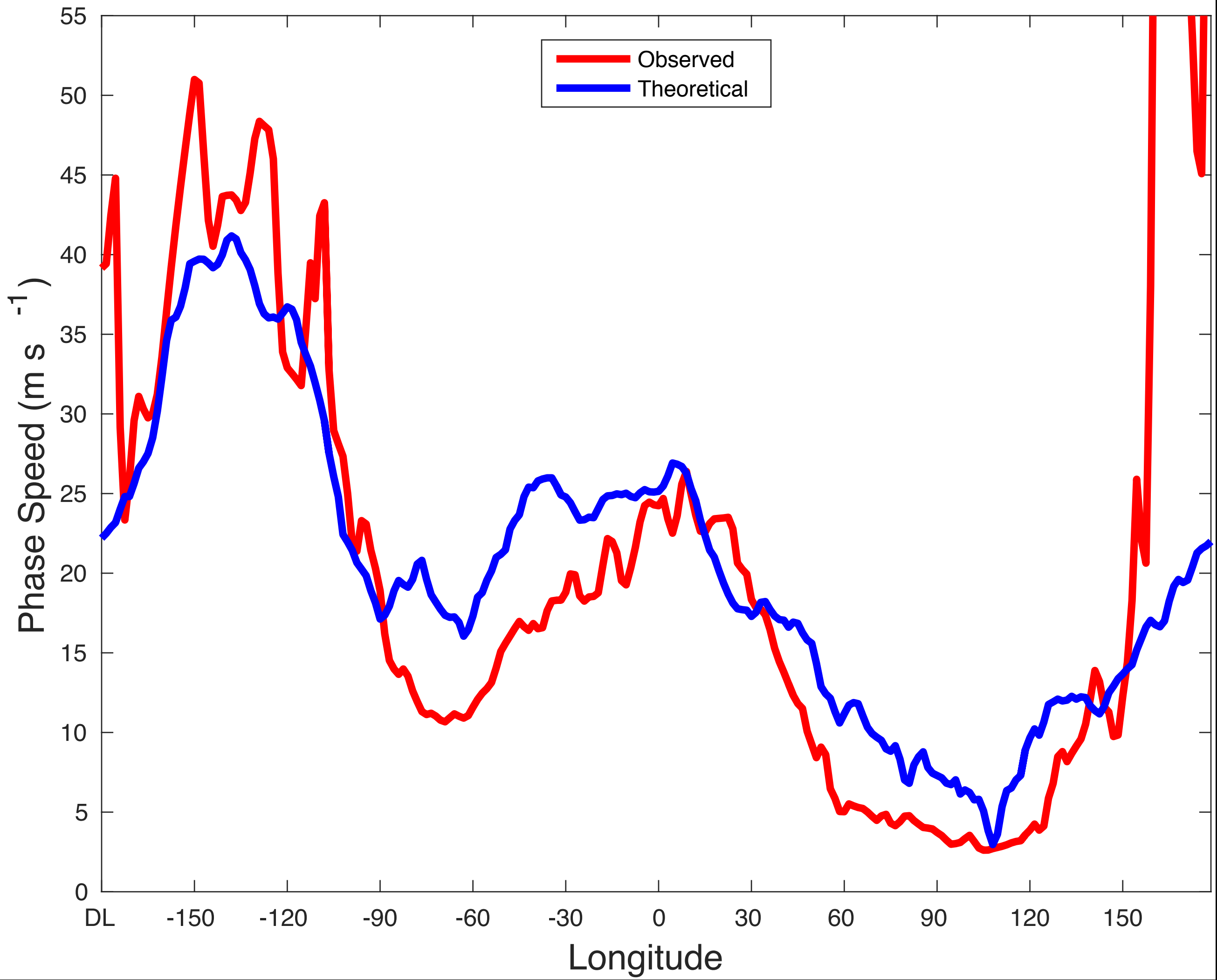

(b)
Pressure (hPa)
100
150
200
250
300
400
500
600
700
850
925
1000
−100
−50
0
50
100
150
200
Longitude relative to χ minimum
0.01
0.008
0.006
0.004
0.002
0
−0.002
−0.004
−0.006
−0.008
−0.01
ω anomaly (Pa s-1)
(b)
5
4
3
2
1
0
−1
−2
−3
−4
−5
u anomaly (m s-1)


Phase Speed (m s⁻¹)
Longitude
DL
-150
-120
-90
-60
-30
0
30
60
90
120
150
0
5
10
15
20
25
30
35
40
45
50
55

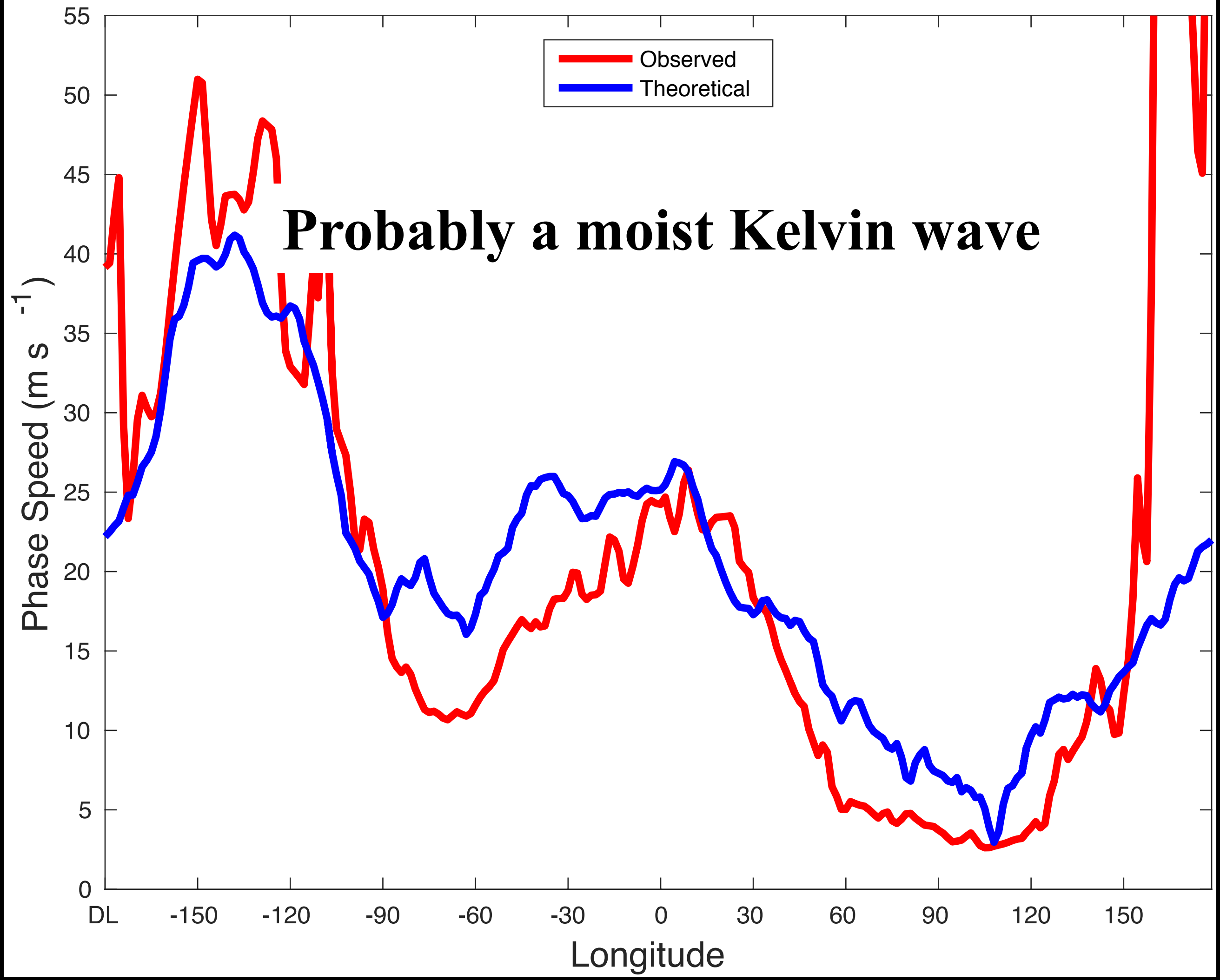
$$\frac{\partial T}{\partial t} - S\omega = Q, Q \approx -\mu S\omega, c = \sqrt{(1-\mu)gh_e}$$

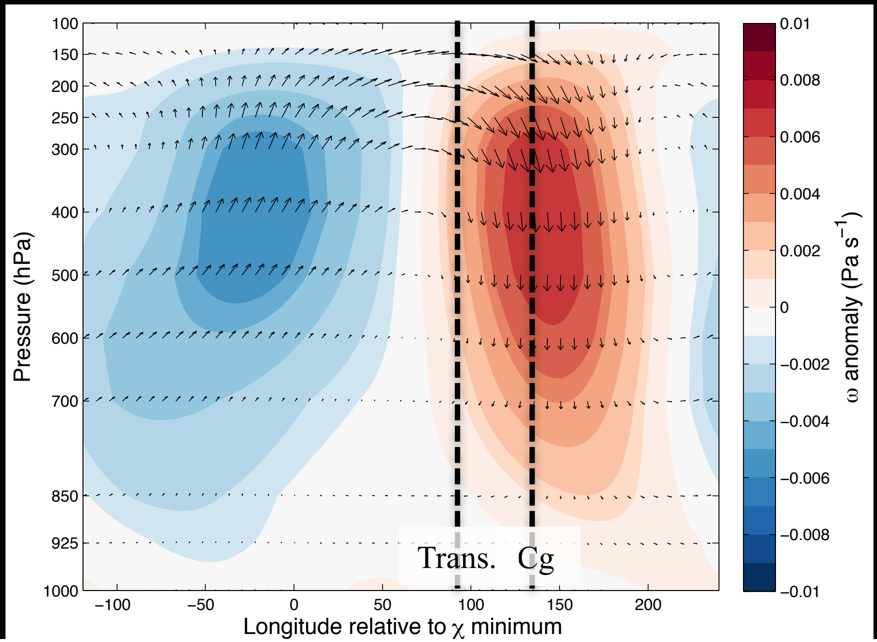


$$\frac{\partial T}{\partial t} - S\omega = Q, Q \approx -\mu S\omega, c = \sqrt{(1-\mu)gh_e}$$

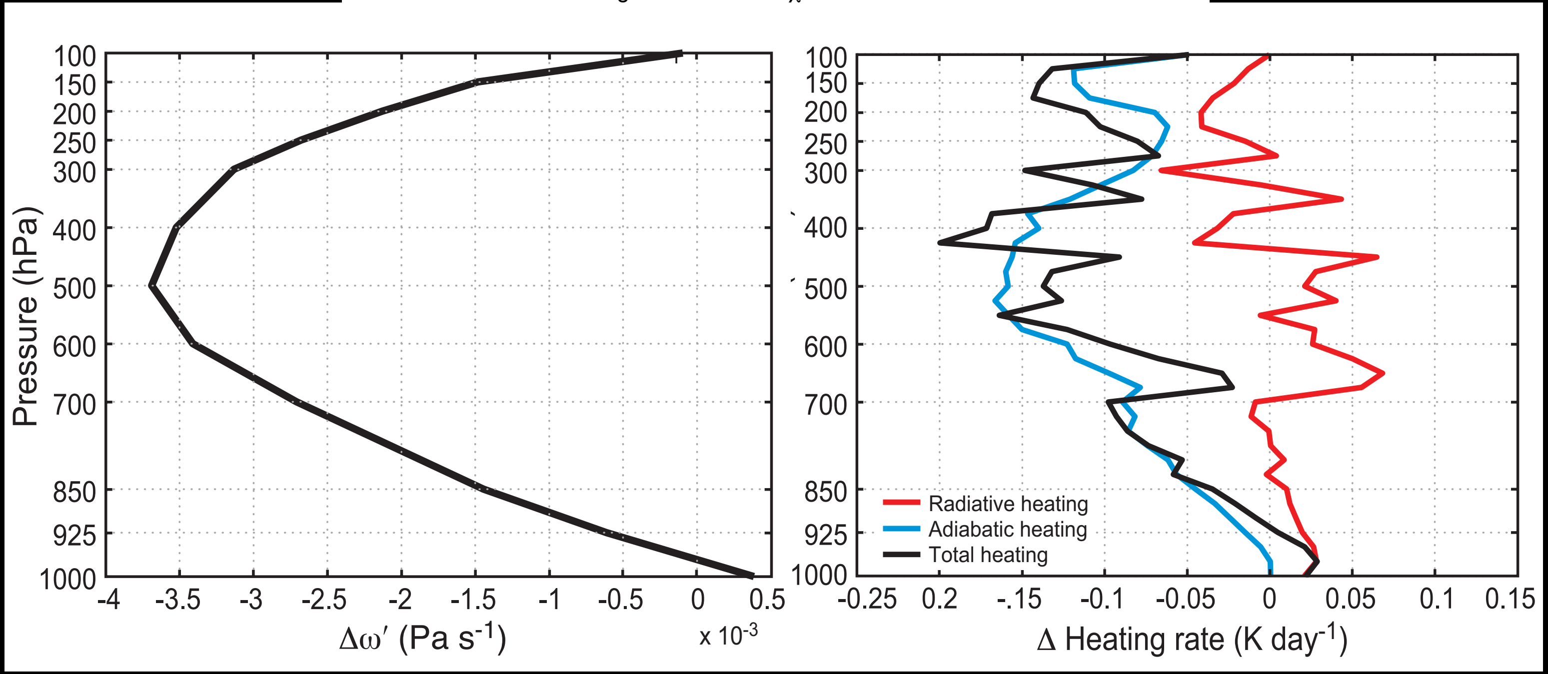


$$\frac{\partial T}{\partial t} - S\omega = Q, Q \approx -\mu S\omega, c = \sqrt{(1-\mu)gh_e}$$



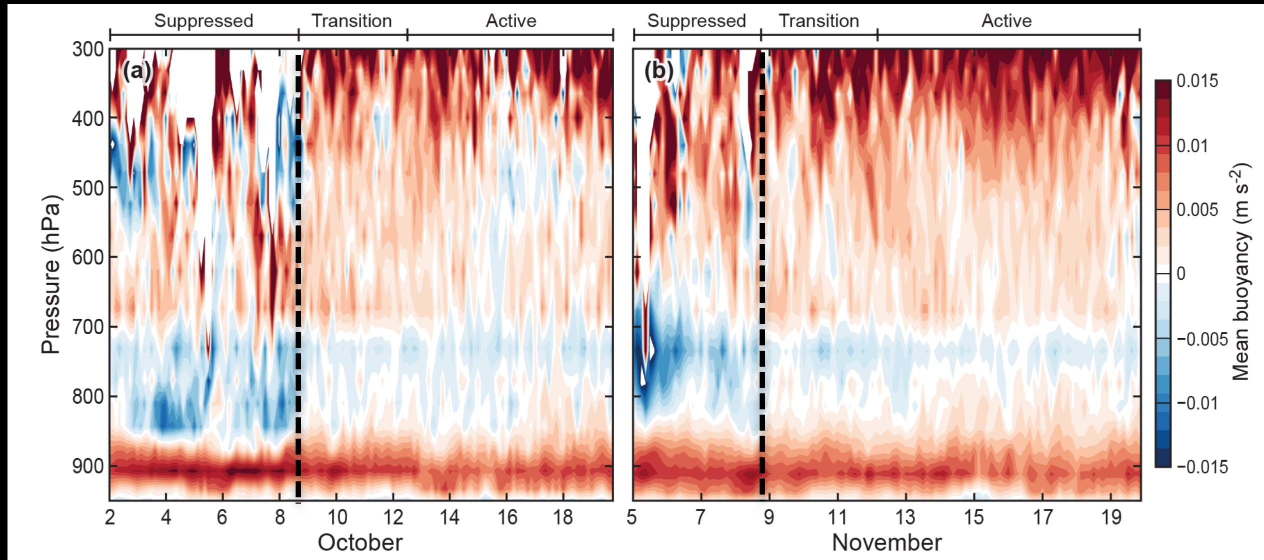


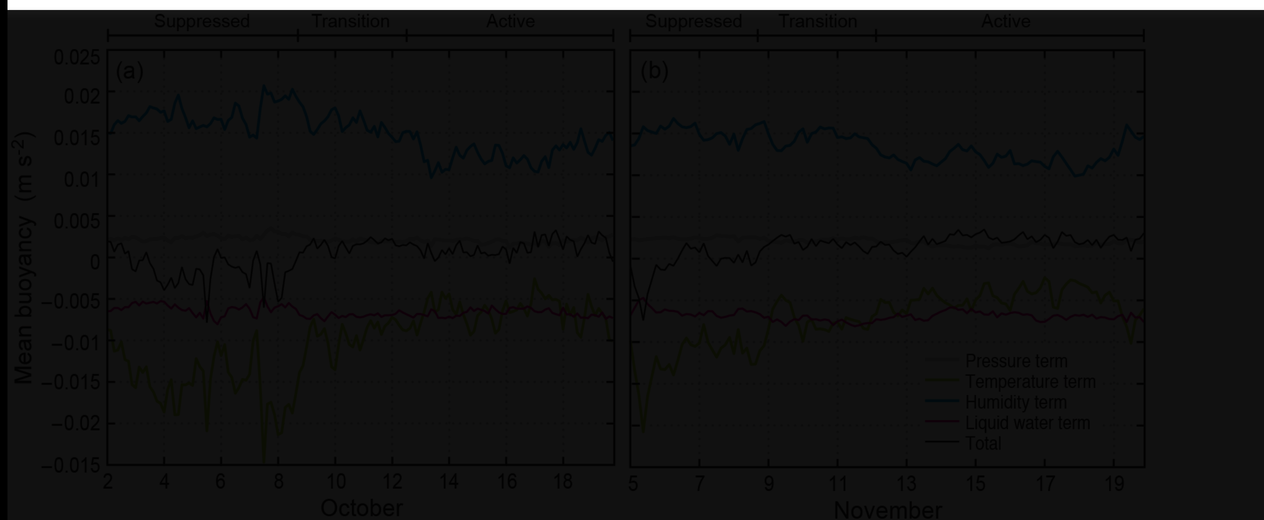
Pressure (hPa)
Longitude relative to χ minimum
ω anomaly (Pa s-1)
Trans.
Cg



Pressure (hPa)
Δω′ (Pa s-1)
x 10-3
Radiative heating
Adiabatic heating
Total heating
Δ Heating rate (K day-1)

Updraft buoyancy for convective echoes with $w \geq 0.3$ m s^{-1}

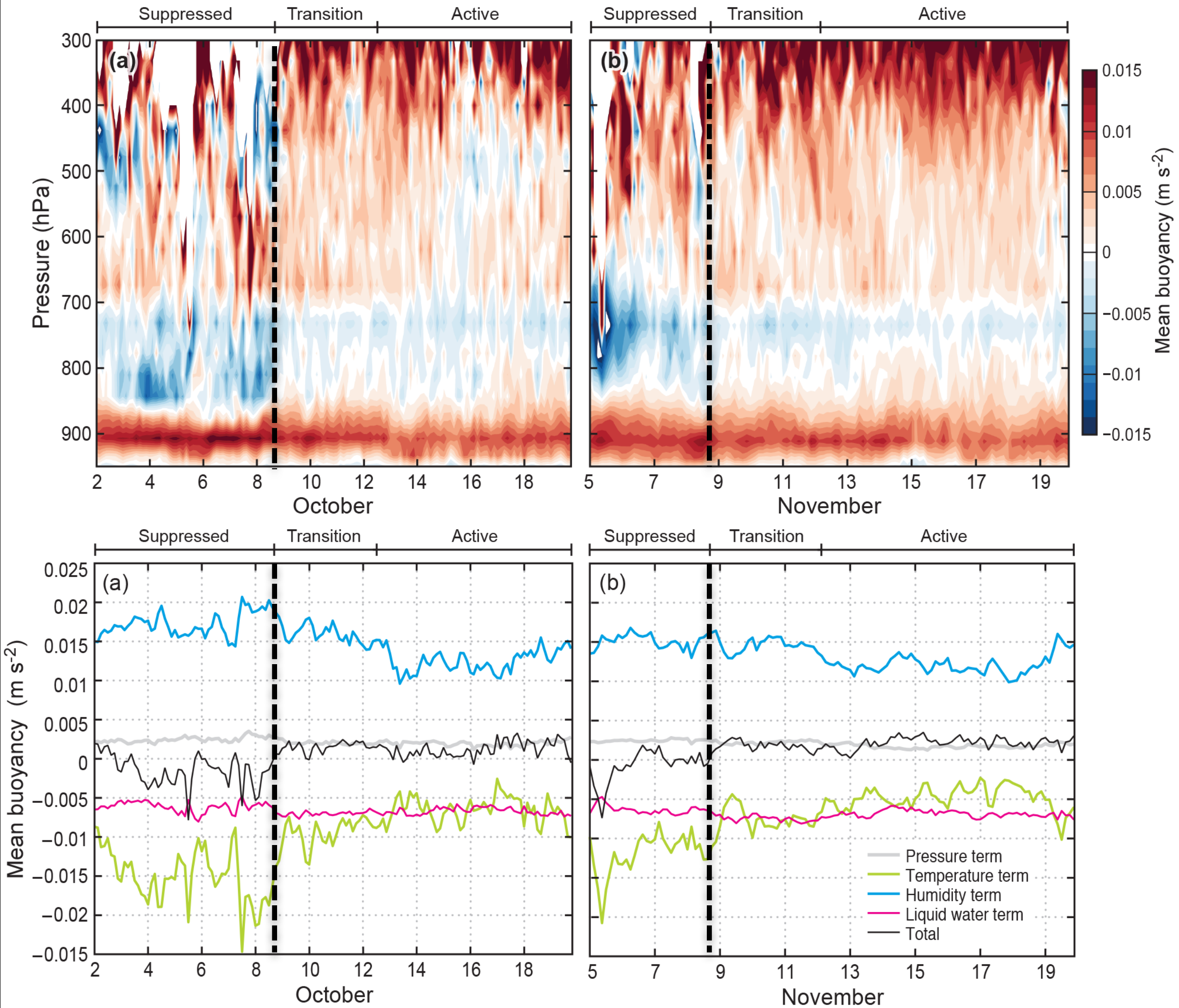




$$B \approx g\left(\underbrace{\frac{T^*}{T_e}}_{Temperature} - \overbrace{\frac{p^*}{p_e}}^{Pressure} + \underbrace{0.608\left(w^*\right)}_{Vapor} - \overbrace{w_H}^{Hydrometeor}\right)$$

Green Gray Blue Red

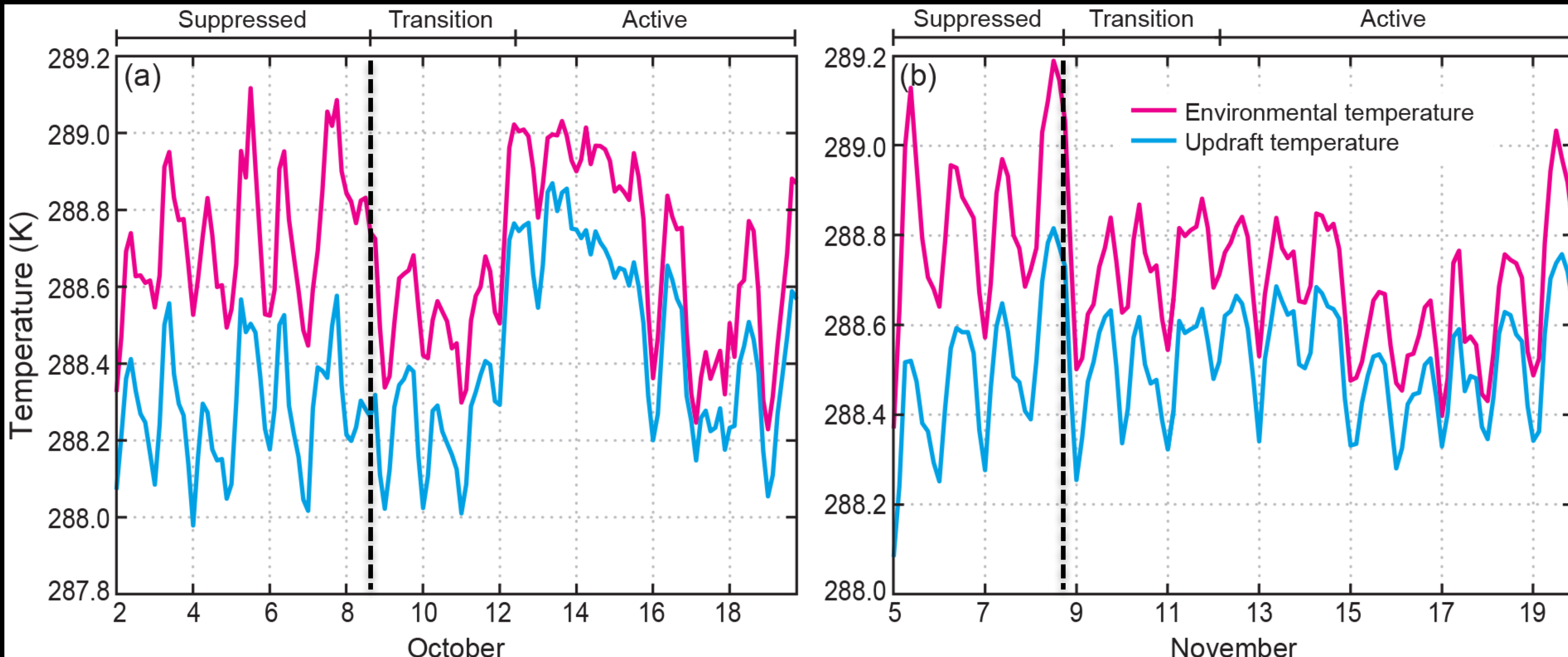
Individual terms in buoyancy equation: Mean in 700–850 mb layer



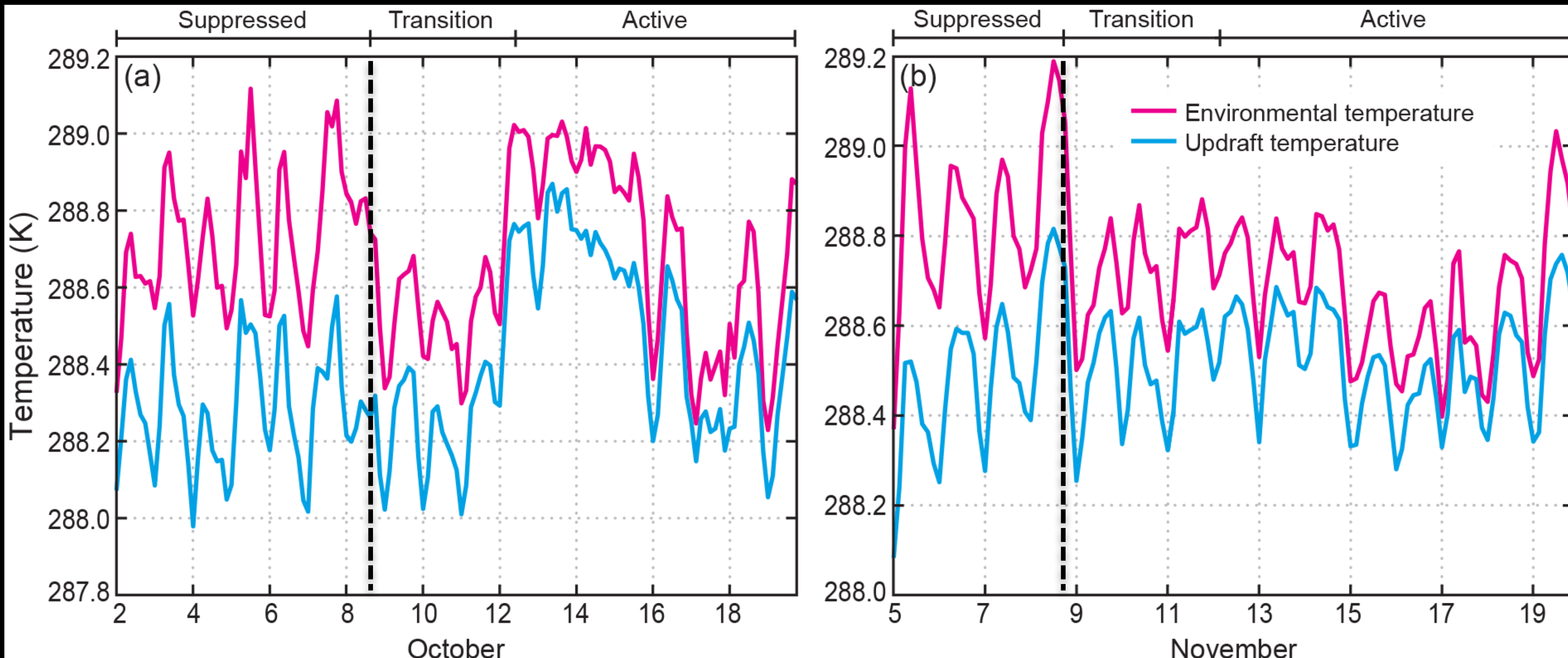
$$B \approx g\left(\underbrace{\frac{T^*}{T_e}}_{Temperature} - \overbrace{\frac{p^*}{p_e}}^{Pressure} + \underbrace{0.608\left(w^*\right)}_{Vapor} - \overbrace{w_H}^{Hydrometeor}\right)$$

Green Gray Blue Red

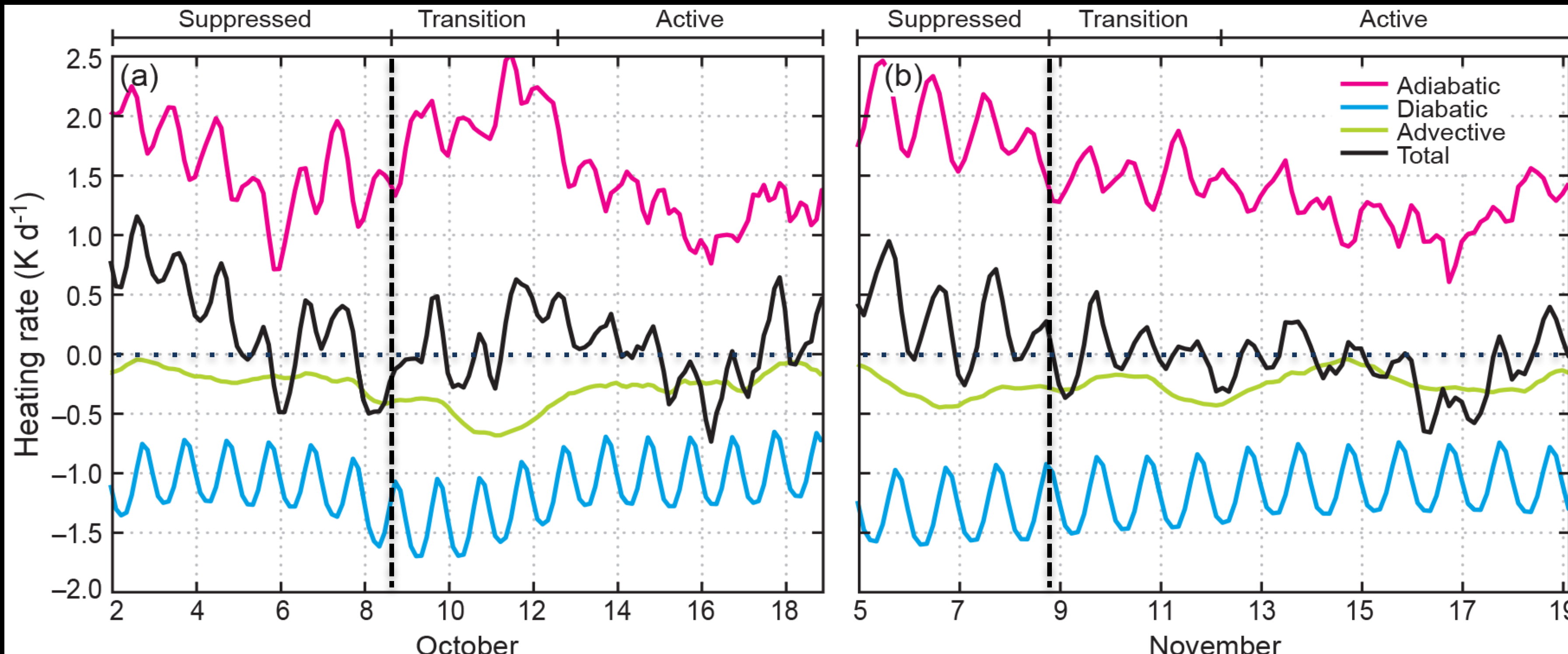
Mean 700–850 mb temperature



Mean 700–850 mb temperature

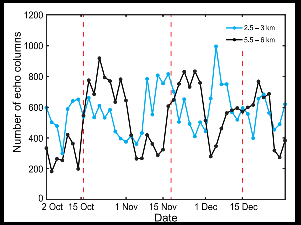


Changes in environmental temperature at start of transition periods are less than 1K!

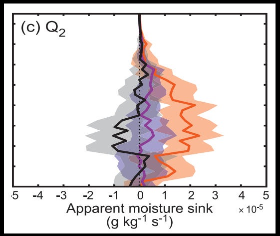


$$\frac{\partial T}{\partial t} = \underbrace{-\mathbf{u}_{\mathrm{h}} \cdot \nabla T}_{advective} \overbrace{- w\left(\frac{g}{c_p} + \Gamma\right)}^{adiabatic} + \underbrace{\frac{J}{c_p}}_{diabatic}$$

Conclusions

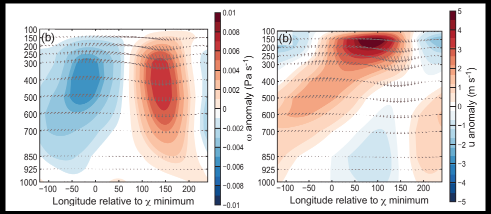


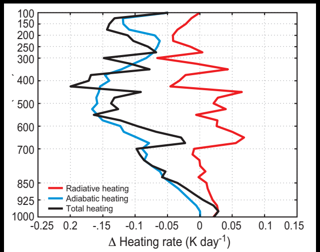
• 3–7 day build up in cloud population during transition periods prior to MJO convective onset.



• During transition periods, moderately deep clouds moisten environment via evaporation, making environment conducive to deeper convection.

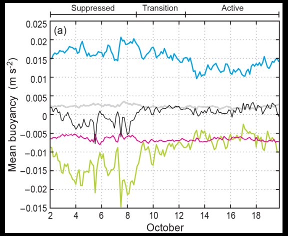
• Circumnavigating wave has impacts on low-wavenumber ω anomalies of O(0.01 Pa s^{-1}).





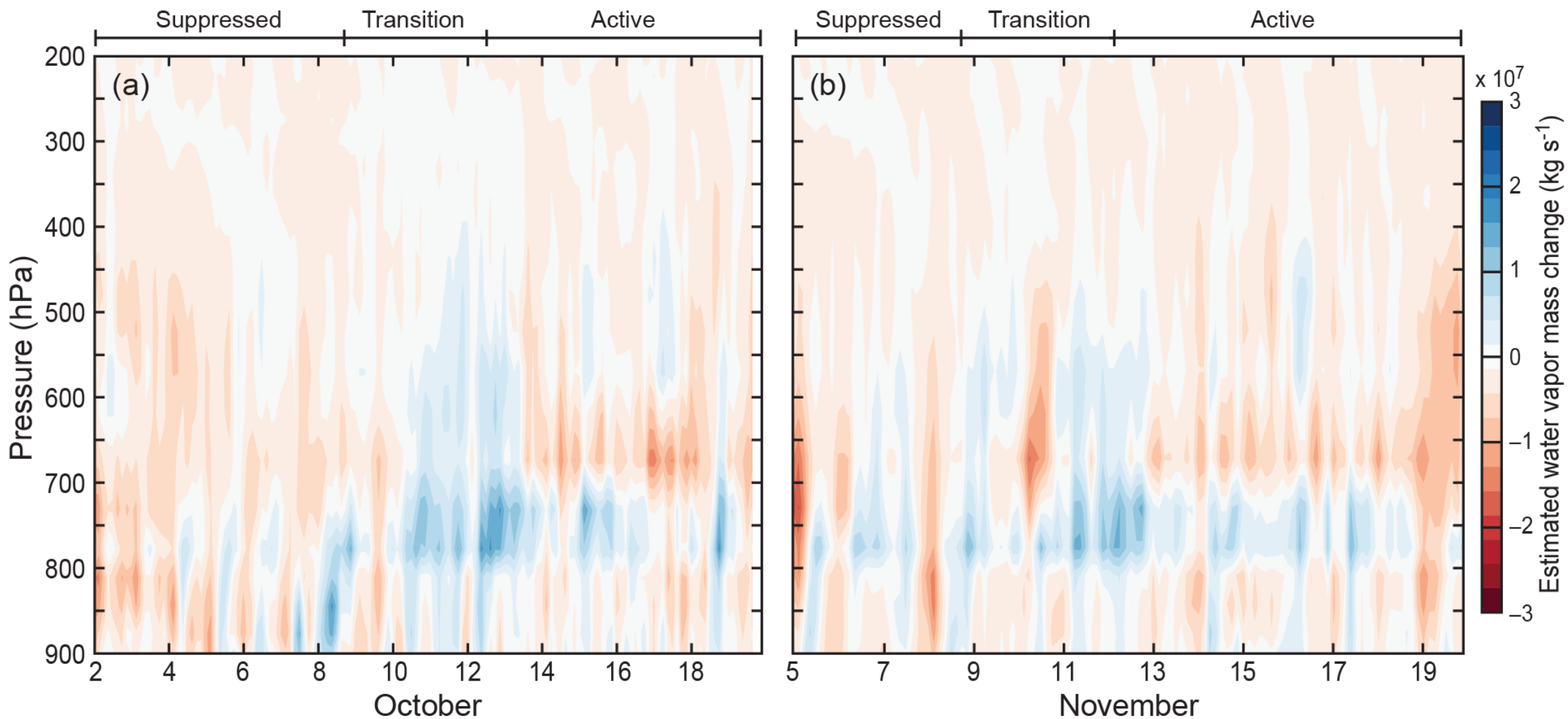
• Changes in vertical velocity cause small changes of O(0.1K) in tropospheric temperature below 500 hPa.

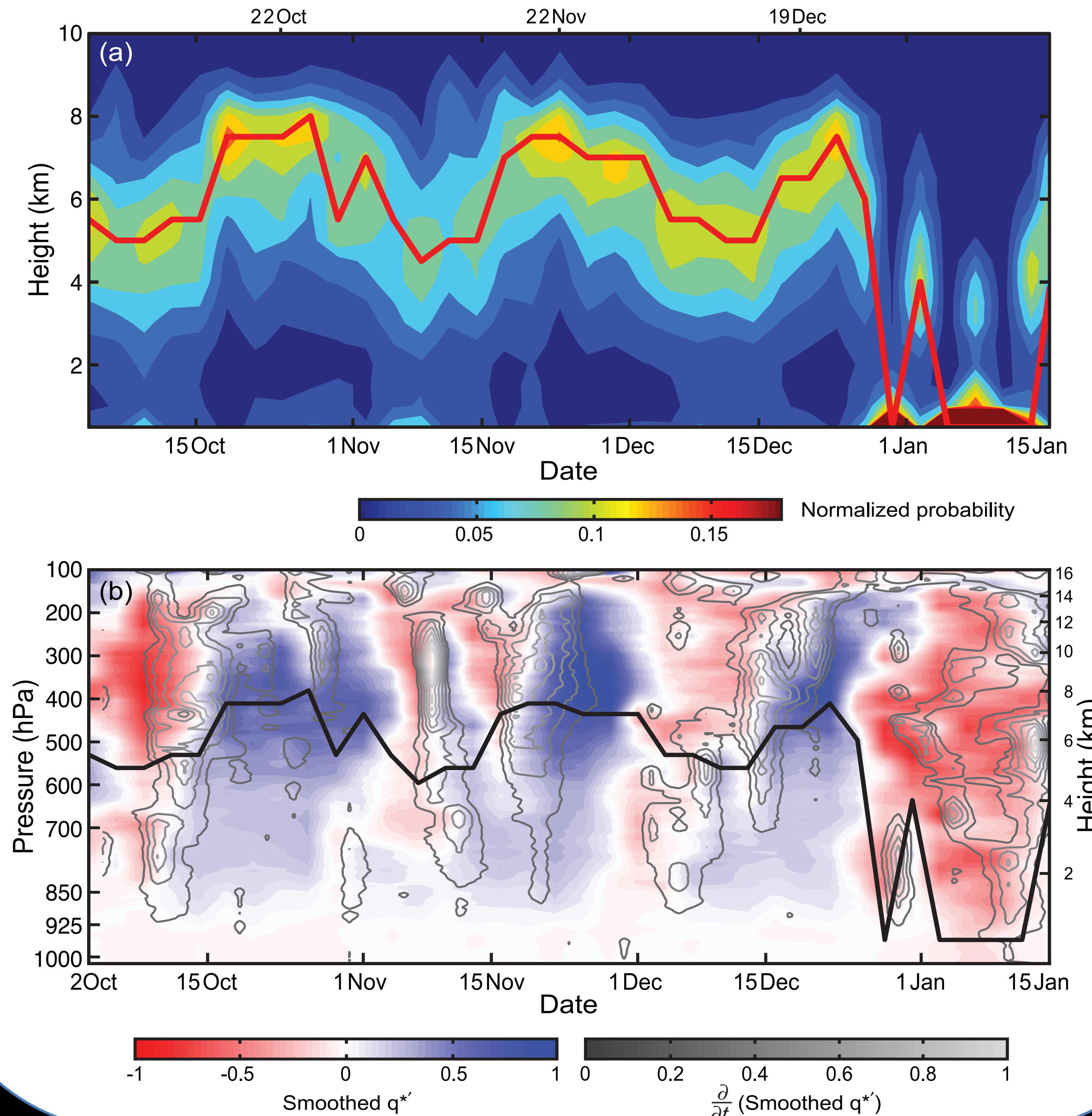
• Small changes in environmental temperature dramatically alter mean buoyancy of cloud updrafts in 700–850 hPa layer.



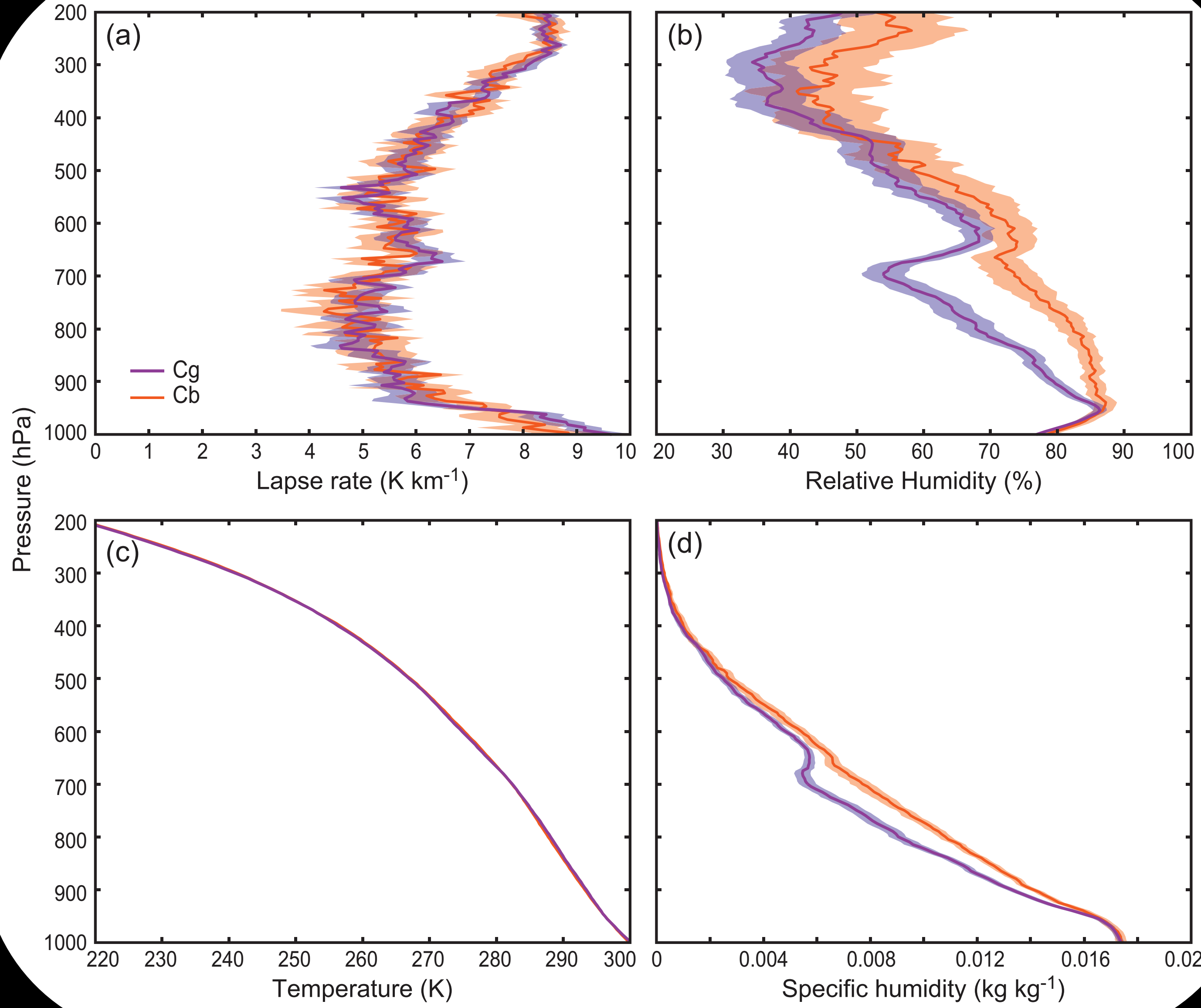

End

Extra Slides

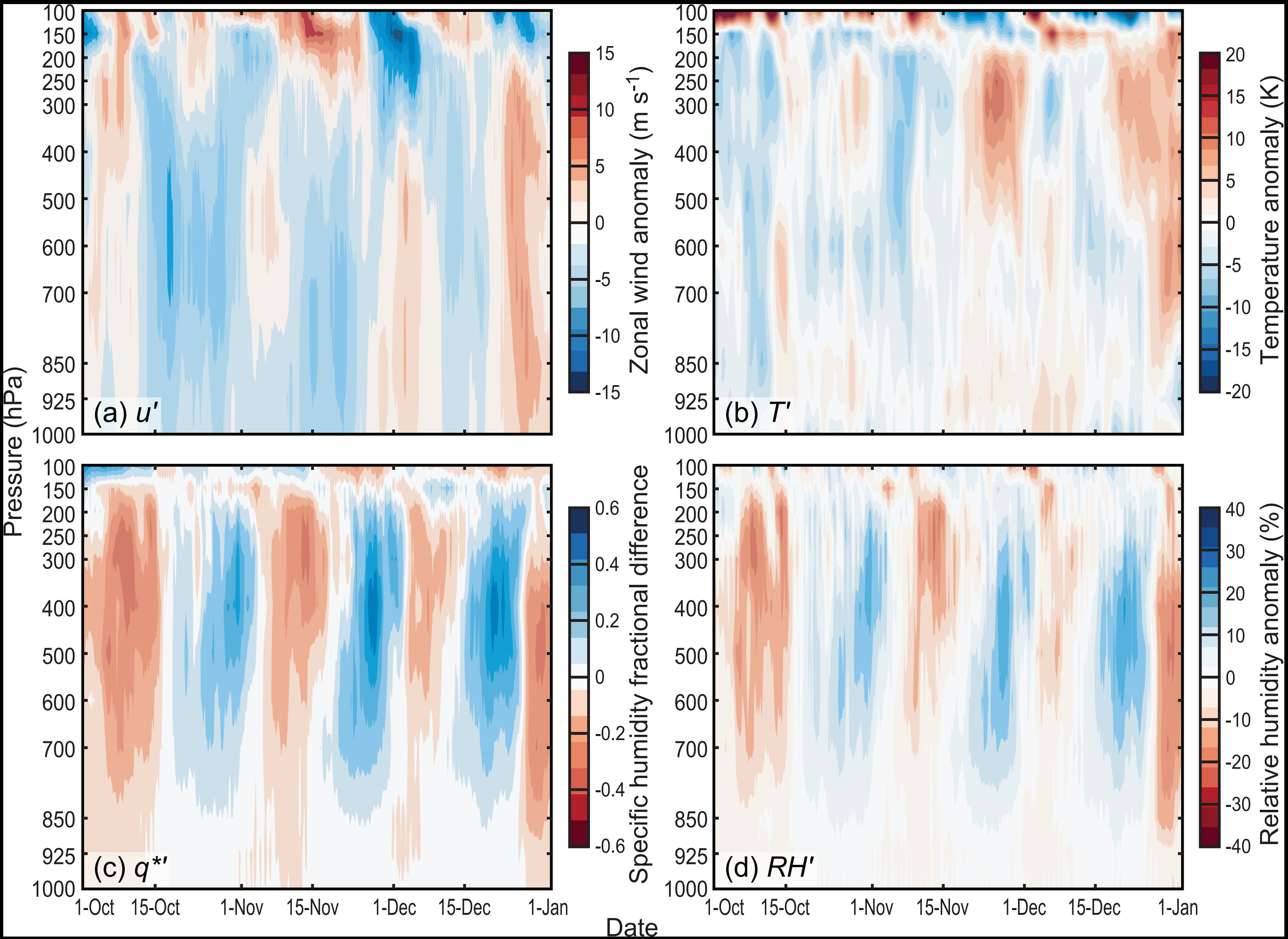

Suppressed
Transition
Active
(a)
Pressure (hPa)
200
300
400
500
600
700
800
900
2
4
6
8
10
12
14
16
18
October
Suppressed
Transition
Active
(b)
5
7
9
11
13
15
17
19
November
x 10^7
3
2
1
0
−1
−2
−3
Estimated water vapor mass change (kg s^-1)

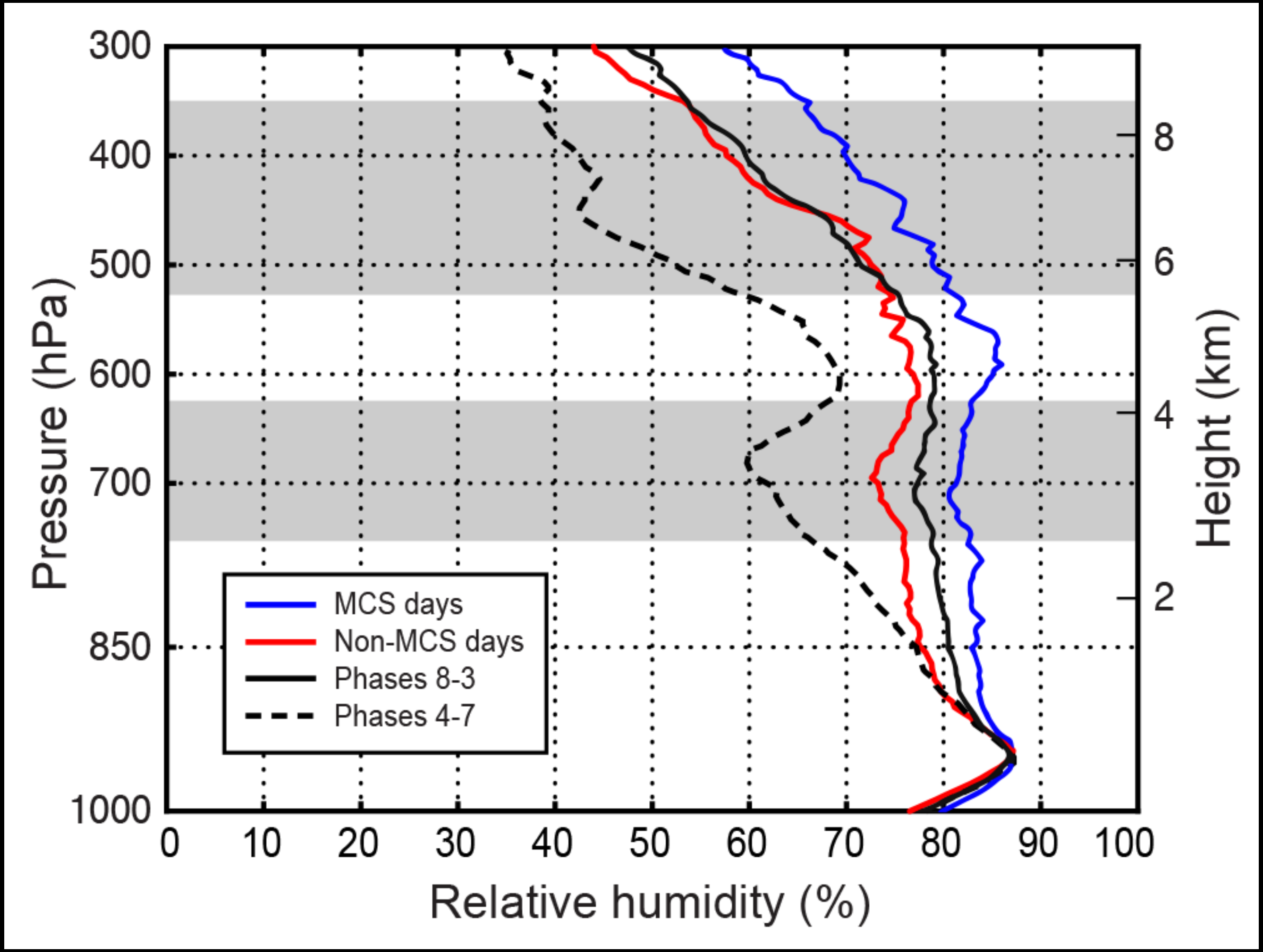


22 Oct
22 Nov
19 Dec
(a)
Height (km)
15 Oct
1 Nov
15 Nov
1 Dec
15 Dec
1 Jan
15 Jan
Date
Normalized probability
(b)
Pressure (hPa)
Height (km)
2 Oct
Smoothed q*′
$\frac{\partial}{\partial t}$ (Smoothed q*′)


(a)
(b)
(c)
(d)
Cg
Cb
Pressure (hPa)
200
300
400
500
600
700
800
900
1000
0
1
2
3
4
5
6
7
8
9
10
Lapse rate (K km-1)
20
30
40
50
60
70
80
90
100
Relative Humidity (%)
220
230
240
250
260
270
280
290
300
Temperature (K)
0
0.004
0.008
0.012
0.016
0.02
Specific humidity (kg kg-1)

ERA-Interim


(a) u′
(b) T′
(c) q*′
(d) RH′
Pressure (hPa)
Date
Zonal wind anomaly (m s-1)
Temperature anomaly (K)
Specific humidity fractional difference
Relative humidity anomaly (%)
1-Oct
15-Oct
1-Nov
15-Nov
1-Dec
15-Dec
1-Jan



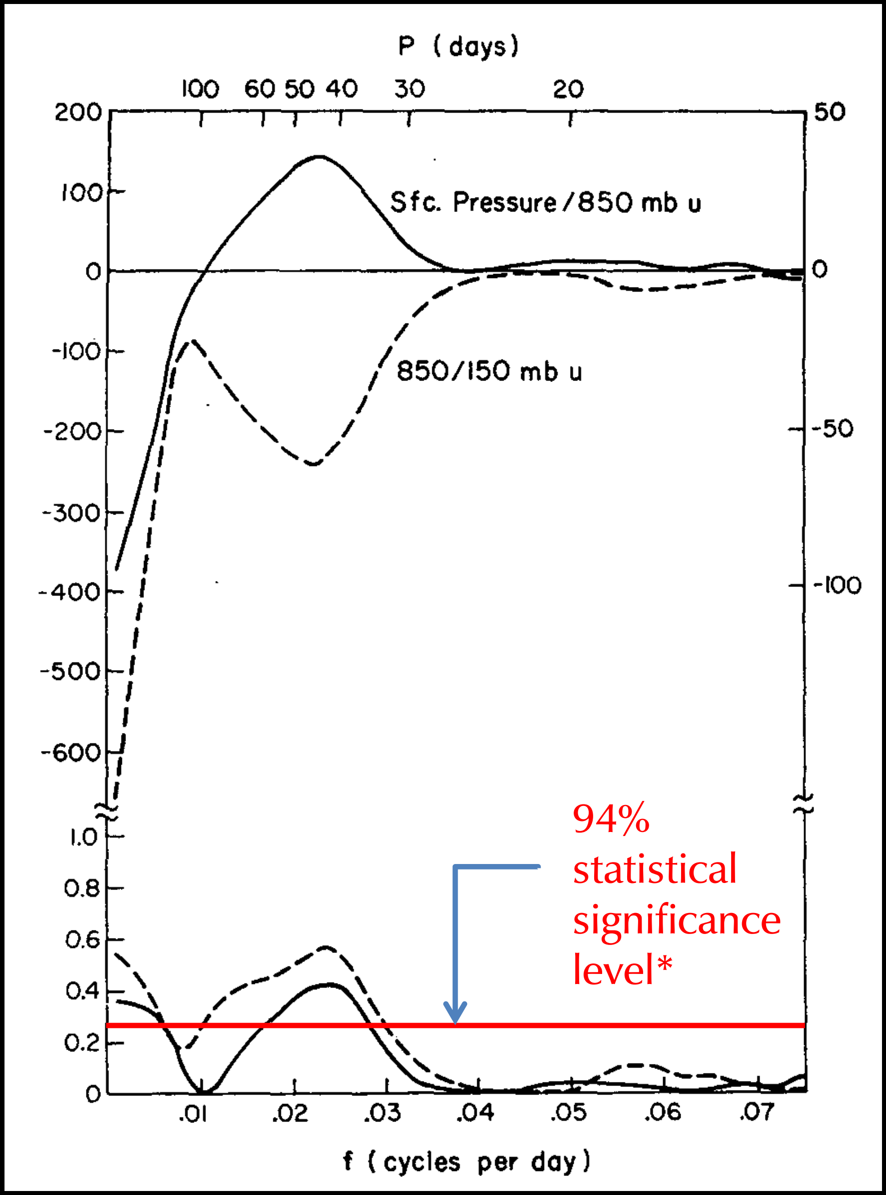
300
400
500
600
700
850
1000
Pressure (hPa)
8
6
4
2
Height (km)
0
10
20
30
40
50
60
70
80
90
100
Relative humidity (%)
MCS days
Non-MCS days
Phases 8-3
Phases 4-7

Timescale of MJO Convective Build-up

What duration is the transition from suppressed to widespread, deep convection?

WRF (V3.5.1) Specifications

- 1–20 October and 4–20 November
- ERA-I forcing with NOAA RTG High-Res SST
- 2km grid spacing, 38 vertical levels
- Microphysics: Thompson
- Radiation: RRTMG
- PBL: MYJ
- Monin-Obukhov surface layer physics
- Noah LSM



**A posteriori*. 99.9% if expected *a priori*.

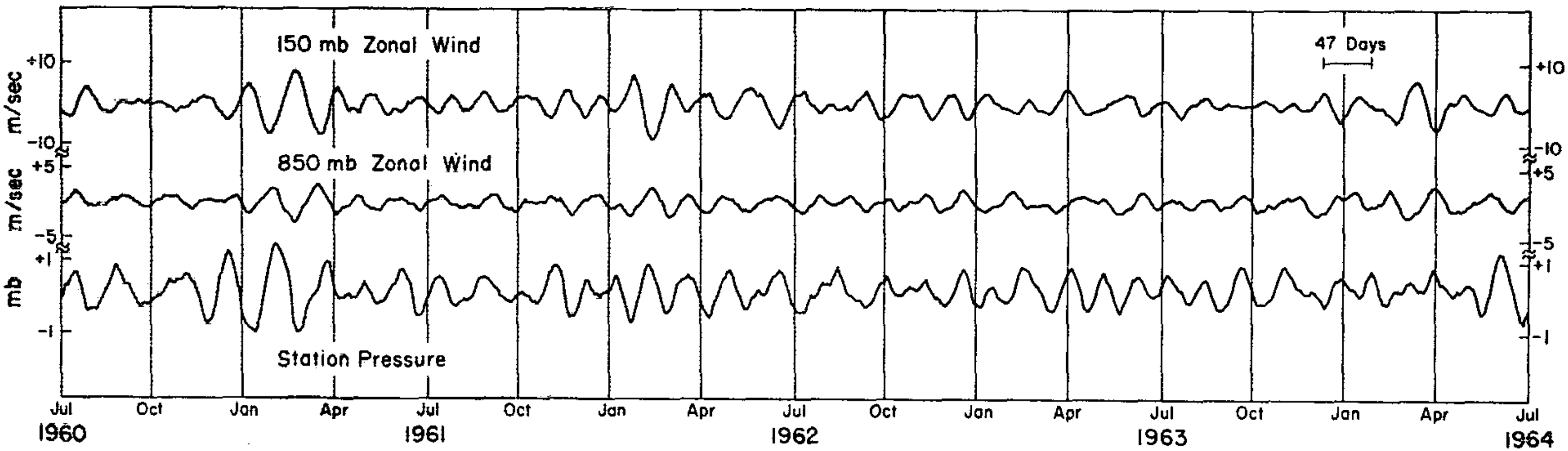
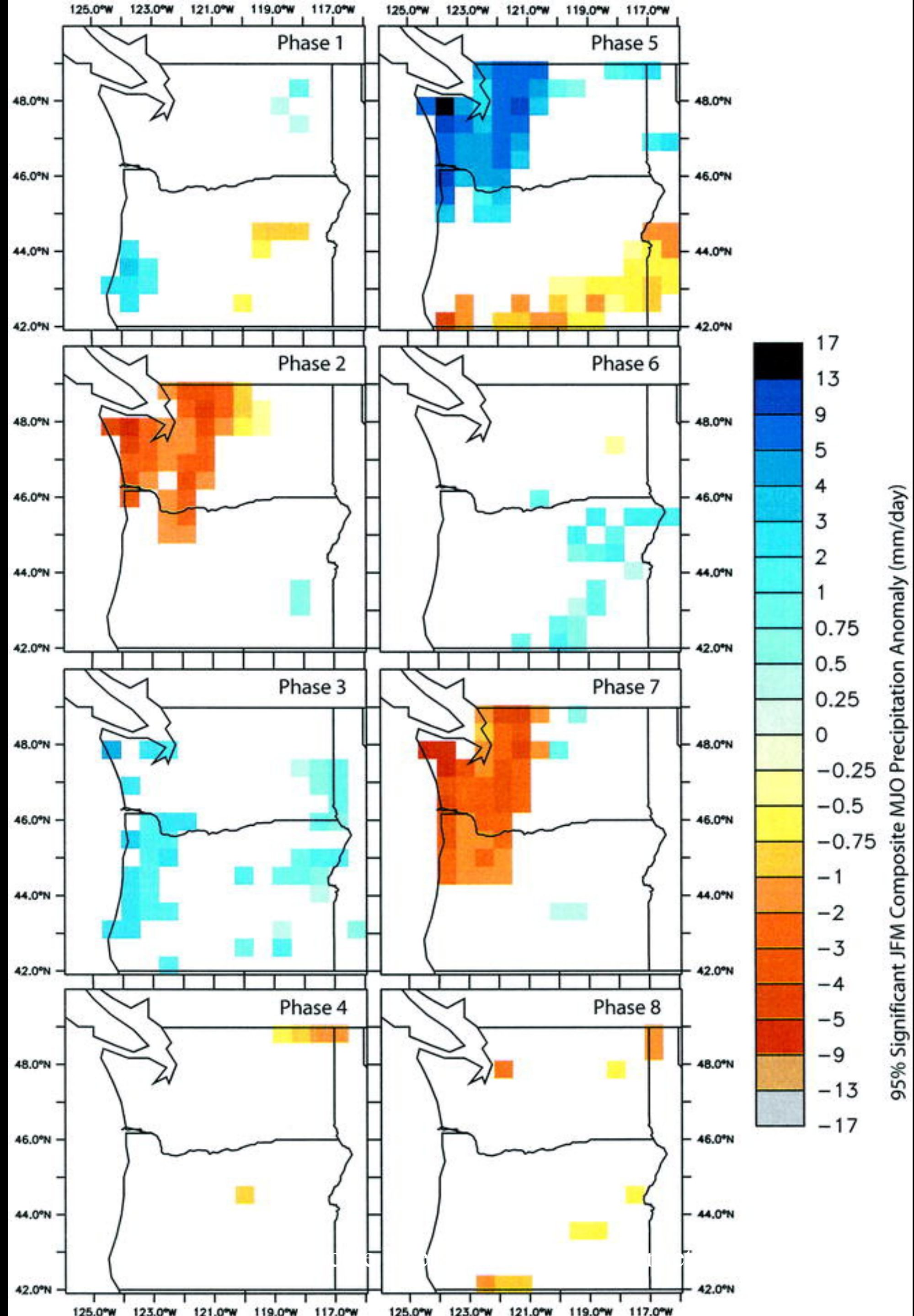
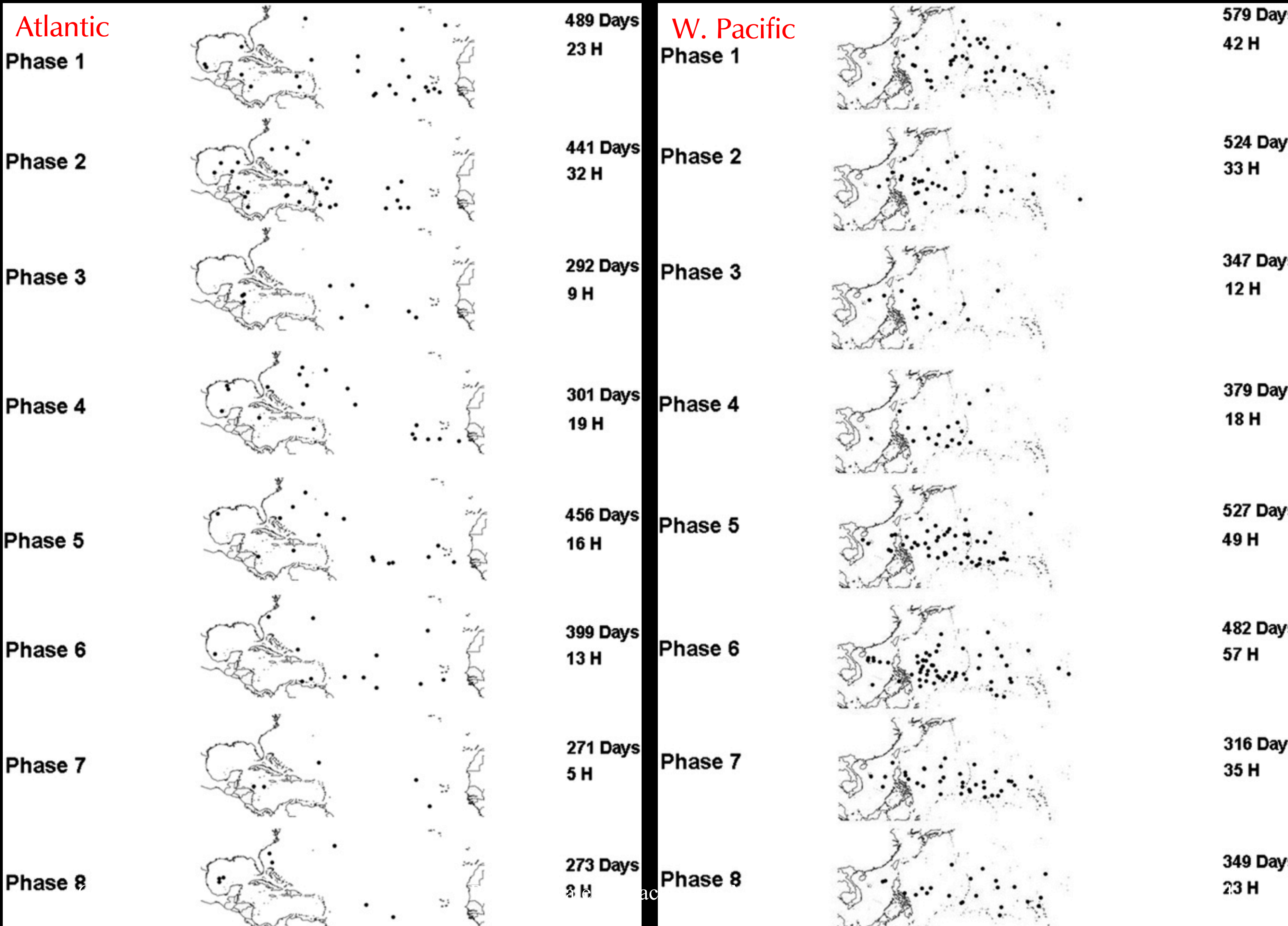


FIG. 5. The 150- and 850-mb u component and station pressure records for Canton Island from July 1960 through June 1964 treated with a 47-day band-pass filter.

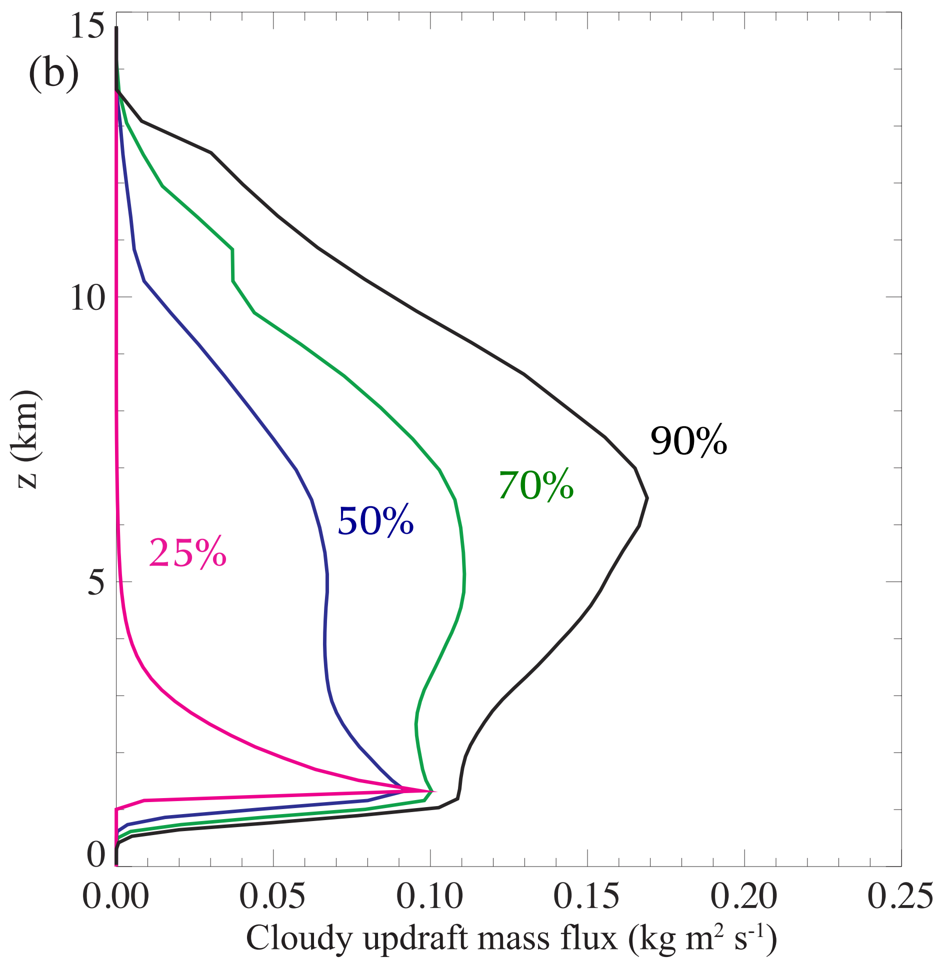
Bond and Vecchi
(2003)



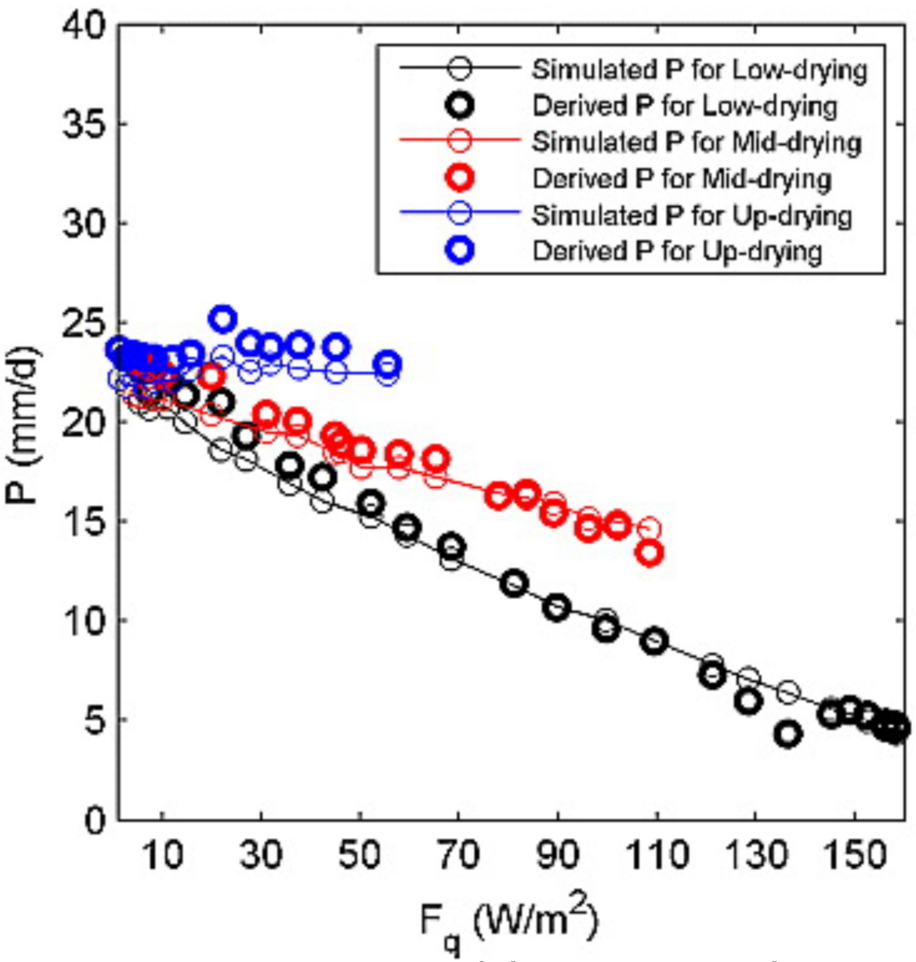
Klotzbach (2014)



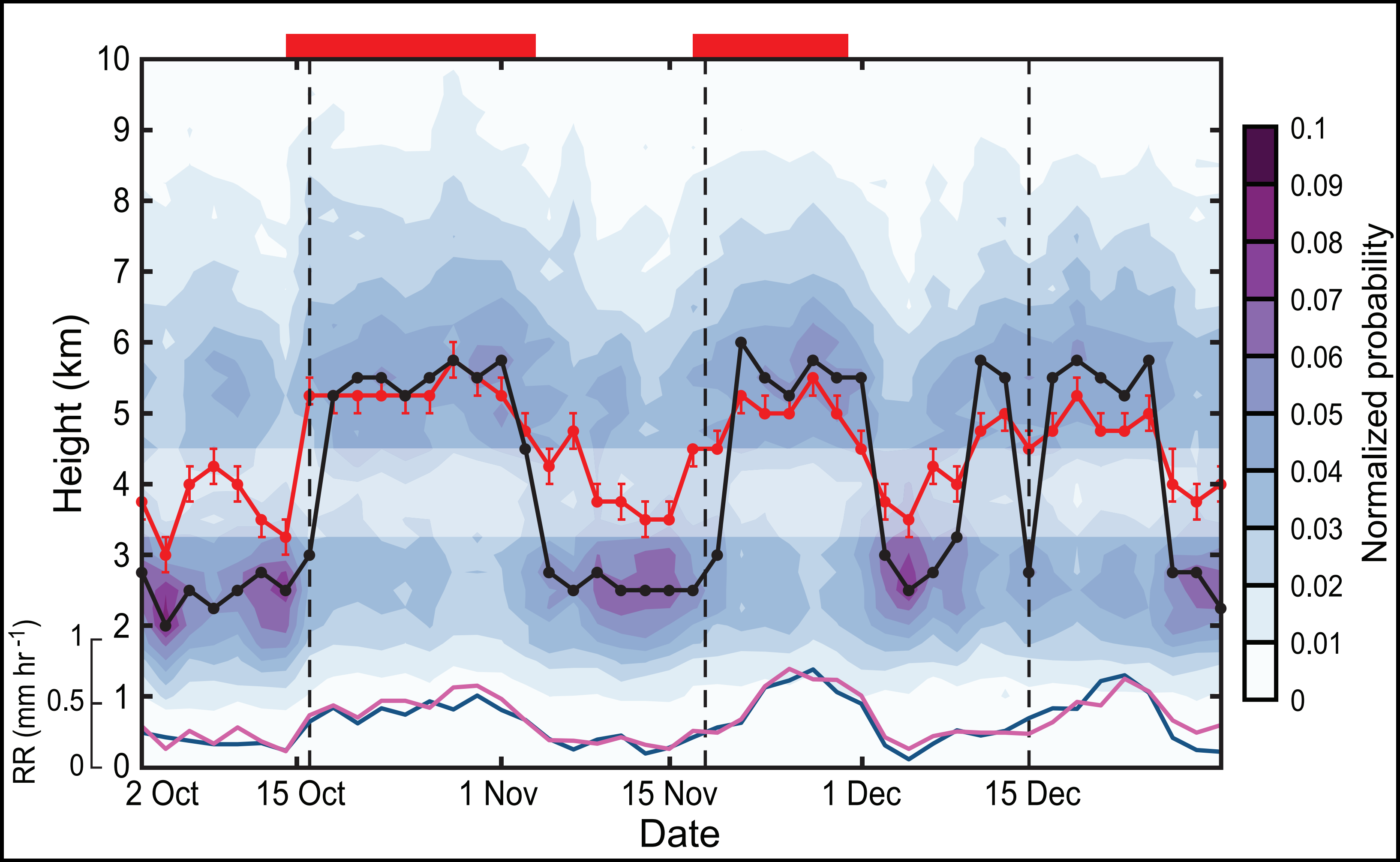
Derbyshire et al. (2004)



Wang and Sobel (2012)



(F_q α Inverse of drying time scale)



TRMM 20dBZ echo tops: 9N–9S; 60–100E

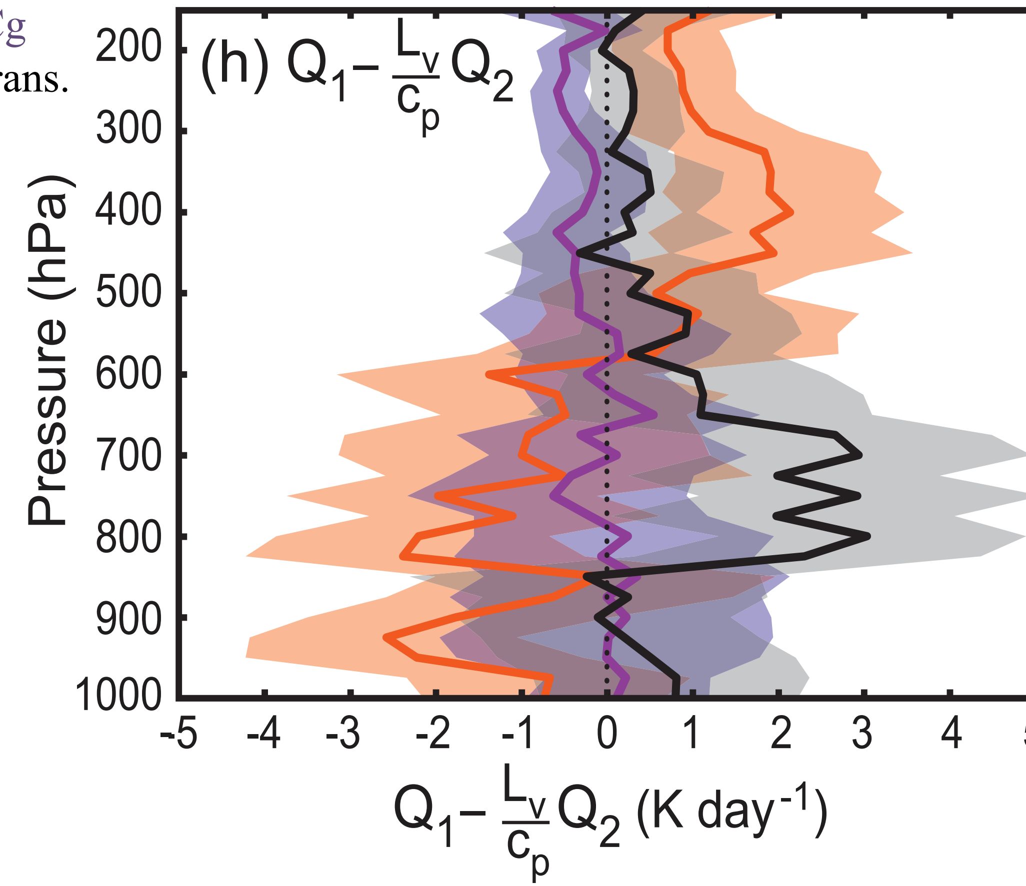
$$\frac{\partial q}{\partial t} = \mathbf{v}_h \cdot \nabla q + \omega \frac{\partial q}{\partial p} + Q_2$$

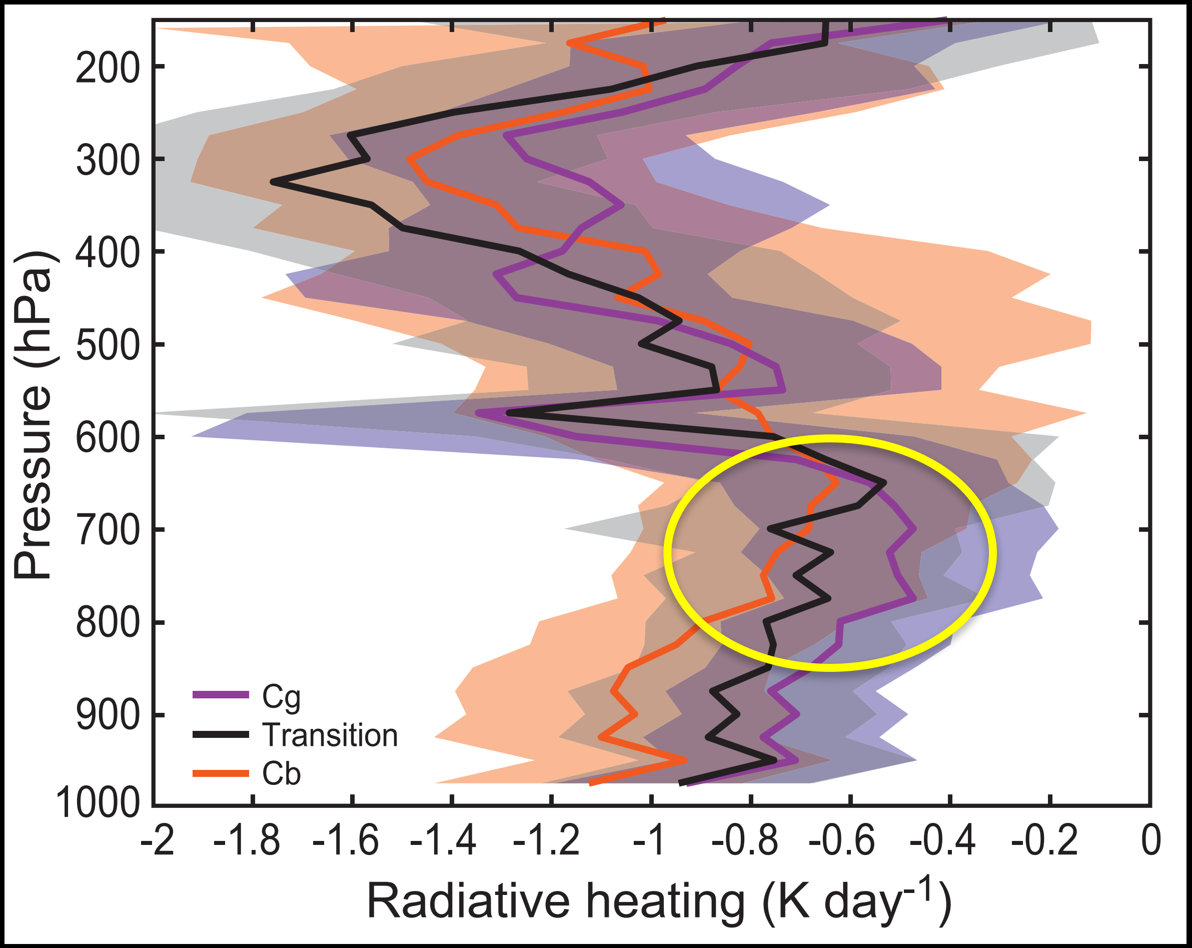
$$Q_2 = \left(\bar{c} - \bar{e}\right) + \frac{\partial}{\partial p}\left(\overline{\omega' q'}\right)$$

$$Q_1 = Q_R + \frac{1}{c_p}\left[L_v\left(\bar{c} - \bar{e}\right) + \frac{\partial}{\partial p}\left(\overline{\omega' s'}\right)\right]$$

$$Q_1 - \frac{L_v}{c_p} Q_2 = Q_R - \frac{1}{c_p}\frac{\partial}{\partial p}\left(\overline{\omega' h'}\right)$$

Purple = Cg
Black = Trans.
Red = Cb




200
300
400
500
600
700
800
900
1000
Pressure (hPa)
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Radiative heating (K day-1)
Cg
Transition
Cb

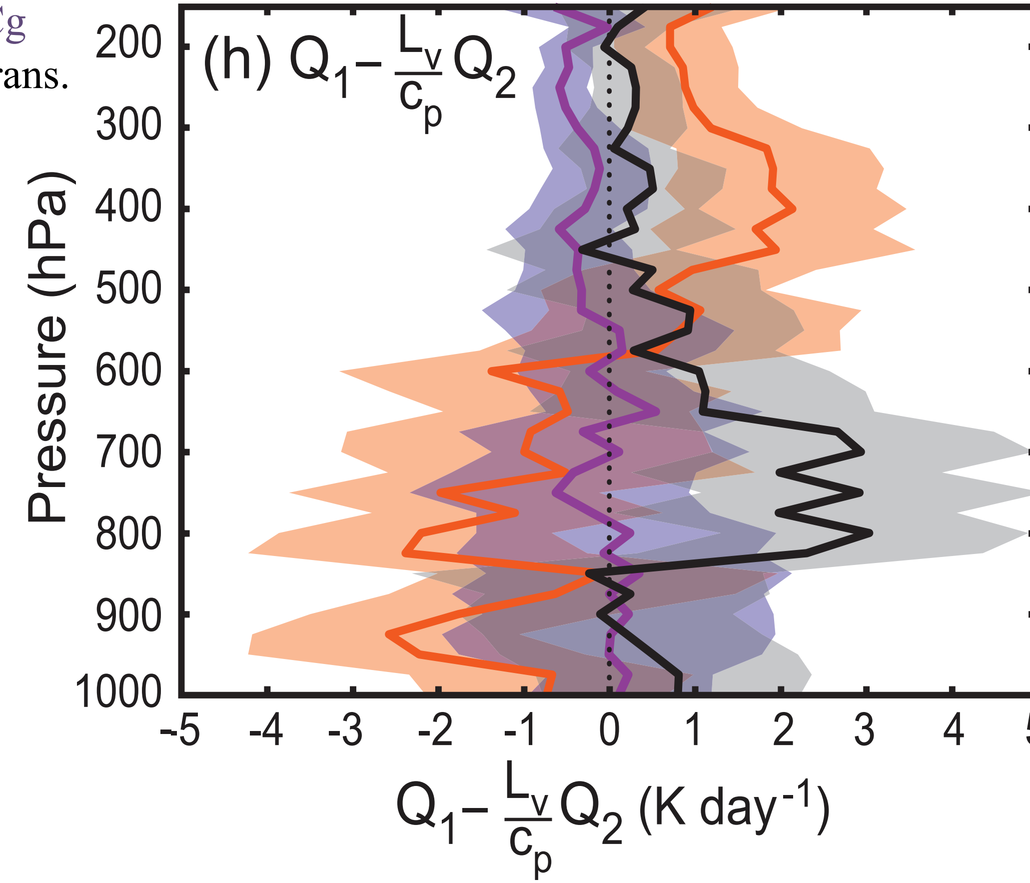
$$\frac{\partial q}{\partial t} = \mathbf{v}_h \cdot \nabla q + \omega \frac{\partial q}{\partial p} + Q_2$$

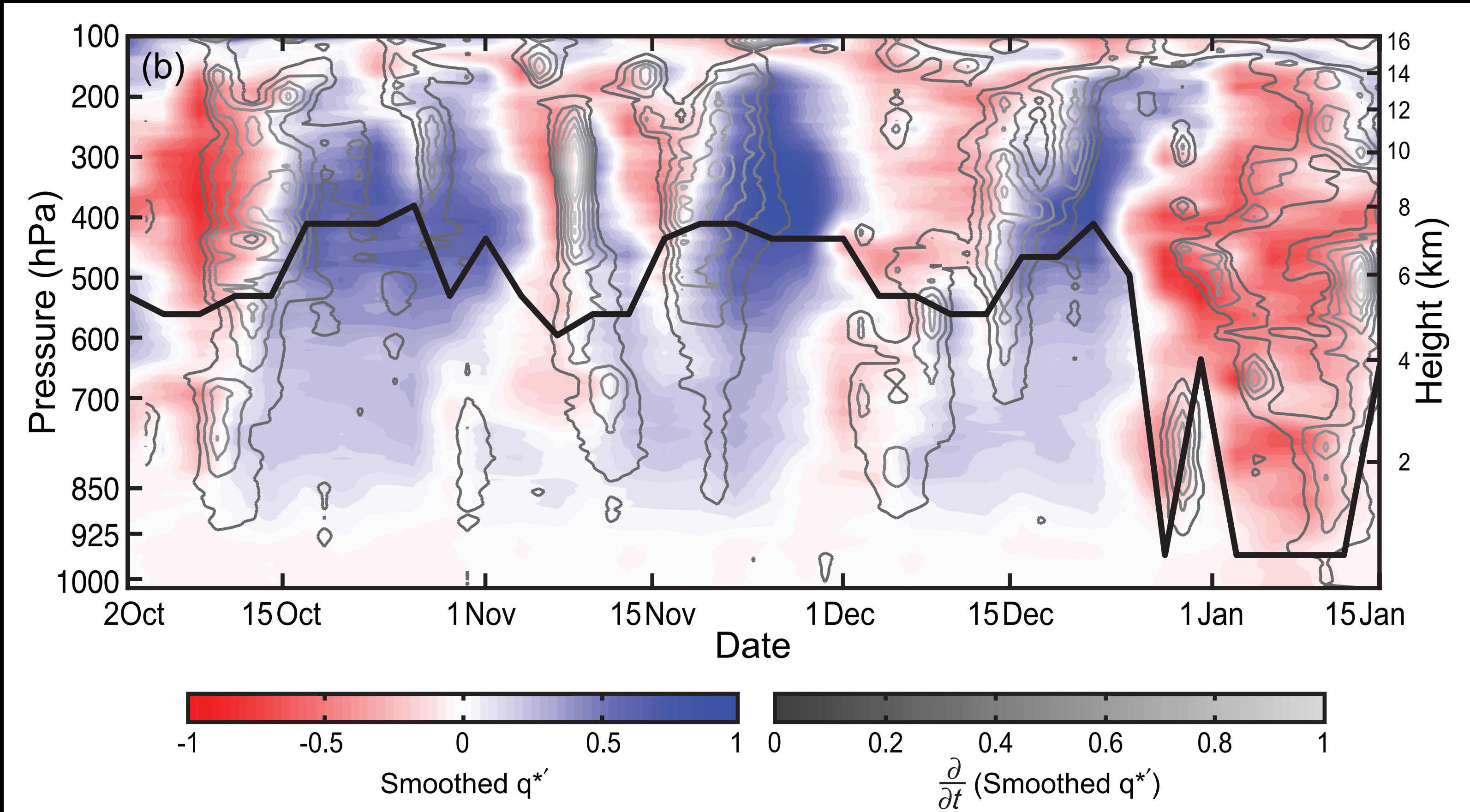
$$Q_2 = \left(\bar{c} - \bar{e}\right) + \frac{\partial}{\partial p}\left(\overline{\omega' q'}\right)$$

$$Q_1 = Q_R + \frac{1}{c_p}\left[L_v\left(\bar{c} - \bar{e}\right) + \frac{\partial}{\partial p}\left(\overline{\omega' s'}\right)\right]$$

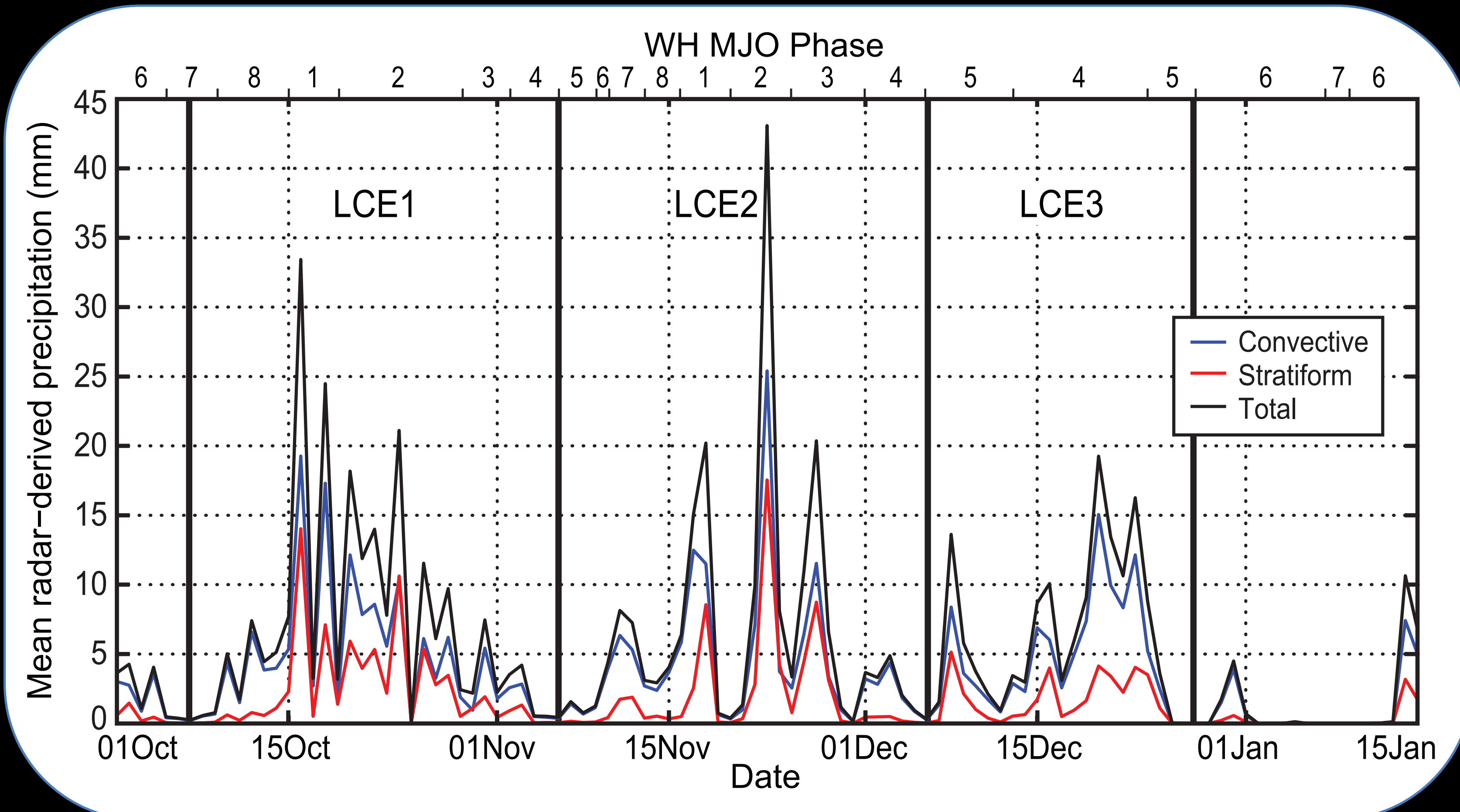
$$Q_1 - \frac{L_v}{c_p} Q_2 = Q_R - \frac{1}{c_p}\frac{\partial}{\partial p}\left(\overline{\omega' h'}\right)$$

Purple = Cg
Black = Trans.
Red = Cb





(b)
Pressure (hPa)
100
200
300
400
500
600
700
850
925
1000
Height (km)
16
14
12
10
8
6
4
2
2Oct
15 Oct
1 Nov
15 Nov
1 Dec
15 Dec
1 Jan
15 Jan
Date
-1
-0.5
0
0.5
1
Smoothed q*′
0
0.2
0.4
0.6
0.8
1
∂/∂t (Smoothed q*′)


WH MJO Phase
6
7
8
1
2
3
4
5
6
7
8
1
2
3
4
5
4
5
6
7
6
LCE1
LCE2
LCE3
Convective
Stratiform
Total
Mean radar−derived precipitation (mm)
45
40
35
30
25
20
15
10
5
0
01Oct
15Oct
01Nov
15Nov
01Dec
15Dec
01Jan
15Jan
Date