20 June 2019

紐約州立大學奧爾巴尼分校

非傳統科氏項
在熱帶大尺度環流中的重要性

博士生: 王珩 (Hing Ong)

口試委員: Paul Roundy, Brian Rose, Robert Fovell, and William Skamarock

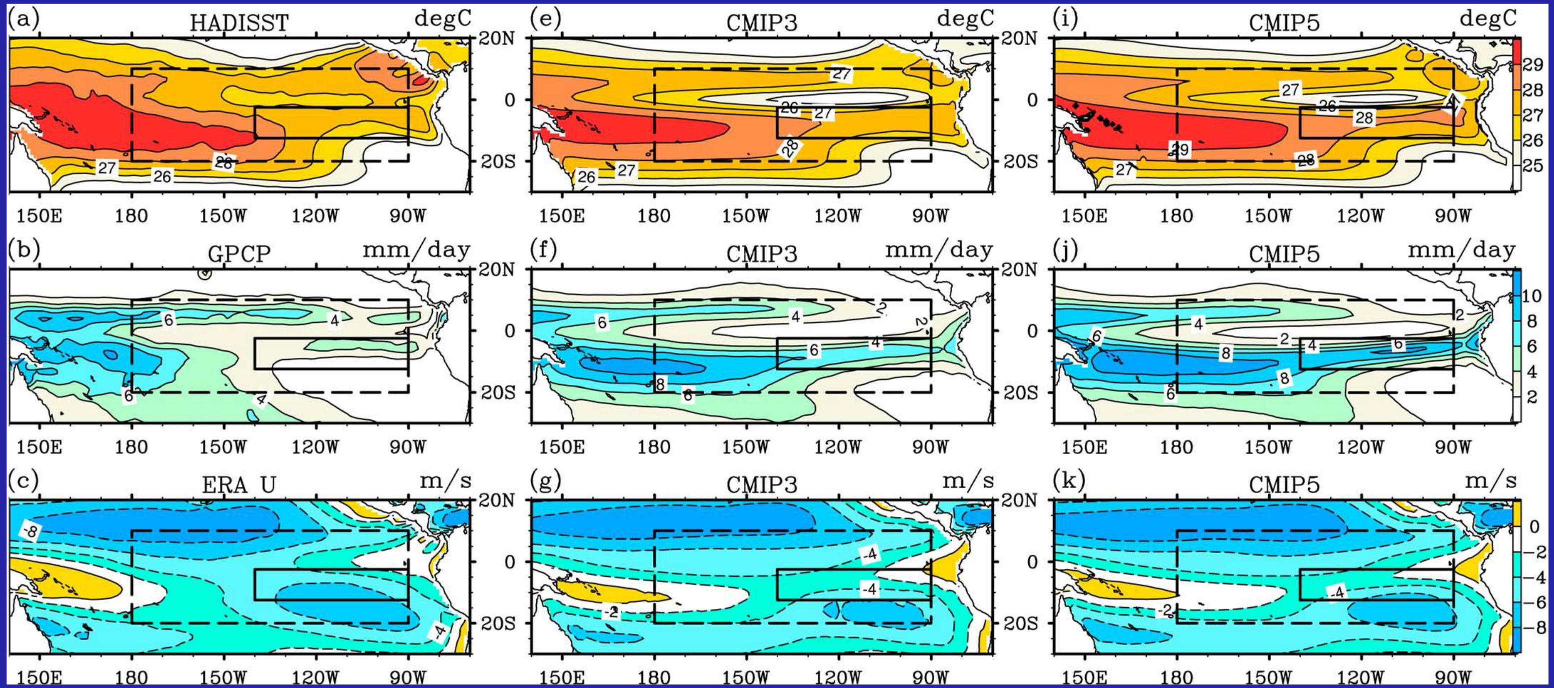
大綱

- 動機之一
- 初步研究非傳統科氏項(NCTs)
    - Prelim. A: 位渦充放理論 (JAS, in revision)
    - Prelim. B: NCTs對受ITCZ強迫之環流之影響 (QJRMS, accepted)
    - Prelim. C: NCTs對自由之赤道波動之影響 (QJRMS, in review)
- 總結與討論

雙重ITCZ偏差
(X. Zhang et al., 2015)

觀測　　CMIP3　　CMIP5

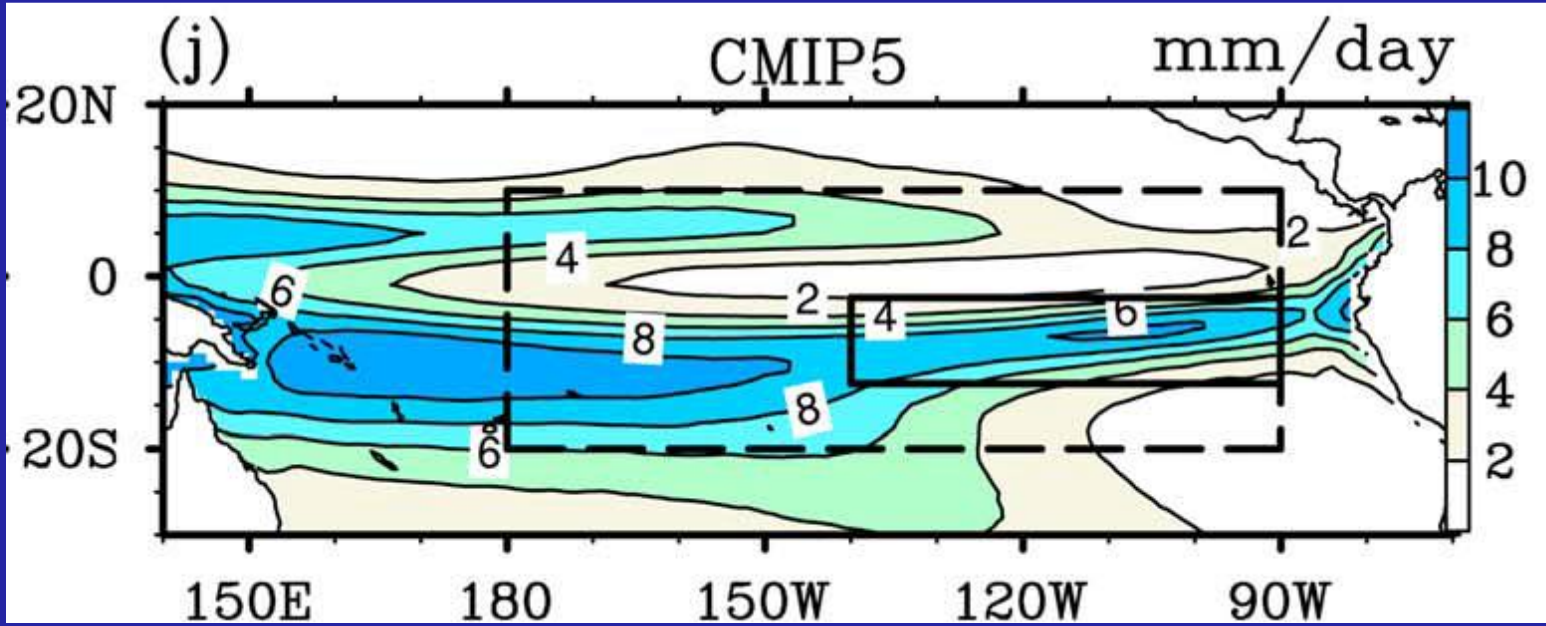
海表溫
降水
東西風



雙重ITCZ偏差
(X. Zhang et al., 2015)

CMIP5

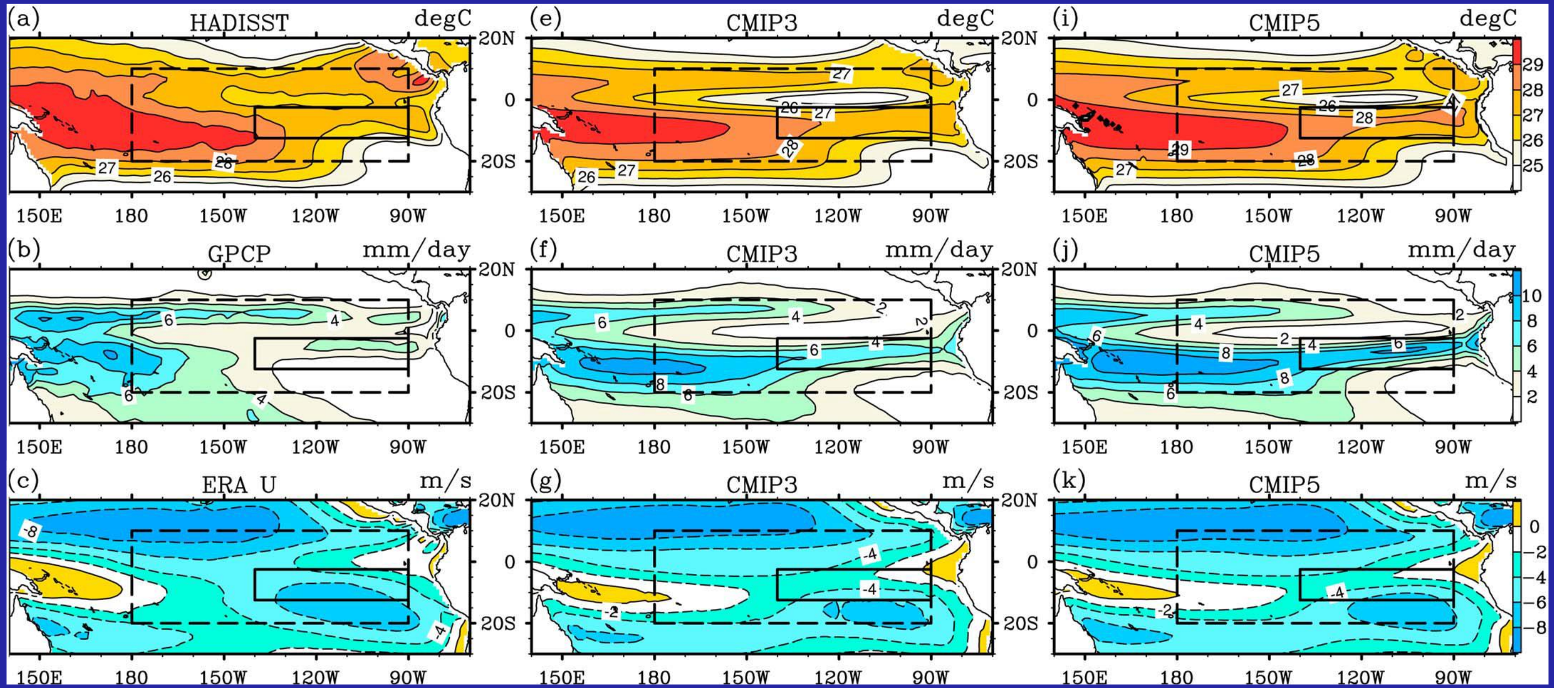
降水



雙重ITCZ偏差
(X. Zhang et al., 2015)

觀測　CMIP3　CMIP5

東西風

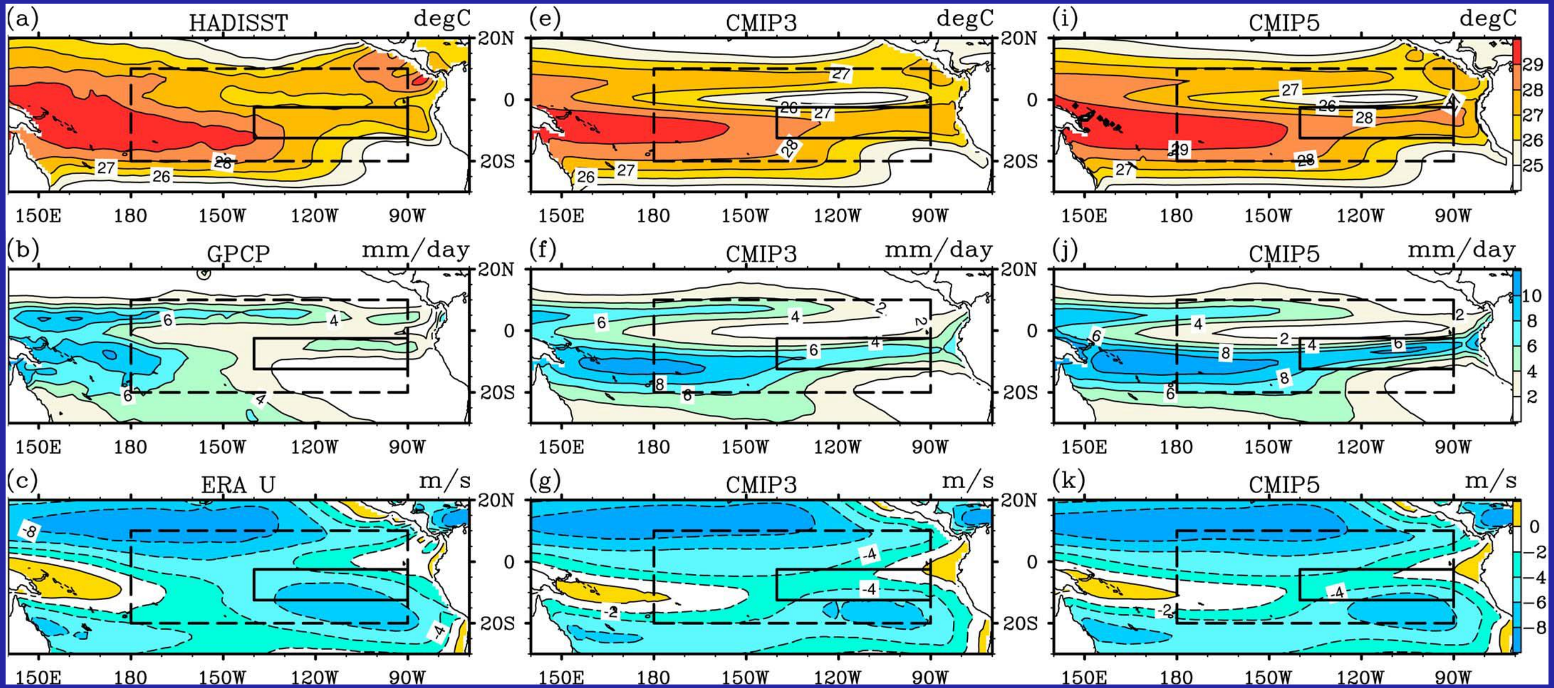


西風偏差

雙重ITCZ偏差
(X. Zhang et al., 2015)

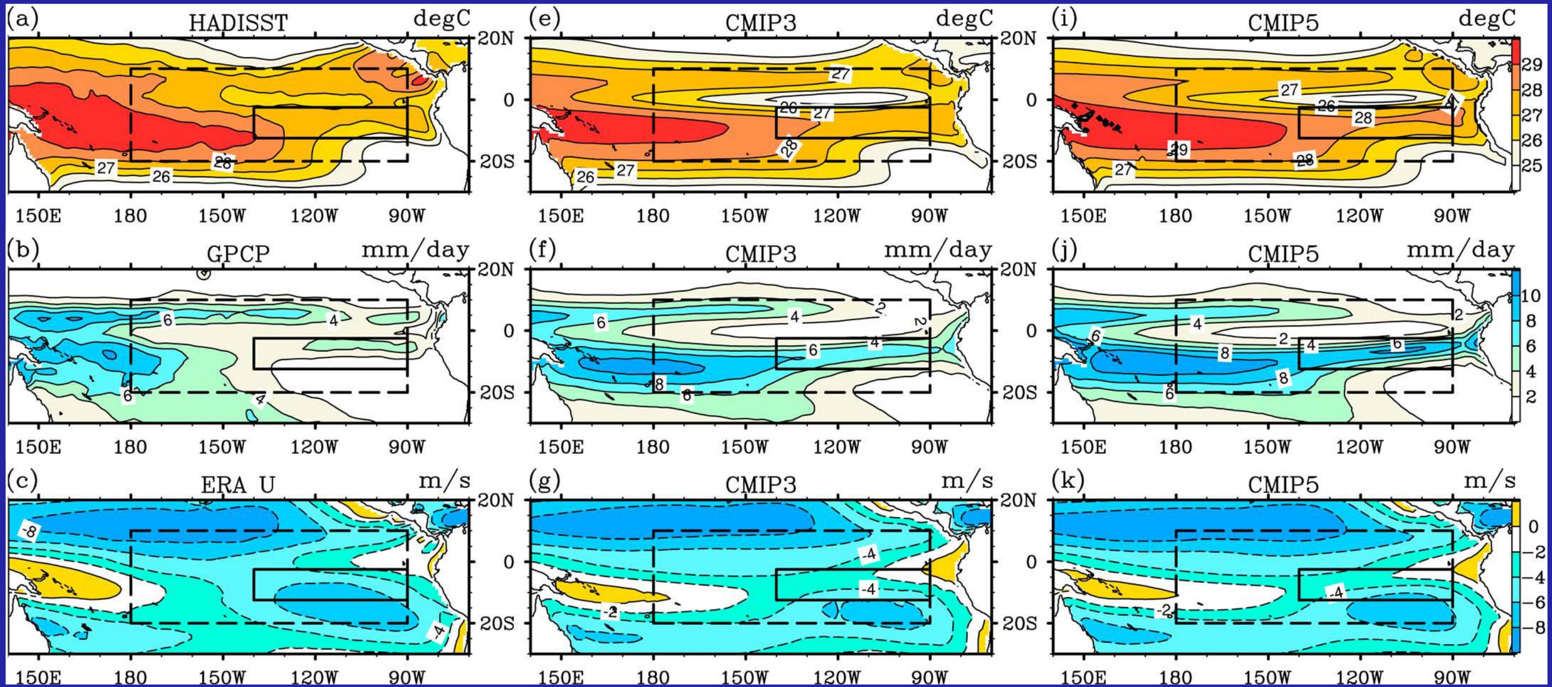
觀測　　CMIP3　　CMIP5

海表溫



西風偏差　　暖海溫偏差

雙重ITCZ偏差
(X. Zhang et al., 2015)



西風偏差

暖海溫偏差

異常南太平洋ITCZ

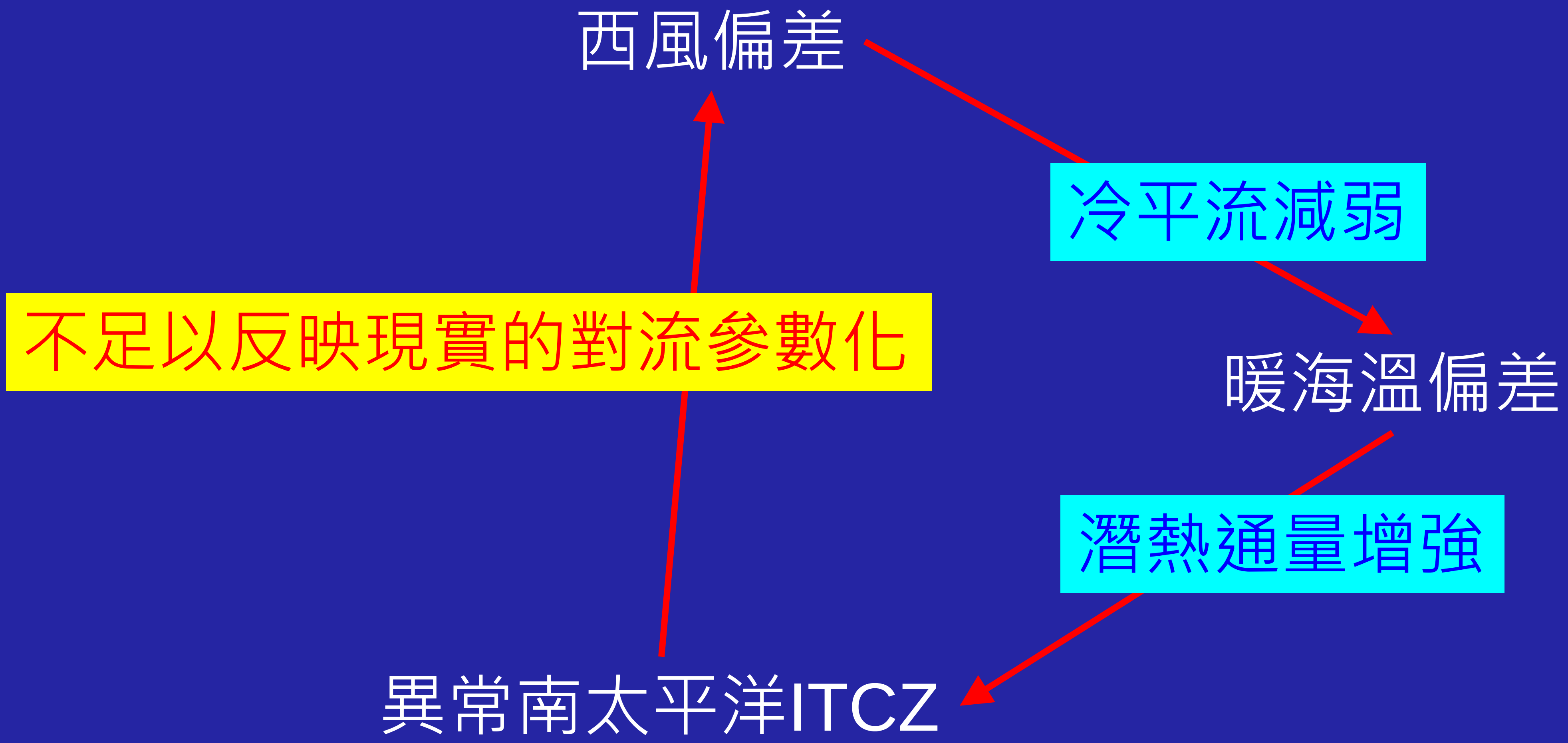
雙重ITCZ偏差
(X. Zhang et al., 2015)

西風偏差

暖海溫偏差

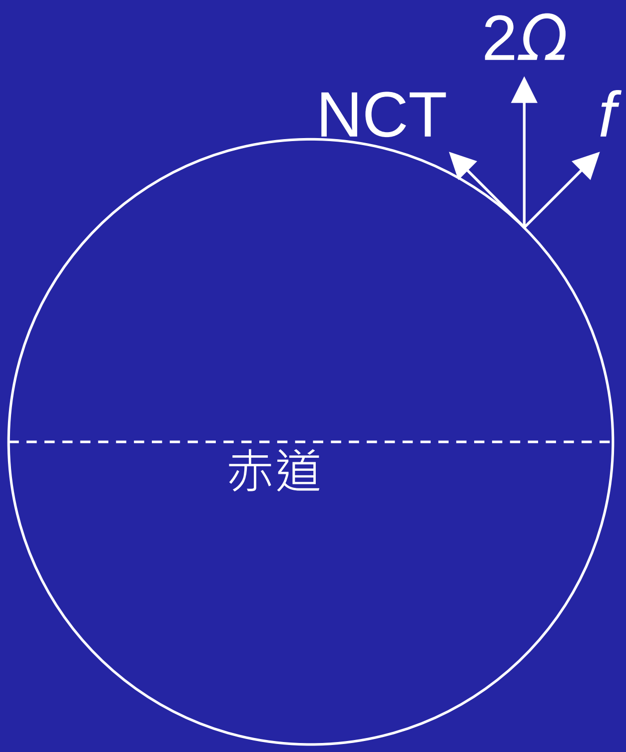
異常南太平洋ITCZ

正回饋
(G. J. Zhang and Song, 2010)



好消息與壞消息

- 好消息: 在特定的GCM中，修正對流參數化的閉合假設能改善雙重ITCZ偏差 (G. J. Zhang and Song 2010)
- 壞消息: 對流參數化的作法太多樣，使特定的修正方法難以一體適用
- 更糟的消息: 異常ITCZ中的西風偏差持續發生在兩個世代的GCM中 (X. Zhang et al., 2015)



新假說

西風偏差

冷平流減弱

暖海溫偏差

潛熱通量增強

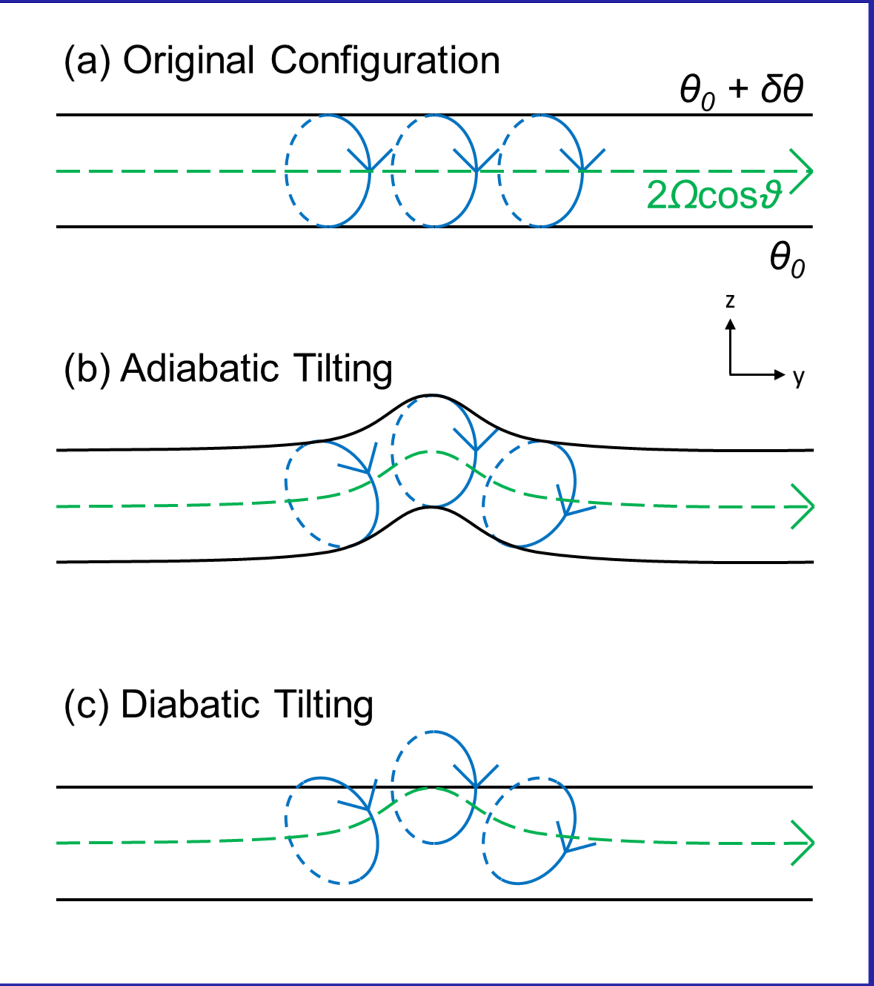
異常南太平洋ITCZ

忽略非傳統科氏項(NCTs)

大綱

- 動機之一
- 初步研究非傳統科氏項(NCTs)
  - Prelim. A: 位渦充放理論 (JAS, in revision)
  - Prelim. B: NCTs對受ITCZ強迫之環流之影響 (QJRMS, accepted)
  - Prelim. C: NCTs對自由之赤道波動之影響 (QJRMS, in review)
- 總結與討論

位渦充放理論

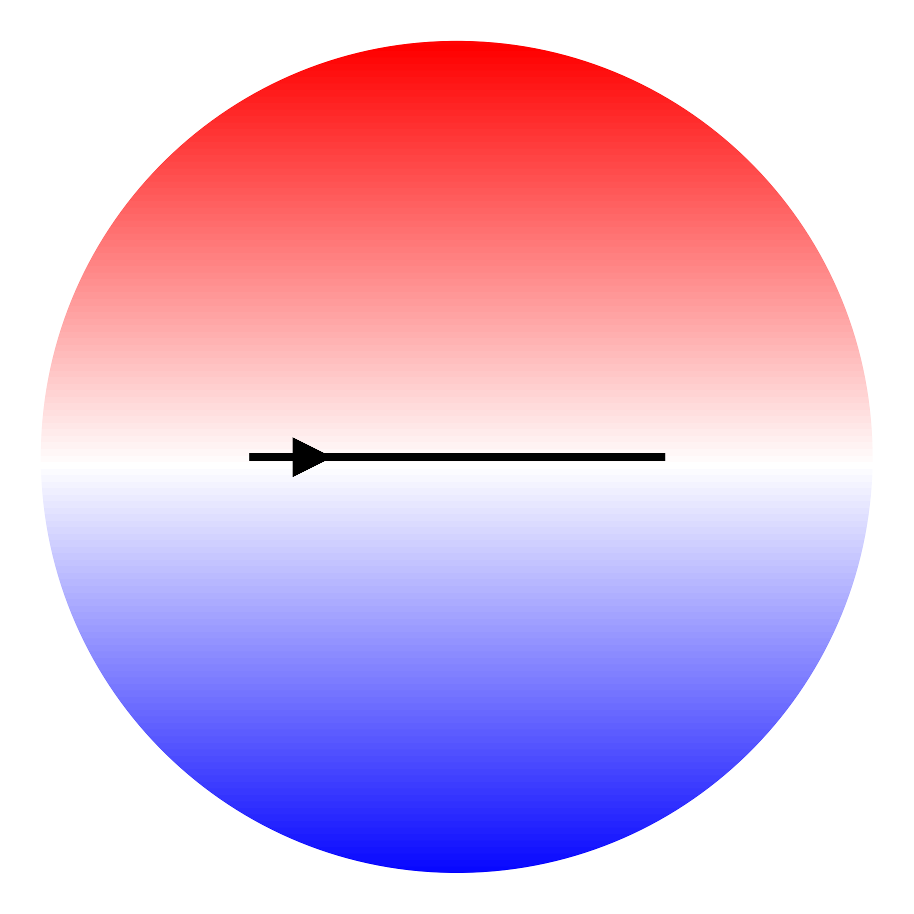


$$\frac{\partial \rho Q}{\partial t} = -\nabla \cdot \mathbf{J}$$

$$\mathbf{J} = \rho \mathbf{v} Q - \dot{\theta}\boldsymbol{\omega}_{\mathbf{a}} - \mathbf{F} \times \nabla\theta$$

- $Q \equiv \frac{\boldsymbol{\omega}_{\mathbf{a}} \cdot \nabla\theta}{\rho}$
- $\dot{\theta}$, 加熱
- $\boldsymbol{\omega}_{\mathbf{a}}$, 絕對渦度

位渦充放理論



$$\frac{\partial \overline{u_{\mathrm{p}}}}{\partial t} = \frac{\bar{J}}{|\nabla \theta|}$$

$$\bar{J} \cong \overline{\rho Q}\bar{v} + \overline{\rho Q' v'} - 2\Omega\bar{\dot{\theta}}\cos\vartheta - \bar{\dot{\theta}}\frac{\overline{\partial u}}{\partial z} - \overline{\dot{\theta}'\frac{\partial u'}{\partial z}}$$

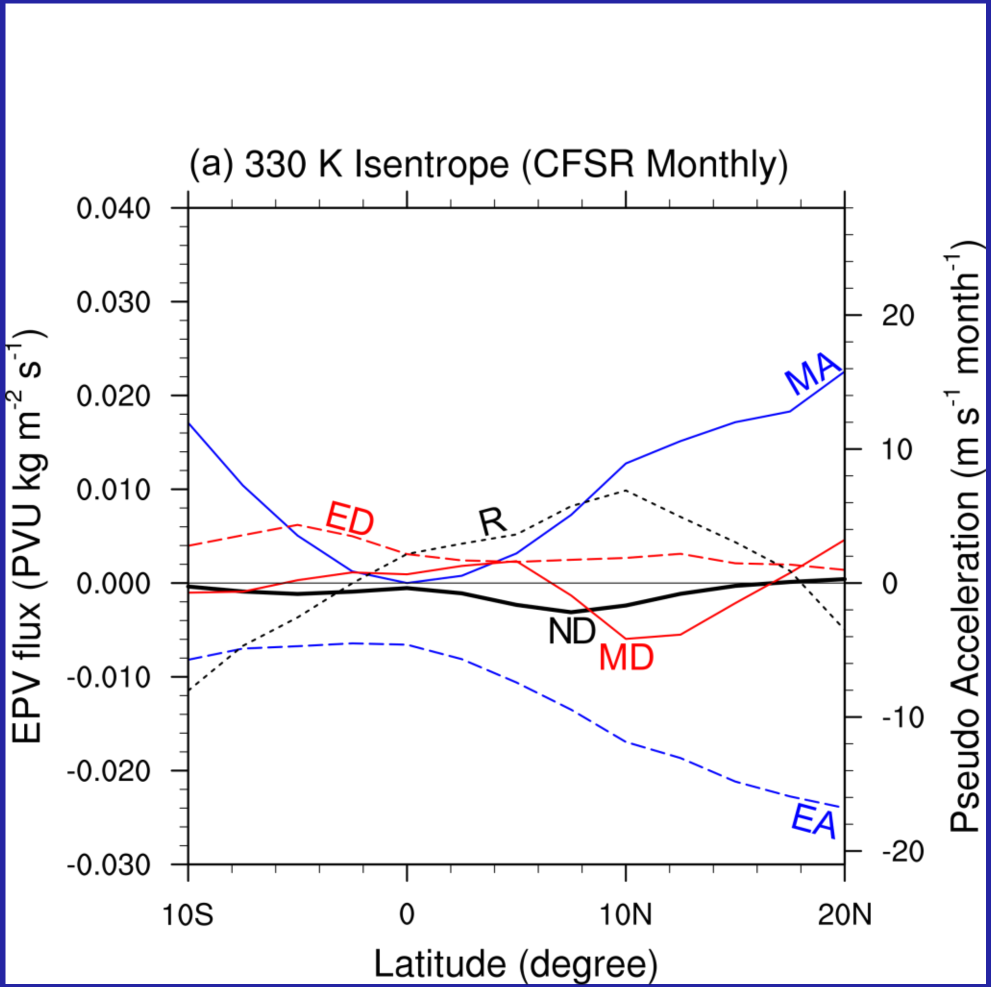
MA EA ND MD ED

- NCT-coupled diabatic heating (ND) discharges EPV, which yields westward acceleration.

位渦收支

$$\bar{J} \cong \overline{\rho Q}\bar{v} + \overline{\rho Q' v'} - 2\Omega\bar{\dot{\theta}}\cos\vartheta - \bar{\dot{\theta}}\overline{\frac{\partial u}{\partial z}} - \overline{\dot{\theta}'\frac{\partial u'}{\partial z}}$$

MA EA ND MD ED



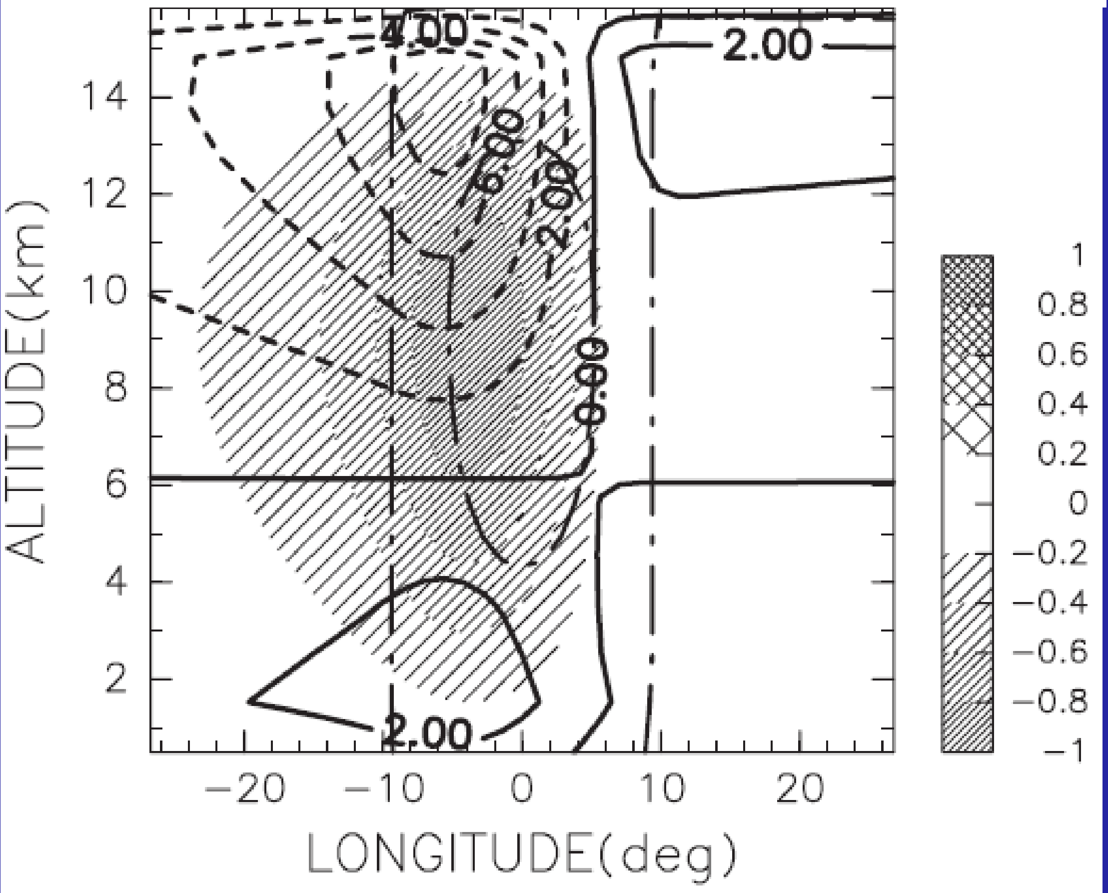
- R (residual) is large.
  - Nonlinear terms (EA, MD, and ED) are uncertain.
- ND flux would be as shown if the diabatic forcing was accurate.
- ND flux is considerable using MA flux as a reference.

大綱

- 動機之一
- 初步研究非傳統科氏項(NCTs)
  - Prelim. A: 位渦充放理論 (JAS, in revision)
  - Prelim. B: NCTs對受ITCZ強迫之環流之影響 (QJRMS, accepted)
  - Prelim. C: NCTs對自由之赤道波動之影響 (QJRMS, in review)
- 總結與討論

回顧: Hayashi and Itoh (2012)

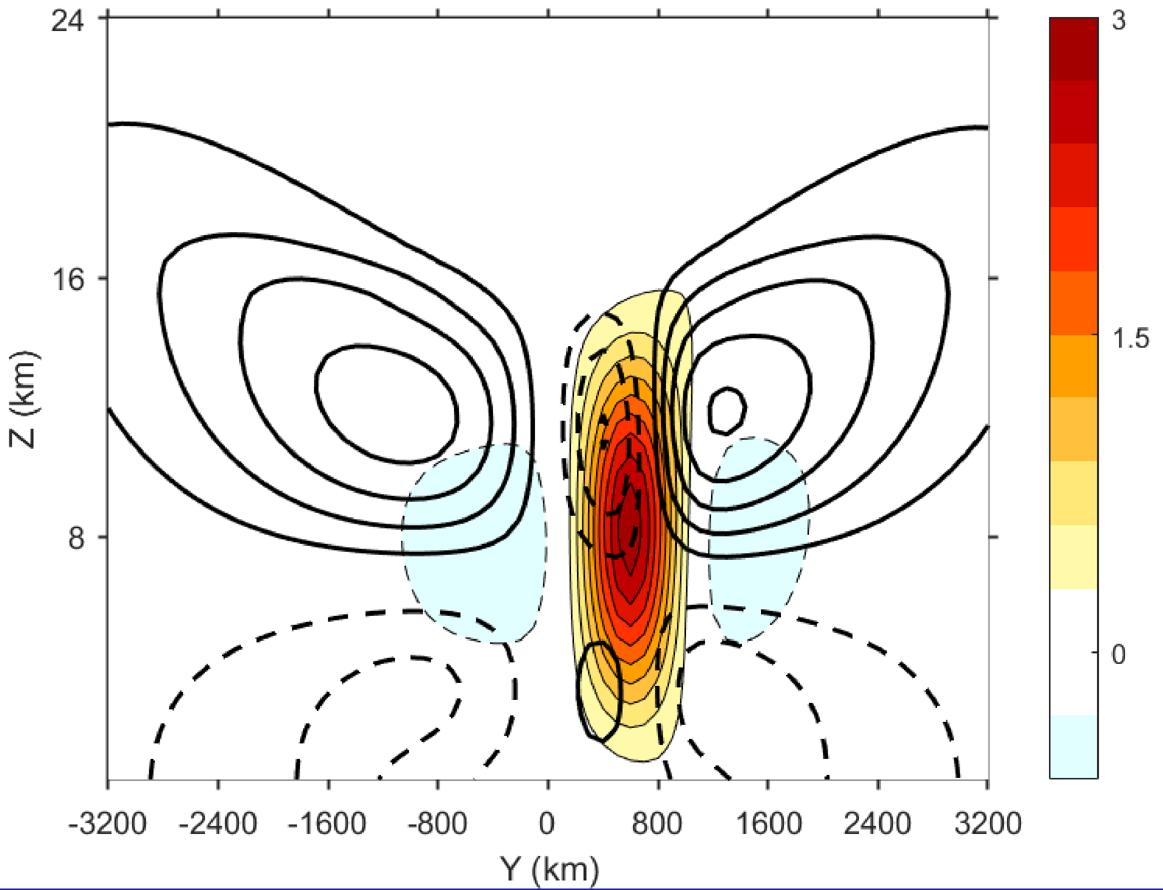
Contours: U wind w/o NCTs
Shadings: U wind w/ NCTs minus w/o NCTs



- 使用線性化的強迫–耗散模式
- 以季內震盪之向東移動之熱源來做為強迫
- 在加熱區中發現西風偏差 (w/o NCTs minus w/ NCTs)

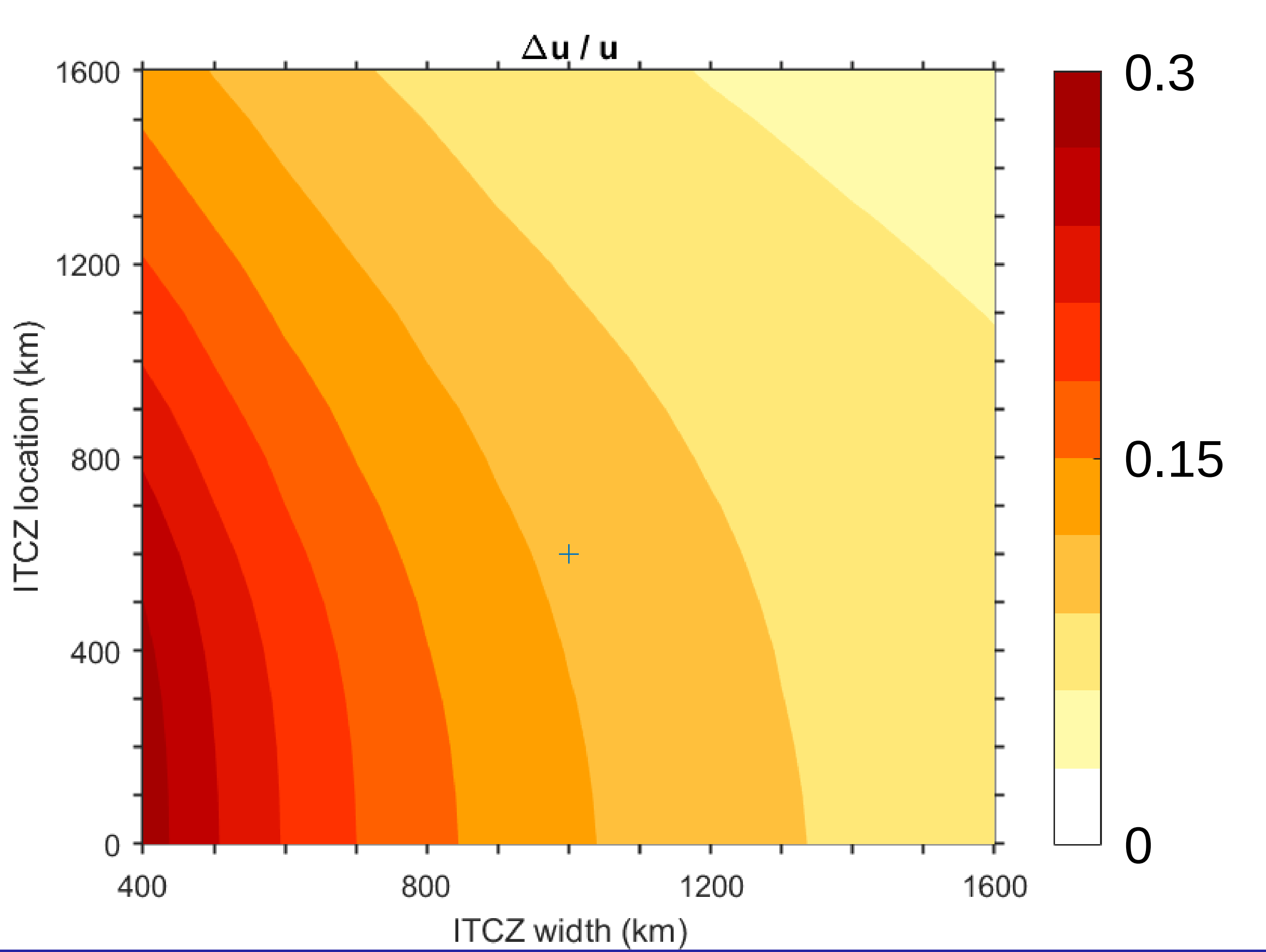
Prelim. B: Ong and Roundy (2019)

Contours: U wind w/ NCTs (5 m s^{-1})
Shadings: U wind w/o NCTs minus w/ NCTs (m s^{-1})



- 簡化該線性化的強迫—耗散模式
- 以穩定之緯向對稱之ITCZ狀熱源來做為強迫
- 在加熱區中發現西風偏差 (w/o NCTs minus w/ NCTs)

標準化西風偏差



$$\frac{max.\ westerly\ bias}{max.\ westerly\ wind}$$

- 0.120 ± 0.007, given
  - ITCZ width: 1000 km
  - ITCZ location: 600 km
  - (mimicking ITCZ in May)
- ITCZ越窄或越接近赤道，標準化西風偏差越大

評估靜力平衡近似之有效性

傳統 (e.g., Vallis, 2017)

- 垂直動量方程

$$\frac{vertical\ acceleration}{reduced\ gravity} \sim \frac{D^2}{L^2} \sim 0.0001$$

- D, characteristic depth
- L, characteristic width

熱帶大尺度替代方案
(Ong & Roundy, 2019)

- 水平動量方程

$$\frac{nontraditional\ Coriolis}{traditional\ Coriolis} \equiv \hat{O} \sim \frac{aD}{YL} \sim 0.1$$

~ 標準化西風偏差

- a, planet radius
- Y, distance from equator

大綱

- 動機之一
- 初步研究非傳統科氏項(NCTs)
  - Prelim. A: 位渦充放理論 (JAS, in revision)
  - Prelim. B: NCTs對受ITCZ強迫之環流之影響 (QJRMS, accepted)
  - Prelim. C: NCTs對自由之赤道波動之影響 (QJRMS, in review)
- 總結與討論

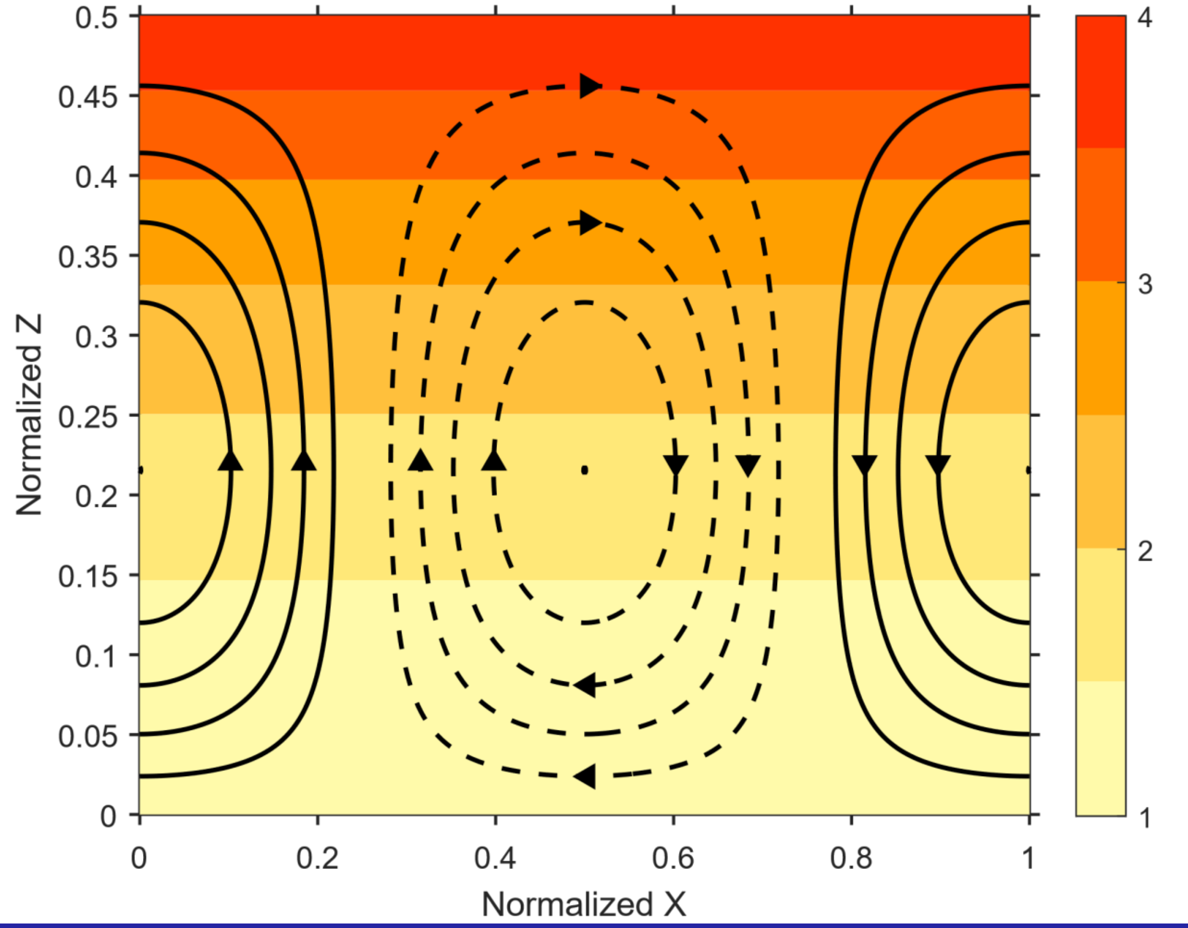
回顧: 赤道波動

	Hydrostatic	Quasi-hydrostatic	Fully nonhydrostatic
Shallow water	Matsuno (1966)		
Boussinesq		Fruman (2009)	Roundy & Janiga (2012)
Anelastic	Holton & Hakim (2012)		The present study

- 在Boussinesq模式中，任一組波動頻散關係皆不受NCTs影響
- 在anelastic模式中，NCTs可能影響波動頻散關係。這是由於壓縮性beta效應

壓縮性beta效應
(Verhoeven & Stellmach, 2014)

Contours: mass streamfunction
Shadings: meridional planetary vorticity / density



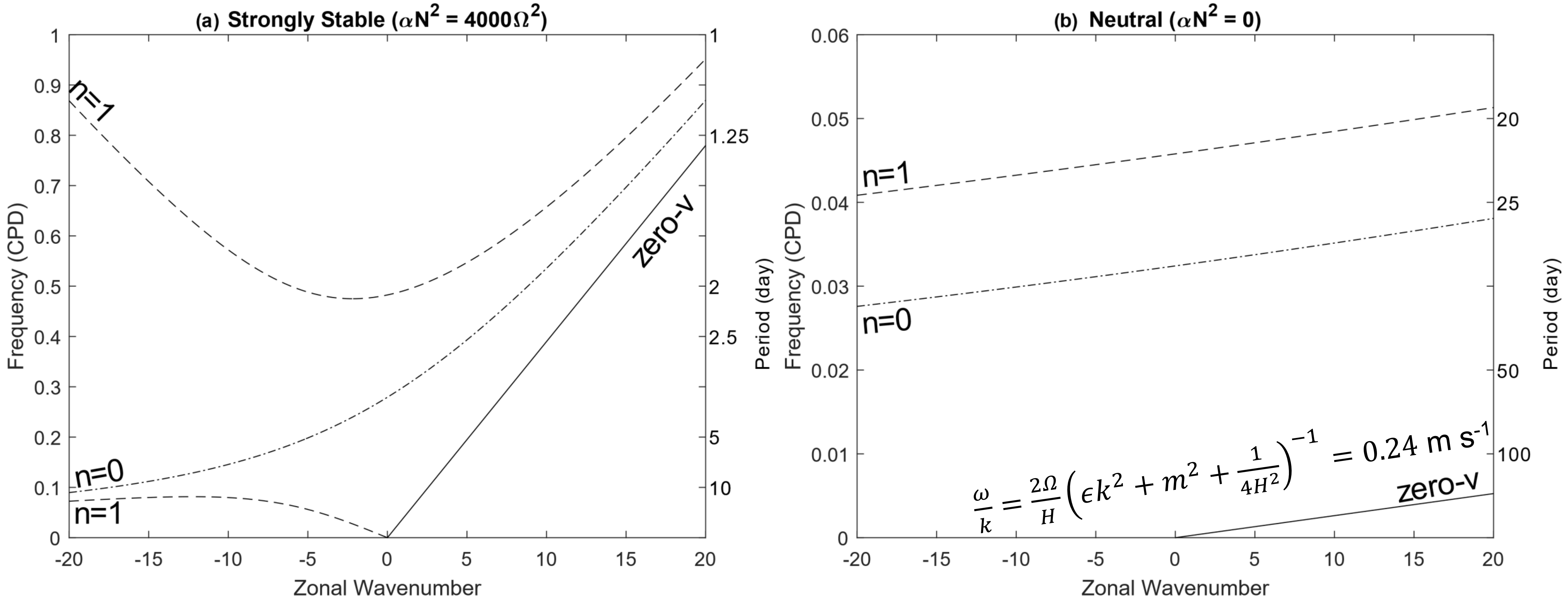
- 南北向渦度方程
  - 線性化
  - 無南北風
  - 無浮力

$$\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}-\frac{\partial w}{\partial x}\right)+\rho w\frac{\mathrm{d}}{\mathrm{dz}}\left(\frac{2\Omega}{\rho}\right)=0$$

  - 平流運算子$w\frac{\mathrm{d}}{\mathrm{dz}}$乘以密度
  - 被平流的物理量: $\frac{2\Omega}{\rho}$

整組的赤道波動解

$\hat{O}$~0.03 $\hat{O}$~1



中性大氣的赤道波動

- 能用來做深層大氣模式的評斷基準
- 在恆星或巨型氣體行星的內部動力中可能很重要
  - 前人認為壓縮性beta效應在這些天體的內部動力中很重要 (e.g., Gilman & Glatzmaier, 1981; Verhoeven & Stellmach, 2014).
- 有限的證據無法排除其在地球上的大尺度 (> 1000 km) 長時間 (> 70 days) 的變化
  - Yano and Bonazzola (2009) 為實質中性的大氣條件提供了有限的證據

大綱

- 動機之一
- 初步研究非傳統科氏項(NCTs)
  - Prelim. A: 位渦充放理論 (JAS, in revision)
  - Prelim. B: NCTs對受ITCZ強迫之環流之影響 (QJRMS, accepted)
  - Prelim. C: NCTs對自由之赤道波動之影響 (QJRMS, in review)
- 總結與討論

總結

- 雖然非傳統科氏項 (NCTs) 被模式忽略，但三項初步研究顯示NCTs的重要性至少有以下三個方面
  - NCTs配上加熱能沿著等熵面傳遞位渦
  - 就大尺度環流對ITCZ狀加熱的反應而言，忽略NCTs造成西風偏差
  - 在密度向上減少的條件下，NCTs能夠將南北向渦度擾動向東傳遞

初步支持新假說

西風偏差

冷平流減弱

暖海溫偏差

潛熱通量增強

異常南太平洋ITCZ

邊界層效應可能將此西風偏差向下傳遞

忽略非傳統科氏項確實能在加熱區產生西風偏差

挑戰

- 目前最大的挑戰是難以取得深層大氣模式
- 已發展完備但難以取得：
  - 英國氣象局Unified Model、日本NICAM
- 正在發展：
  - 德國氣象局ICON (Borchert et al., 2018, in review)
  - 美國海軍NEPTUNE (P. Alex Reinecke, personal communication)
  - GFDL FV3 (Hann-Ming Juang, personal communication)
  - NCAR MPAS
- 已可取得但較為簡化：MITgcm

Acknowledgment

- Committee: Paul, Brian Rose, Rob, Bill
- Former advisor: Wei-Chyung
- DAES staffs: Chaina, Ash, Annie, Barb, Kevin Tyle
- Office mates: Ahmed, Alex Tomoff
- Family: Wen-Chi and Ik-Liong (Mosa)
- Other people who stimulated all these ideas
  - Hung-Chi Kuo for Advanced Atmospheric Dynamics course
  - Marat Khairoutdinov for his talk on 26 Mar 2018

Supplementary

Momentum equations

$$\frac{\mathrm{D}u}{\mathrm{D}t} - \left(2\Omega + \frac{u}{a\cos\vartheta}\right)(v\sin\vartheta - w\cos\vartheta) + \frac{1}{\rho a\cos\vartheta}\frac{\partial p}{\partial\lambda} = F_\lambda$$

$$\frac{\mathrm{D}v}{\mathrm{D}t} + \frac{wv}{r} + \left(2\Omega + \frac{u}{a\cos\vartheta}\right)u\sin\vartheta + \frac{1}{\rho a}\frac{\partial p}{\partial\vartheta} = F_\vartheta$$

$$\frac{\mathrm{D}w}{\mathrm{D}t} - \frac{u^2+v^2}{r} - 2\Omega u\cos\vartheta + \frac{1}{\rho}\frac{\partial p}{\partial z} = -g + F_r$$

Momentum equations

$$\frac{\mathrm{D}u}{\mathrm{D}t} - \left(2\Omega + \frac{u}{a\cos\vartheta}\right)(v\sin\vartheta \qquad\qquad) + \frac{1}{\rho\, a\cos\vartheta}\frac{\partial p}{\partial\lambda} = F_\lambda$$

$$\frac{\mathrm{D}v}{\mathrm{D}t} \qquad + \left(2\Omega + \frac{u}{a\cos\vartheta}\right)u\sin\vartheta + \frac{1}{\rho\, a}\frac{\partial p}{\partial\vartheta} = F_\vartheta$$

$$\frac{\mathrm{D}w}{\mathrm{D}t} \qquad\qquad + \frac{1}{\rho}\frac{\partial p}{\partial z} = -g + F_z$$

Model requirements

- Testing the hypothesis requires a model that
  - Couples atmosphere and ocean to simulate the wind-SST-precipitation positive feedback
  - Can switch between deep (w/ NCTs) and shallow (w/o NCTs) atmospheric dynamical cores
    - So that the contrasts between the results can be attributed to NCTs

Why MPAS?

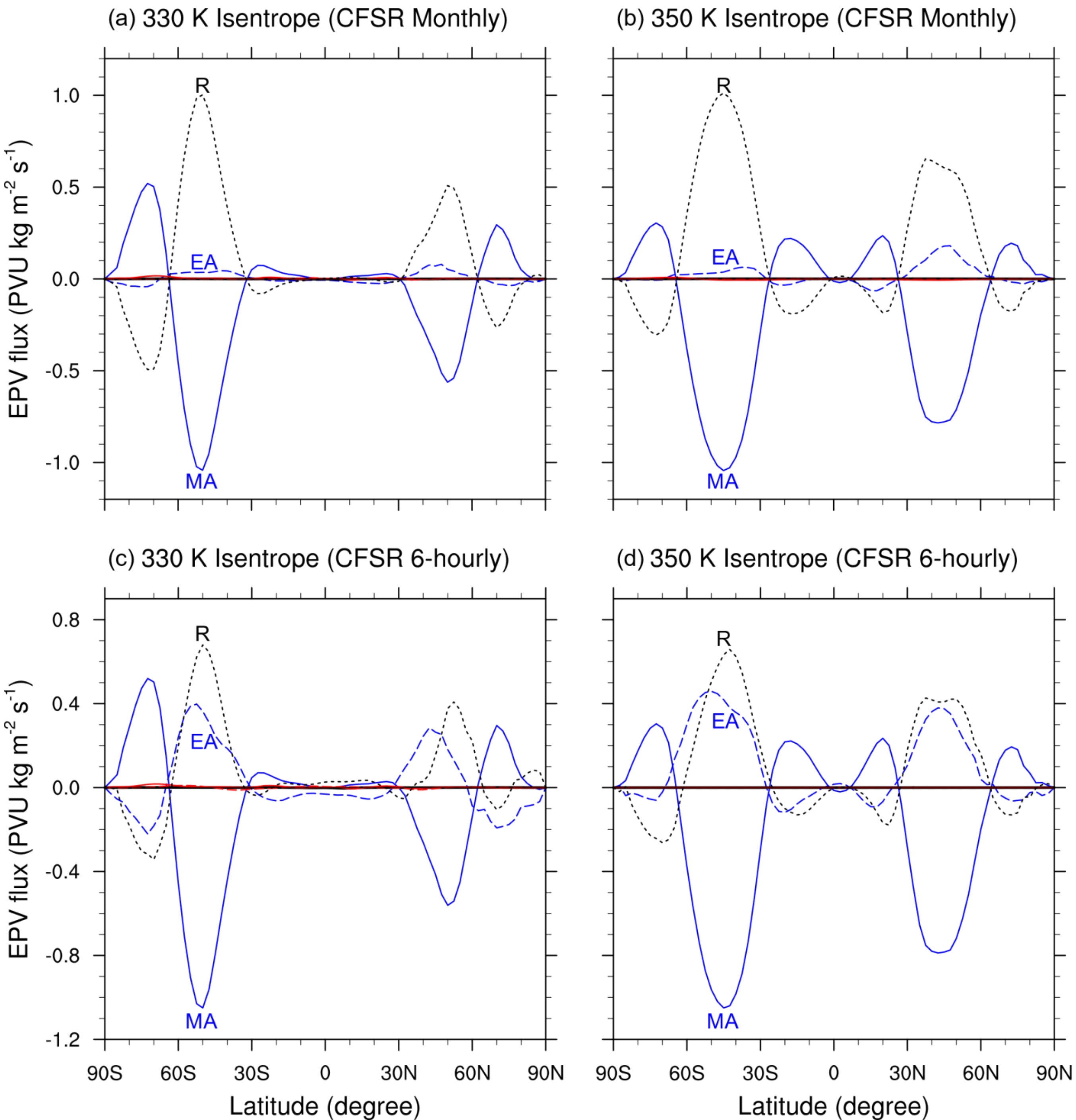
- Many deep (w/ NCTs) atmospheric dynamical cores are under development, including GFDL’s FV3, U.S. Navy’s NEPTUNE, and DWD’s ICON.
- Developing a deep core for MPAS can provide
  - A freely available deep core to the public
  - More diversity to a future deep core ensemble

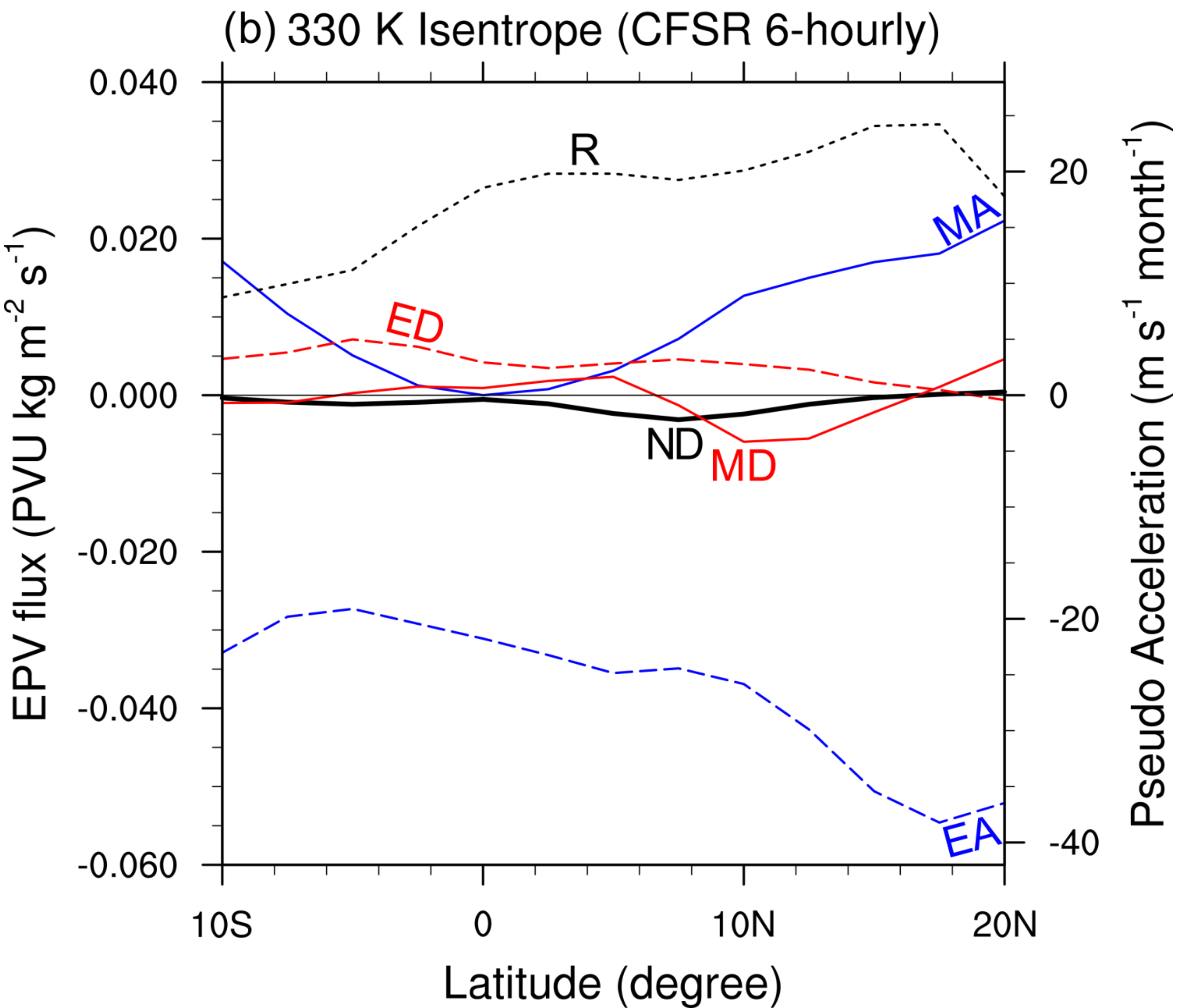
How to adapt MPAS?

- Restore the complete Coriolis and metric terms to the momentum equations.
- Use the vertically varying distance from planet center (deep) instead of the constant planet radius (shallow) in
  - The length of grid cell edges for horizontal flux operations
  - The distance between grid cell centers for horizontal gradient operations
  - The area of the grid cell for vertical flux operations

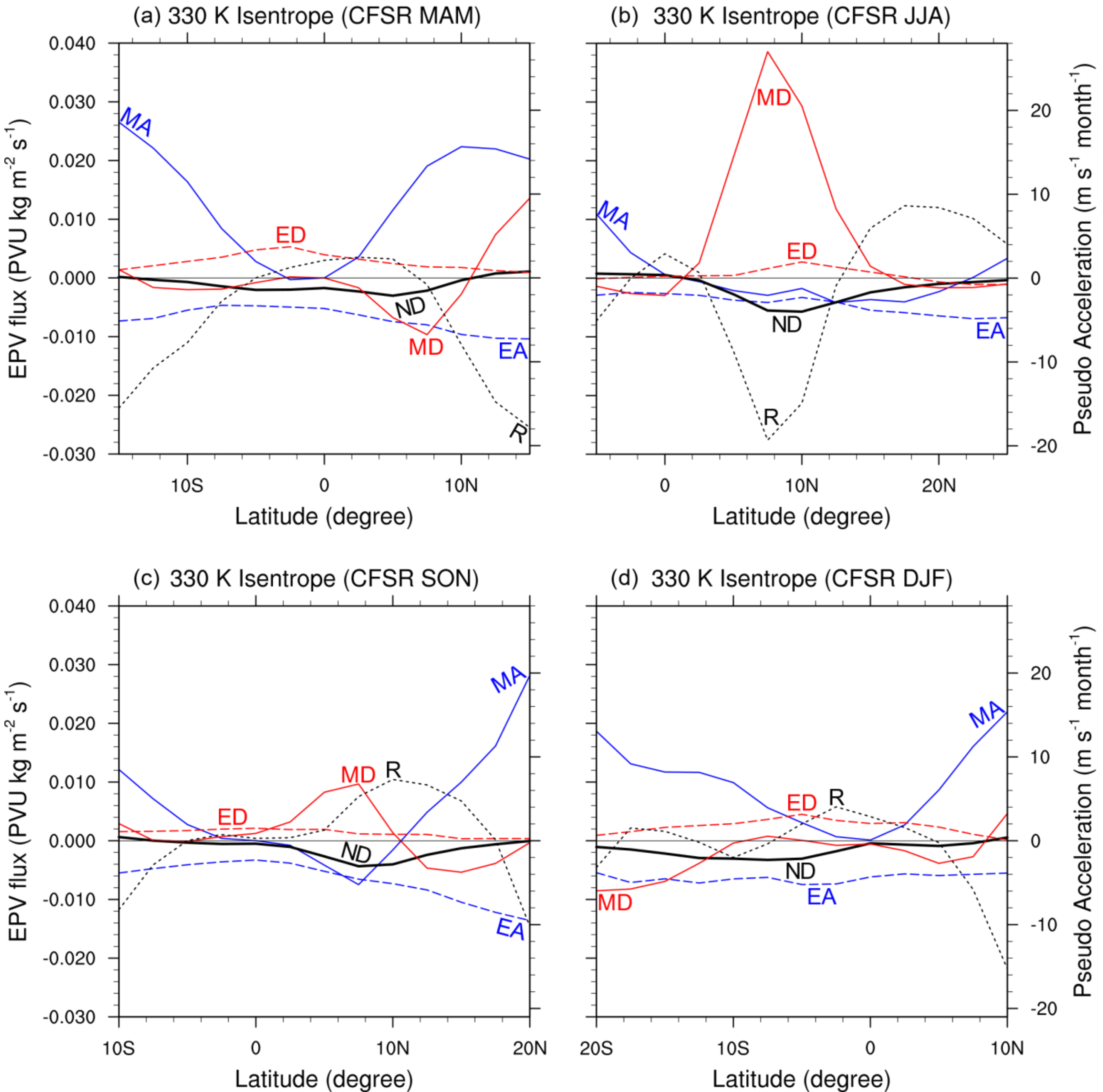
Benchmarks for deep cores

- Numerical benchmarks
  - Non-deep-core-targeting
    - General circulation test (Held and Suarez, 1994)
  - Deep-core-targeting
    - Baroclinic wave test (Ullrich et al., 2014)
- Analytical benchmarks
  - Non-deep-core-targeting
    - Sound wave test (Borchert et al., 2018, in review)
  - Deep-core-targeting
    - Compression Rossby wave test (Prelim. C)

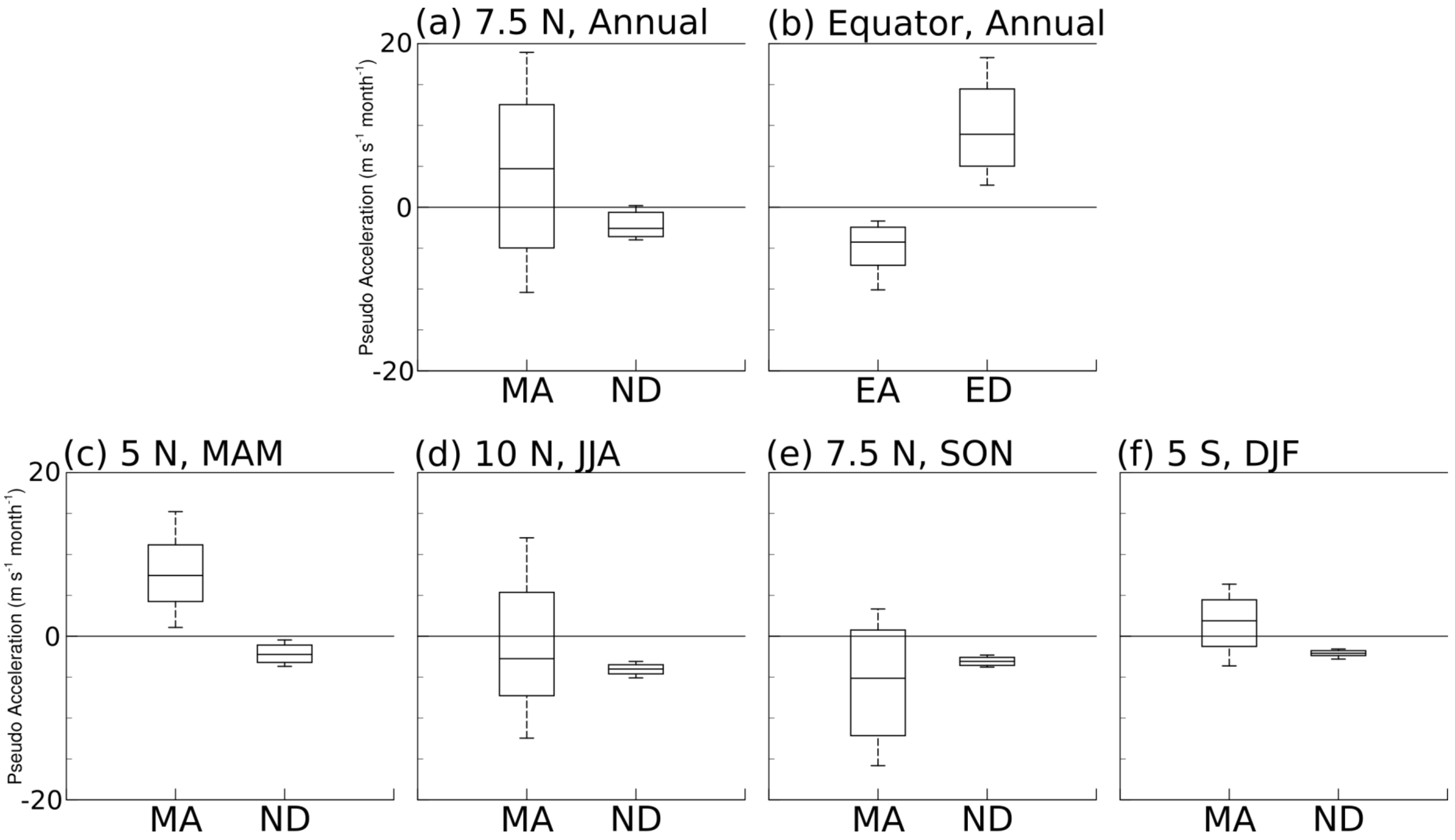

(a) 330 K Isentrope (CFSR Monthly)
(b) 350 K Isentrope (CFSR Monthly)
(c) 330 K Isentrope (CFSR 6-hourly)
(d) 350 K Isentrope (CFSR 6-hourly)
EPV flux (PVU kg m^{-2} s^{-1})
Latitude (degree)
R
EA
MA
1.0
0.5
0.0
-0.5
-1.0
0.8
0.4
-0.4
-0.8
-1.2
90S
60S
30S
0
30N
60N
90N

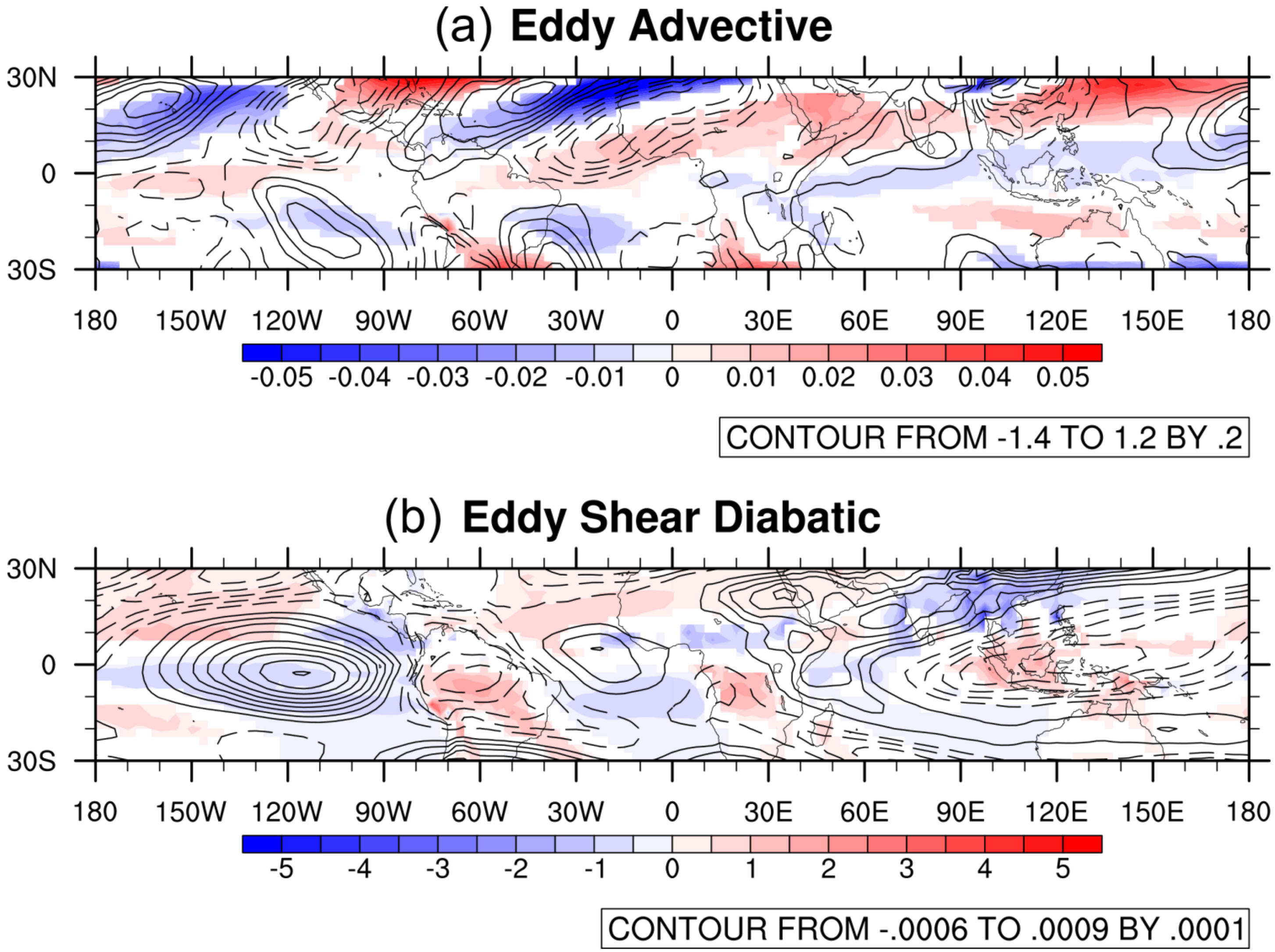


(b) 330 K Isentrope (CFSR 6-hourly)
0.040
0.020
0.000
-0.020
-0.040
-0.060
EPV flux (PVU kg m-2 s-1)
20
0
-20
-40
Pseudo Acceleration (m s-1 month-1)
10S
0
10N
20N
Latitude (degree)
R
MA
ED
ND
MD
EA

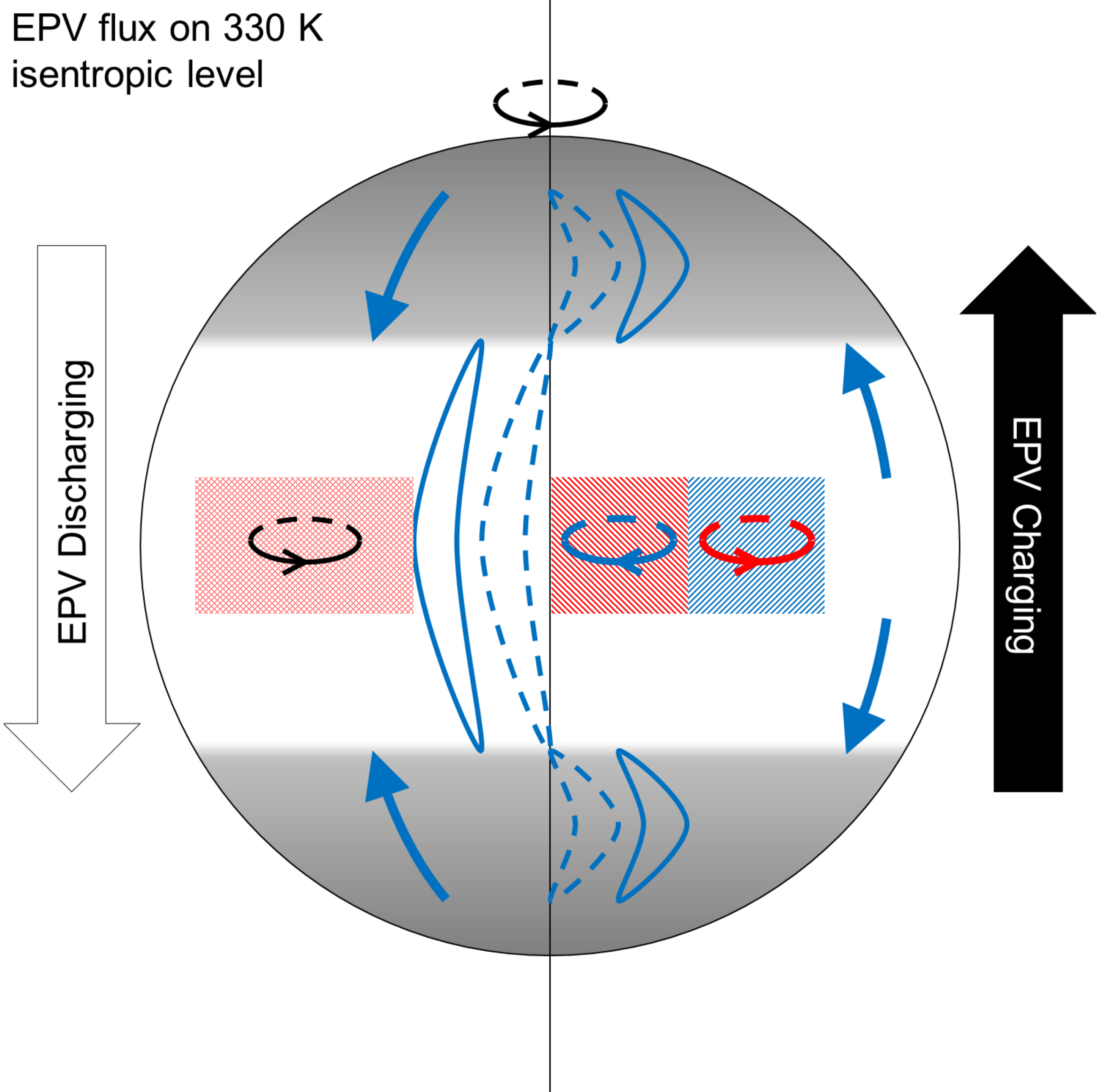


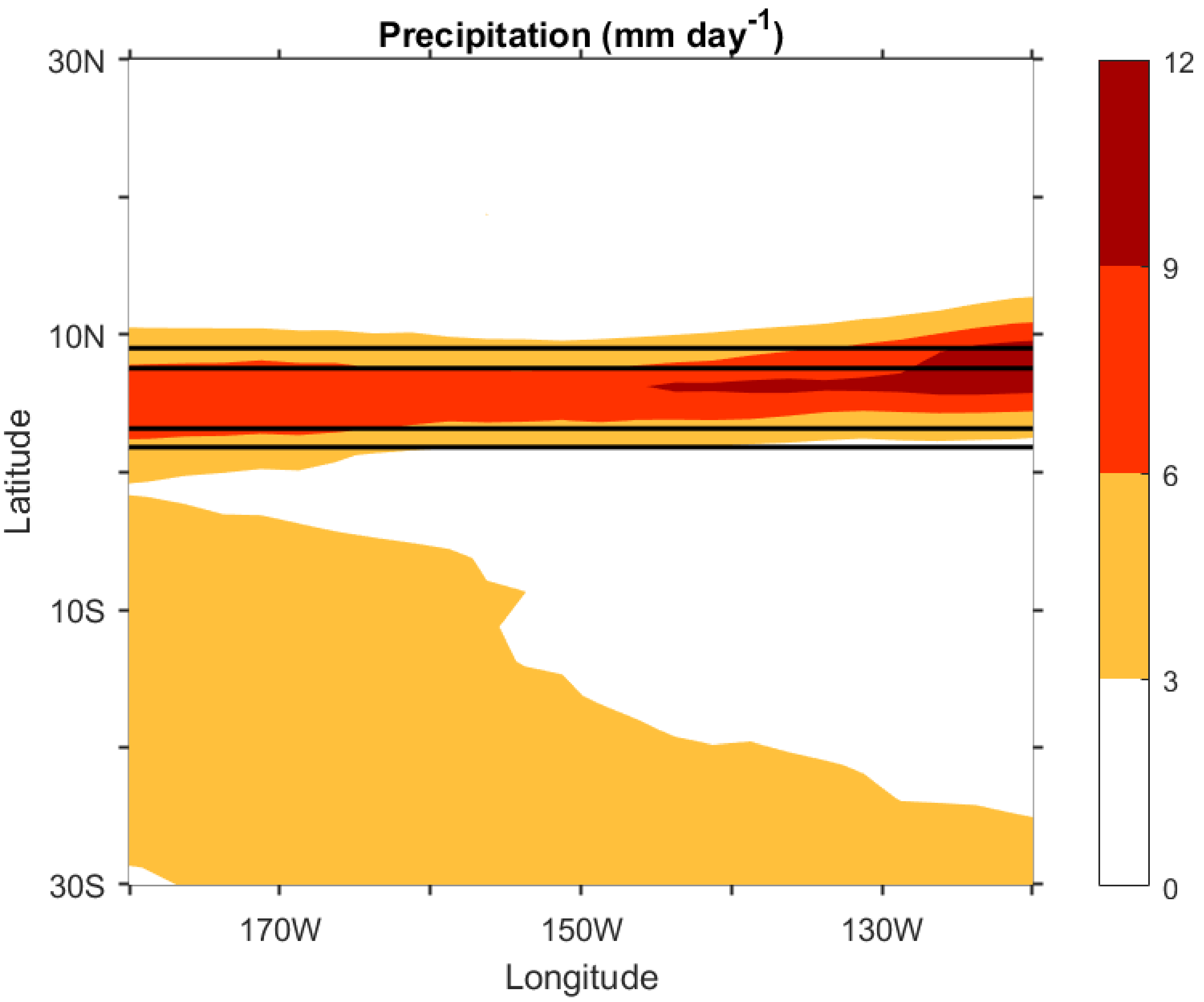
(a) 330 K Isentrope (CFSR MAM)
(b) 330 K Isentrope (CFSR JJA)
(c) 330 K Isentrope (CFSR SON)
(d) 330 K Isentrope (CFSR DJF)
EPV flux (PVU kg m-2 s-1)
Pseudo Acceleration (m s-1 month-1)
Latitude (degree)
0.040
0.030
0.020
0.010
0.000
-0.010
-0.020
-0.030
20
10
0
-10
-20
10S
0
10N
20N
20S
MA
MD
ED
ND
EA
R


(a) 7.5 N, Annual
(b) Equator, Annual
(c) 5 N, MAM
(d) 10 N, JJA
(e) 7.5 N, SON
(f) 5 S, DJF
Pseudo Acceleration (m s-1 month-1)
20
0
-20
MA
ND
EA
ED

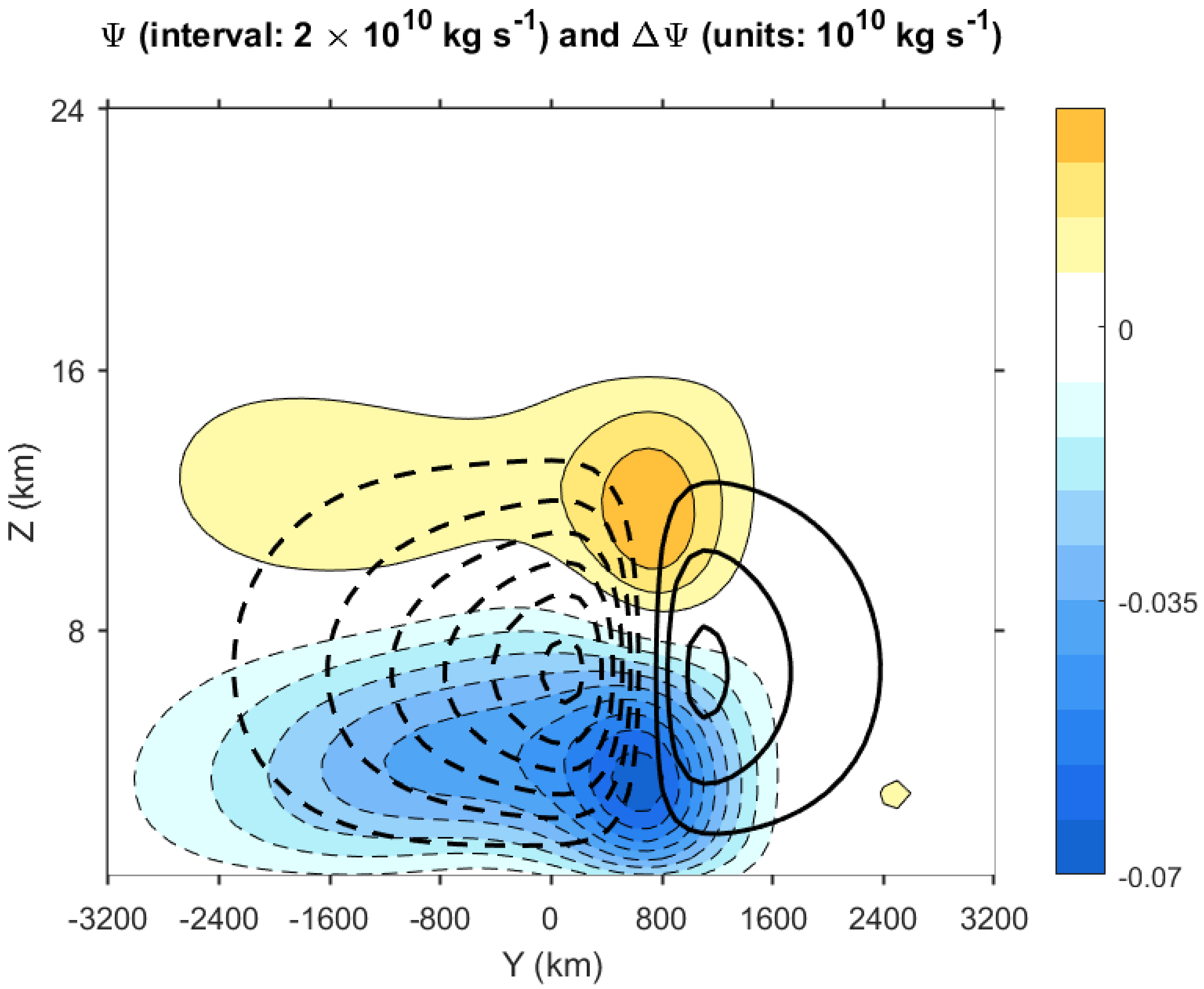


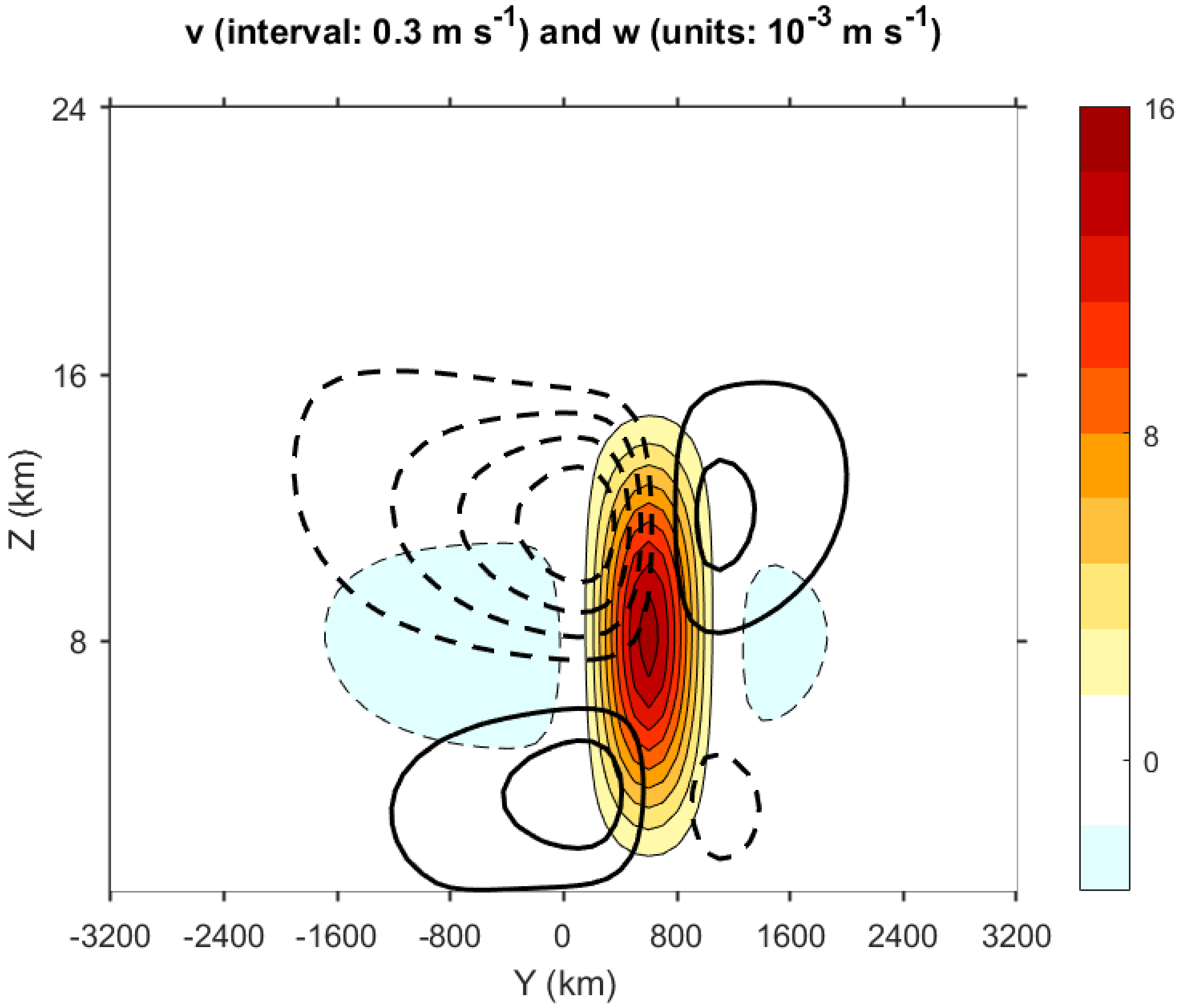
(a) Eddy Advective
30N
0
30S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
-0.05 -0.04 -0.03 -0.02 -0.01 0 0.01 0.02 0.03 0.04 0.05
CONTOUR FROM -1.4 TO 1.2 BY .2
(b) Eddy Shear Diabatic
30N
0
30S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
-5 -4 -3 -2 -1 0 1 2 3 4 5
CONTOUR FROM -.0006 TO .0009 BY .0001


EPV flux on 330 K
isentropic level
EPV Discharging
EPV Charging

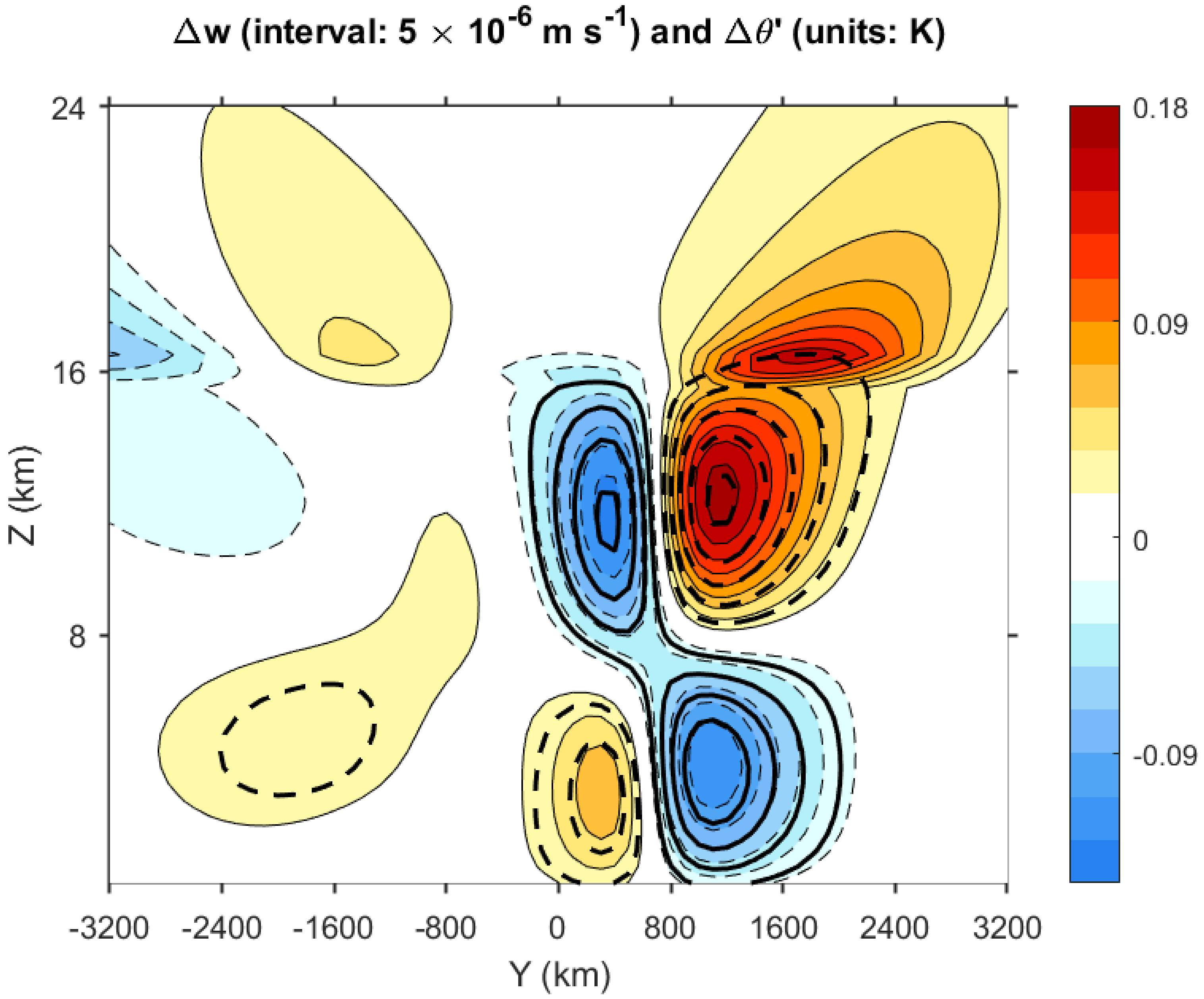


Precipitation (mm day^{-1})
30N
10N
10S
30S
Latitude
170W
150W
130W
Longitude
12
9
6
3
0


Ψ (interval: 2 × 10^10 kg s^-1) and ΔΨ (units: 10^10 kg s^-1)
24
16
8
Z (km)
-3200
-2400
-1600
-800
0
800
1600
2400
3200
Y (km)
0
-0.035
-0.07

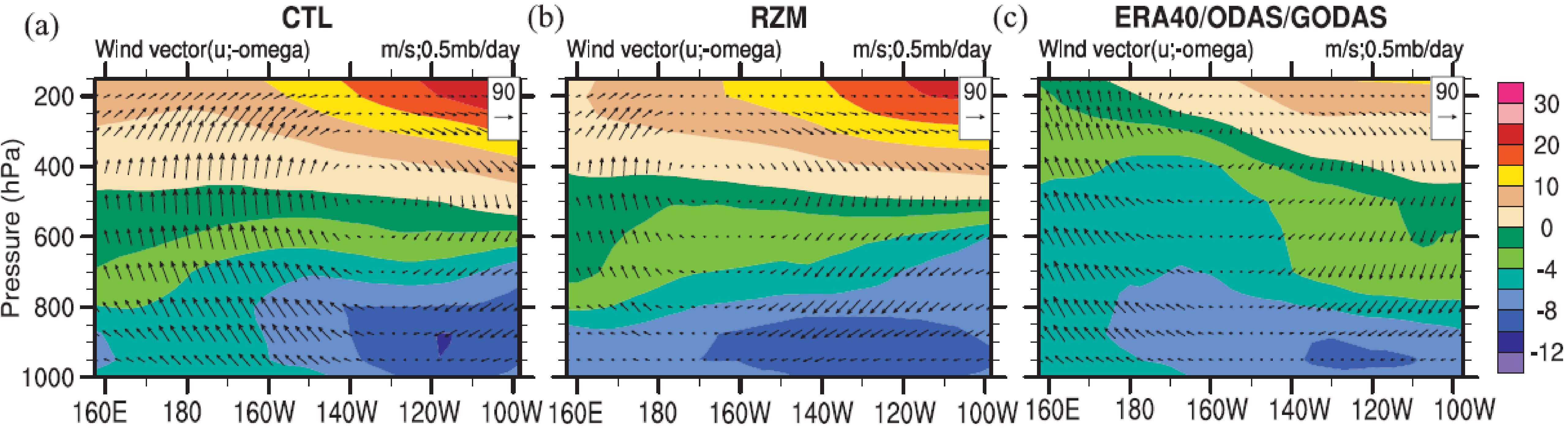


v (interval: 0.3 m s-1) and w (units: 10-3 m s-1)
24
16
8
Z (km)
-3200
-2400
-1600
-800
0
800
1600
2400
3200
Y (km)
16
8
0

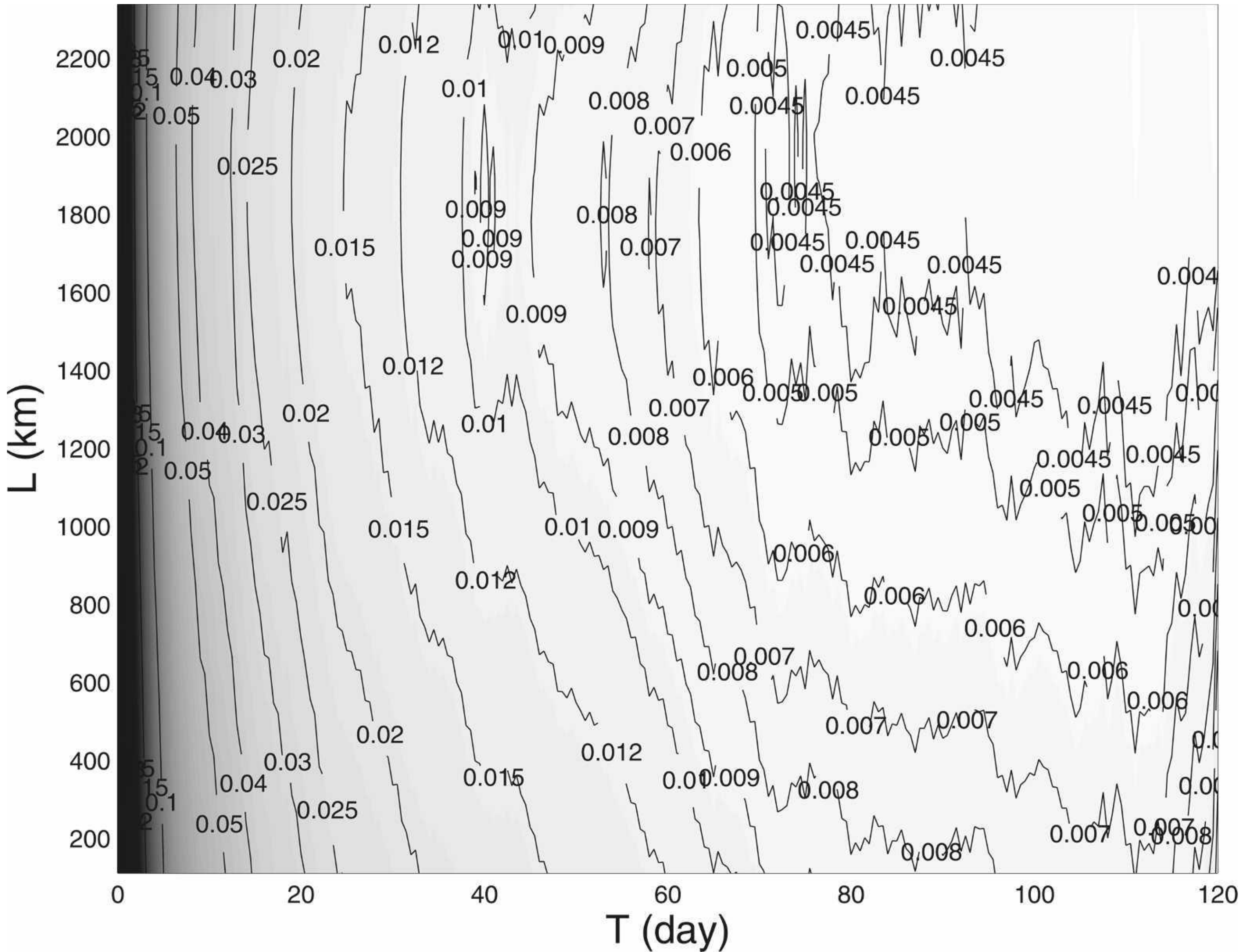


Δw (interval: 5 × 10-6 m s-1) and Δθ' (units: K)
24
16
8
Z (km)
-3200
-2400
-1600
-800
0
800
1600
2400
3200
Y (km)
0.18
0.09
0
-0.09

G. J. Zhang and Song (2010)



Yano and Bonazzola (2009)



Forced-dissipative model

$$\alpha\theta' + \frac{\mathrm{d}\tilde{\theta}}{\mathrm{d}z} w = \frac{\tilde{\theta}}{c_p \tilde{T}} \dot{Q}$$

$$\alpha u - \beta y v + 2\Omega w = 0$$

$$\alpha v + \beta y u + \frac{\partial}{\partial y}\left(c_p \tilde{\theta} \Pi'\right) = 0$$

$$\alpha w - 2\Omega u + \frac{\partial}{\partial z}\left(c_p \tilde{\theta} \Pi'\right) - \frac{g}{\tilde{\theta}} \theta' = 0$$

$$\frac{\partial}{\partial y}(\tilde{\rho} v) + \frac{\partial}{\partial z}(\tilde{\rho} w) = 0$$

$$\dot{Q}(y,z) = \dot{Q}_{\mathrm{max}} \mathrm{e}^{\frac{-(y-\mu)^2}{2\sigma^2}} \sin^2\left(\frac{\pi z}{16\ \mathrm{km}}\right) \mathrm{e}^{\frac{\gamma z}{2H}} - R(z)$$

$$(\alpha^2 + 4\Omega^2 + N^2)\frac{\partial^2 \Psi}{\partial y^2} + 2(2\Omega\beta y)\frac{\partial^2 \Psi}{\partial y \partial z} + (\alpha^2 + \beta^2 y^2)\frac{\partial^2 \Psi}{\partial z^2} + \left(\frac{2\Omega\beta y}{H}\right)\frac{\partial \Psi}{\partial y} + \left(\frac{\alpha^2}{H} + \frac{\beta^2 y^2}{H} + 2\Omega\beta\right)\frac{\partial \Psi}{\partial z} = \frac{\tilde{\rho} g}{c_p \tilde{T}} \frac{\partial \dot{Q}}{\partial y}$$

Compressional Rossby waves

$$\frac{\partial b}{\partial t} + \alpha N^2 w = 0$$

$$\frac{\partial u}{\partial t} - \beta y v + 2\Omega w + \frac{\partial \varphi}{\partial x} = 0$$

$$\frac{\partial v}{\partial t} + \beta y u + \frac{\partial \varphi}{\partial y} = 0$$

$$\epsilon \frac{\partial w}{\partial t} - 2\Omega u + \frac{\partial \varphi}{\partial z} - b = 0$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} - \frac{w}{H} = 0$$

$$\rho u \equiv \partial \Psi / \partial z \;\&\; \rho w \equiv -\partial \Psi / \partial x$$

$$\frac{\partial}{\partial t}\left(\epsilon \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial z^2} + \frac{1}{H}\frac{\partial \Psi}{\partial z}\right) - \frac{2\Omega}{H}\frac{\partial \Psi}{\partial x} = 0$$

$$\Psi = \hat{\Psi} \exp(-z/2H) \exp[i(kx + mz - \omega t)]$$

$$\frac{\omega}{k} = \frac{2\Omega}{H}\left(\epsilon k^2 + m^2 + \frac{1}{4H^2}\right)^{-1}$$

Complete set of equatorial waves

$$\{u, v, w, b, \varphi\} = \{\hat{u}(y), \hat{v}(y), \hat{w}(y), \hat{b}(y), \hat{\varphi}(y)\} \exp(z/2H) \exp[i(kx + mz - \omega t + \phi)]$$

$$\varphi = \varphi_0 \exp\left(\frac{z}{2H} - \frac{\alpha N^2 + \frac{\Omega\omega}{Hk} - \epsilon\omega^2}{\alpha N^2 + 4\Omega^2 - \epsilon\omega^2}\frac{\beta k}{\omega}\frac{y^2}{2}\right) \exp\left[i\left(kx - \omega t + mz + \frac{-2\Omega\beta m}{\alpha N^2 + 4\Omega^2 - \epsilon\omega^2}\frac{y^2}{2} + \phi\right)\right]$$

$$-k^2(\alpha N^2 - \epsilon\omega^2) - k\frac{2\Omega\omega}{H} + \omega^2\left(m^2 + \frac{1}{4H^2}\right) = 0$$

$$v = v_0 \mathrm{H}_n\left(\frac{y}{L}\right) \exp\left(\frac{z}{2H} - \frac{y^2}{2L^2}\right) \exp\left[i\left(kx - \omega t + mz + \frac{\Gamma y^2}{2} + \phi\right)\right]$$

$$L^2 = \frac{\alpha N^2 + 4\Omega^2 - \epsilon\omega^2}{\beta\sqrt{(\alpha N^2 - \epsilon\omega^2)\left(m^2 + \frac{1}{4H^2}\right) + \frac{\Omega^2}{H^2}}}$$

$$\Gamma = \frac{-2\Omega\beta m}{\alpha N^2 + 4\Omega^2 - \epsilon\omega^2}$$

$$-\left(k^2 + \frac{k\beta}{\omega}\right)\left(\alpha N^2 + \frac{\Omega\omega}{Hk} - \epsilon\omega^2\right) + \omega^2\left(m^2 + \frac{1}{4H^2} - \frac{\Omega k}{H\omega}\right) = (2n+1)\frac{\alpha N^2 + 4\Omega^2 - \epsilon\omega^2}{L^2}$$