Understanding the local and global impacts of model physics changes

Mark Rodwell

Work with Thomas Jung

4 September 2008

Thanks to: …

Motivation

The real world and GCMs are complex systems …

- Can use hierarchy of simpler models to understand processes and develop parametrizations.

But …

- The fully complex system may behave differently. For example due to interactions.
- It is the fully complex system that is used to produce the forecast!

Hence …

- There is a need to develop diagnostics that help us understand the physics, dynamics and interactions within the fully complex system.

Talk Outline

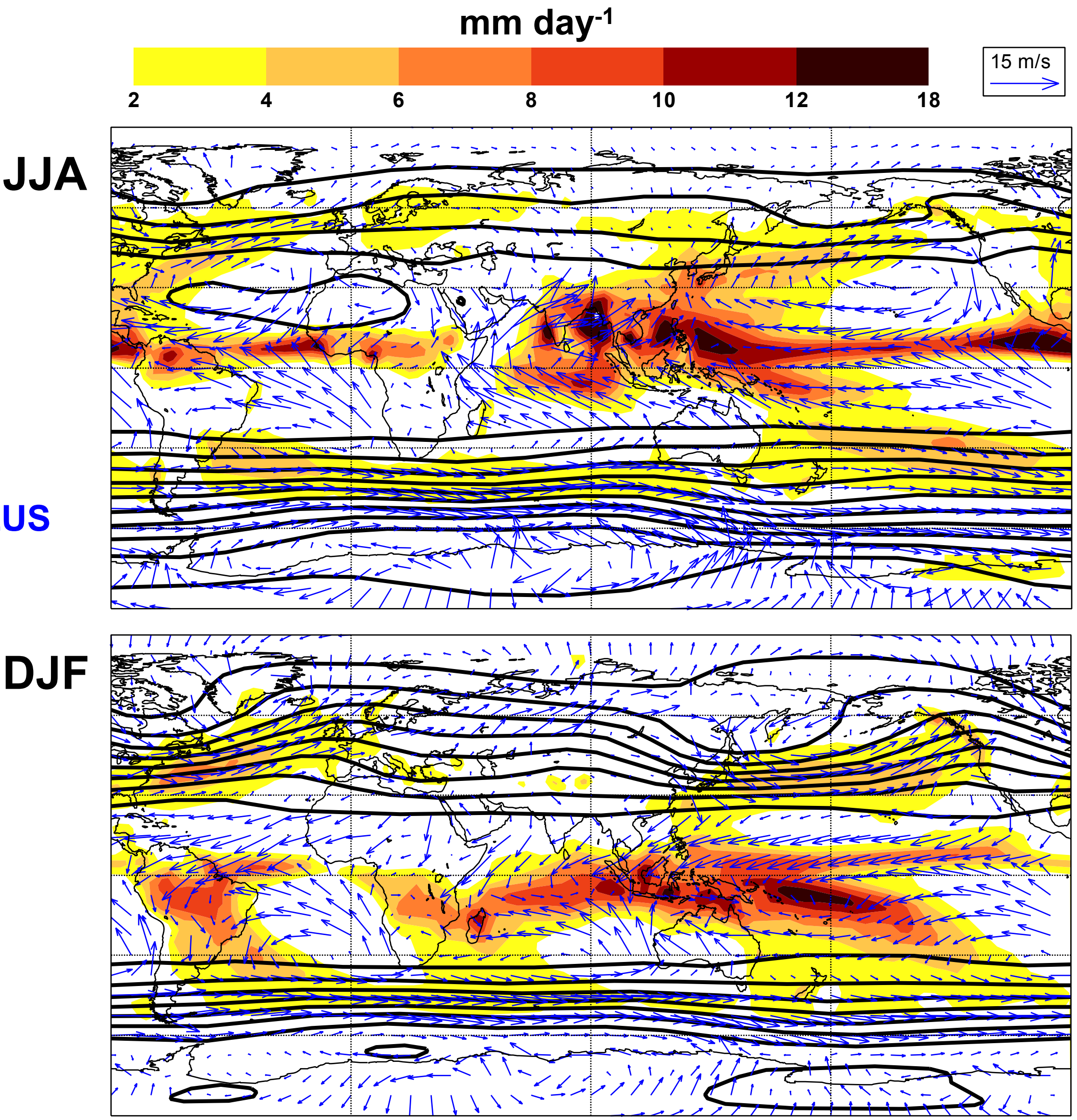
- **Annual cycle of the global circulation**
  - Systematic errors in seasonal integrations
  - Introduction to the case study: aerosol change
  - Statistically significant global changes
- **Understanding the local physics**
  - Analysis Increments and Initial Tendencies
  - Perturbed physics example: reducing climate change uncertainty
- **Understanding the tropic-wide response**
  - Tropical waves
  - Coupling with convection
- **Understanding the extra-tropical response**
  - The tropical control of the divergent wind
  - Balances in the vorticity equation
  - Extra-tropical physics and PV

Pedagogical!
See Rodwell & Jung (2008)

Annual Cycle of the Global Circulation

Mean Annual Cycle: Precipitation, $\underline{V}_{925}$ & Z_{500}

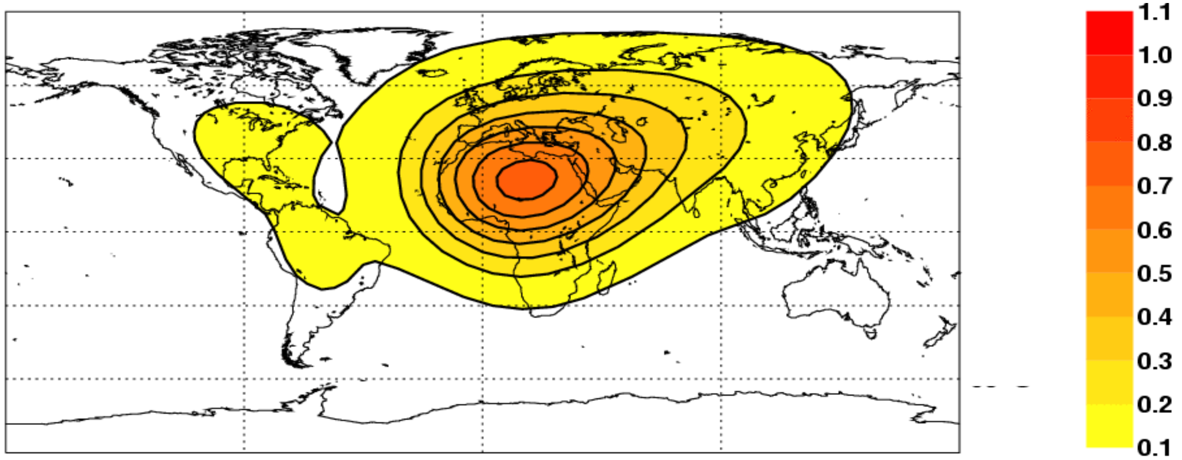
- **INTER-TROPICAL CONVERGENCE ZONE**
- **MONSOONS**
  - **SEASONAL CYCLE OF RAINS**
  - **CONVECTIVE HEATING**
- **SUBTROPICAL ANTICYCLONES**
  - **DUALITY WITH MONSOON HEATING**
  - **RADIATIVELY IMPORTANT STRATOCUMULUS**
  - **DEEP CONVECTION (SPCZ ETC)**
- **EXTRATROPICAL STORMTRACKS**
  - **STRONG VORTICITY GRADIENTS**
  - **SENSITIVITY TO TROPICAL FORCING**



Precipitation: Xie-Arkin 1979/80 – 1998/99
$\underline{V}_{925}$: ERA40 1962-01
Z_{500}: ERA40 1962-01, CI=10 dam

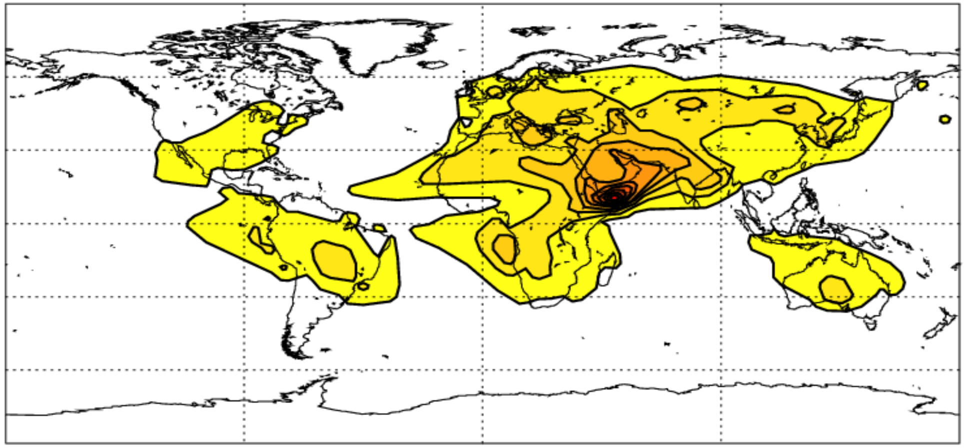
Old and New Aerosol Optical Thickness

OLD
(NO ANNUAL CYCLE)



OPTICAL DEPTH d AT 550nm

NEW
(JULY)



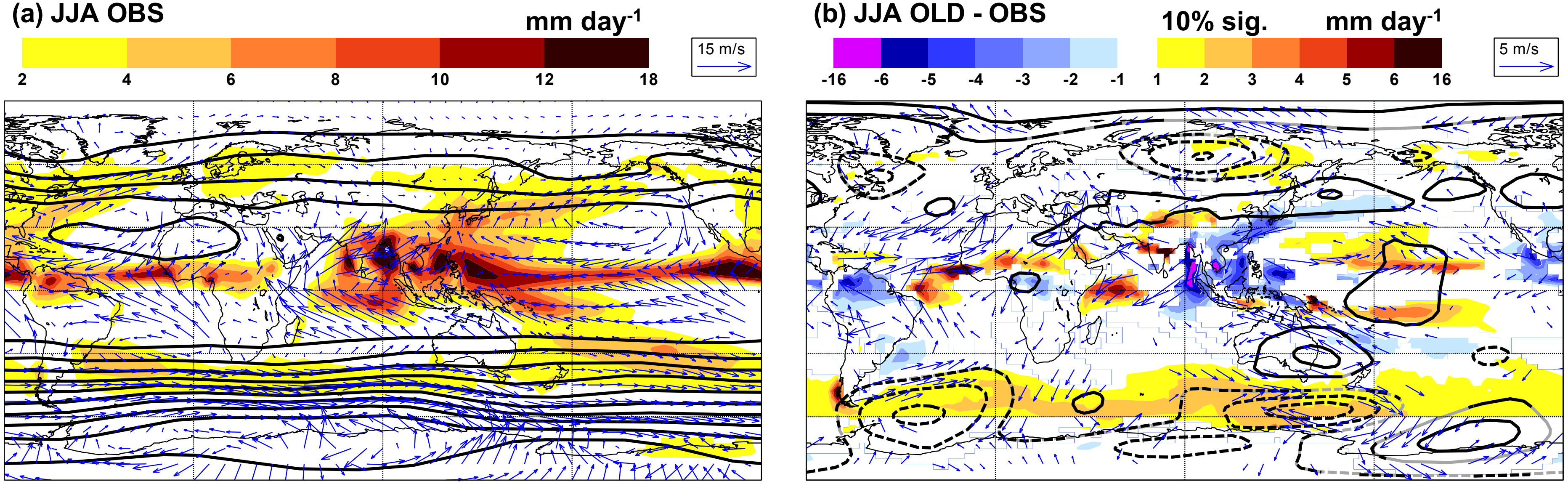
- **SOIL DUST IS IMPORTANT**
- **SOIL DUST ABSORBS AS WELL AS SCATTERS**

ATTENUATION FACTOR = e^{-d}

SINGLE SCATTERING ALBEDO FOR DESERT AEROSOL ≈ 0.9

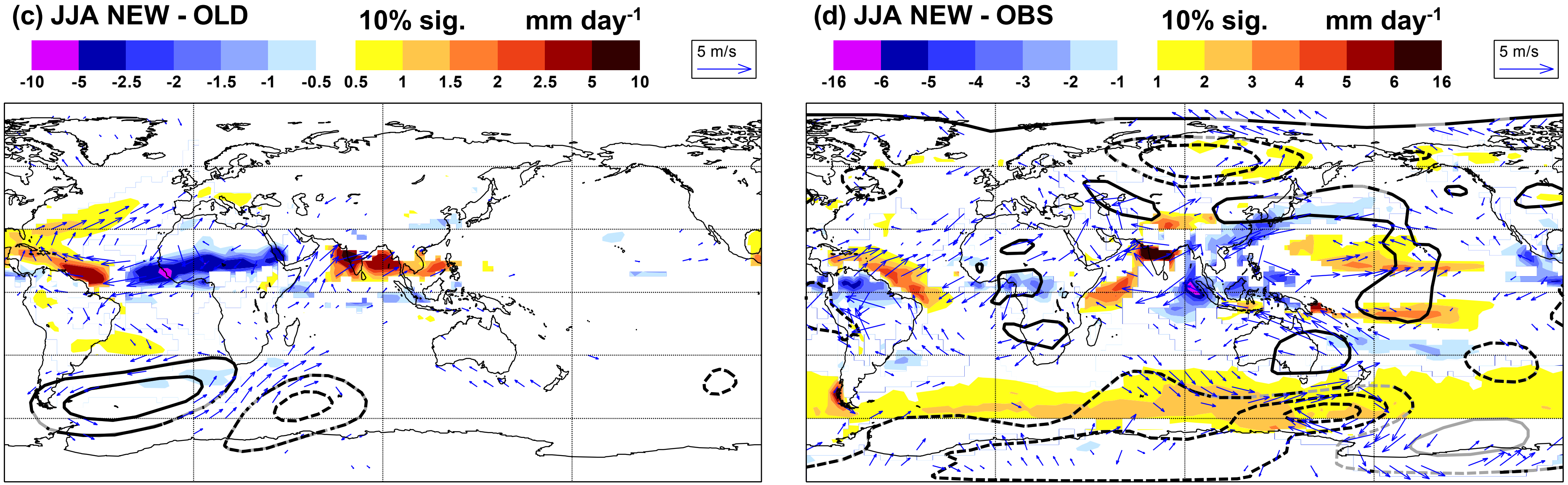
Old: C26R1 (Tanre et al. 1984), New: C26R3 (Tegen et al. 1997).

June – August Precipitation, v925 and Z500



(a) JJA OBS

(b) JJA OLD - OBS



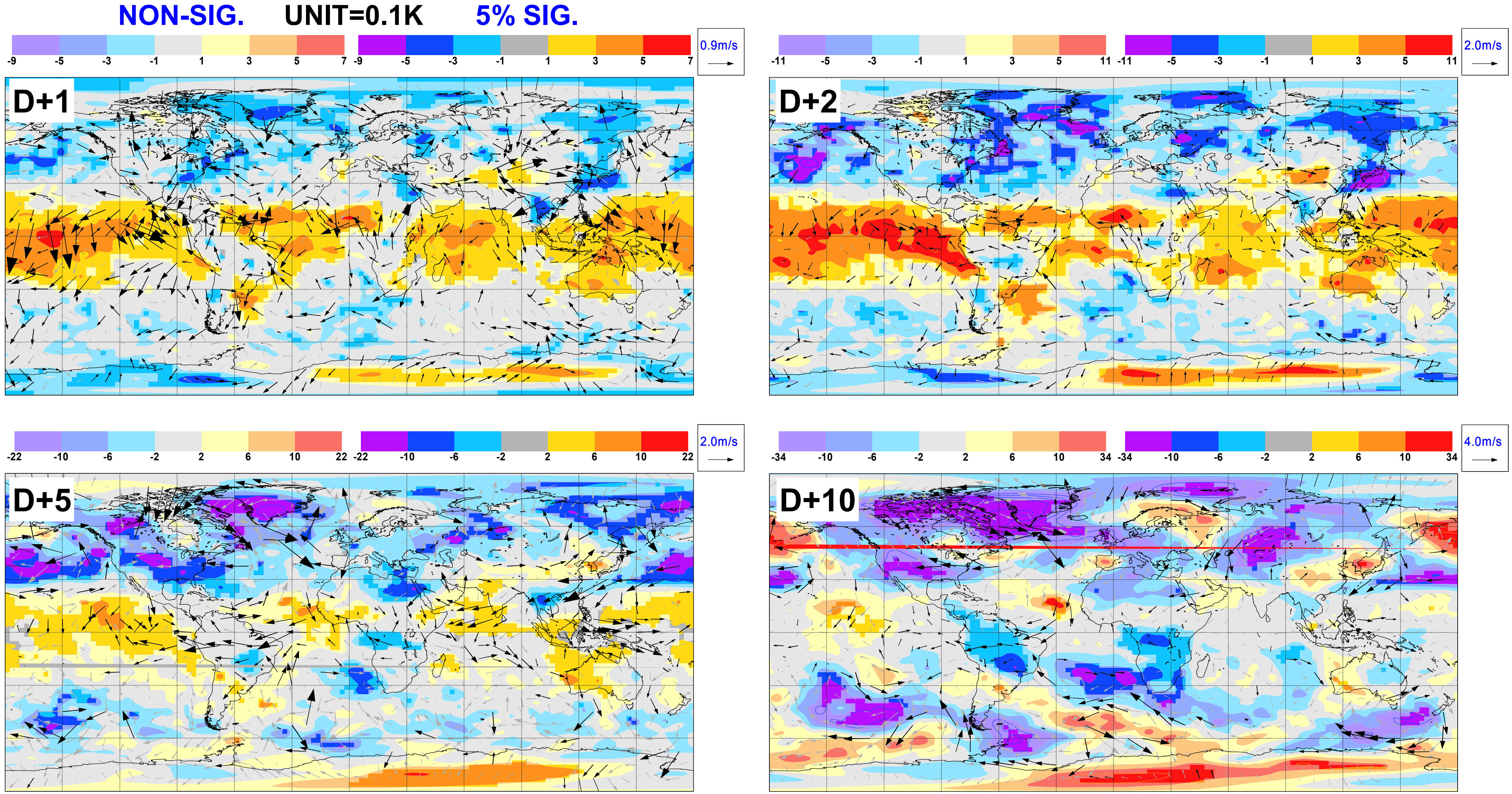
(c) JJA NEW - OLD

(d) JJA NEW - OBS

Precip: Xie-Arkin 1980–1999. V925, Z500: ERA40 1962-01, (a) 10, (b)-(d) 2 dam. 26R3 seasonal data for the same period

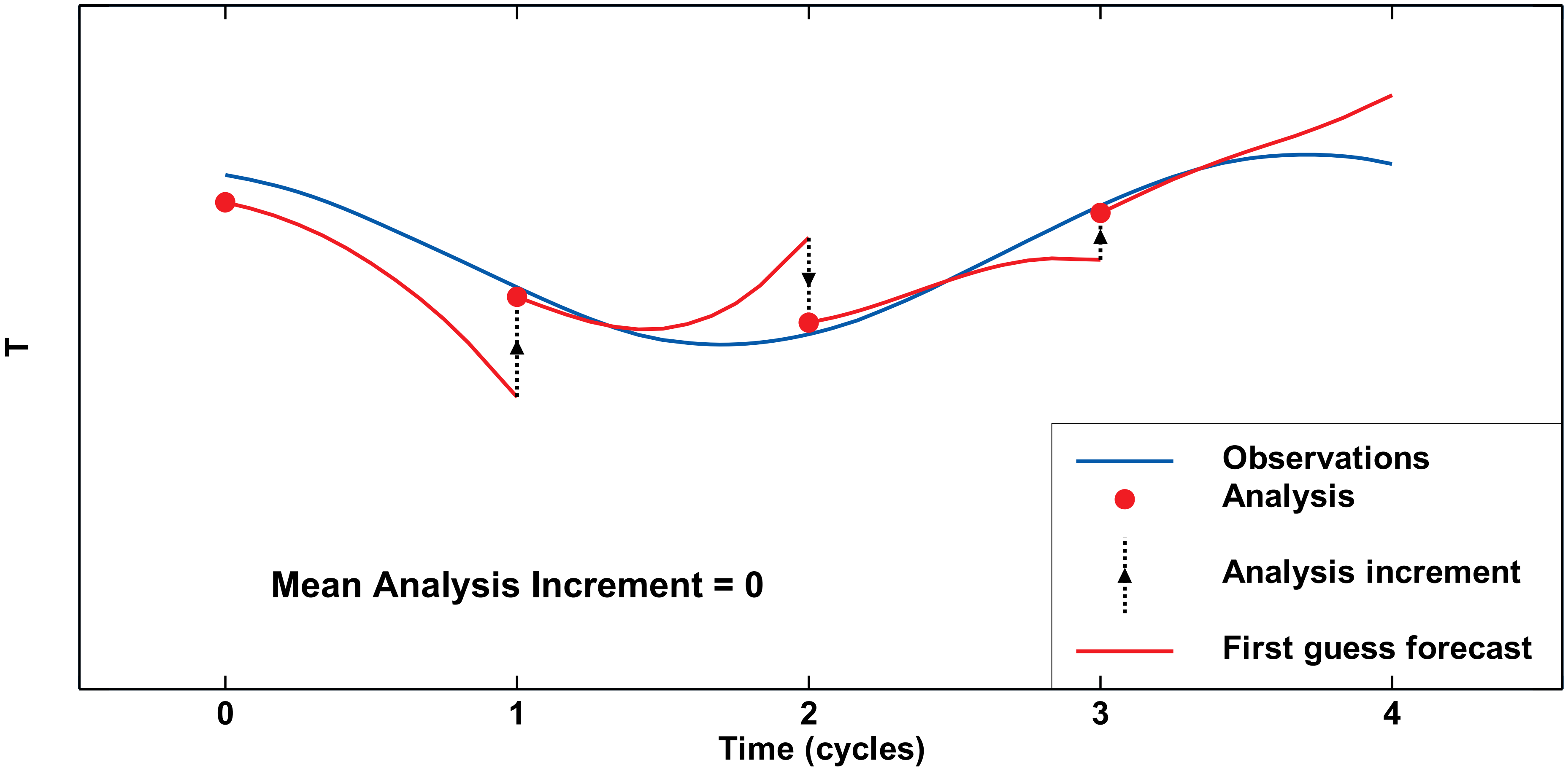
Understanding the Local Physics

DJF T500 Medium-range Mean Forecast Error



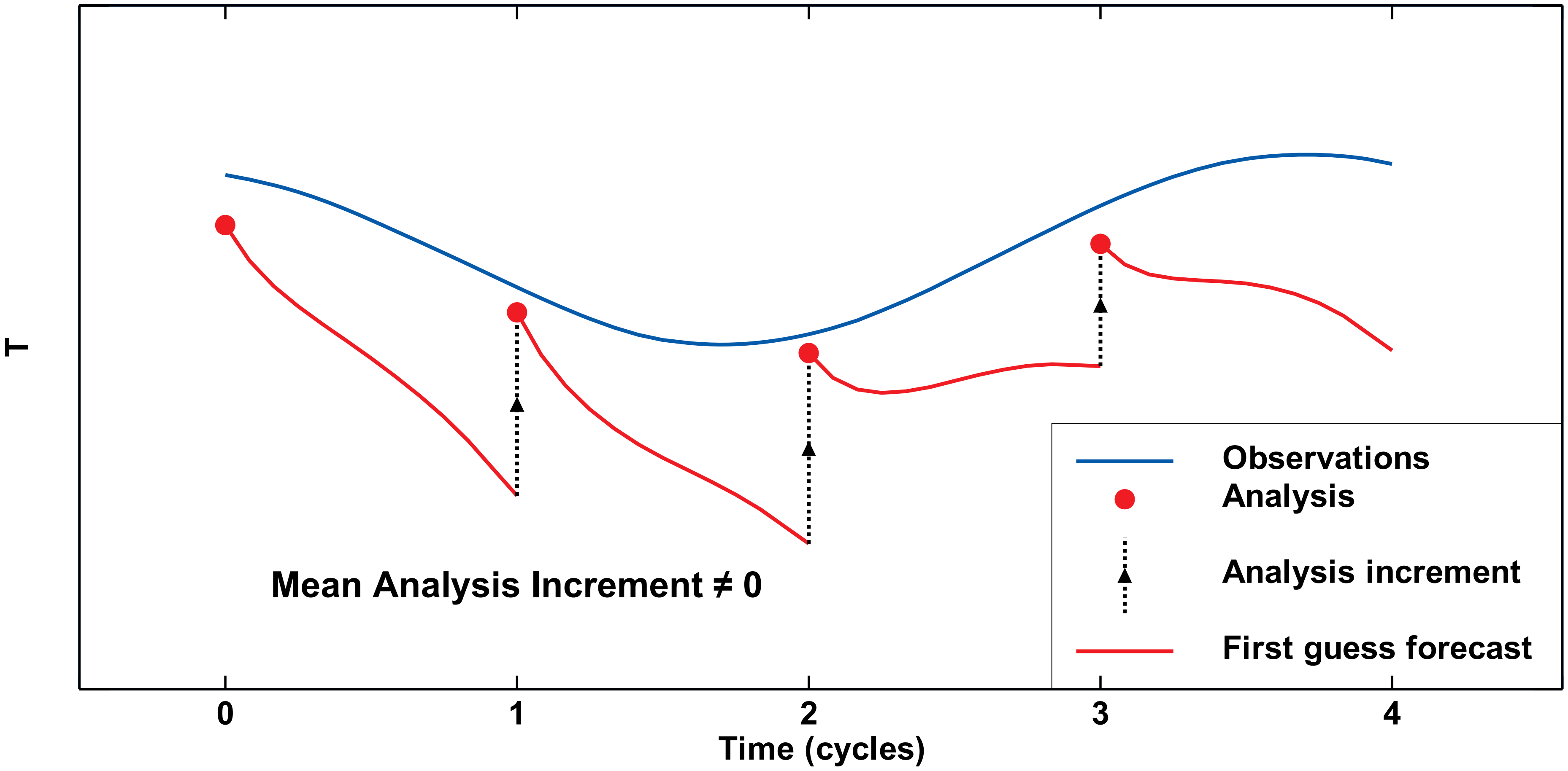
Based on DJF 2006/7 operational analyses and forecasts. Significant values (5% level) in deep colours.

Data Assimilation Cycle: Perfect Model



(Imperfect, unbiased observations)

Data Assimilation Cycle: Imperfect Model



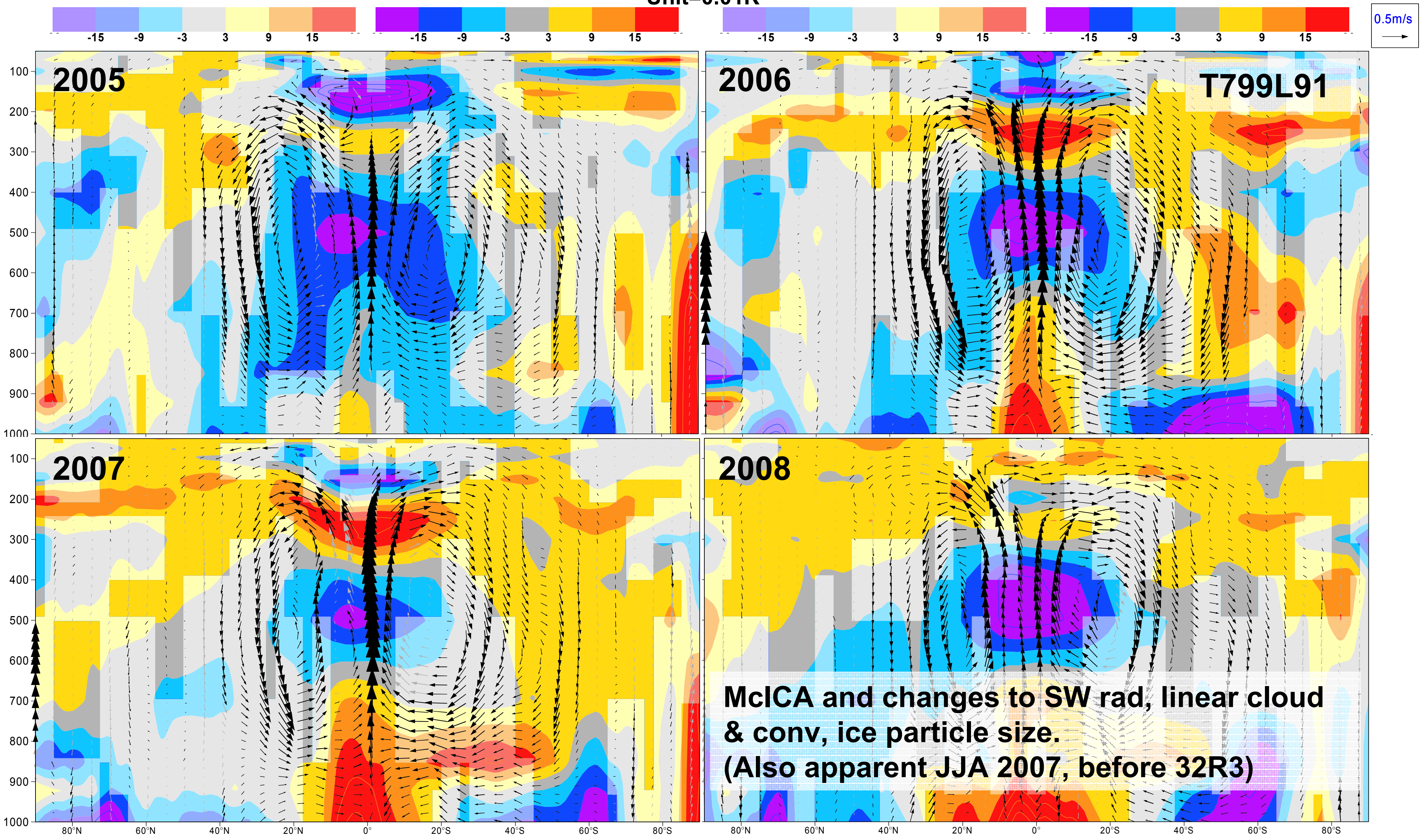
−Mean Analysis Increment = Mean Net Initial Tendency ("I.T." in, *e.g.*, Kcycle^{-1})

= Mean Convective I.T. + Mean Radiative I.T. + … + Mean Dynamical I.T.

(summed over all processes in the model)

MAM Mean Analysis Increments: T and (v,w)

Unit=0.01K

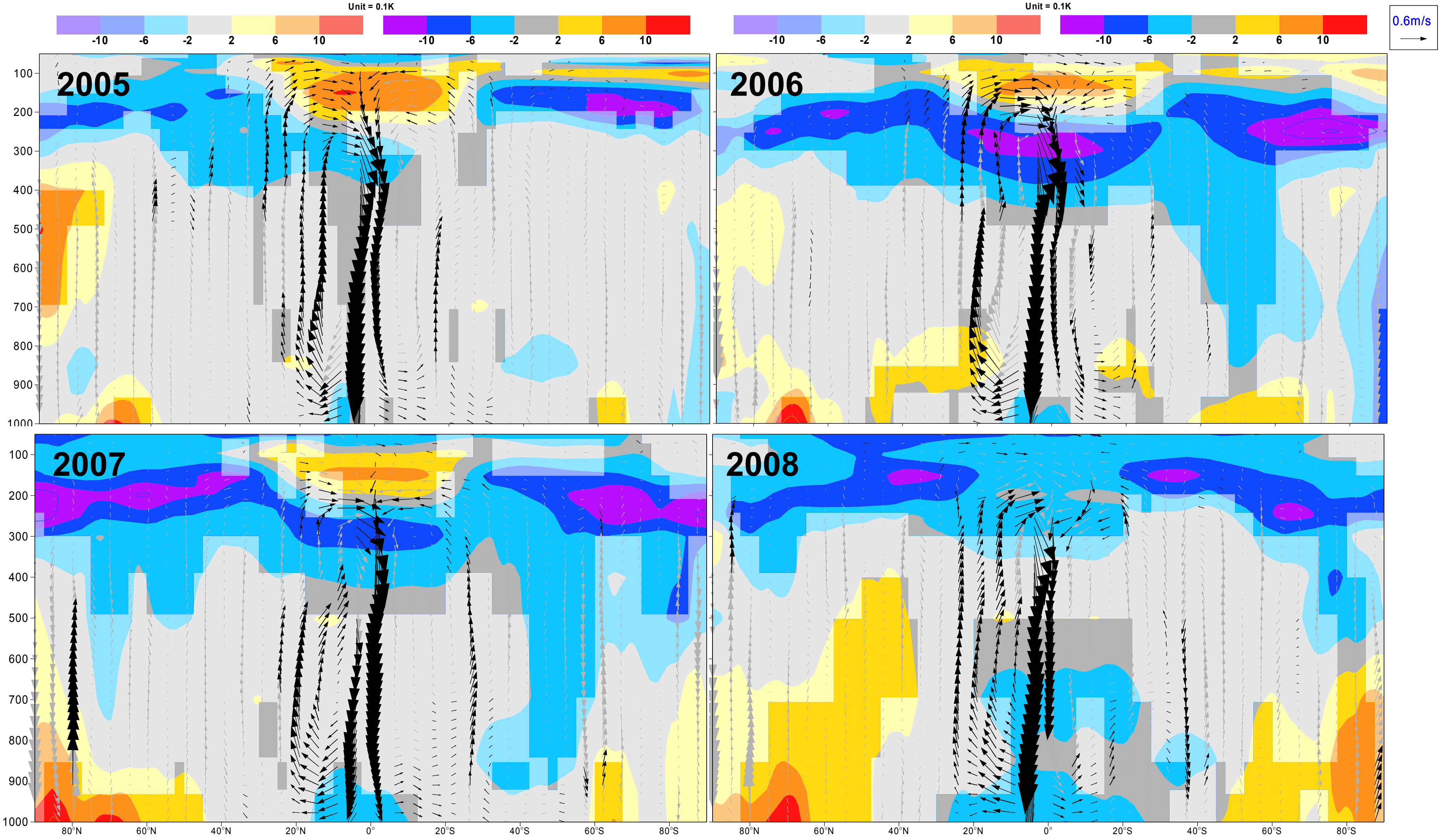


McICA and changes to SW rad, linear cloud & conv, ice particle size.
(Also apparent JJA 2007, before 32R3)

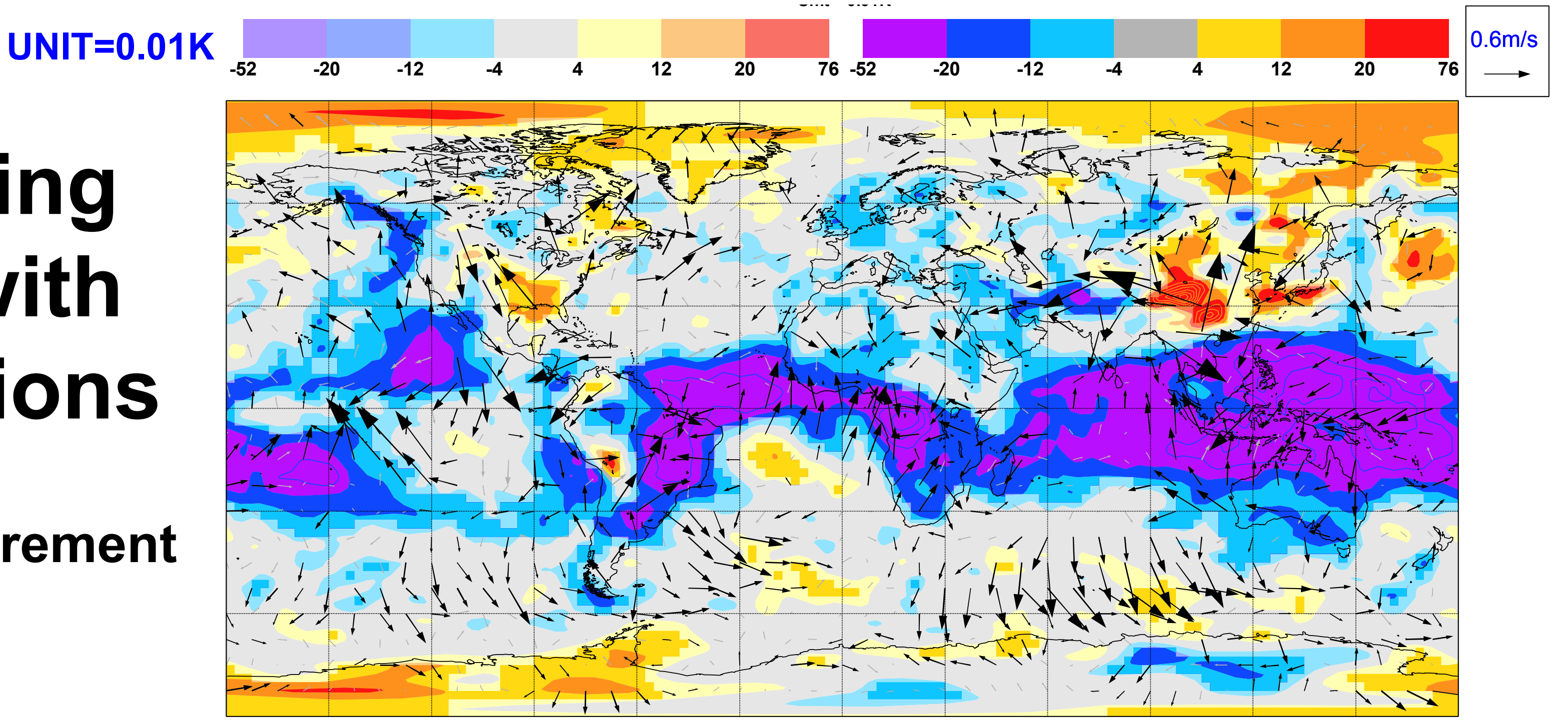
Diagnostics

MJR

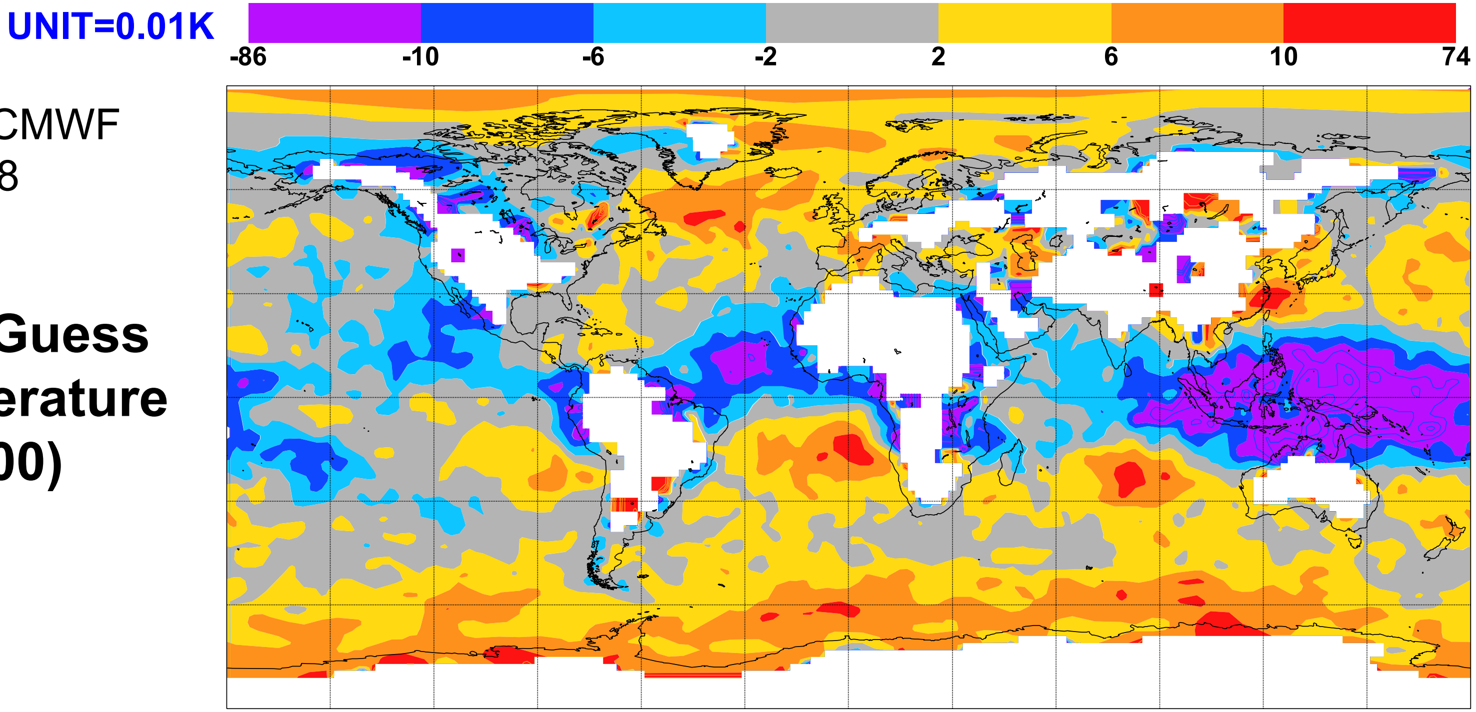
MAM Mean Forecast Error D+5: T and (v,w)



Confronting models with observations



T500 Analysis Increment

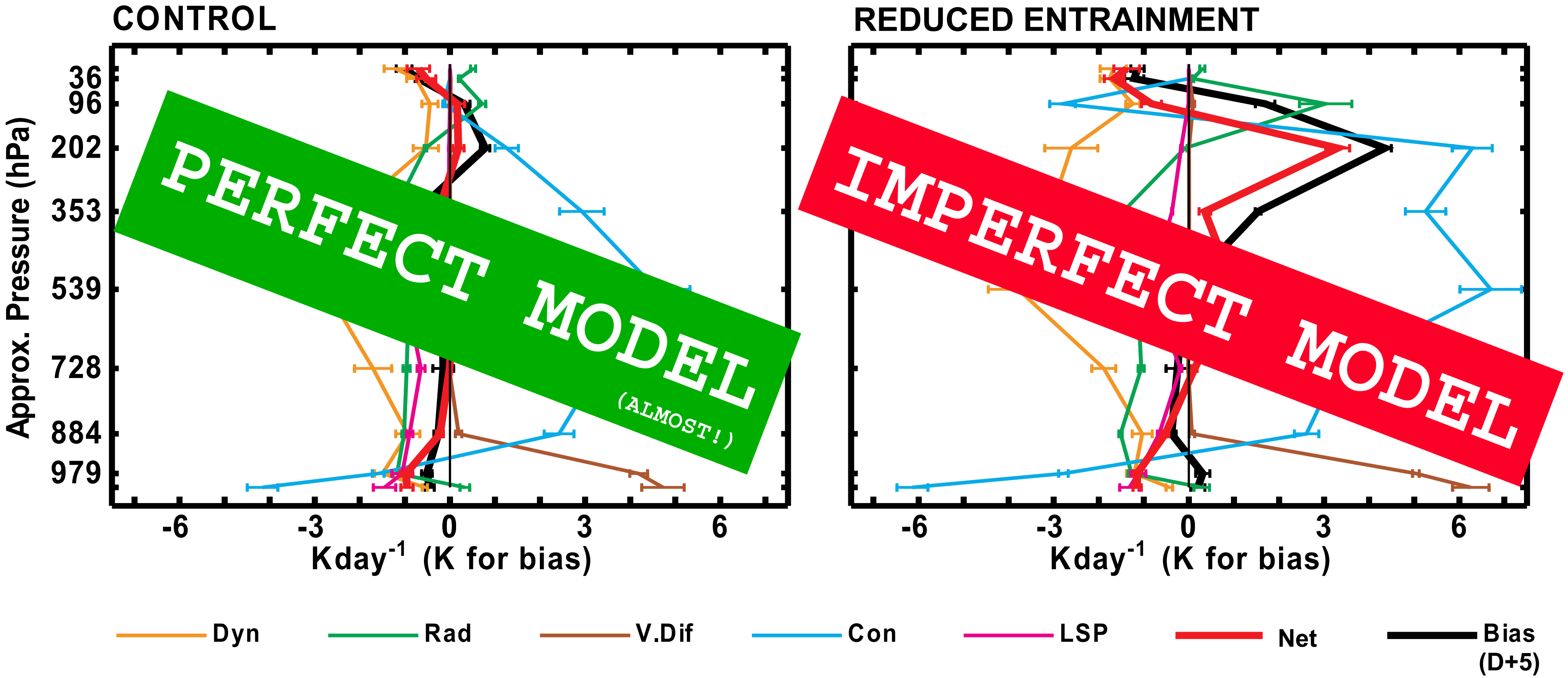


See Rodwell & Jung, ECMWF Newsletter Autumn 2008

Observed – First Guess
Brightness Temperature
AIRS ch 215 (~T500)

DJF 2007/8

Amazon Initial Process Tendencies



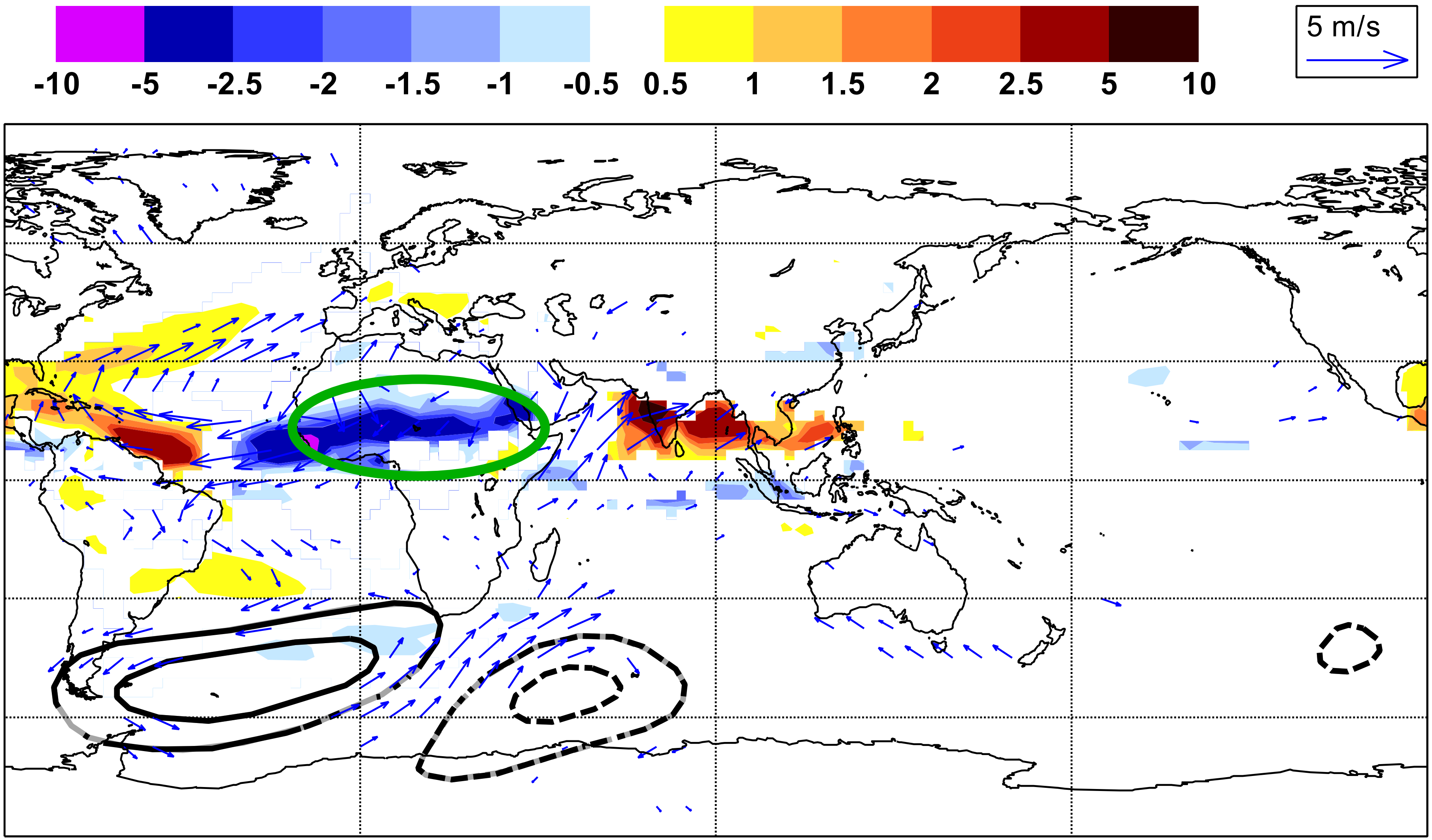
PROCESS TENDENCIES BALANCE WELL – LEADING TO A SMALL NET TENDENCY

IMBALANCE LEADS TO LARGE NET TENDENCIES – INDICATIVE OF PHYSICS ERROR

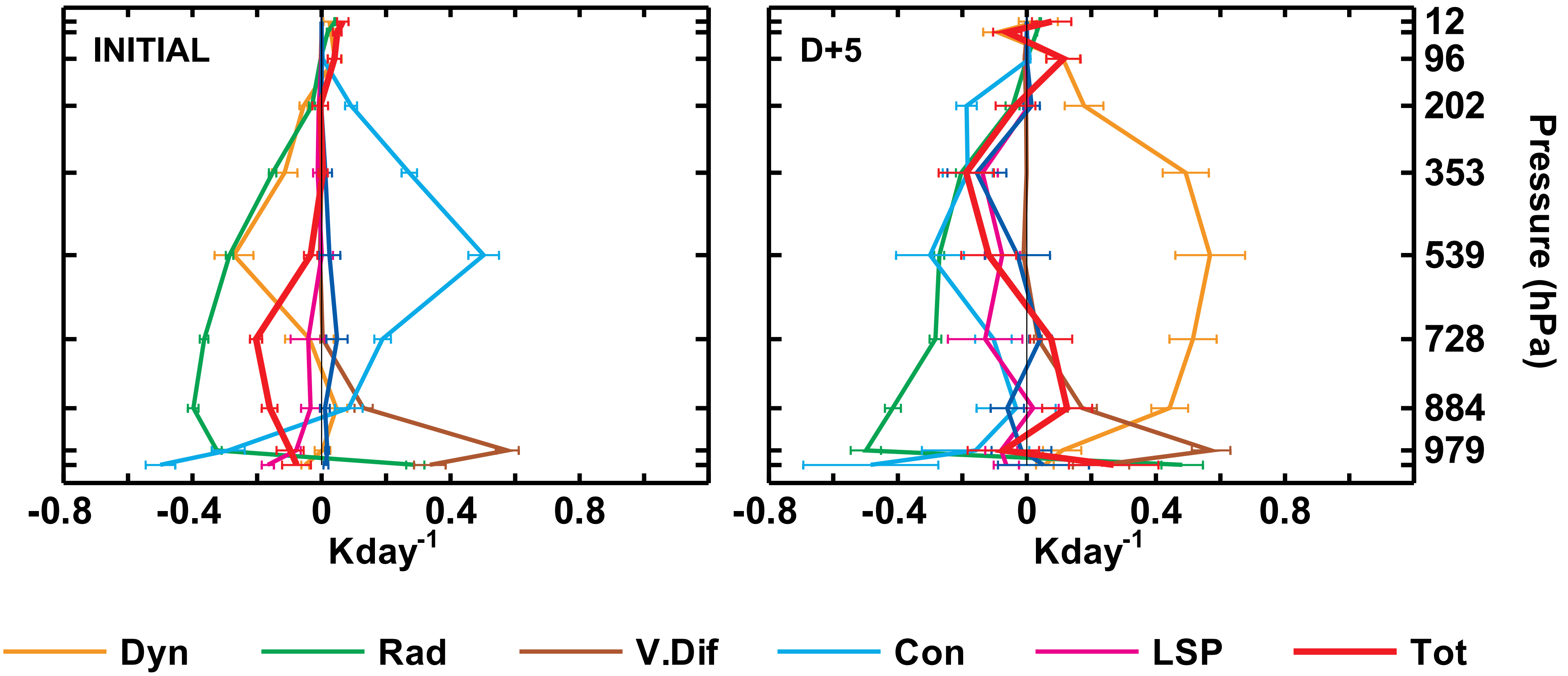
Amazon = [300ºE-320ºE, 20ºS-0ºN]. Mean of 31 days X 4 forecasts per day X 12 timesteps per forecast (January 2005). 70% confidence intervals are based on daily means. CONTROL model = 29R1,T159,L60,1800S.

JJA Precipitation, v925 and Z500. New-Old

mm day^{-1}. 10% Sig.



North Africa Jul 2004 T Tendencies (New-Old)

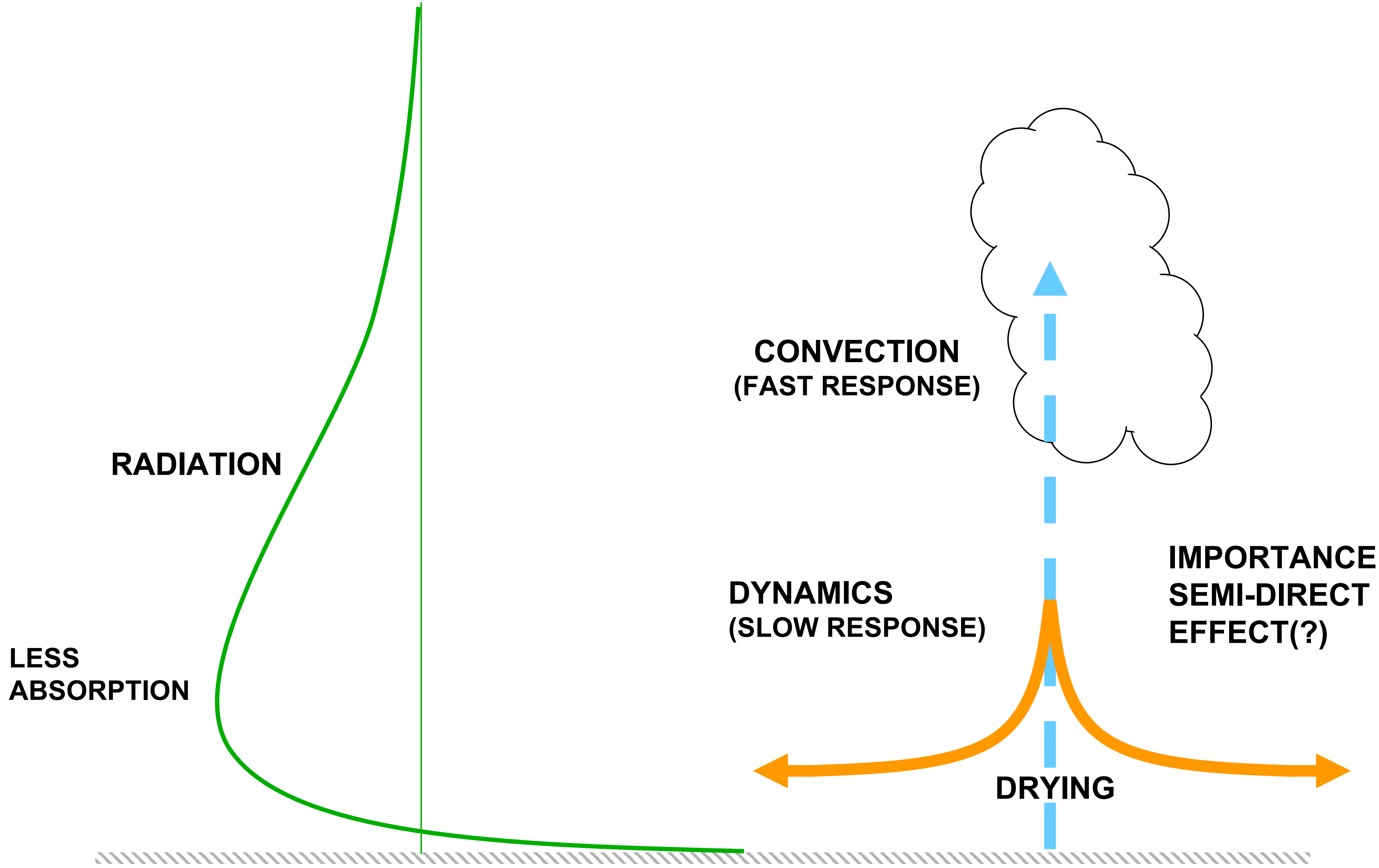


RADIATIATION CHANGES DESTABILISE PROFILE AND LEAD TO MORE CONVECTION …

… BUT ULTIMATELY LEAD TO MORE DESCENT AND LESS OVERALL PRECIPITATION

North Africa = [5ºN-15ºN, 20ºW-40ºE]. Mean of 31 days X 4 forecasts per day X 12 timesteps per forecast. 70% confidence intervals are based on daily means. CONTROL model = 29R1,T159,L60,1800S.

Local Response to Aerosol Reduction



RADIATION

LESS
ABSORPTION

CONVECTION
(FAST RESPONSE)

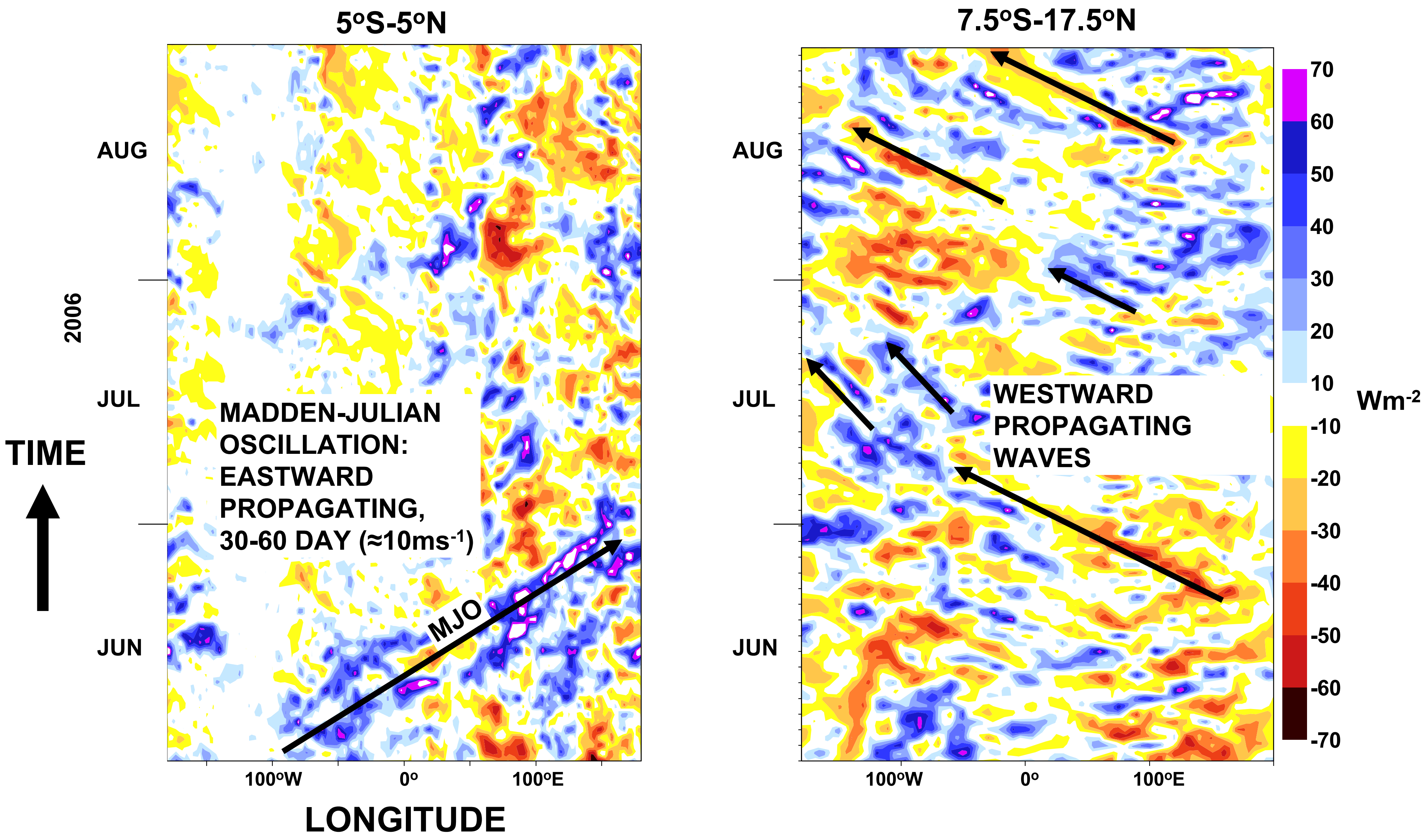
DYNAMICS
(SLOW RESPONSE)

IMPORTANCE OF
SEMI-DIRECT
EFFECT(?)

DRYING

Understanding the Tropic-wide Response

Tropical Waves: Outgoing Long-wave Radiation



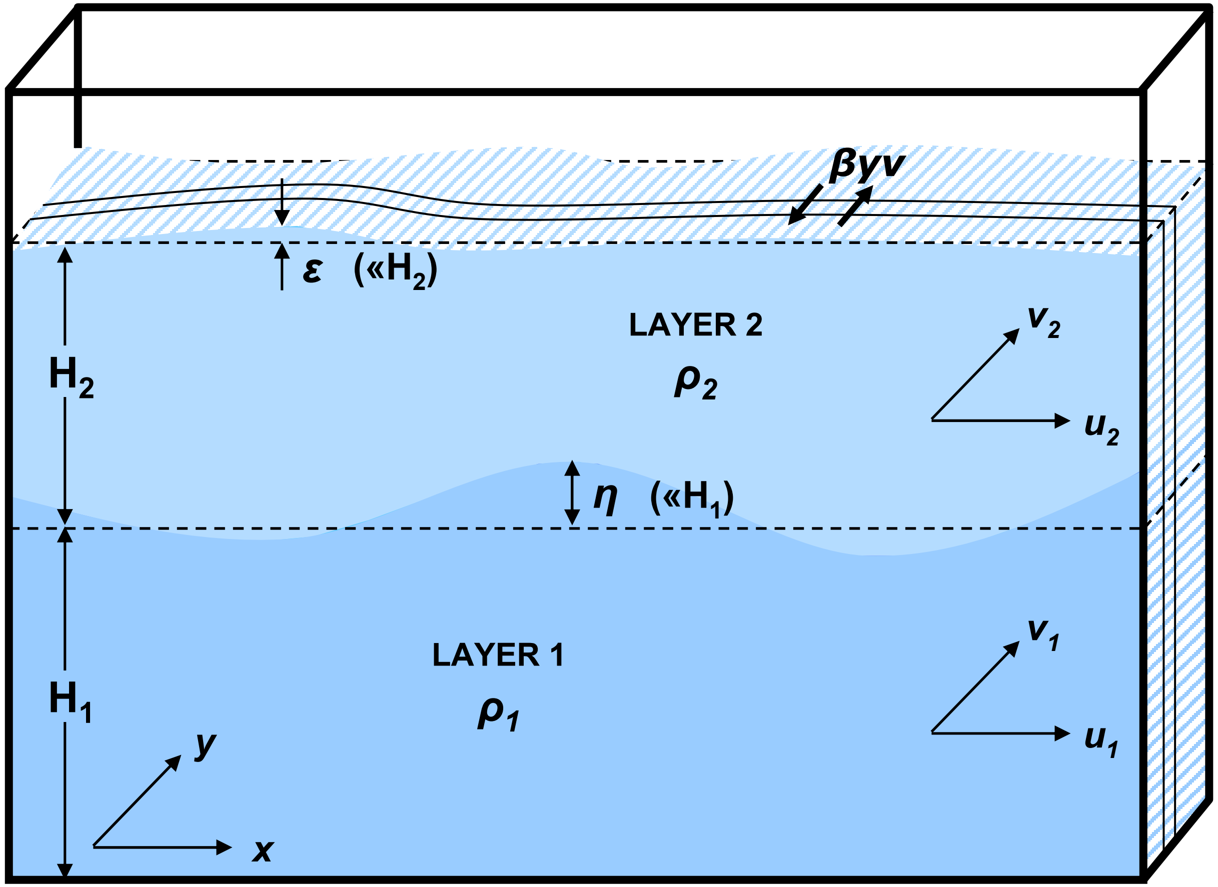
MADDEN-JULIAN OSCILLATION: EASTWARD PROPAGATING, 30-60 DAY (≈10ms^{-1})

WESTWARD PROPAGATING WAVES

Plots from Thomas Jung. OLR data from NOAA

Shallow Water Equations on the β-plane

(Here, for understanding tropical atmospheric waves)



$g' \equiv g\left(1-\frac{\rho_2}{\rho_1}\right)$ "reduced gravity"

$c_e^2 \equiv g'\frac{H_1 H_2}{H_1+H_2} \equiv gH_e$ $c_e \approx 20$ to $80\,\mathrm{ms}^{-2}$

c_e is the propagation speed of a barotropic gravity wave in single layer of depth H_e

Baroclinic mode:

$\varepsilon \ll \eta$

$u \equiv u_1 - u_2$

$v \equiv v_1 - v_2$

Momentum:

$$\frac{\partial u}{\partial t} - \beta y v + g'\frac{\partial \eta}{\partial x} \approx 0$$

$$\frac{\partial v}{\partial t} + \beta y u + g'\frac{\partial \eta}{\partial y} \approx 0$$

Continuity:

$$\left(\frac{1}{H_1}+\frac{1}{H_2}\right)\frac{\partial \eta}{\partial t} + \left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) \approx 0$$

Solving for v:

$$\frac{\partial}{\partial t}\left\{\frac{\partial^2 v}{\partial t^2} + \beta^2 y^2 v - c_e^2\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)\right\} - c_e^2 \beta \frac{\partial v}{\partial x} = 0$$

Free Equatorial Waves

V=0:

$$u = u_0 e^{-y^2/2} e^{ik(x-c_e t)}$$

East propagating **Kelvin Wave**

- Non-dispersive
- In geostrophic balance

V≠0:

$$v = \hat{v}(y) e^{i(kx-\omega t)}$$

Substitute into equation for v

Structures

(Meridional structures are solutions to Schrodinger's simple harmonic oscillator)

$$\hat{v}(y) = \begin{bmatrix} 1 \\ 2y \\ 4y^2 - 1 \\ 8y^3 - 12y \\ \vdots \\ H_n(y) \end{bmatrix} e^{-y^2/2}$$

Hermite Polynomials: $H_n(y)$

- Each successive polynomial has one more node
- Modes alternate asymmetric / symmetric about equator

Dispersion

(How phase speed is related to spatial scale)

$$\left(\frac{\omega^2}{c_e^2} - k^2 - \frac{\beta k}{\omega} \right) = (2n+1) \frac{\beta}{c_e}$$

$$(n = 0,1,2,\ldots)$$

For n ≠0: 3 values of ω for each k

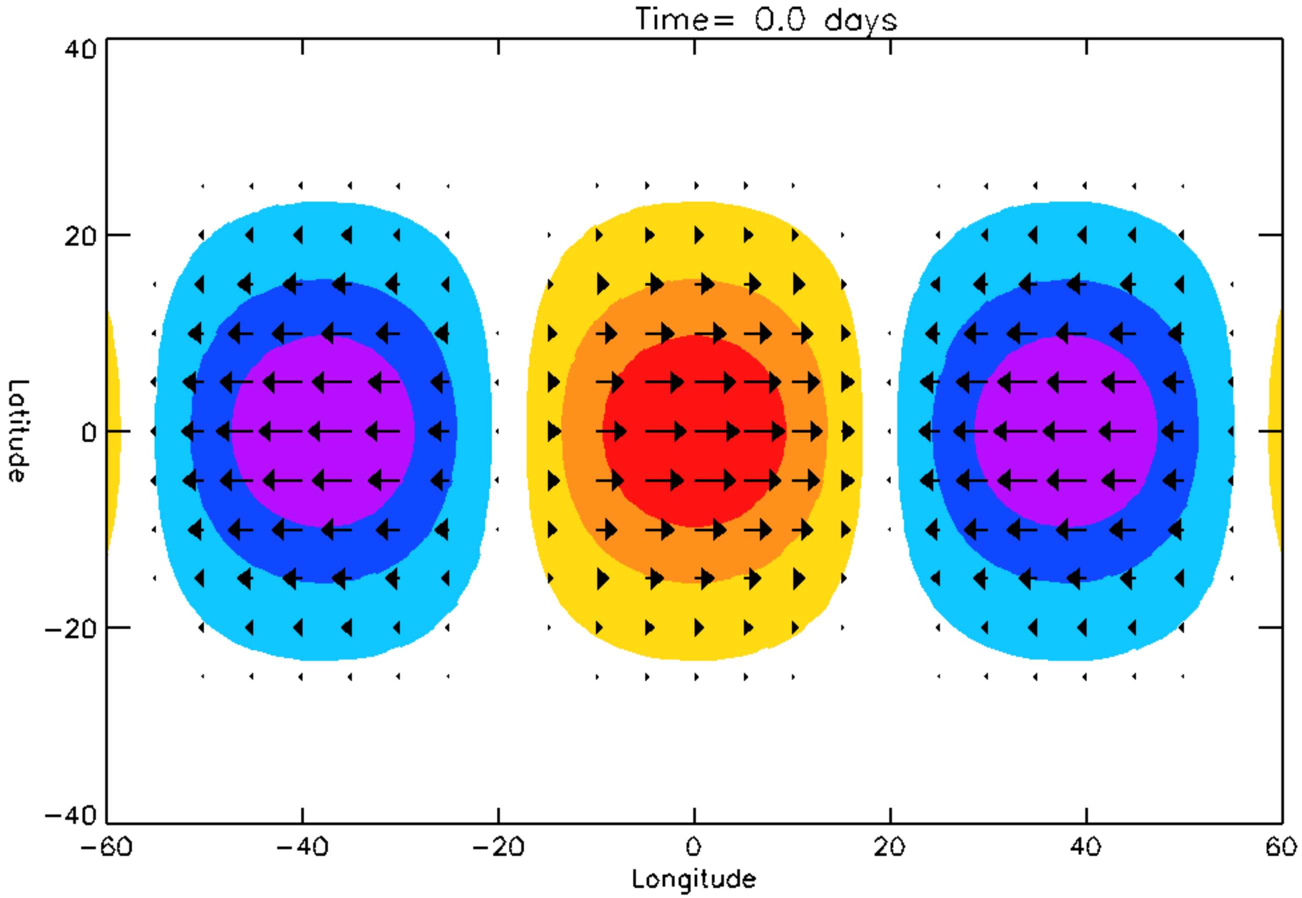
- West propagating **Rossby Wave**
- E & W propagating **Gravity Wave**

For n=0: 2 values of ω for each k

- E & W prop. **Mixed Rossby-Gravity**

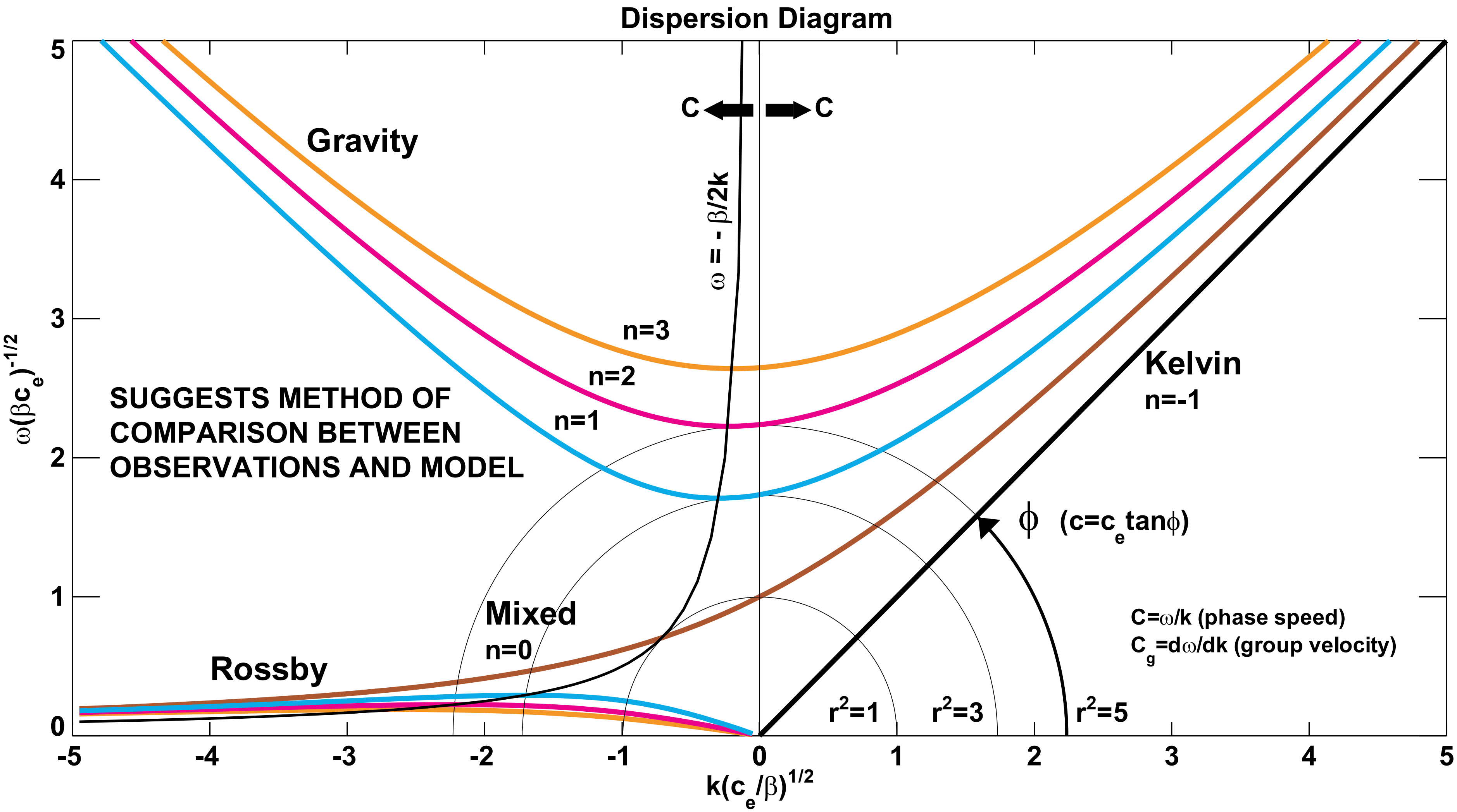
y has been non-dimensionalised by the factor $(\beta / c_e)^{1/2}$

Wave Spotting



Colours show height perturbation (red positive, blue negative), arrows show lower-level winds

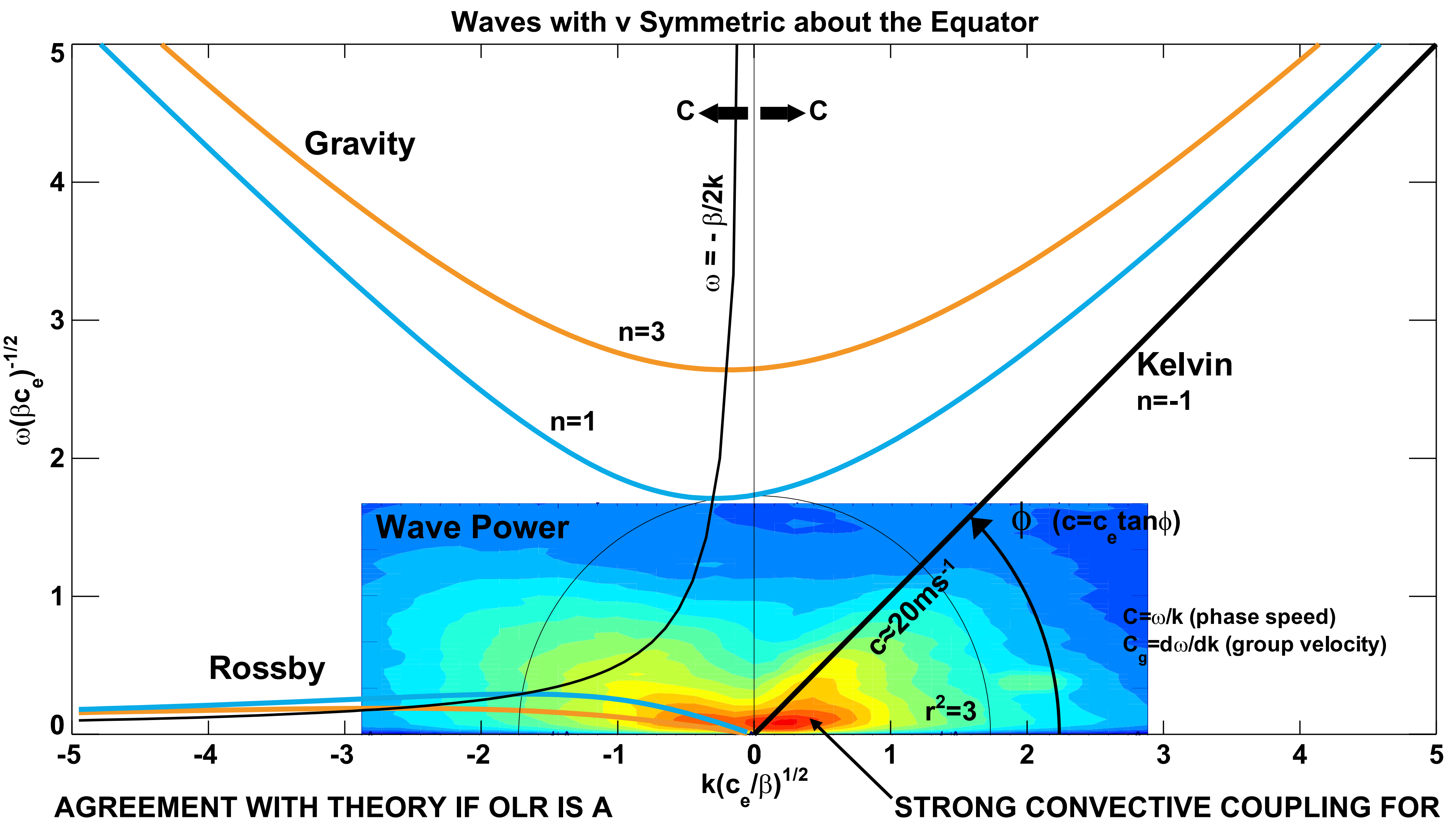
Interpretation of Free Equatorial Waves



SUGGESTS METHOD OF COMPARISON BETWEEN OBSERVATIONS AND MODEL

$C=\omega/k$ (phase speed)
$C_g=d\omega/dk$ (group velocity)

Symmetric waves. Observed OLR (NOAA)

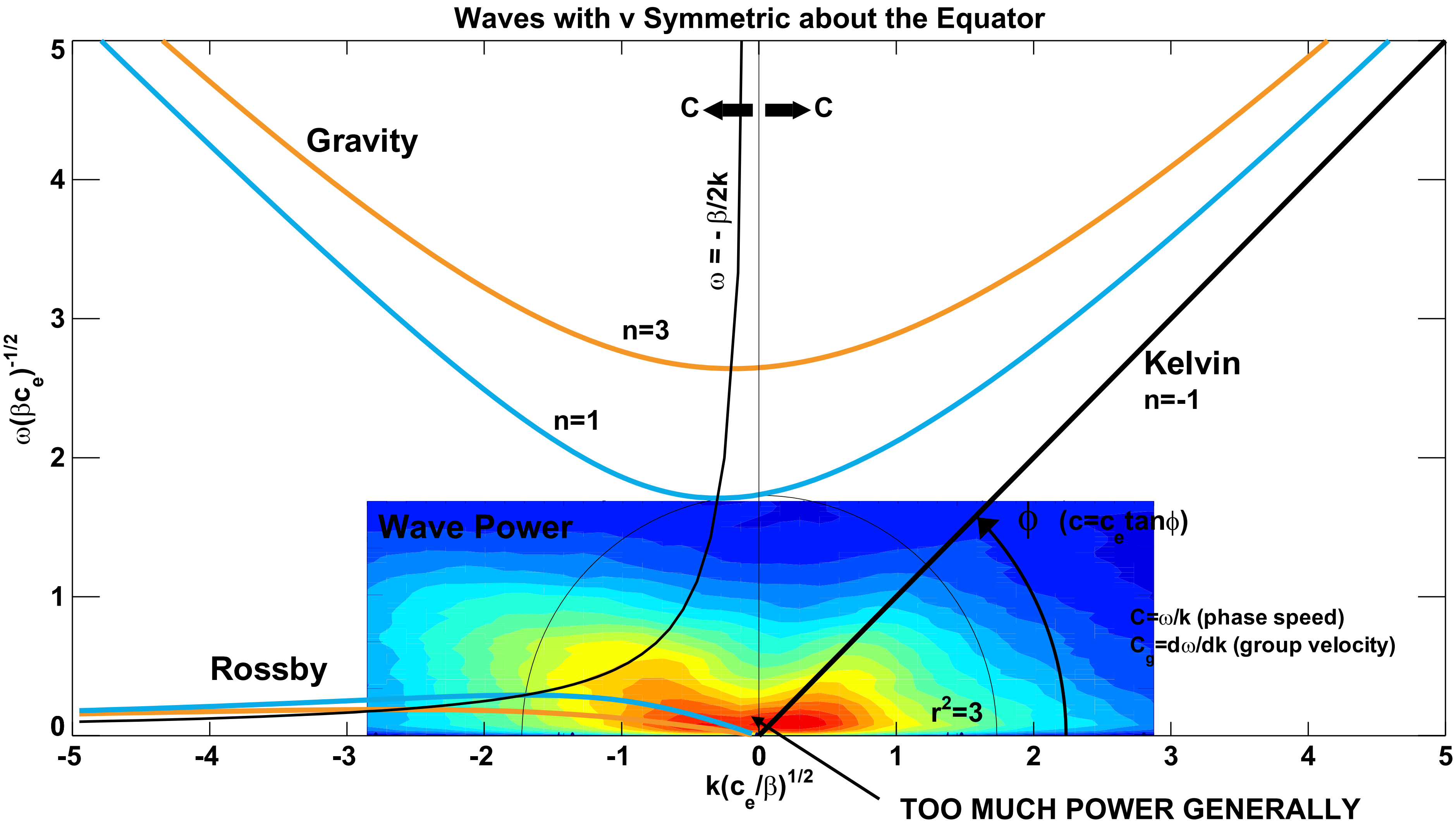


AGREEMENT WITH THEORY IF OLR IS A "SLAVE" TO THE FREE WAVES, LINEARITY ETC.

STRONG CONVECTIVE COUPLING FOR MJO AS IT DOESN'T LIE ON ANY LINE(?)

DJF 1990-2005. Following Wheeler and Kiladis (1999). Convective coupling generally reduces phase speed

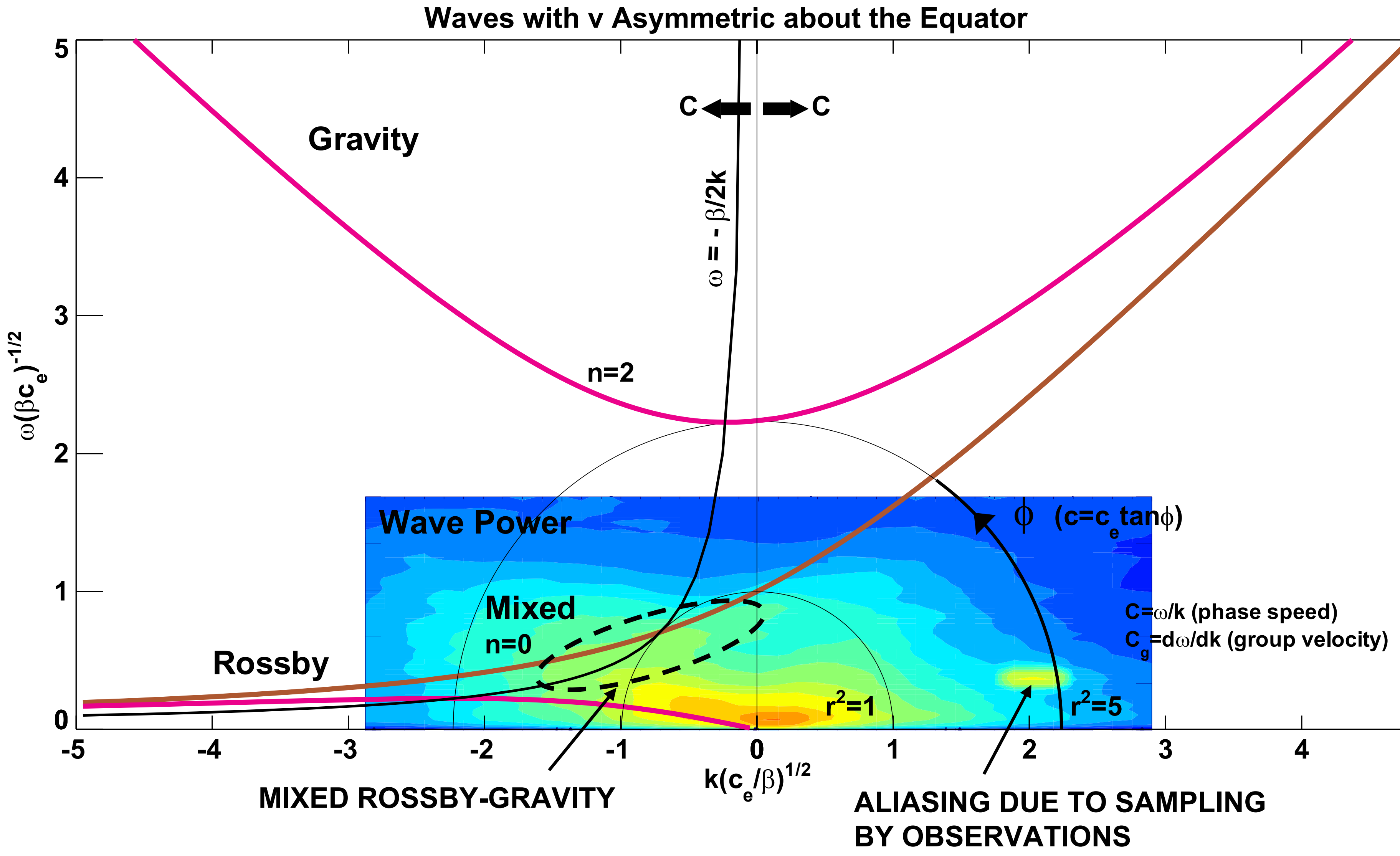
Symmetric waves. Simulated OLR (ECMWF)



TOO MUCH POWER GENERALLY AT LOW FREQUENCIES

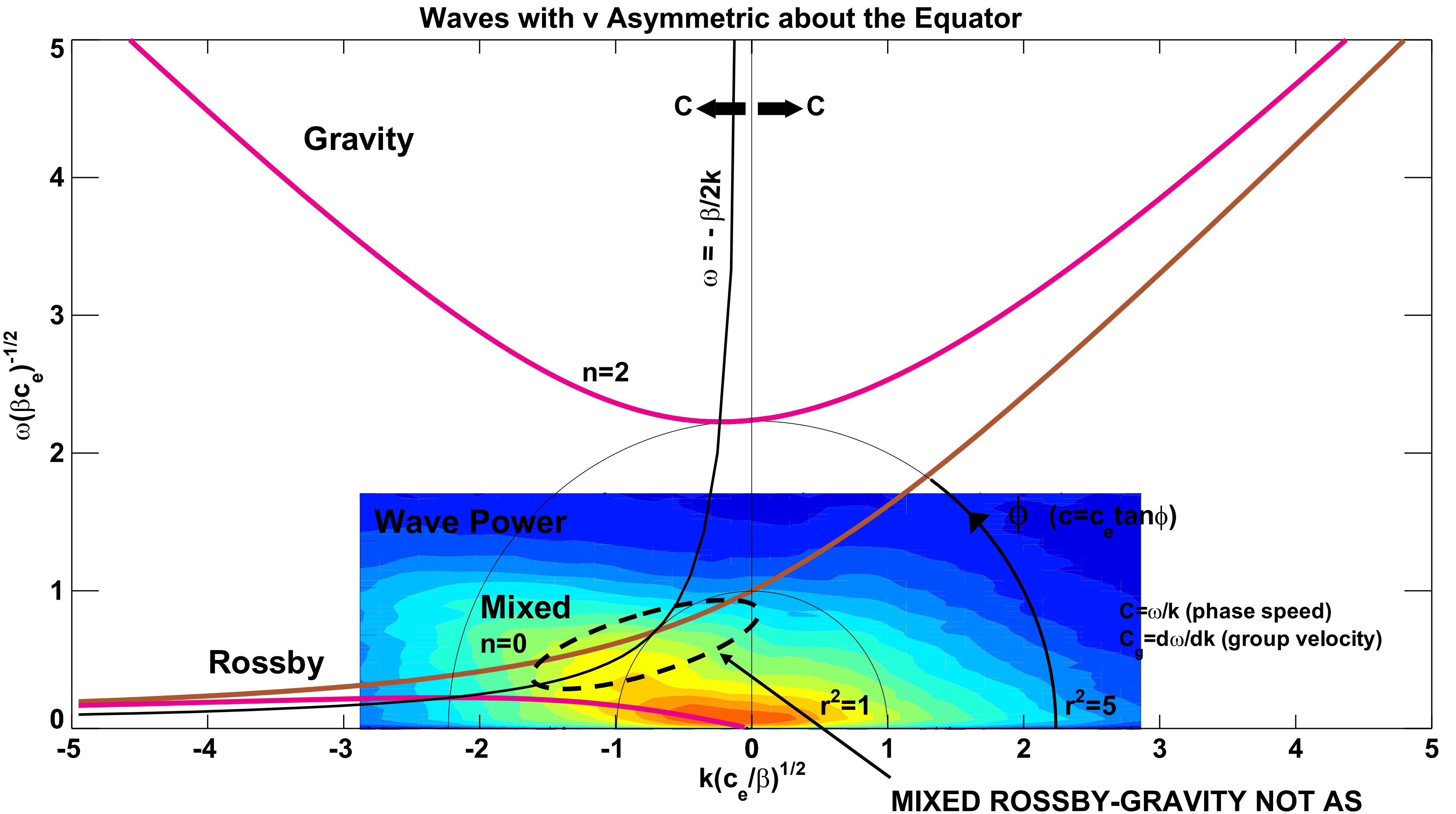
Model cycle: 32R3, resolution: T159L91, DJF 1990-2005

Asymmetric waves. Observed OLR (NOAA)



DJF 1990-2005

Asymmetric waves. Simulated OLR (ECMWF)



MIXED ROSSBY-GRAVITY NOT AS EVIDENT AS IN THE OBSERVATIONS

Model cycle: 32R3, resolution: T159L91, DJF 1990-2005

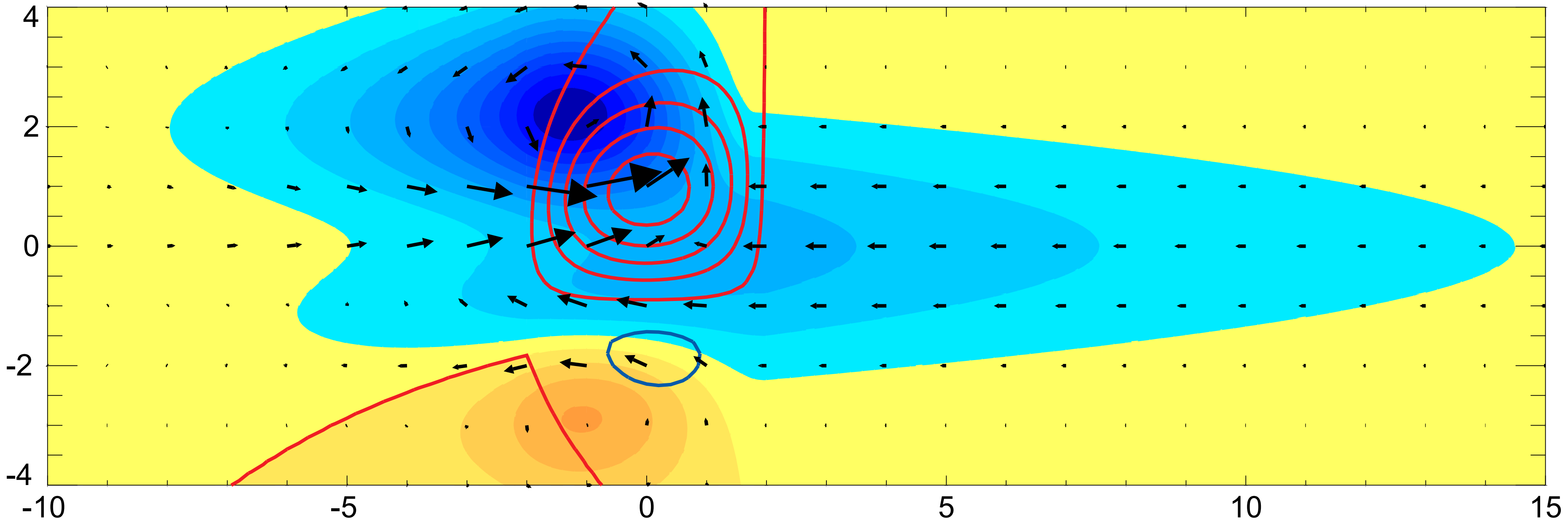
Gill's steady solution to monsoon heating

DAMPING/HEATING TERMS TAKE THE PLACE OF THE TIME DERIVATIVES

EXPLICITLY SOLVE FOR THE X-DEPENDENCE

GOOD AGREEMENT WITH THE AEROSOL CHANGE RESULTS (OPPOSITE SIGN):

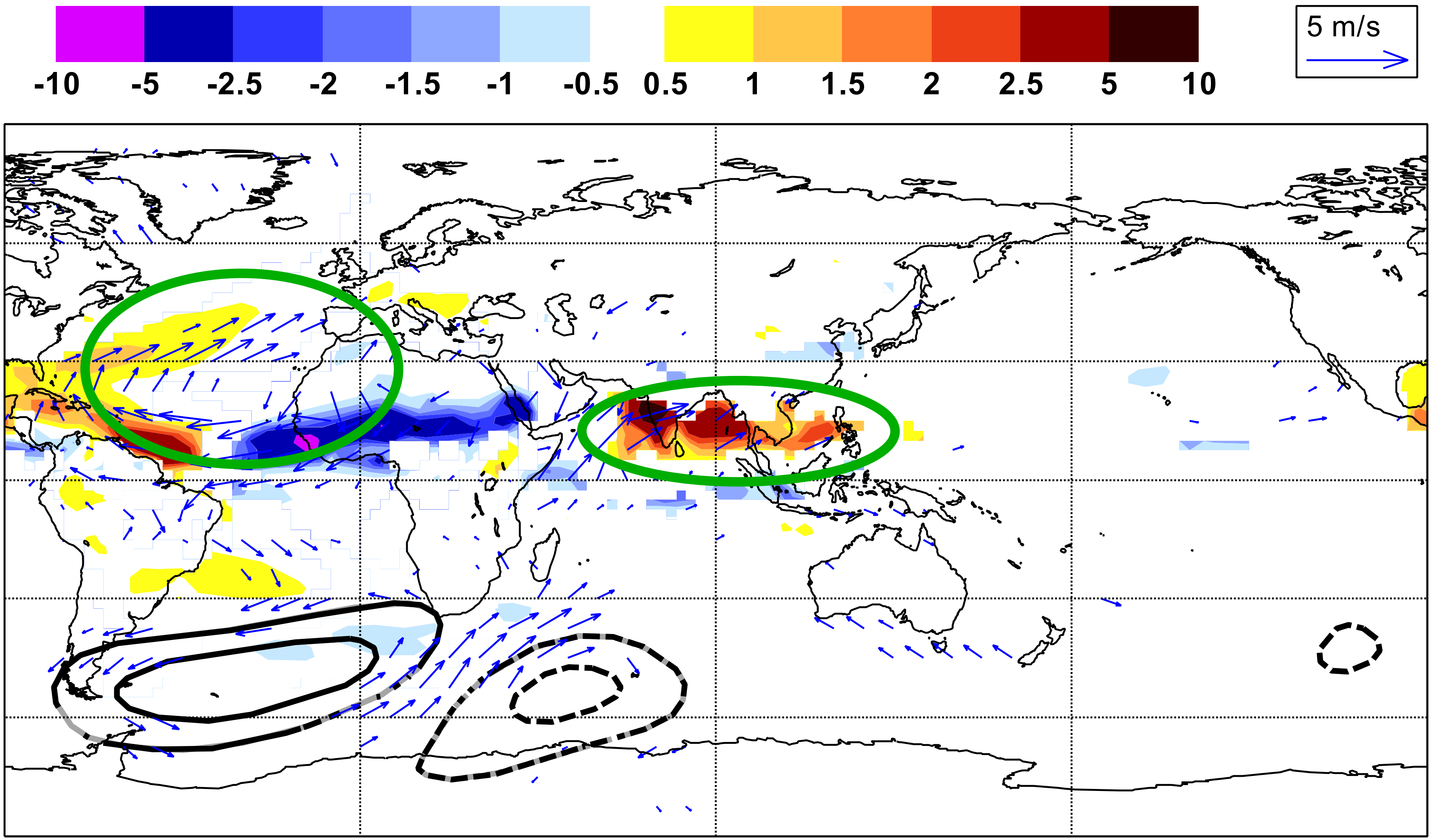
- **NORTH ATLANTIC SUBTROPICAL ANTICYCLONE**
- **CONVECTIVE COUPLING IN KELVIN WAVE REGIME**



Colours show perturbation pressure, vectors show velocity field for lower level, contours show vertical motion (blue = -0.1, red = 0.0,0.3,0.6,…)

Following Gill (1980). See also Matsuno (1966)

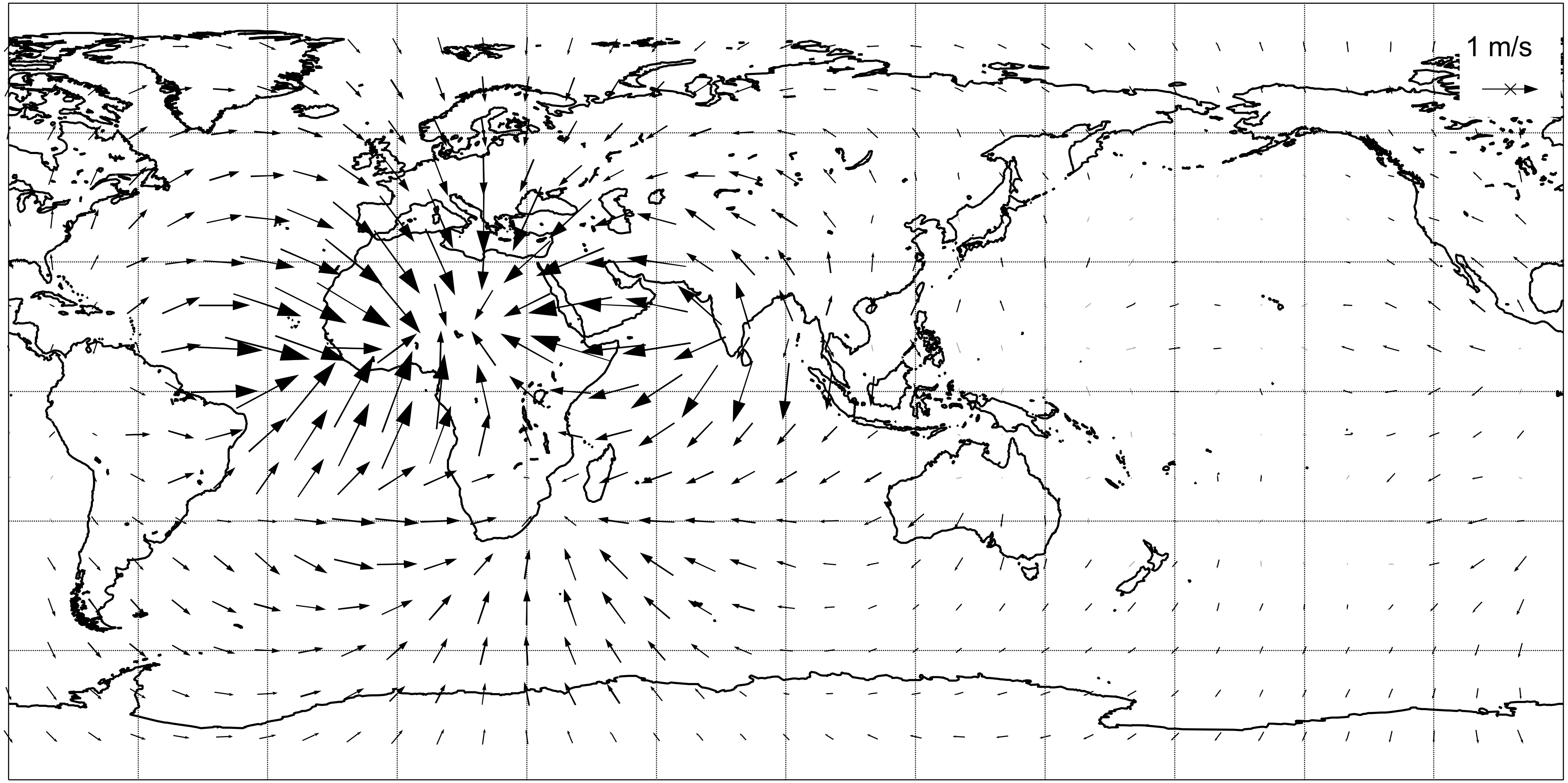
JJA Precipitation, v925 and Z500. New-Old



mm day^{-1}. 10% Sig.

Understanding the Extra-tropical Response

Upper Troposphere Divergent Wind Anomaly



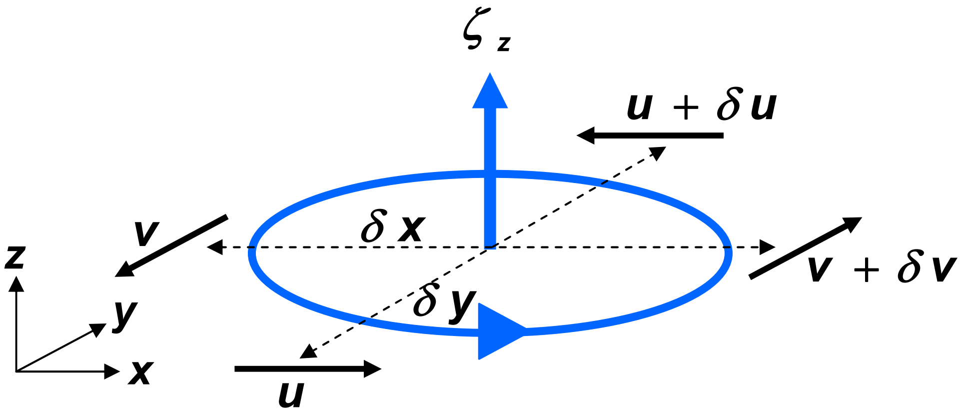
New minus Old aerosol. Anomaly is integrated between 100 and 300 hPa

The Vorticity Equation

Motivation (2D flow) :

$$\zeta_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad \left(\equiv \underline{\hat{k}} \cdot \underline{\nabla}_z \times \underline{v}\right)$$

$\underline{\hat{k}}$ is the unit “vertical” vector and
$\underline{\nabla}_z \times$ is the horizontal curl operator

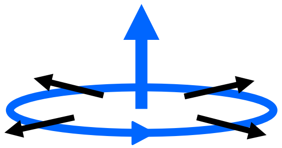


Curl of the 3D momentum equation in absolute frame of reference:

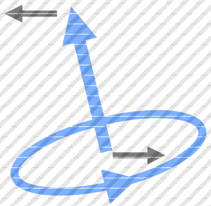
$$\frac{d\underline{\zeta}}{dt} = -\underline{\zeta}\left(\underline{\nabla}\cdot\underline{u}\right) + \left(\underline{\zeta}\cdot\underline{\nabla}\right)\underline{u} + \frac{1}{\rho^2}\underline{\nabla}\rho\times\underline{\nabla}p + \underline{\nabla}\times\underline{F}_u$$

Lagrangian tendency in absolute vorticity

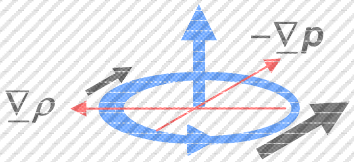
Divergence



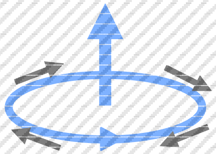
Tilting



Baroclinic



Friction



NEGLECT THESE TERMS

Barotropic Vorticity Equation

- Making the shallow atmosphere approximations and assuming barotropic, frictionless, horizontal flow

$$\begin{aligned}\frac{\partial \zeta}{\partial \boldsymbol{t}} + \underline{\boldsymbol{v}}_{\psi} \cdot \underline{\nabla} \zeta &= -\underline{\nabla} \cdot \left(\underline{\boldsymbol{v}}_{\chi} \zeta \right) \\ &= -\zeta \underline{\nabla} \cdot \underline{\boldsymbol{v}}_{\chi} - \underline{\boldsymbol{v}}_{\chi} \cdot \underline{\nabla} \zeta\end{aligned}$$

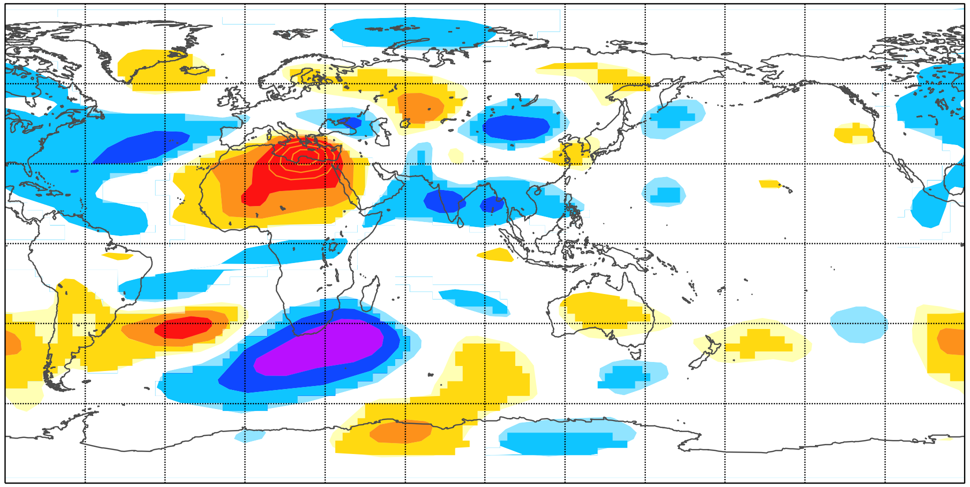
"Rossby Wave Source"

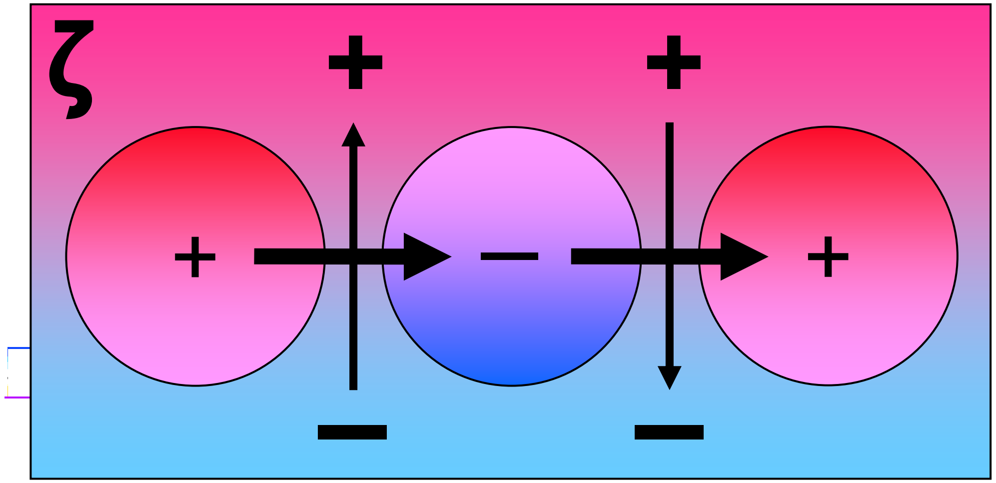
- Application to simple models: Sardeshmukh and Hoskins (1988).
- For use in complex GCMs, it is found here to be useful to vertically integrate this equation between 100 and 300 hPa.
- Is the extra-tropical mean response a linear stationary-wave solution?

$$\underline{\boldsymbol{v}}'_{\psi} \cdot \underline{\nabla} \overline{\zeta} + \underline{\overline{\boldsymbol{v}}}_{\psi} \cdot \underline{\nabla} \zeta' \approx -\overline{\zeta} \underline{\nabla} \cdot \underline{\boldsymbol{v}}'_{\chi} - \underline{\boldsymbol{v}}'_{\chi} \cdot \underline{\nabla} \overline{\zeta} \quad \textbf{(?)}$$

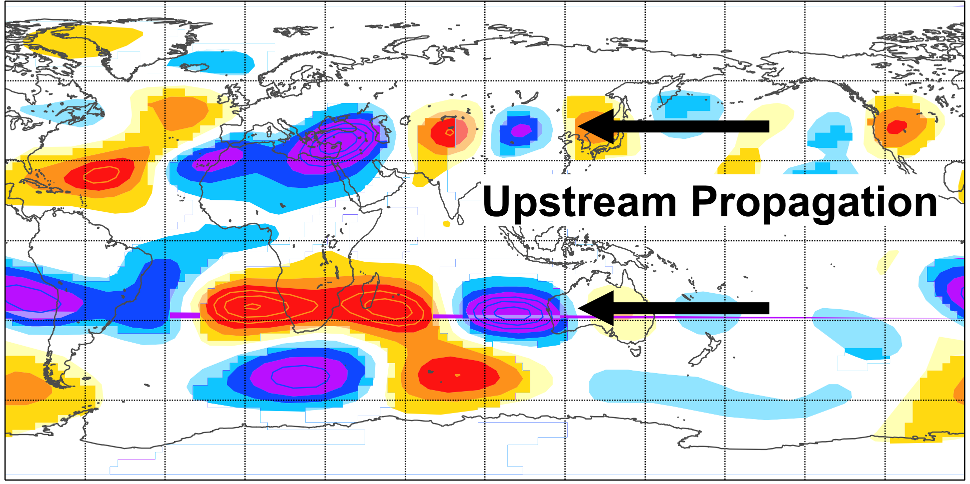
JJA Balance in Vorticity Equation New-Old

Rossby Wave Source

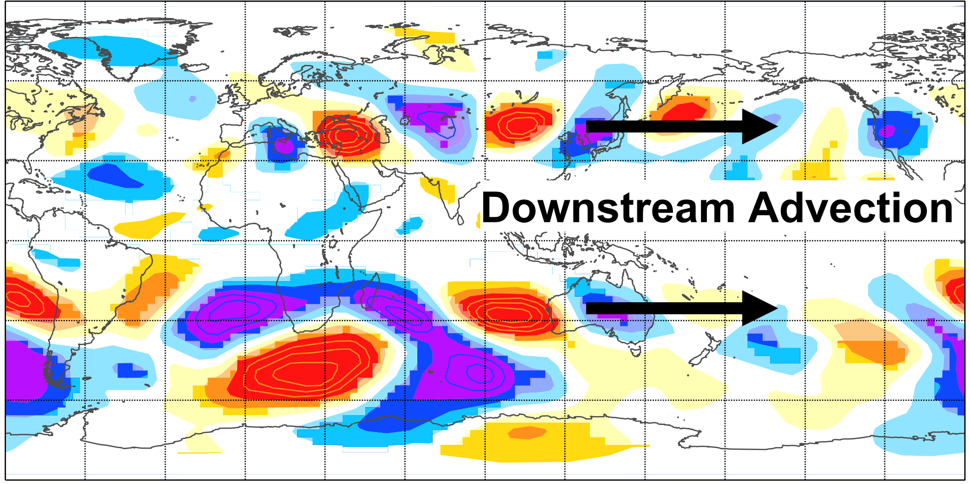




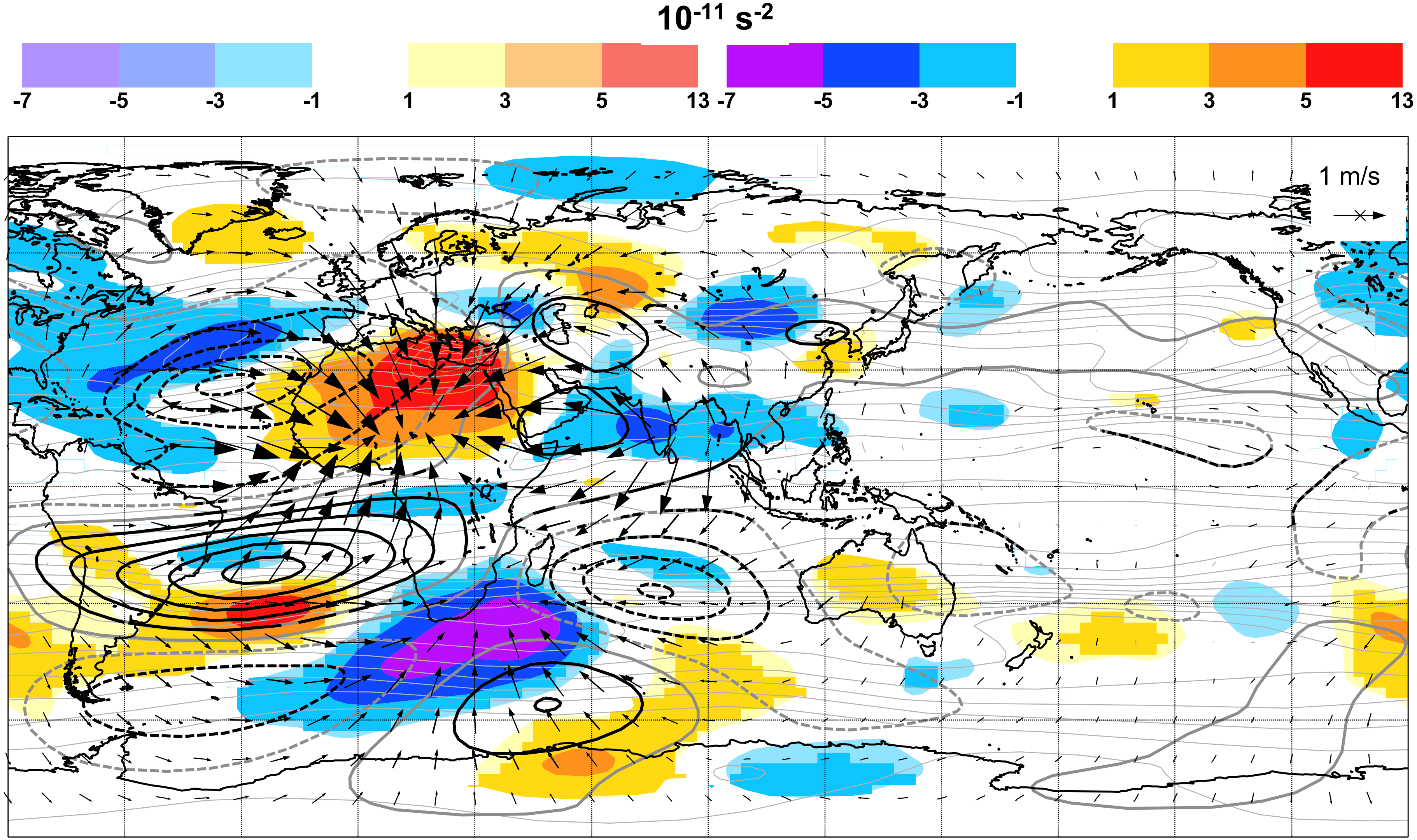
Advection by Anomalous Rotational Wind



Advection of Anomalous Vorticity



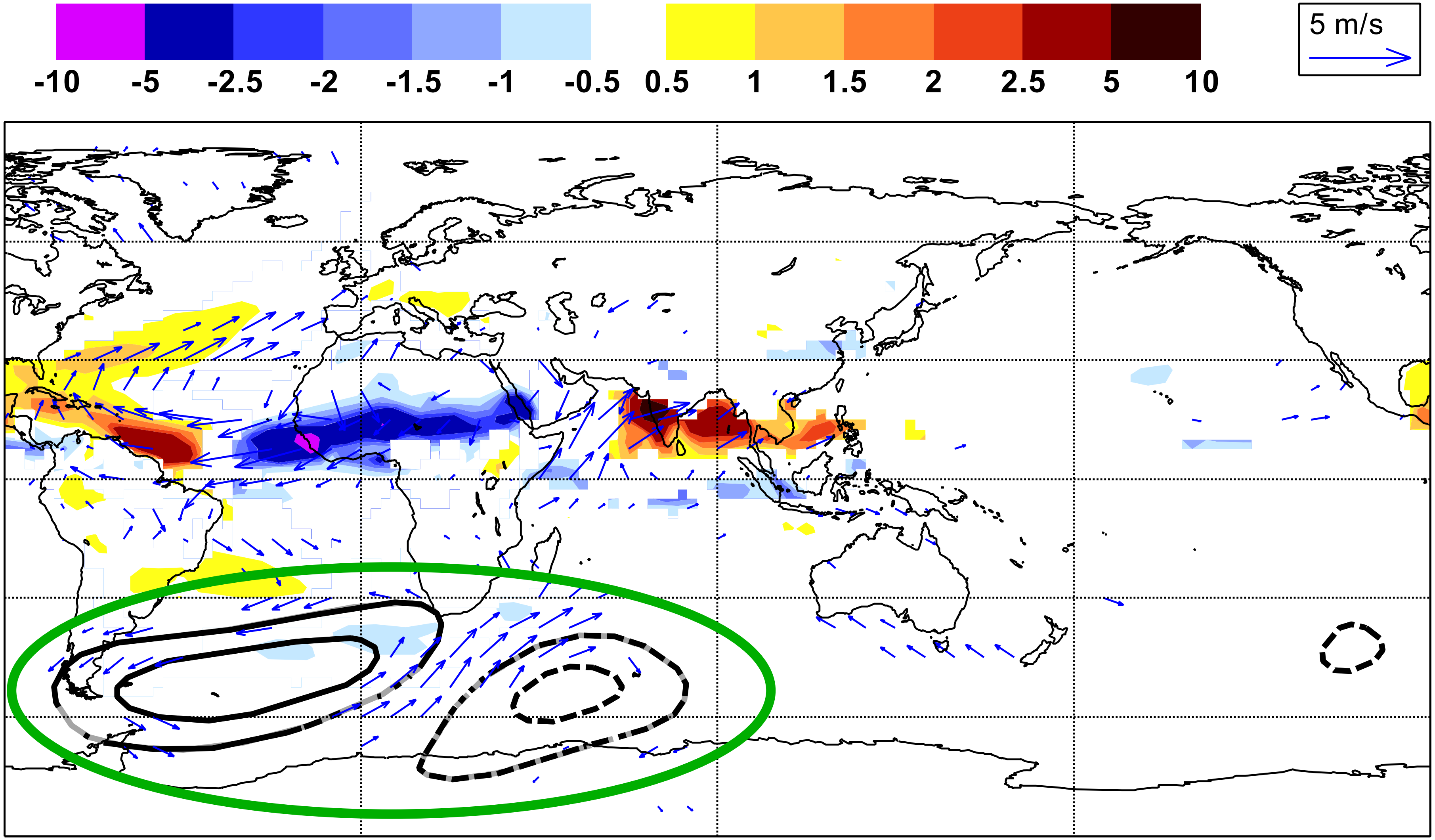
JJA New-Old RWS, $\underline{v}_\chi$,Ψ and mean ζ



Rossby wave paths agree beautifully with those predicted by Hoskins and Ambrizzi (1995)

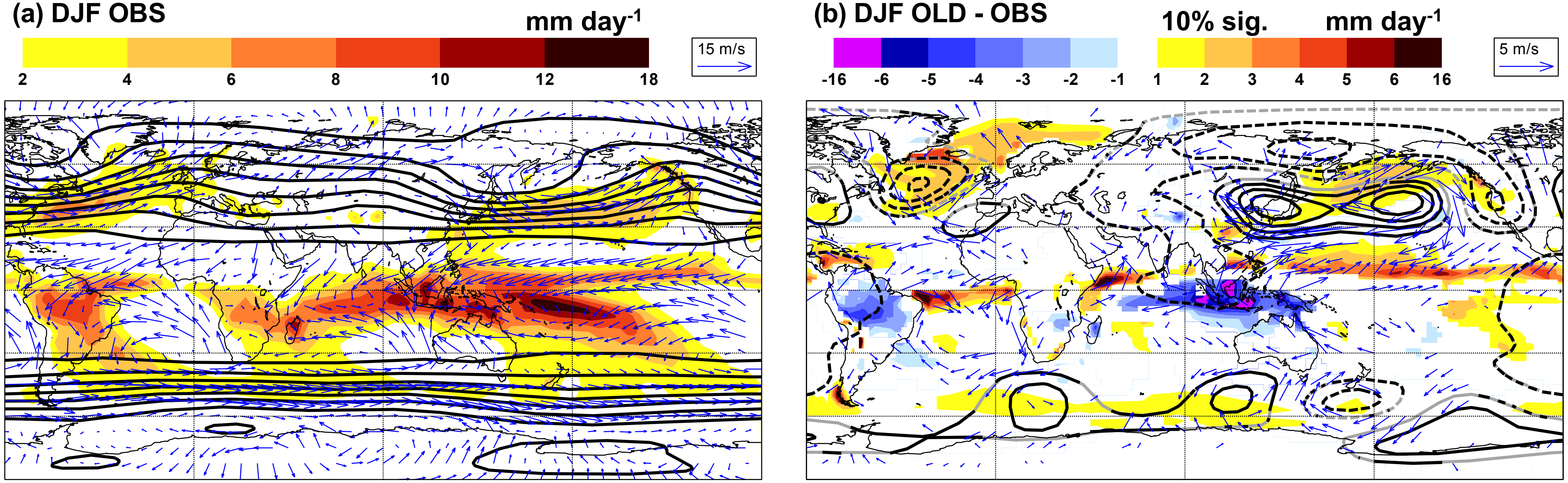
JJA Precipitation, v925 and Z500. New-Old

mm day^{-1}. 10% Sig.

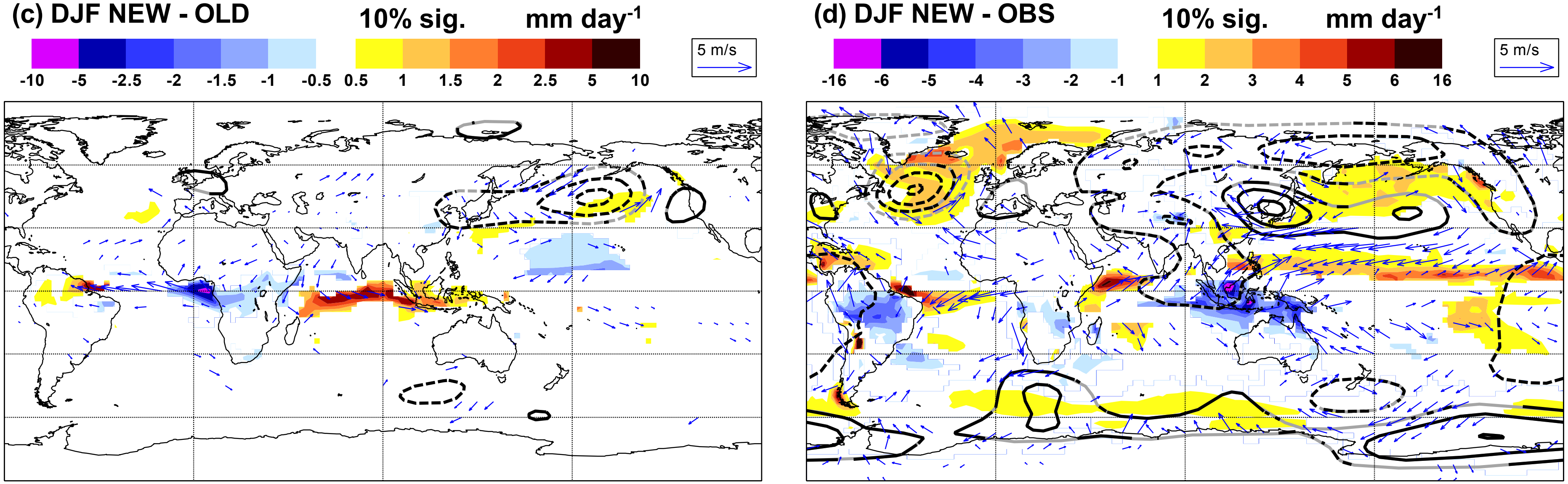


The December—February Season

DJF Precipitation, v925 and Z500


(a) DJF OBS

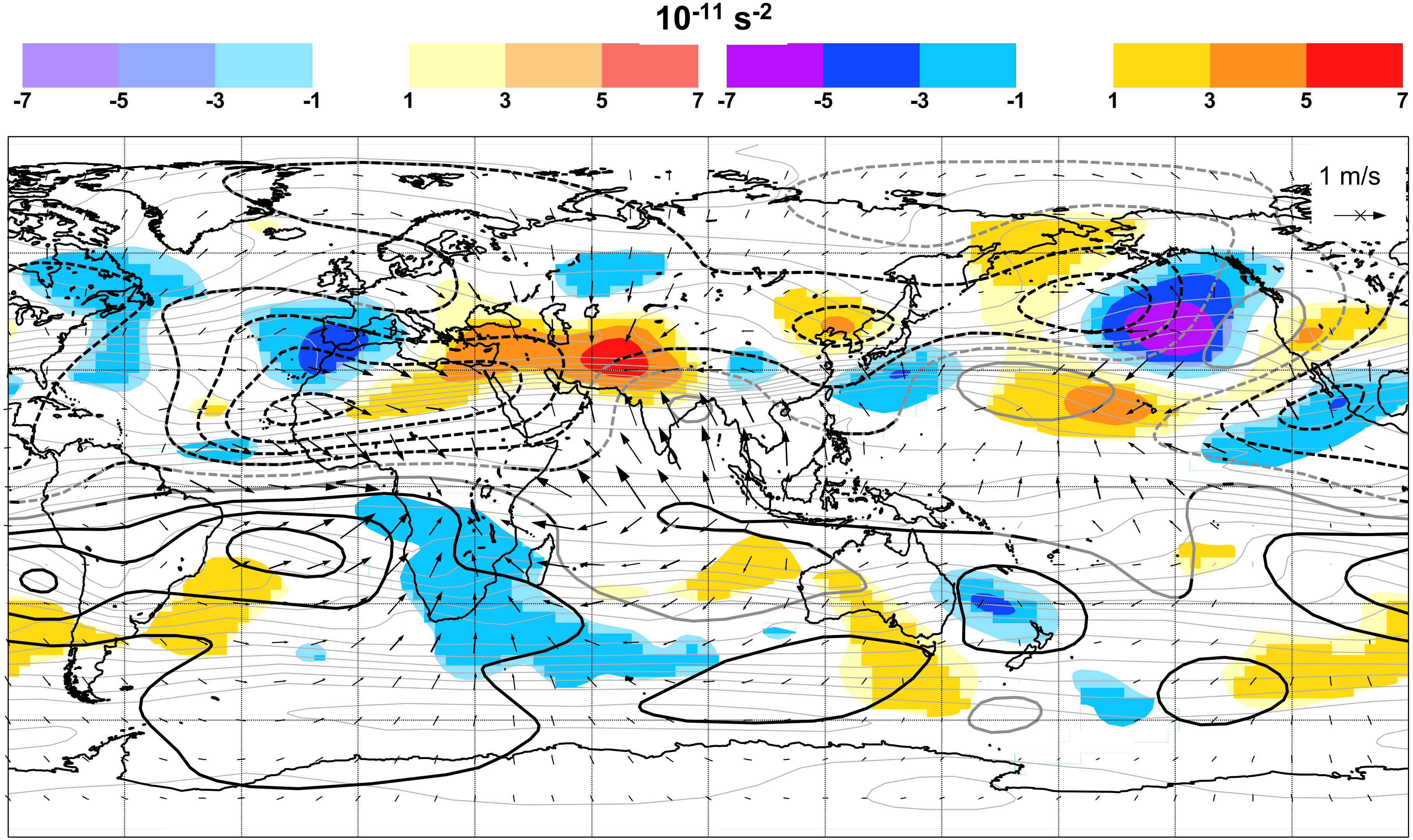
(b) DJF OLD - OBS


(c) DJF NEW - OLD

(d) DJF NEW - OBS

Precip: Xie-Arkin 1980–1999. V925, Z500: ERA40 1962-01, (a) 10, (b)-(d) 2 dam. 26R3 seasonal data for the same period

DJF New-Old RWS, $\underline{v}_{\chi}$,Ψ and mean ζ



Precipitation / RWS agreement suggests possibility for interaction with extra-tropical physics

Rossby wave path agrees with that predicted by Hoskins and Ambrizzi (1993)

Summary

- **Physics changes have global implications!**
  - Statistical tests can reveal **which** aspects are attributable to a change
  - To understand **why**, a set of diagnostic tools is needed
- **Analysis Increments and Initial Tendencies**
  - Useful to help understand local physics changes (and subsequent interactions)
  - Different from climate simulations and single column experiments
- **Equatorial waves**
  - Help explain the mean tropic-wide response
  - Linear waves can ‘set the scene’
  - Coupling with convection enhances the response
- **Extra-tropical Rossby waves**
  - Help explain the mean extra-tropical response
  - Understanding is aided by linearity
  - Extra-tropical interaction with physics could be studied with PV approach