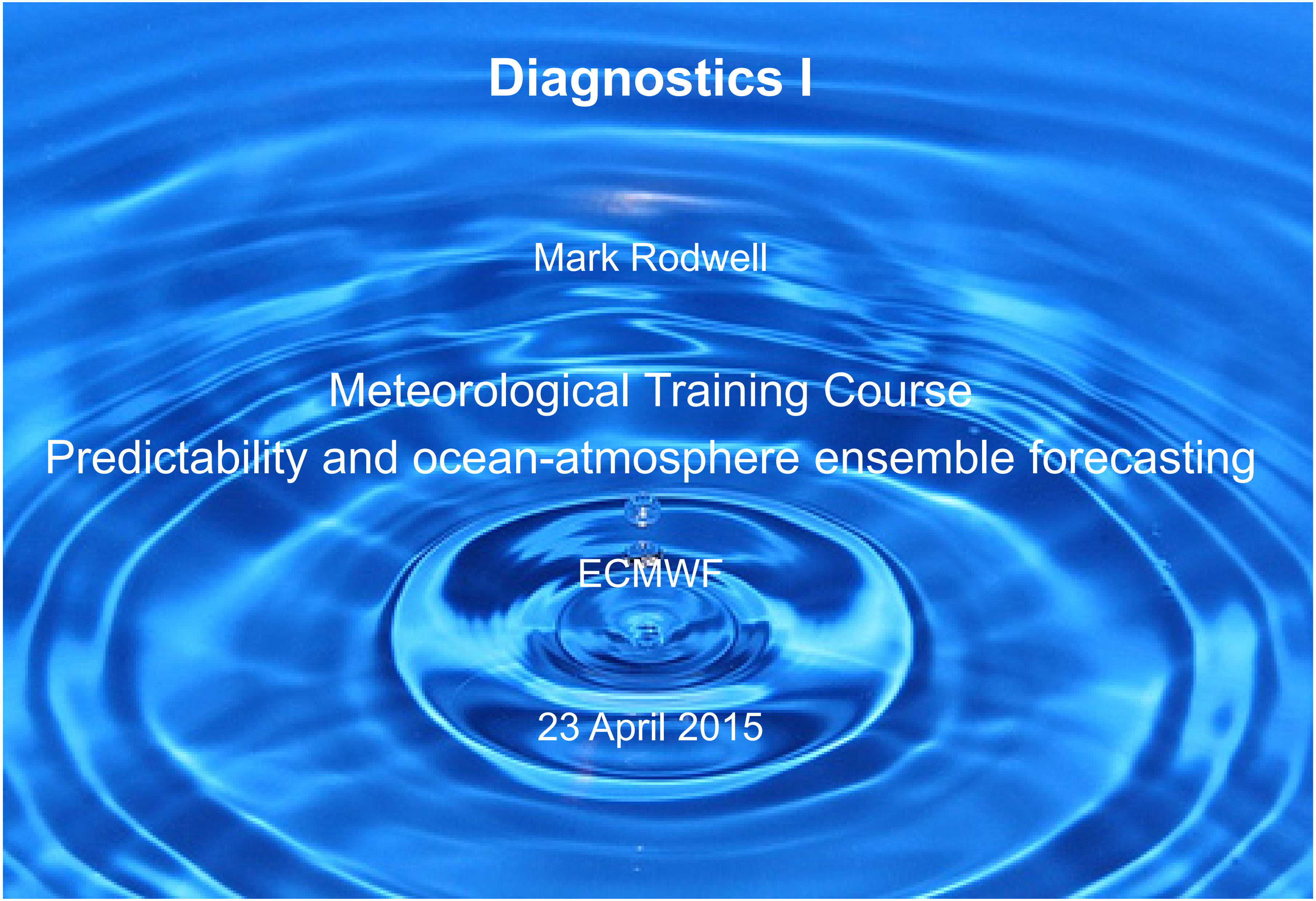


Diagnostics I

Mark Rodwell

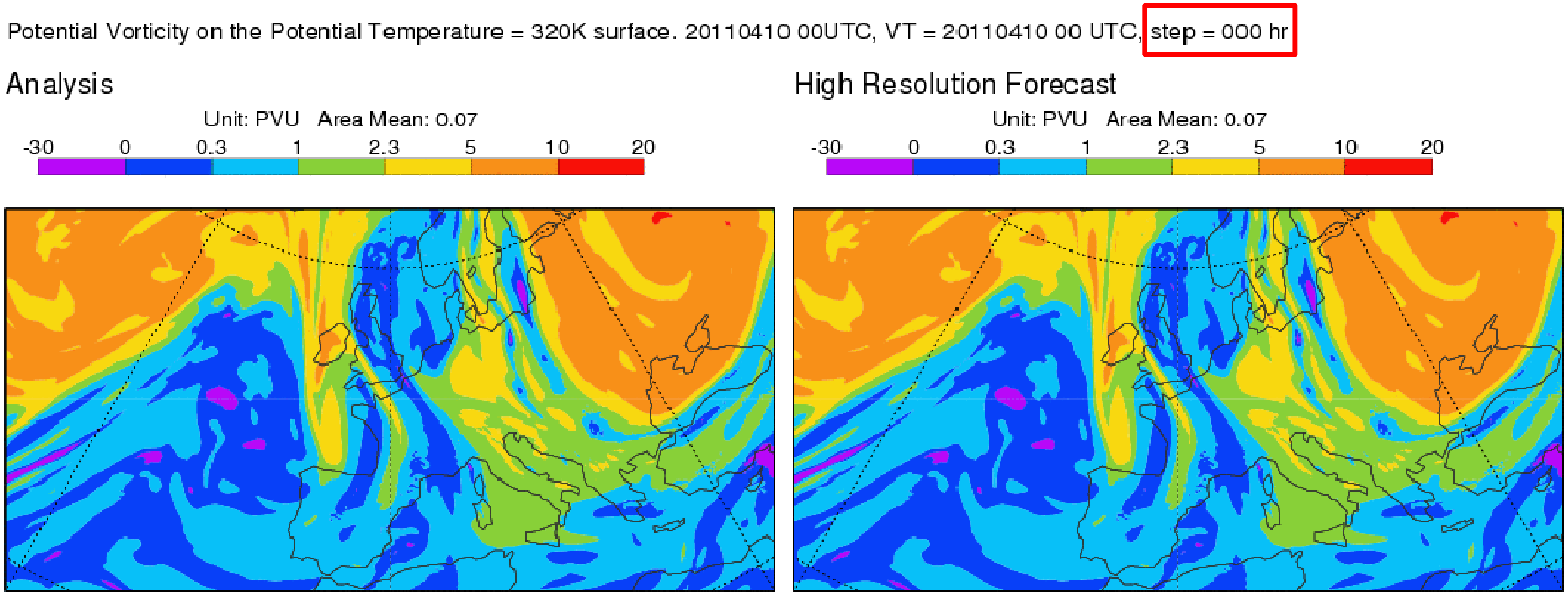
Meteorological Training Course
Predictability and ocean-atmosphere ensemble forecasting

ECMWF

23 April 2015

Motivation

Deterministic forecasting (initial conditions)

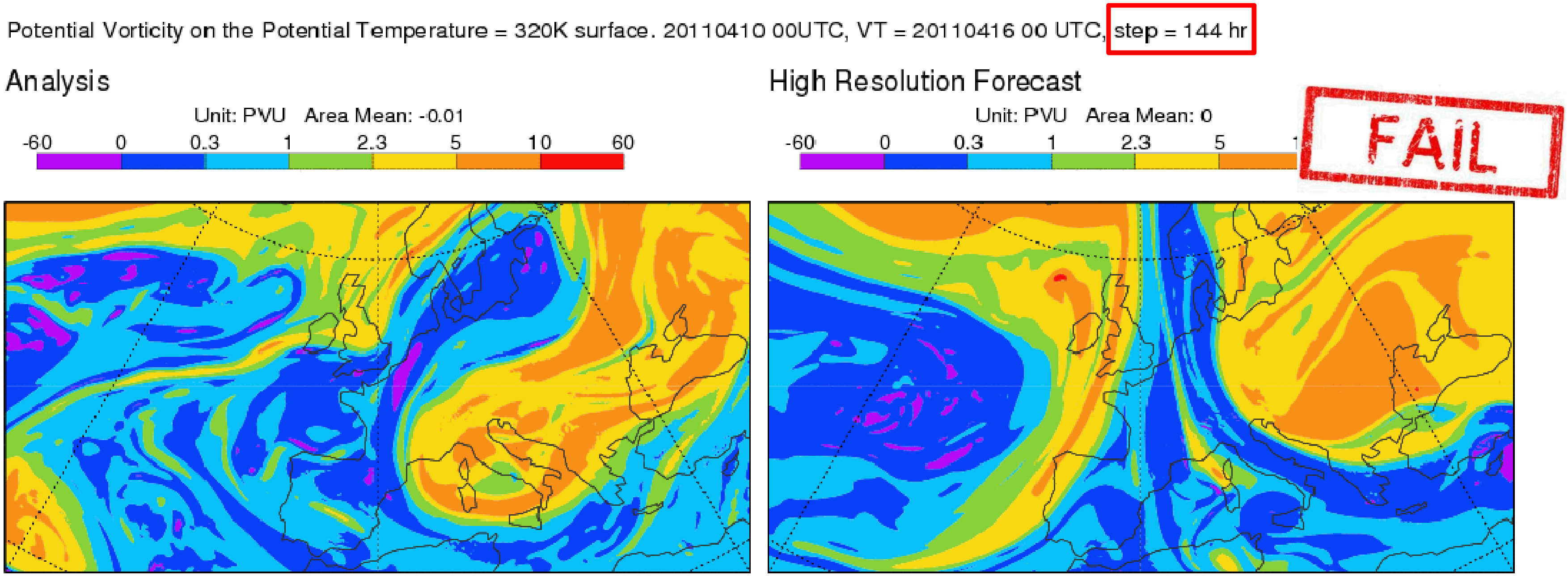


Potential Vorticity on the Potential Temperature = 320K surface. 20110410 00UTC, VT = 20110410 00 UTC, step = 000 hr

Analysis

High Resolution Forecast

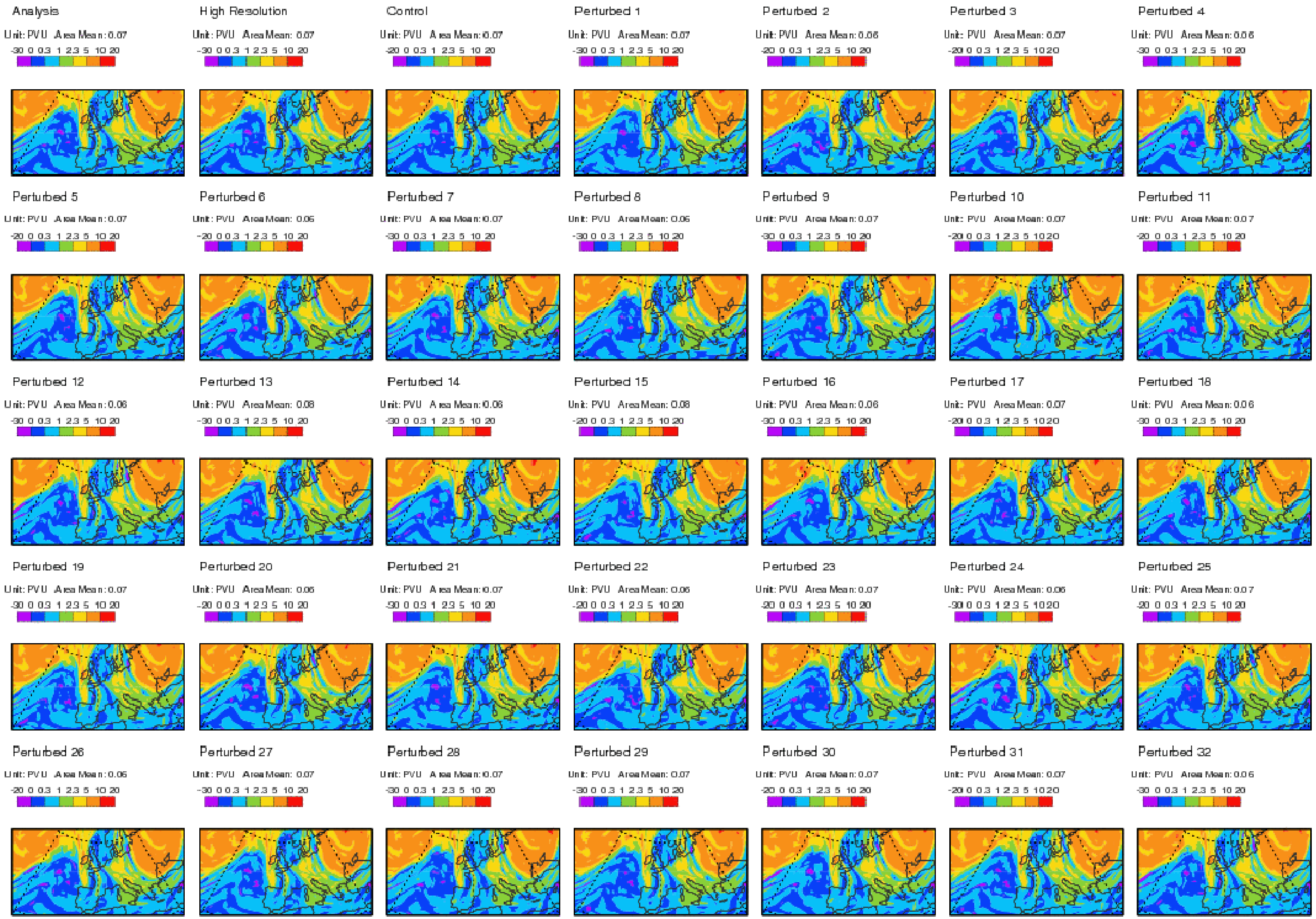
Deterministic forecasting (flow evolution to day-6)



It is difficult, by day-6, to disentangle model error from the natural growth of initial condition uncertainty (chaos)

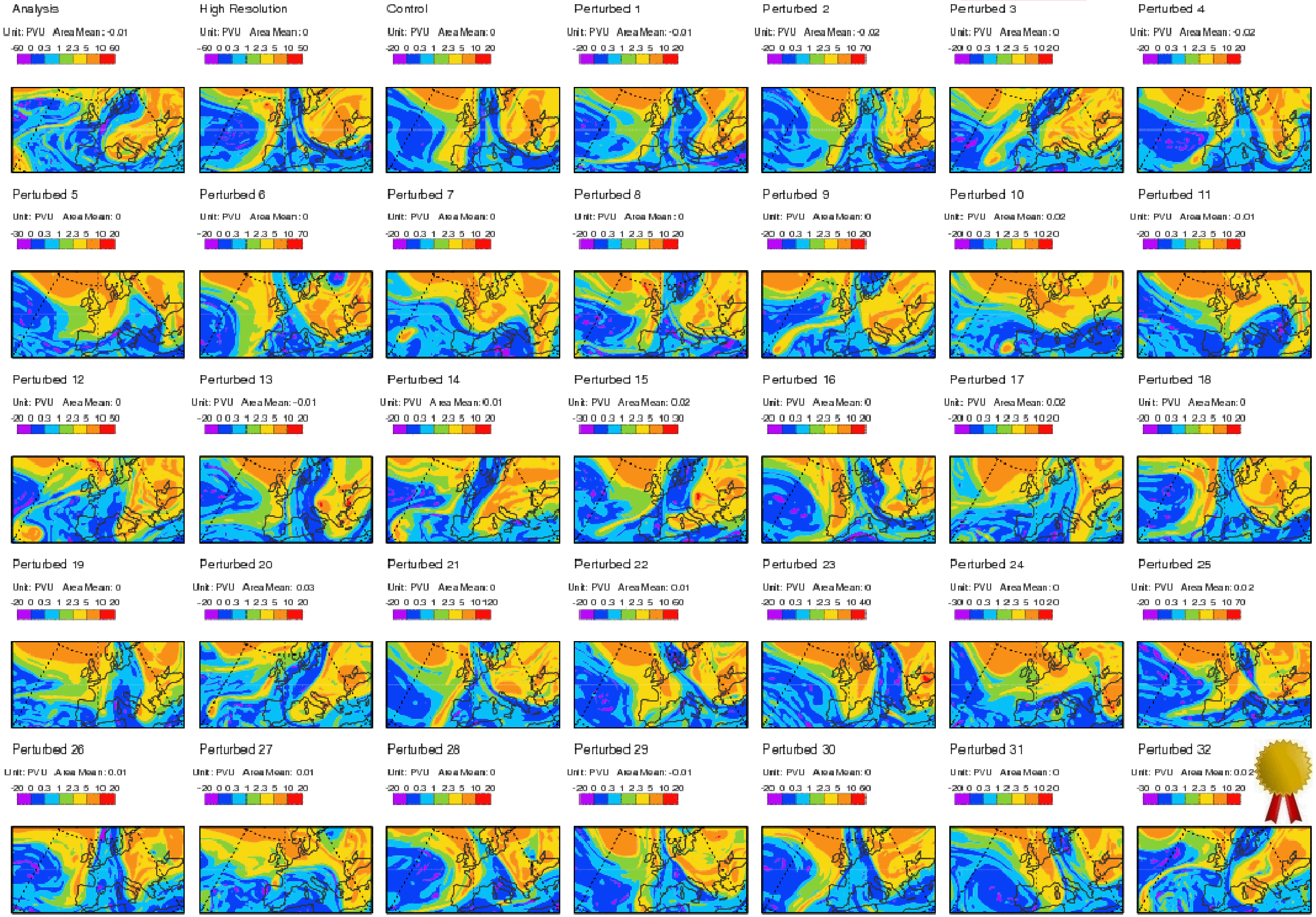
Ensemble forecasting (initial conditions)

Potential Vorticity on the Potential Temperature = 320K surface. 20110410 00UTC, VT = 20110410 00 UTC, step = 000 hr

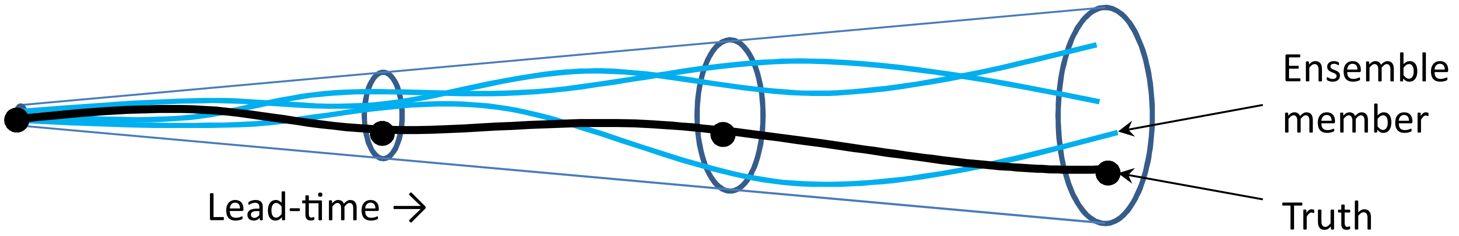


Ensemble forecasting (flow evolution to day-6)

Potential Vorticity on the Potential Temperature = 320K surface. 20110410 00UTC, VT = 20110416 00 UTC, step = 144 hr



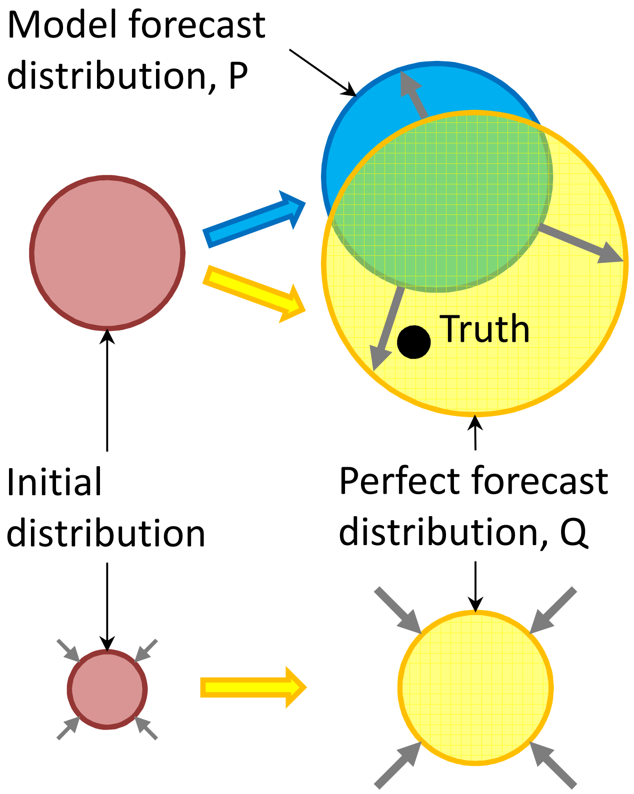
The goal of probabilistic forecasting



Ensemble member

Lead-time →

Truth



Model forecast distribution, P

Truth

Initial distribution

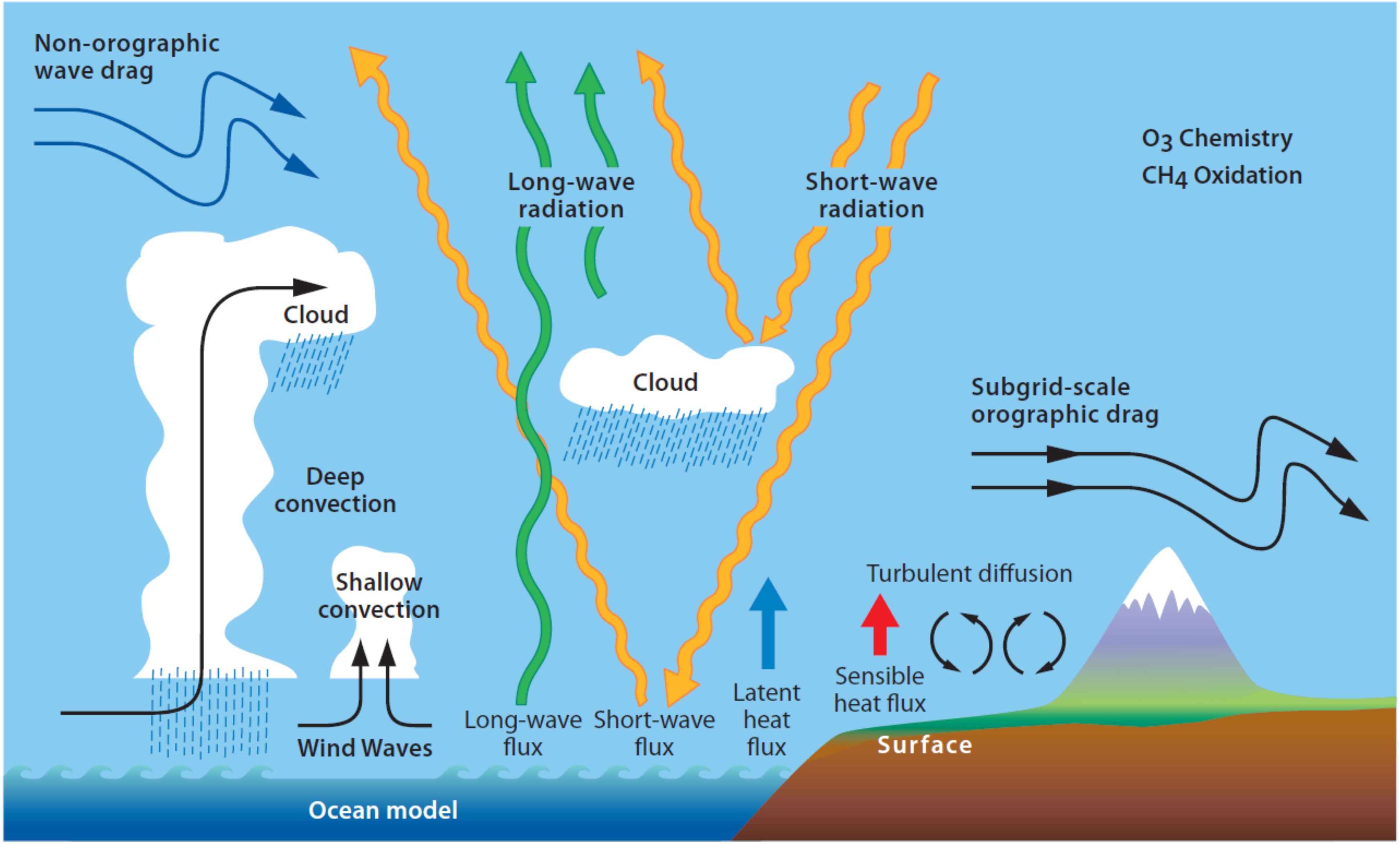
Perfect forecast distribution, Q

Reliability : P→Q

Resolution : Q→δ

Initial tendency diagnostics

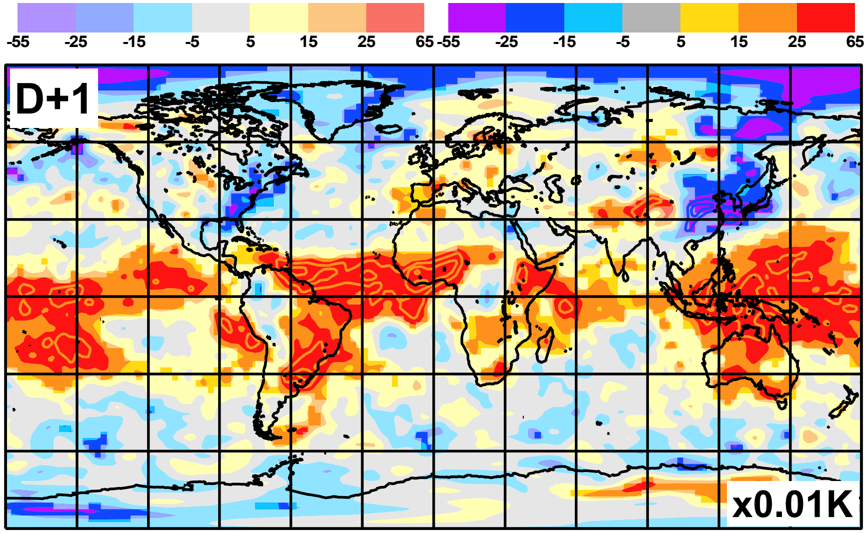
The complexity of present-day model physics

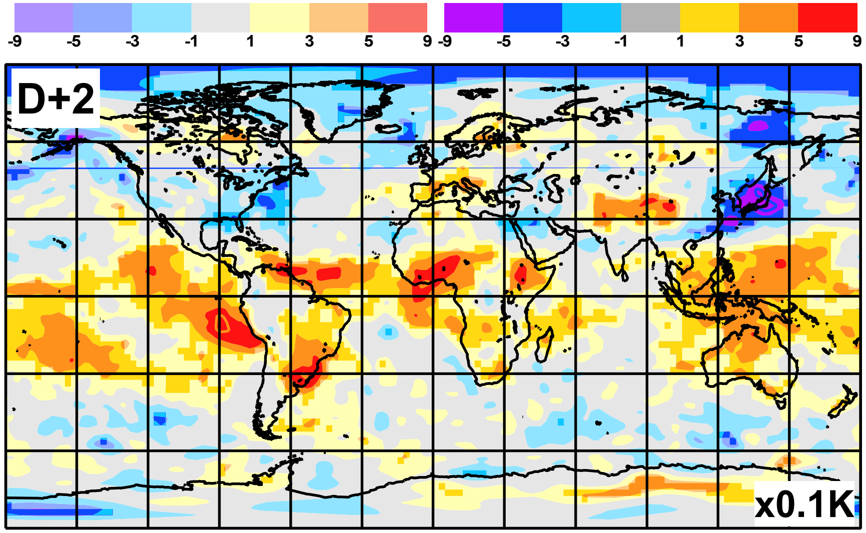


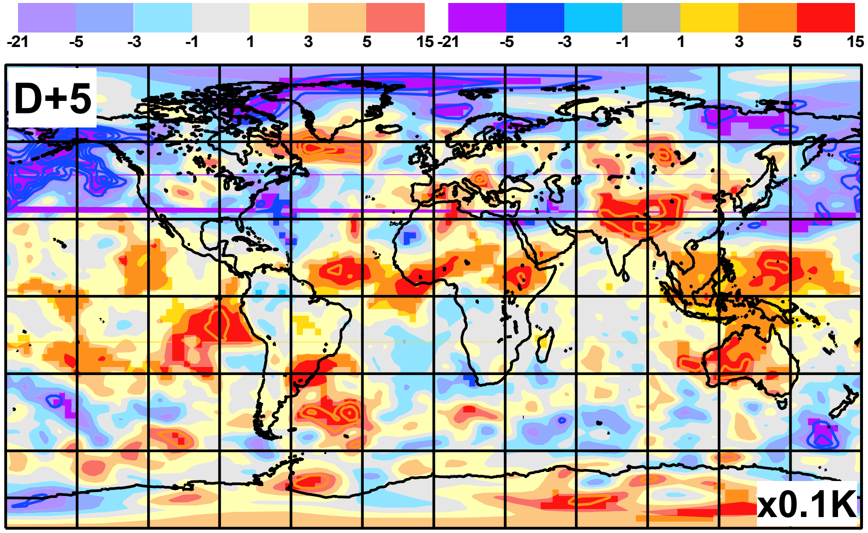
The complexity of today's models, with numerous interactions between physical processes and the resolved flow (including teleconnections), can make it very difficult to isolate the offending process(es). Single column and LES models can help, but these do not take into account the evolution of the resolved flow.

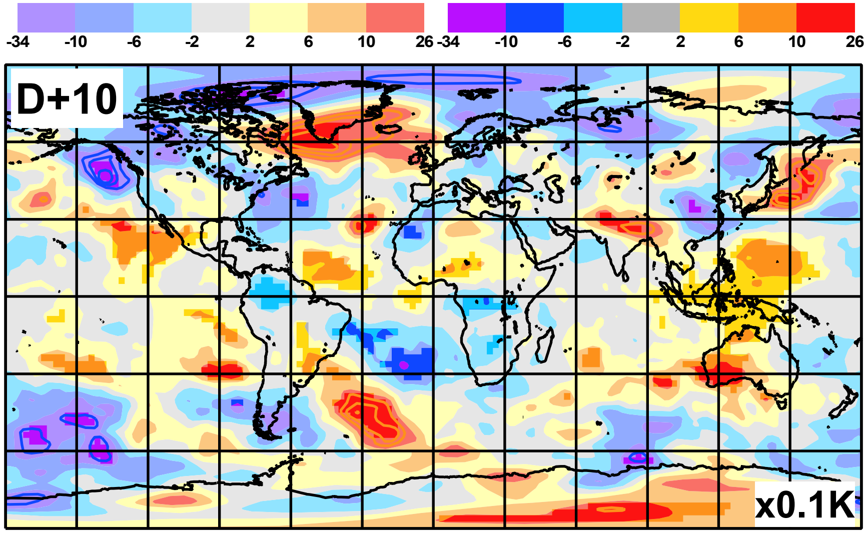
Figure from Peter Bechtold

T500 forecast error as function of lead-time





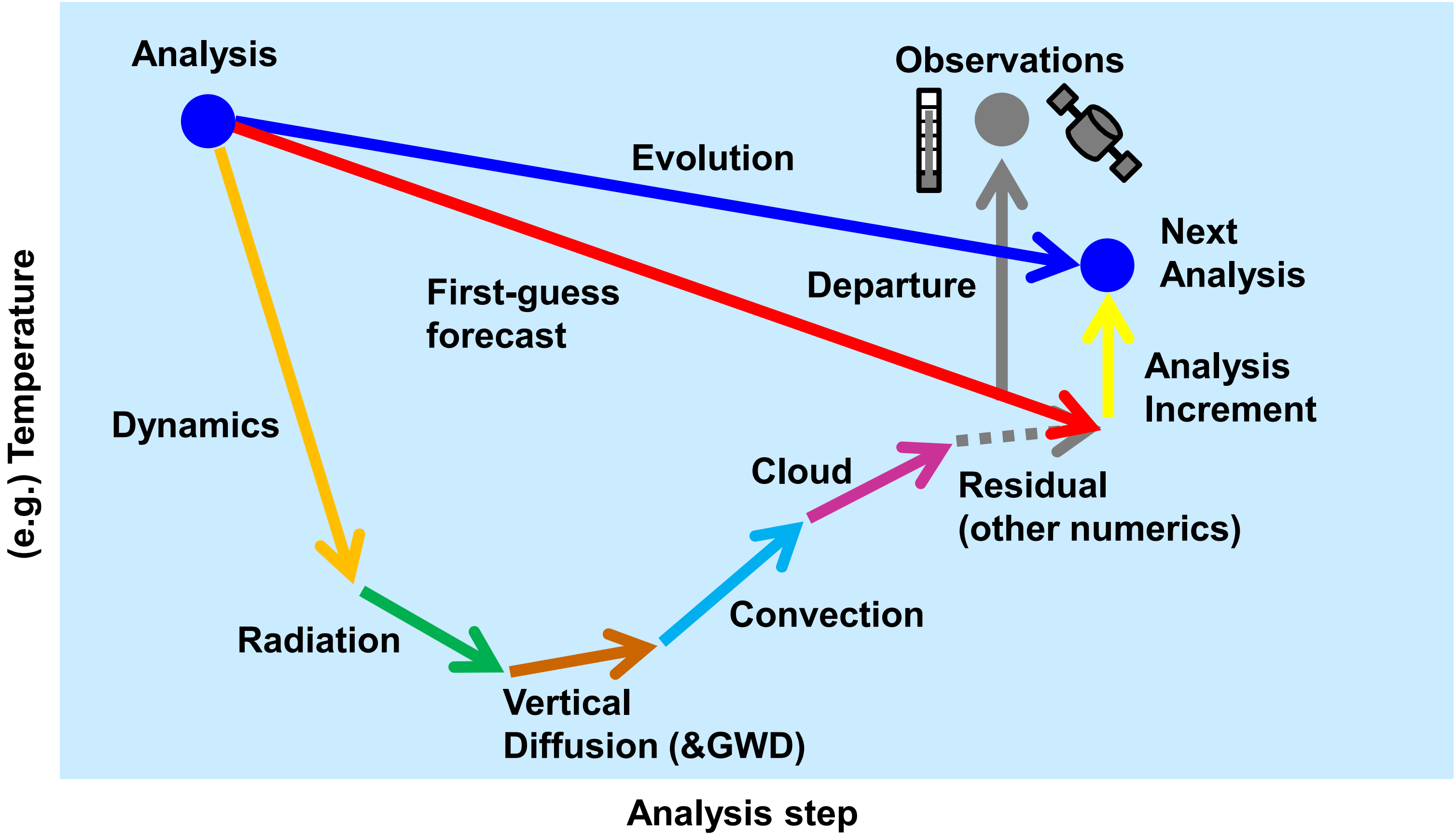




Based on DJF 2007/8 operational analyses and forecasts. Significant values (5% level) in deep colours.

Diagnosis of analysis & deterministic model error

Schematic of the data assimilation process – a diagnostic perspective



Analysis increment corrects first-guess error, and draws next analysis closer to observations.

First-guess = sum of all processes.

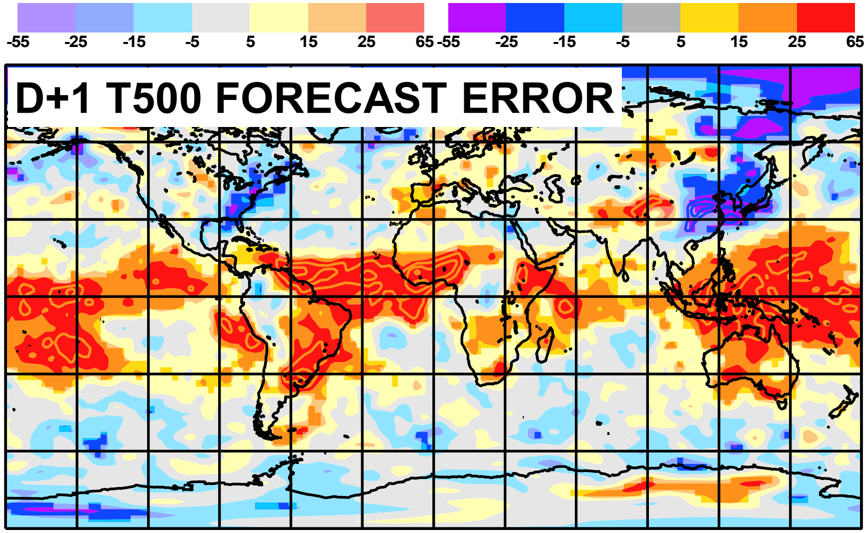
Relationship between increment and individual process tendencies can help identify key errors.

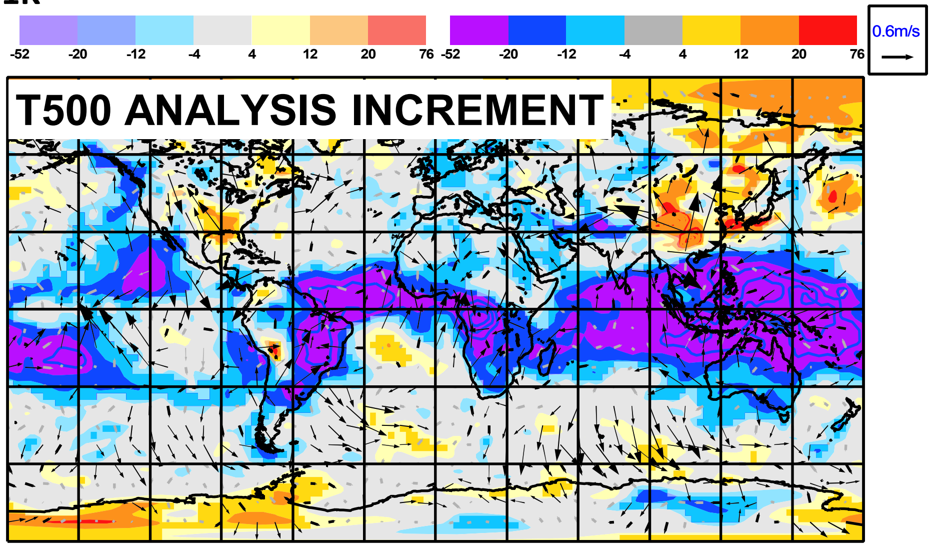
"Initial Tendency" approach discussed by Klinker & Sardeshmukh (1992). Refined by Rodwell & Palmer (2007)

Confronting models with observations

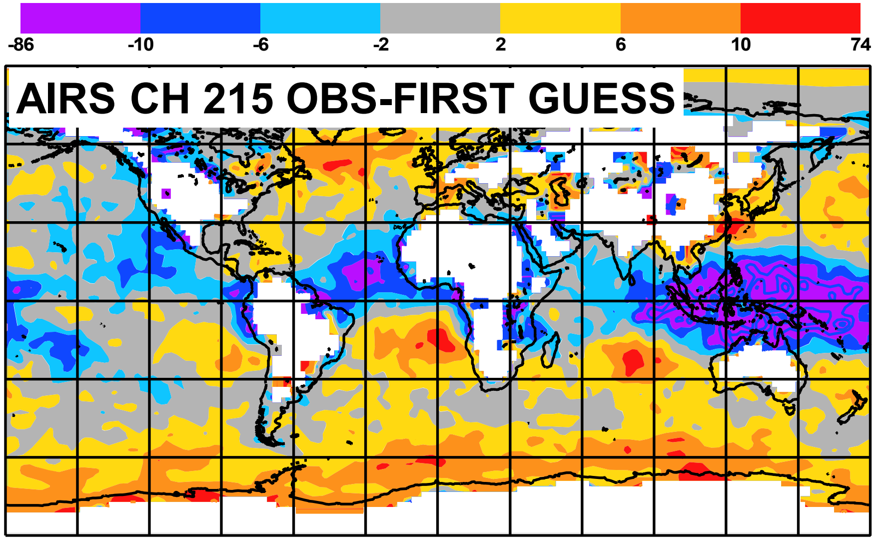
Not discussed in lecture

UNIT=0.01K


D+1 T500 FORECAST ERROR


T500 ANALYSIS INCREMENT

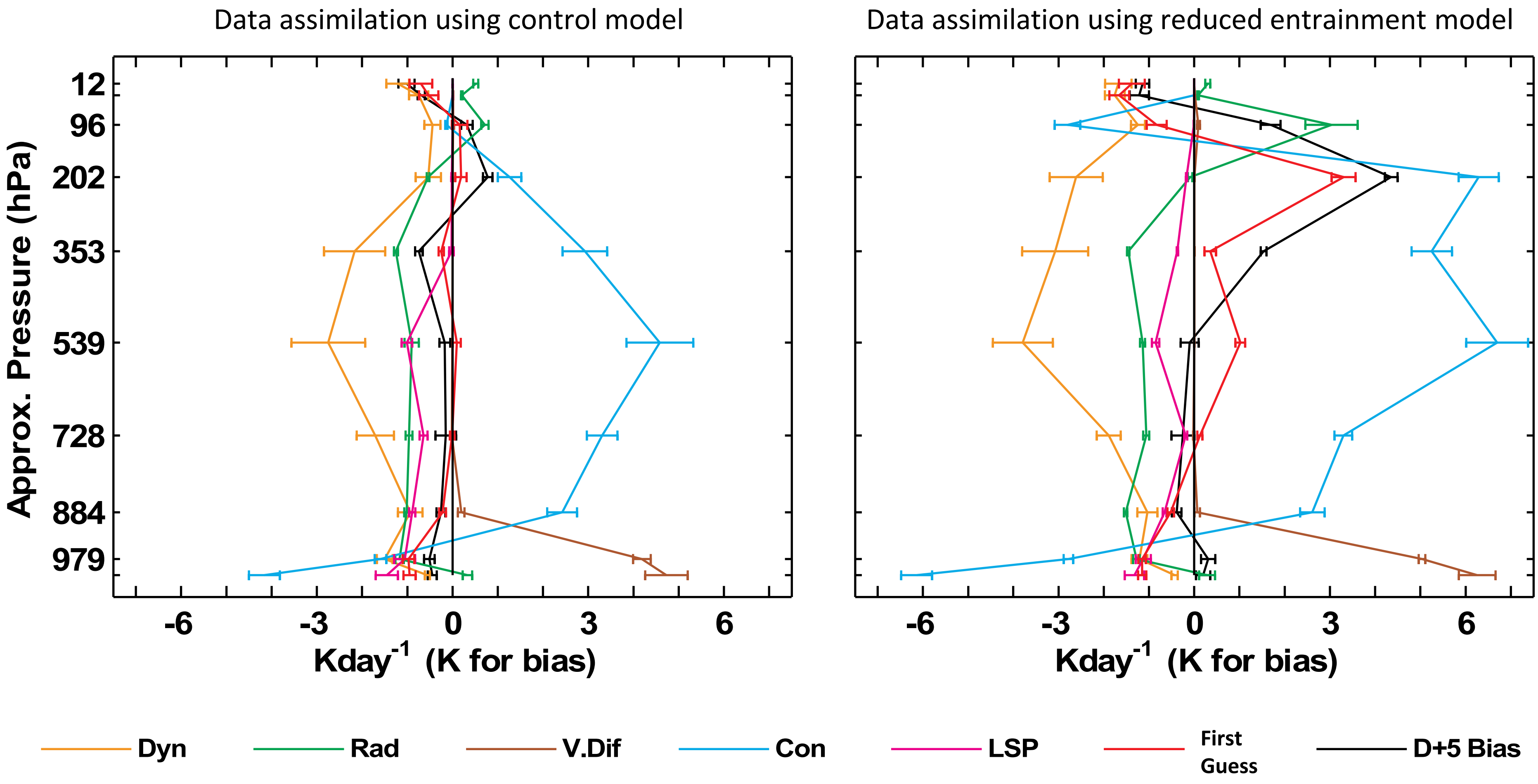
- **Every 1° square has data every cycle**
  - **~6 Million data values**
- **Independent vertical modes of information:**
  - **IASI / AIRS: ~ 15**
  - **HIRS / AMSUA: ~ 5 (~ 2 IN TROP)**
- **Anchors (no variational bias correction):**
  - **Radiosonde**
  - **AMSUA-14**
  - **Radio Occultation**


AIRS CH 215 OBS-FIRST GUESS

Based on DJF 2007/8 operational analyses and forecasts. Significant values (5% level) in deep colours.
AIRS CH 215 BRIGHTNESS TEMPERATURE ~T500

1st example: Method questions 12K warming

Temperature tendency profiles over the Amazon (300-320ºE, 20ºS-0ºN)

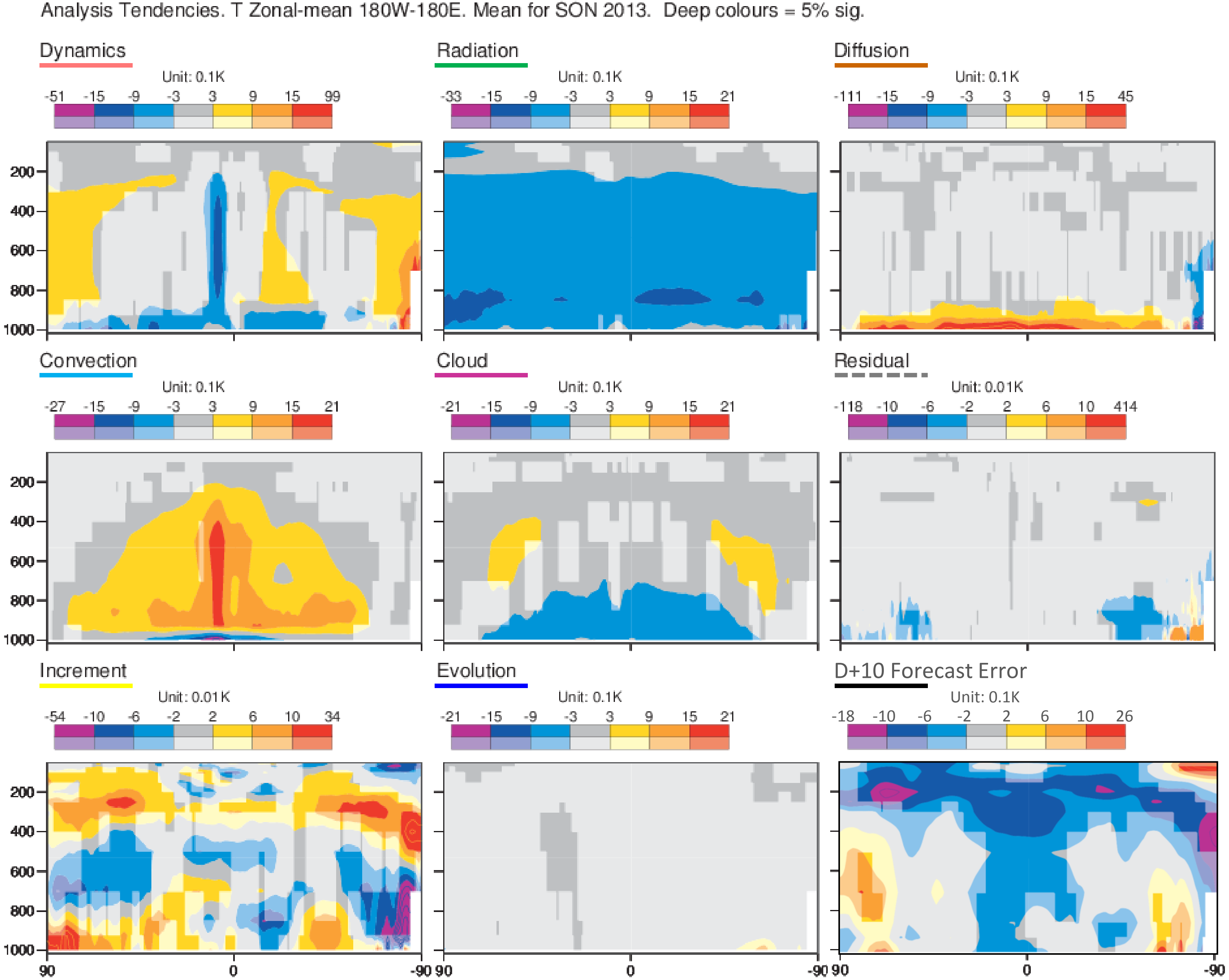


Mean first guess tendency, red, (the sum of all processes) is ‘quite small’: A reference value for the realism of the model’s physics

Greatly increased time-mean first-guess tendency: Perturbation leads to poorer physics. Reject this perturbation from climate ensemble?

Rodwell and Palmer (2007). 6hr tendencies. 31 days (January 2005) X 4 forecasts per day. 70% conf.int. T159, L60,1800s.

Initial temperature tendencies and D+10 error



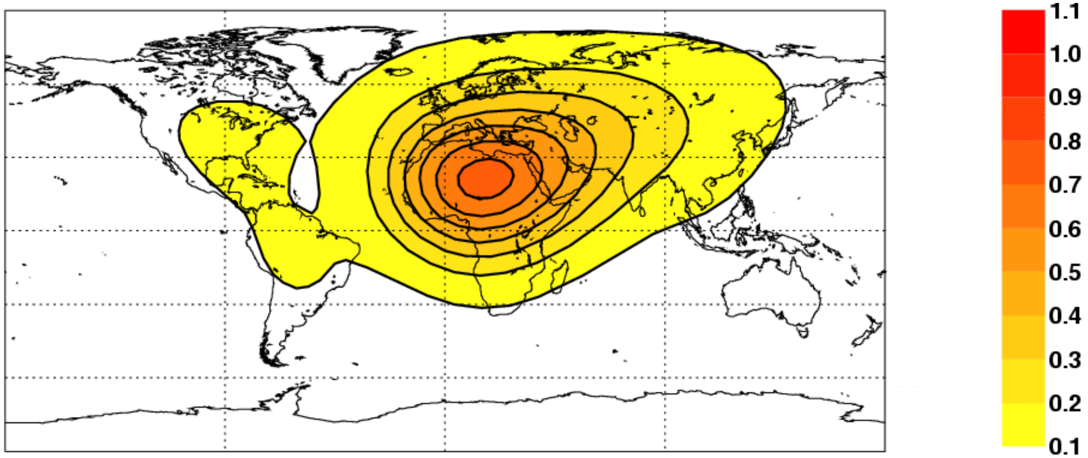
Strong upper-tropospheric increments (where radiation is not balanced by dynamics)

Error grows x10 by D+10 (due to poorly constrained humidities?)

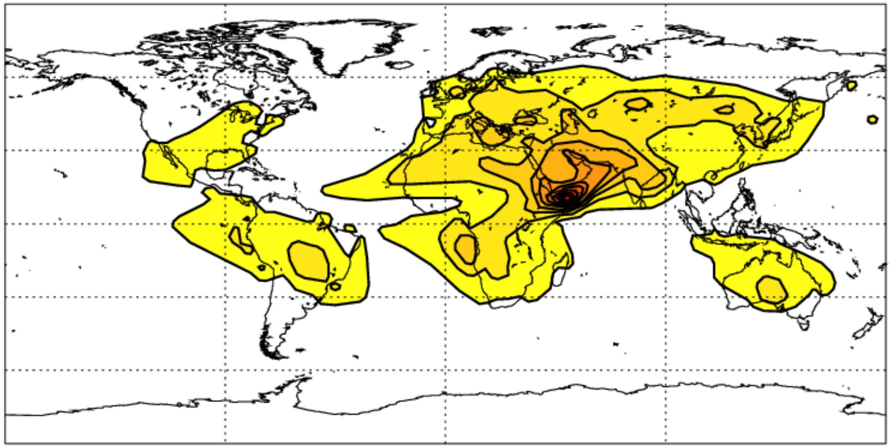
Note that increment and residual plotted with smaller contour interval. D+10 error also has different interval.

Old and New Aerosol Optical Thickness

OLD
(NO ANNUAL CYCLE)



NEW
(JULY)



OPTICAL DEPTH d AT 550nm

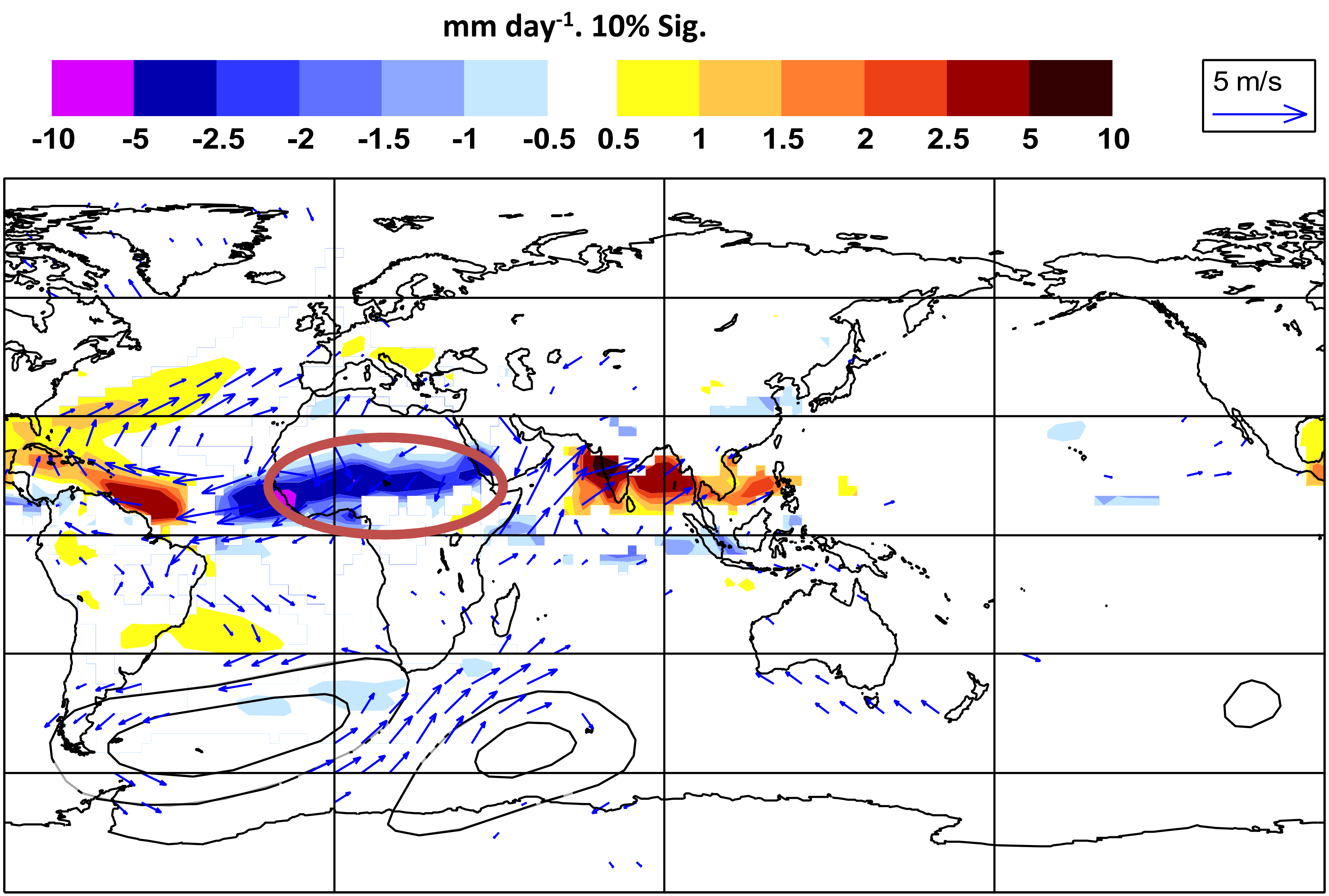
ATTENUATION FACTOR = e^{-d}

SINGLE SCATTERING ALBEDO FOR DESERT AEROSOL ≈ 0.9

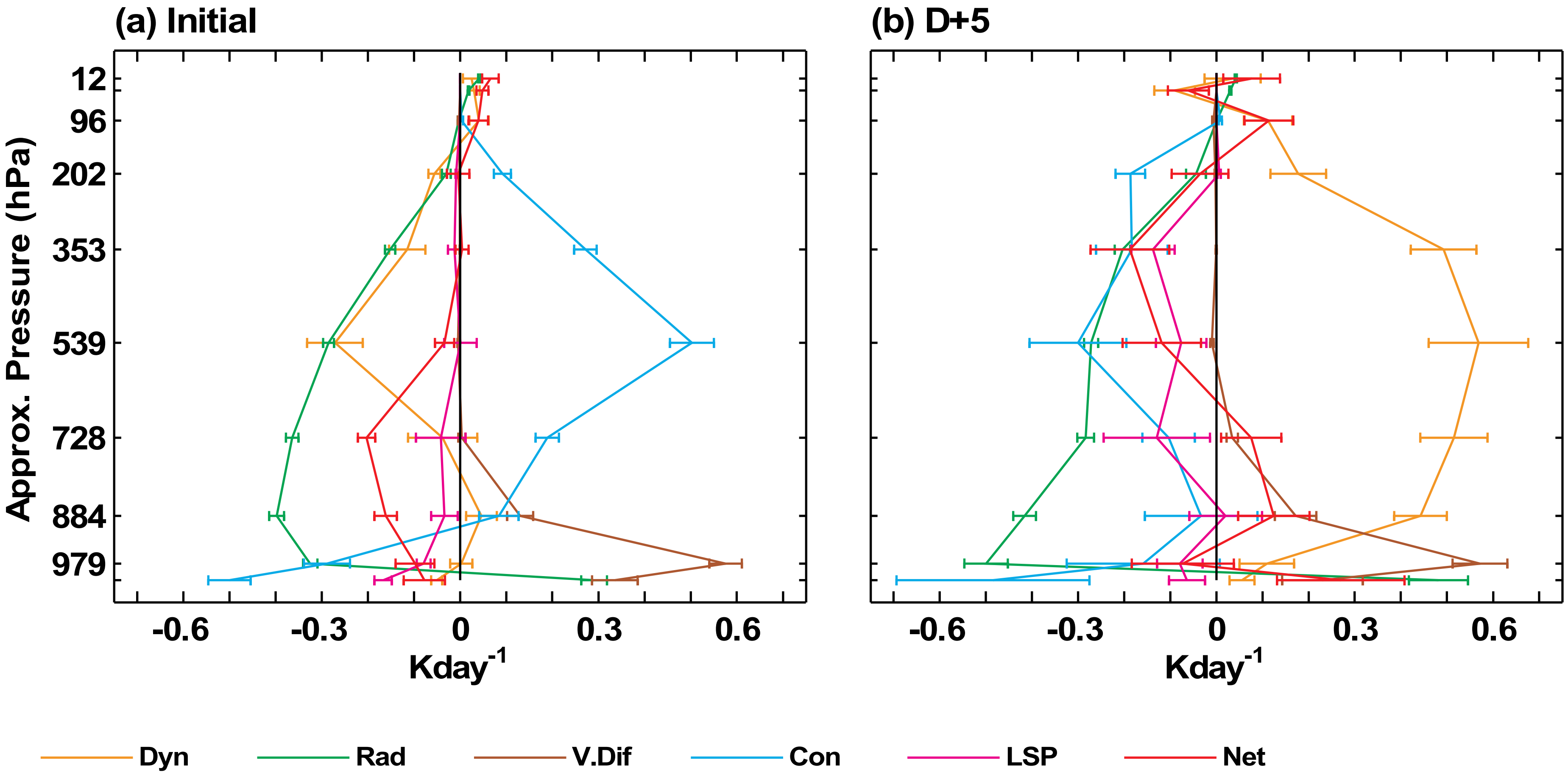
- **SOIL DUST IS LARGE COMPONENT**
- **SOIL DUST ABSORBS AS WELL AS SCATTERS**

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

JJA Precipitation, v925 and Z500. New-Old



North Africa Jul 2004 T Tendencies (New-Old)



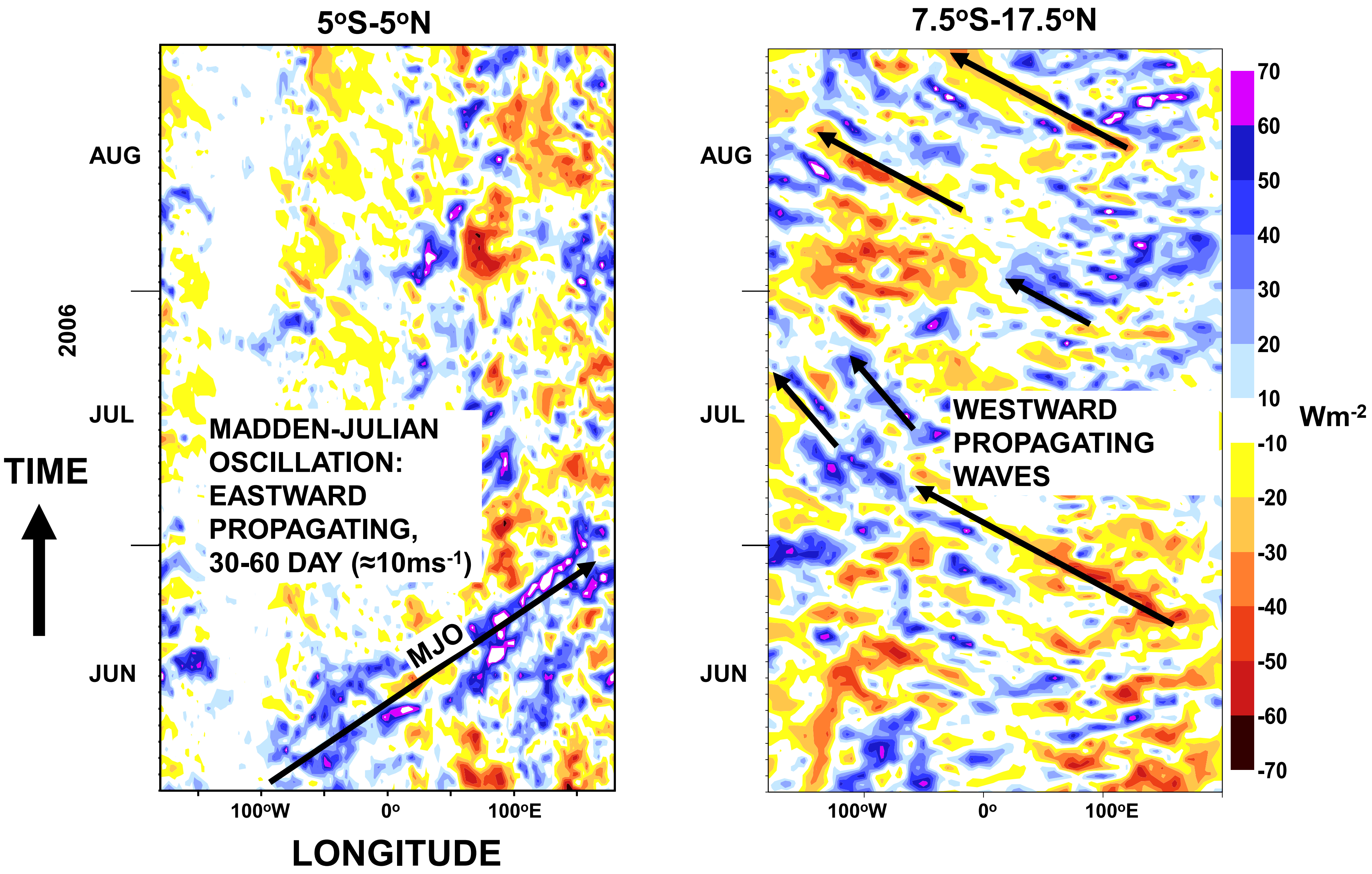
RADIATIATION CHANGES DESTABILISE PROFILE AND LEAD TO MORE CONVECTION …

… BUT ULTIMATELY LEAD TO MORE DESCENT AND LESS OVERALL PRECIPITATION

North Africa = [5^{o}N-15^{o}N, 20^{o}W-40^{o}E]. 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.

Wave-propagation of signals, errors & uncertainty

Tropical Waves: Outgoing Long-wave Radiation



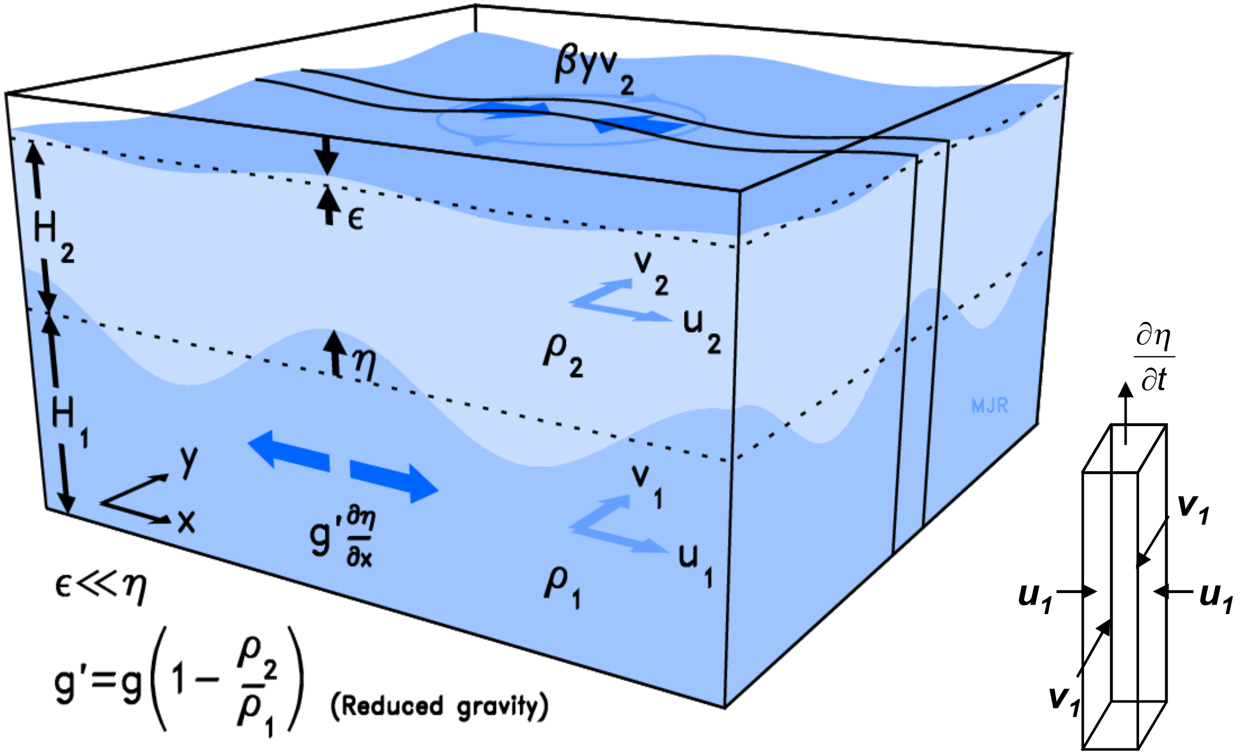
MADDEN-JULIAN OSCILLATION: EASTWARD PROPAGATING, 30-60 DAY (≈10ms^{-1})

WESTWARD PROPAGATING WAVES

Data from NOAA

Equatorial Waves

(Use of the shallow water equations on the β-plane (f=βy) for understanding tropical atmospheric waves)



$\epsilon \ll \eta$

$g' = g\left(1 - \frac{\rho_2}{\rho_1}\right)$ (Reduced gravity)

$u \equiv u_1 - u_2 \quad v \equiv v_1 - v_2$ (Baroclinic mode)

Momentum:

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

$$\frac{\partial v}{\partial t} + \beta y u + g'\frac{\partial \eta}{\partial y} \approx 0 \qquad (1)$$

Continuity:

$$\frac{\partial \eta}{\partial t} + \frac{c_e^2}{g'}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \approx 0 \qquad (2)$$

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

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

Solving for v:

$$\frac{\partial}{\partial t}\left\{\frac{\partial^2 v}{\partial t^2} + \beta^2 y^2 v - c_e^2\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)\right\} - c_e^2 \beta \frac{\partial v}{\partial x} = 0 \qquad (3)$$

Note: No coupling with convection in this model

Limiting solutions

🟩 Phase speed

⭕ ⭕ η & v

🟥 🟦 η tendency

Kelvin waves: **v≡0, u in geostrophic balance with meridional pressure gradient**

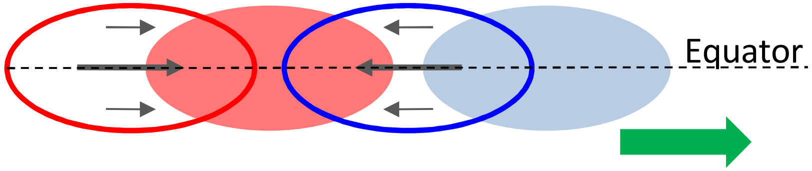
$$\frac{\partial u}{\partial t} = -g'\frac{\partial \eta}{\partial x}$$

$$\beta y u = -g'\frac{\partial \eta}{\partial y}$$

Geostrophic balance
u,*η* in phase

$$\frac{\partial \eta}{\partial t} = -\frac{c_e^2}{g'}\frac{\partial u}{\partial x}$$

Eastward propagation →



$$\frac{\partial^2 \eta}{\partial t^2} = c_e^2\frac{\partial^2 \eta}{\partial x^2}$$

$$\eta \propto \sin(kx-\omega t)\hat{\eta}(y)$$

$$\text{phase speed} = \frac{\omega}{k} = c_e\,,\ \hat{\eta}(y) = e^{-\frac{\beta}{2c_e}y^2}$$

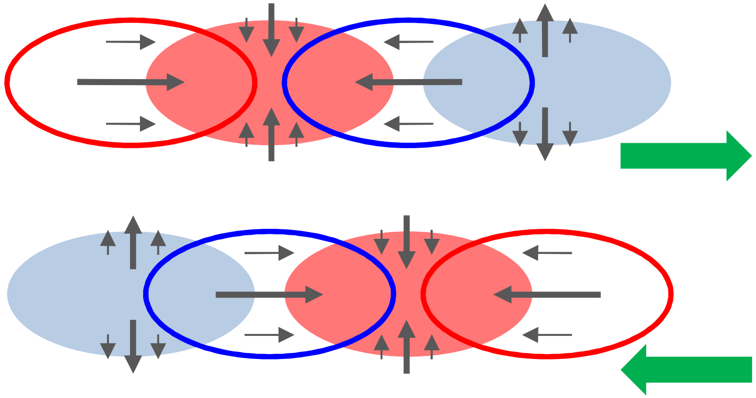
Gravity waves: **Fast, pressure gradient force dominates**

$$\frac{\partial u}{\partial t} = -g'\frac{\partial \eta}{\partial x}$$

u,*η* in phase: →
out of phase: ←

$$\frac{\partial v}{\partial t} = -g'\frac{\partial \eta}{\partial y}$$

$$\frac{\partial \eta}{\partial t} = -\frac{c_e^2}{g'}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)$$



$$\frac{\partial^2 \eta}{\partial t^2} = c_e^2\left(\frac{\partial^2 \eta}{\partial x^2}+\frac{\partial^2 \eta}{\partial y^2}\right)$$

$$\eta \propto \sin(kx-\omega t)\hat{\eta}(y)$$

$$\text{phase speed} = \frac{\omega}{k} = \pm c_e\left(1-\frac{1}{k^2\hat{\eta}}\frac{\partial^2 \hat{\eta}}{\partial y^2}\right)^{\frac{1}{2}}$$

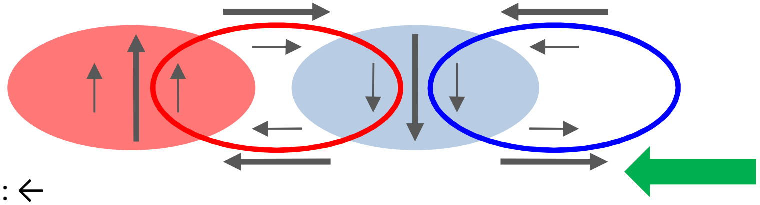
$$\to \pm c_e \text{ as } k \to \infty$$

Rossby waves: **Slow, Coriolis affect important, closer to geostrophic balance, less convergence. Take curl of (1)**

$$\frac{\partial \xi}{\partial t} = -\beta y\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) - \beta v$$

$$\approx -\beta v$$

Vorticity anomaly strengthened to west, weakened to east: ←



$$\frac{\partial \nabla^2 \psi}{\partial t} = -\beta\frac{\partial \psi}{\partial x}$$

$$\psi \propto \sin(kx-\omega t)\hat{\psi}(y)$$

$$\text{phase speed} = \frac{\omega}{k} = -\frac{\beta}{k^2}\left(1-\frac{1}{k^2\hat{\psi}}\frac{\partial^2 \hat{\psi}}{\partial y^2}\right)^{-1}$$

$$\to -\frac{\beta}{k^2} \text{ as } k \to \infty$$

Free Equatorial Waves

Not discussed in lecture

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*

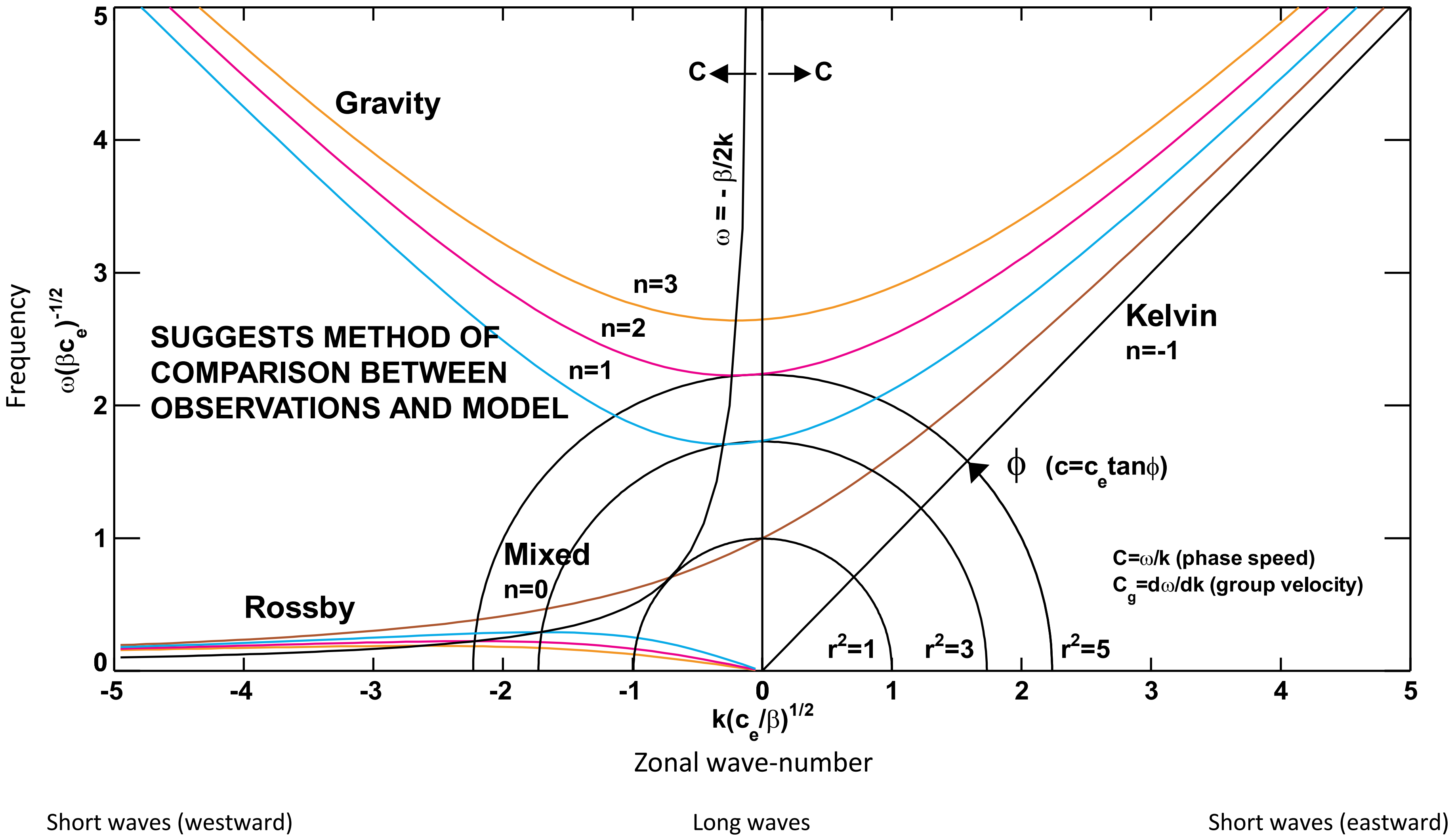
- E & W prop. **Mixed Rossby-Gravity**

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

(Gravity: associated with first two terms on lhs, Rossby: with last two terms on lhs, Mixed: all three terms)

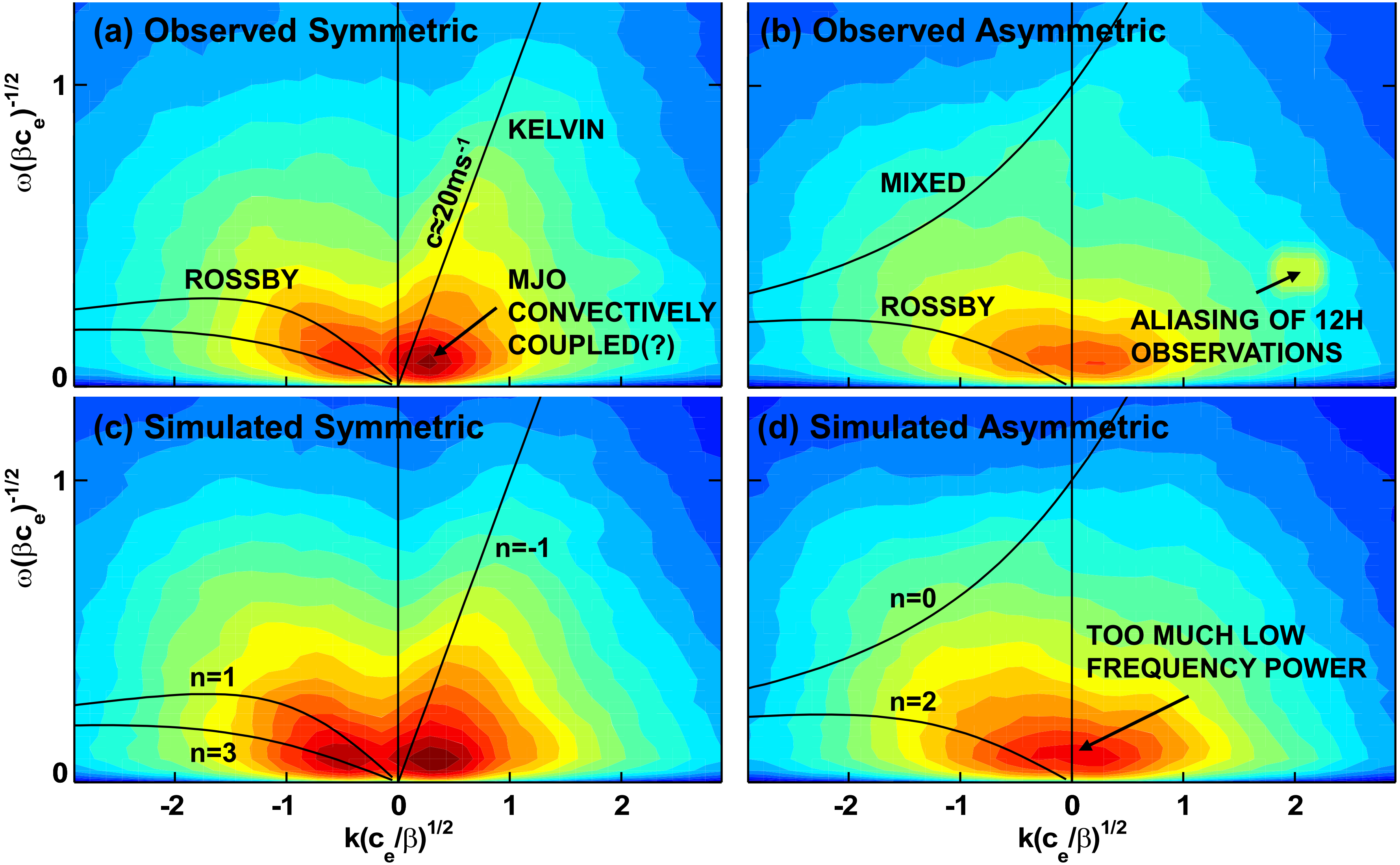
Interpretation of Free Equatorial Waves

Dispersion Diagram



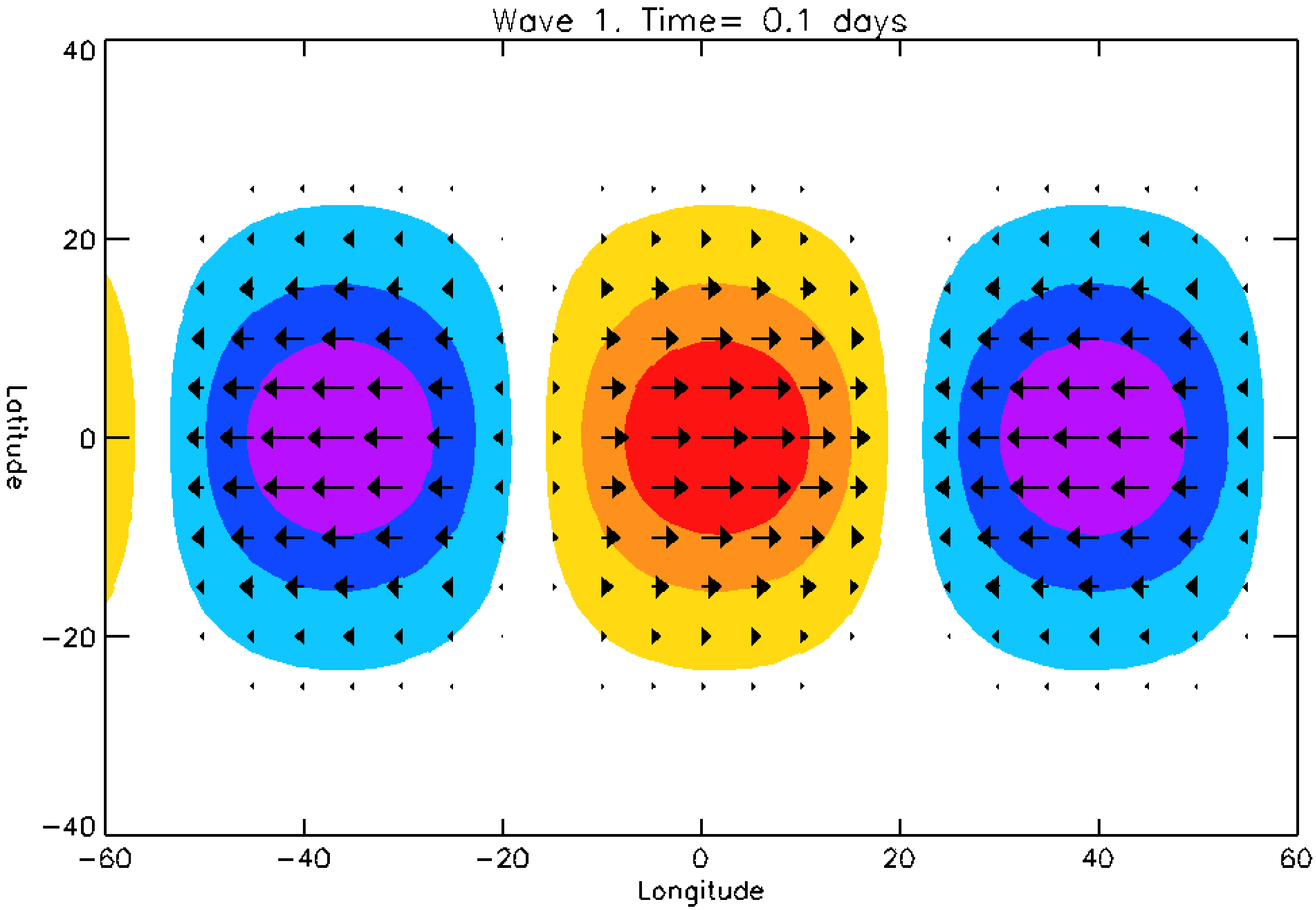
SUGGESTS METHOD OF COMPARISON BETWEEN OBSERVATIONS AND MODEL

Wave Power OLR DJF 1990-05 NOAA & 32R3



Agreement with shallow water theory if OLR is a ‘slave’ th the free waves, linearity, etc.

Wave Spotting



Wave spotting: Your Answers

Wave	Kelvin	Mixed Rossby-Gravity	Rossby	Eastward Gravity	Westward Gravity
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					

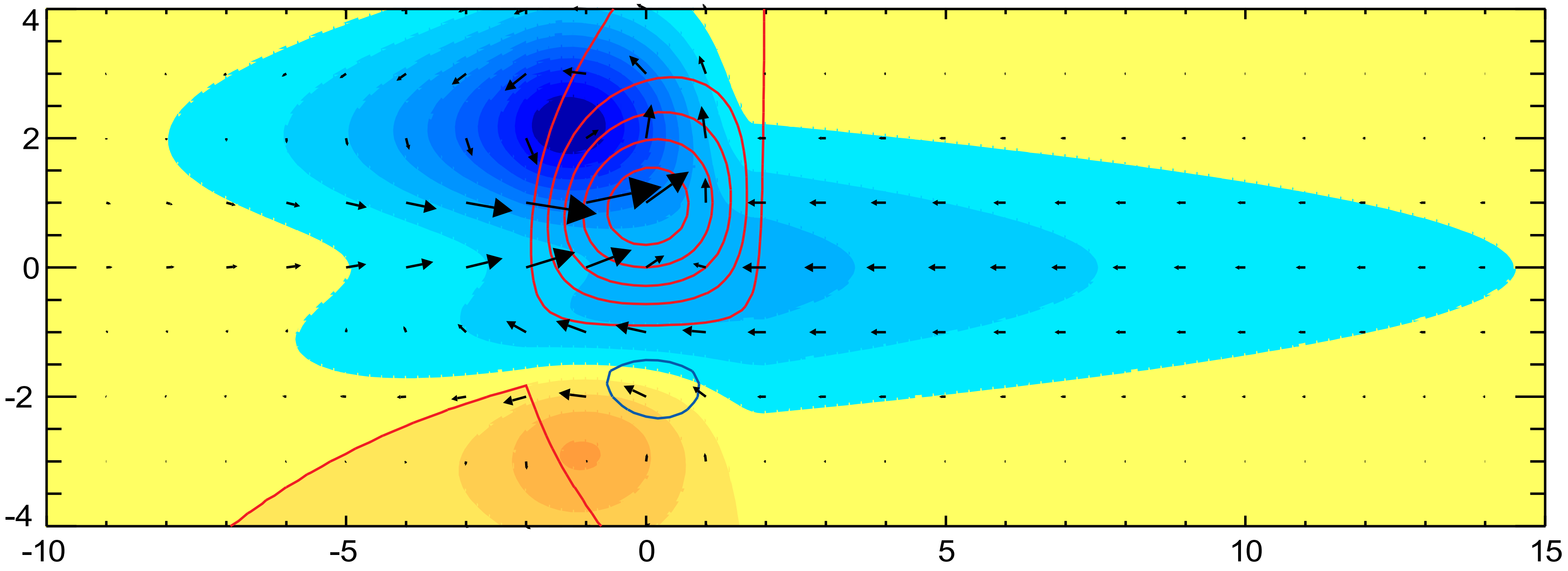
Gill's steady solution to monsoon heating

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):

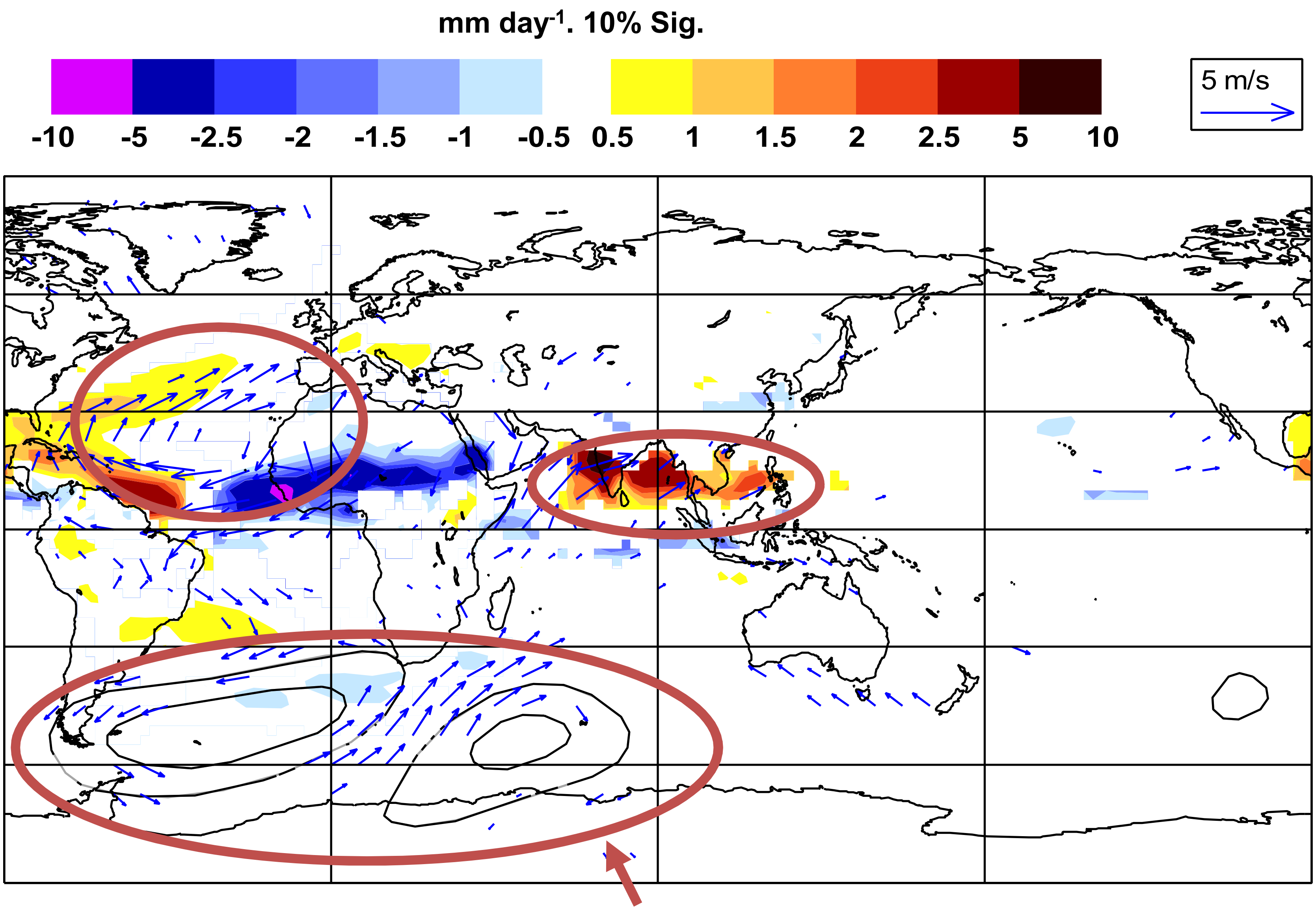
- **NORTH ATLANTIC SUBTROPICAL ANTICYCLONE**
- **CONVECTIVE COUPLING IN KELVIN WAVE REGIME**



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,…)

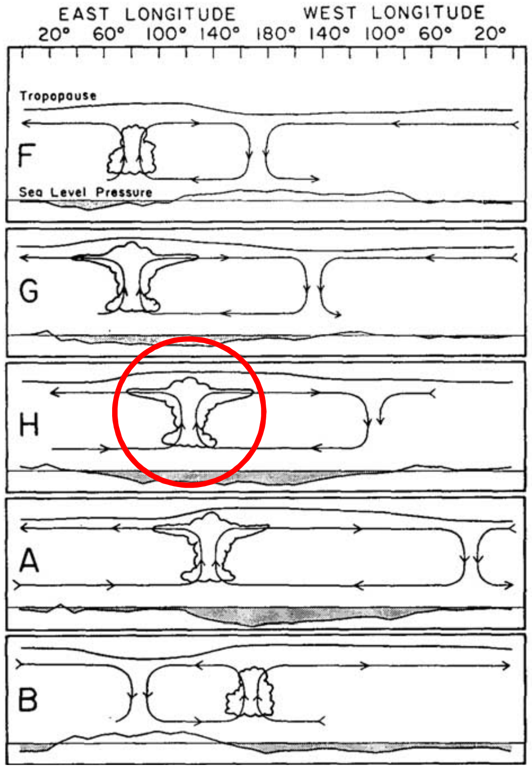
Following Gill (1980). See also Matsuno (1966)

JJA Precipitation, v925 and Z500. New-Old



The Extratropical Response will be explained in the next lecture!

Mean zonal wind tendency (60-180°E) during MJO

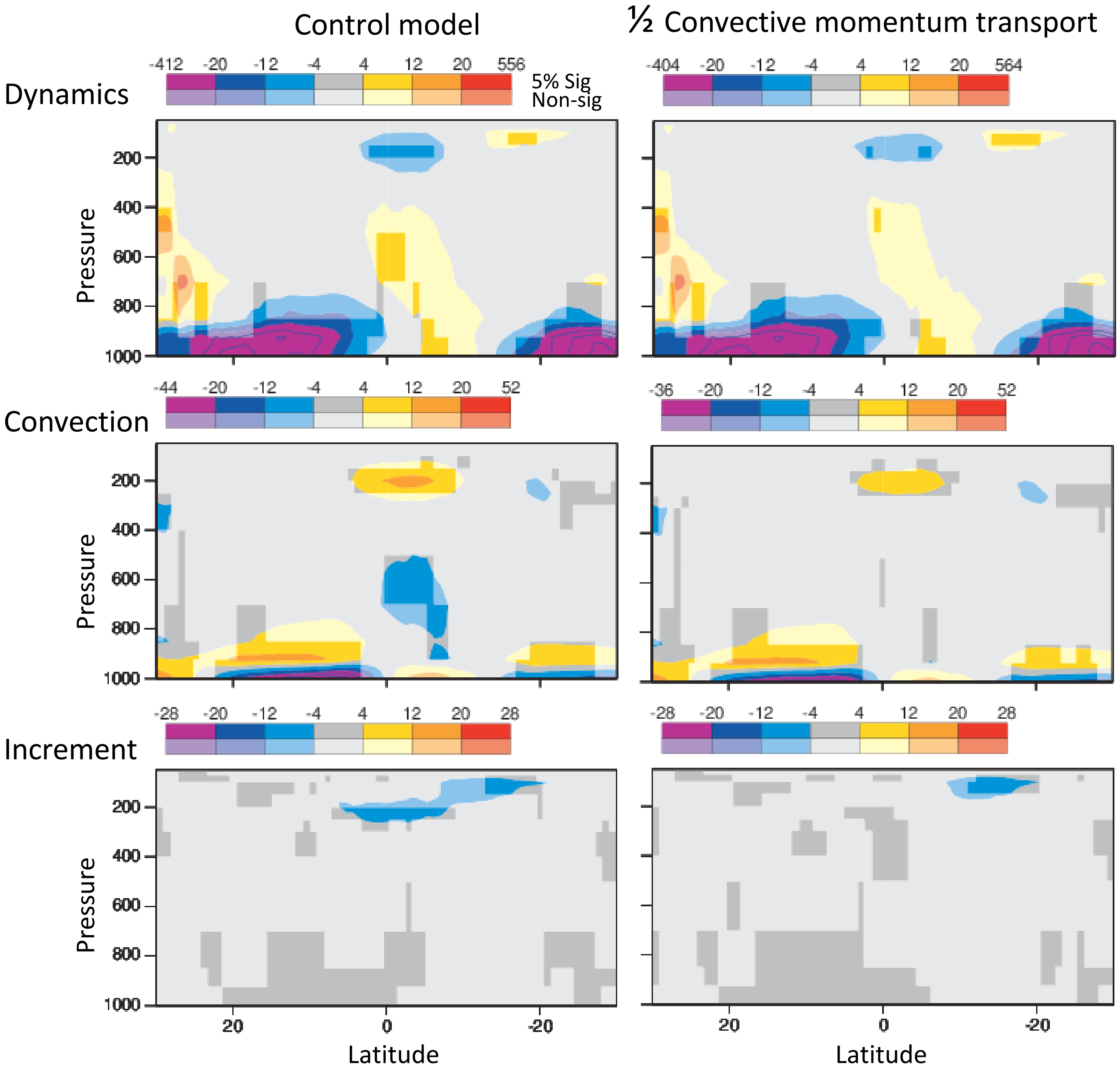


From Madden and Julian (1972)

Period : 20130201-27 (MJO convection active over warm-pool)

Better balance with dynamics when convective momentum transport is halved

Work with Peter Bechtold, Anton Beljaars , Jian Ling, Philippe Lopez, Frederic Vitart & Chidong Zhang



Summary

- Reliability and resolution
  - “Truth lies within the distribution sampled by the ensemble members, and this distribution is as sharp as possible”.
  - Improvement ‘ensured’ through optimisation of Proper scores (CRPS)
- Initial Tendencies
  - Process oriented assessment
  - Can help identify root-causes of errors
- Equatorial waves
  - Natural modes of (dry) tropical variability
  - Good way to understand propagation of error and uncertainty in Tropics