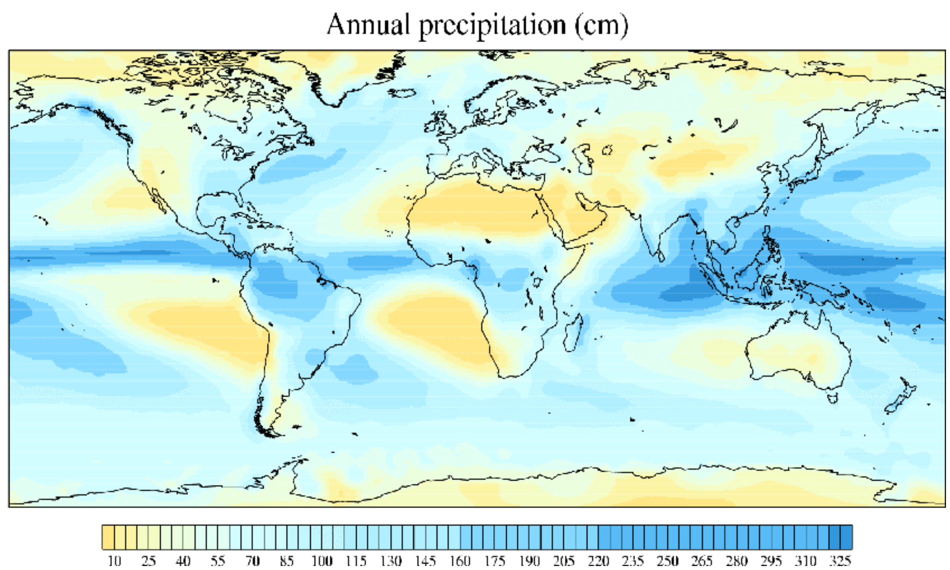
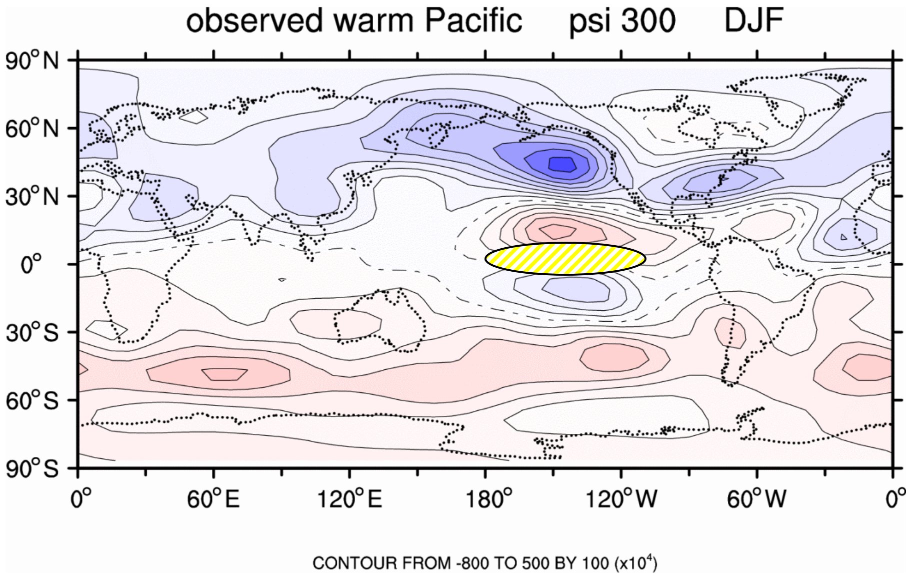
Annual mean precipitation



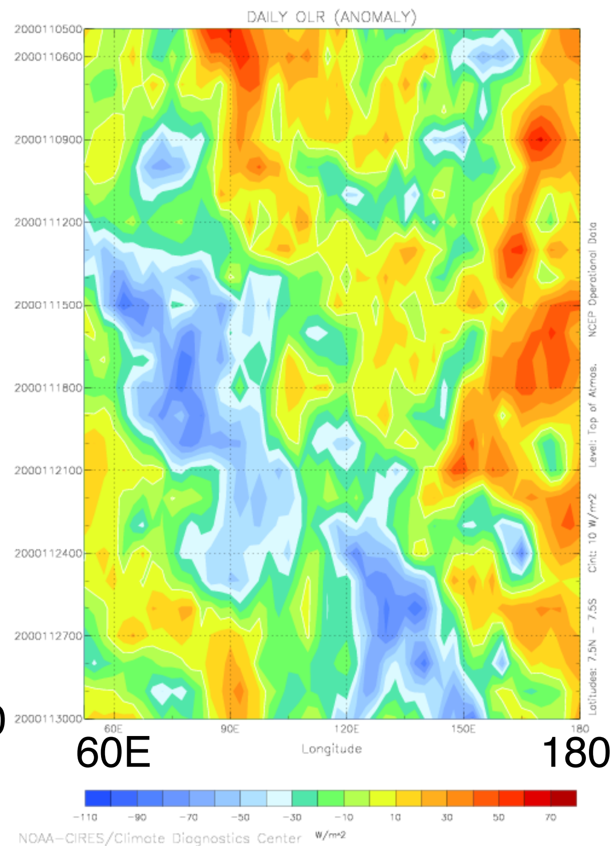
Wallace & Hobbs

Nature's response to El Nino heating



OLR anomalies

5Nov00



30Nov00

60E 180

Milliff et al., www.cora.nwra.com/~morzel/mjo.html

July - September 1987 OLR

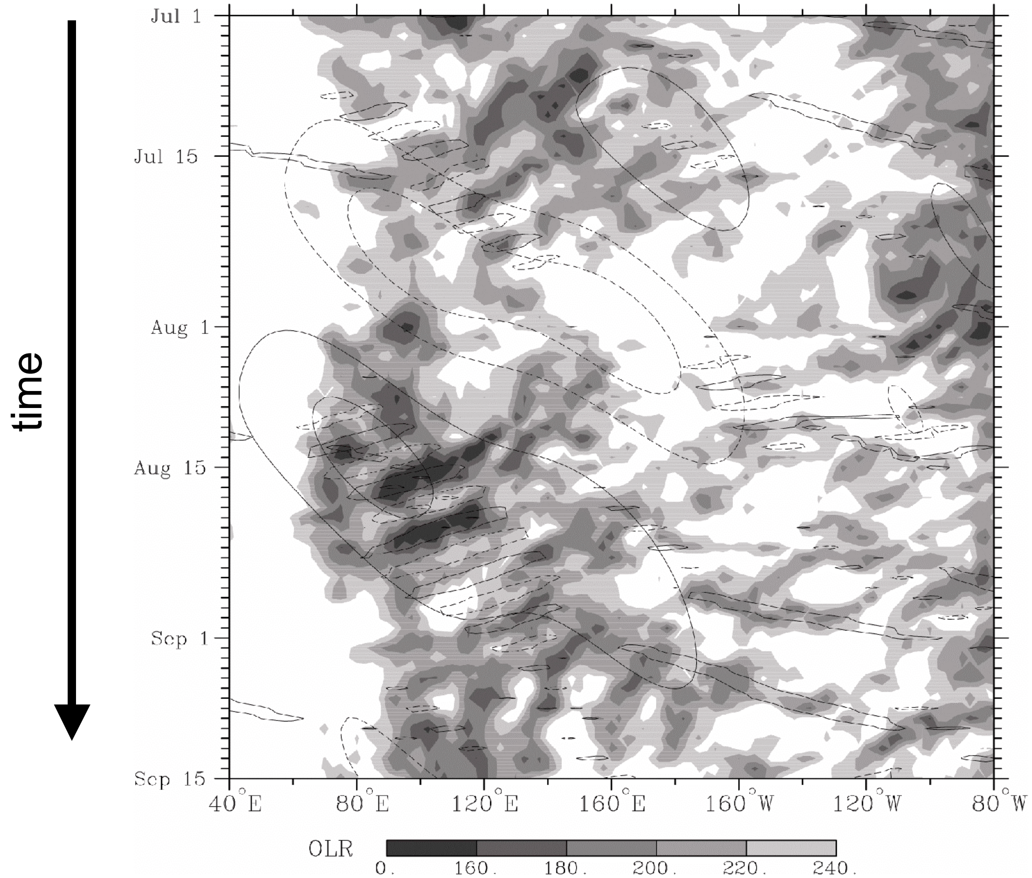
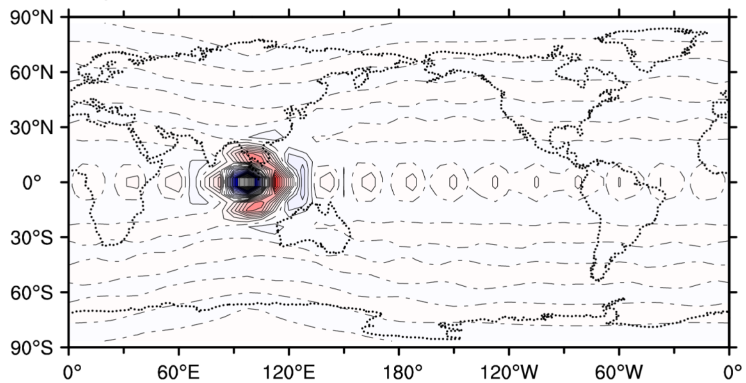


FIG. 6. Time–longitude plot of total OLR (shading, as indicated), filtered ISO, and MRG–TD OLR (contours, solid negative, contour interval 10 W m^{-2}, zero contour omitted), and filtered Kelvin wave OLR (contoured at -12 W m^{-2} only), averaged from 2.5° to 15°N, from 1 Jul to 15 Sep 1987.

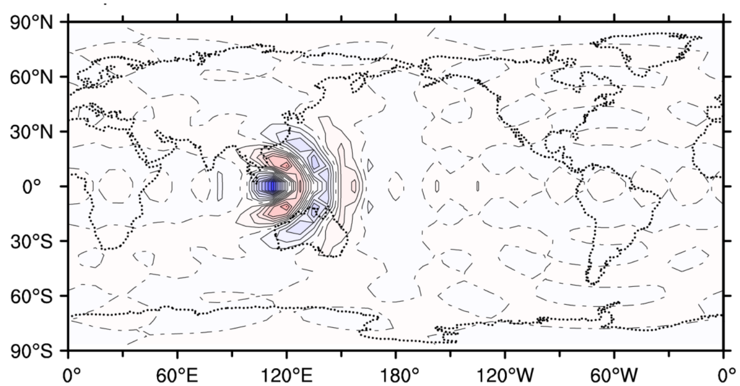
Straub & Kiladis (2003)

Initial pulse in linear model → dispersion

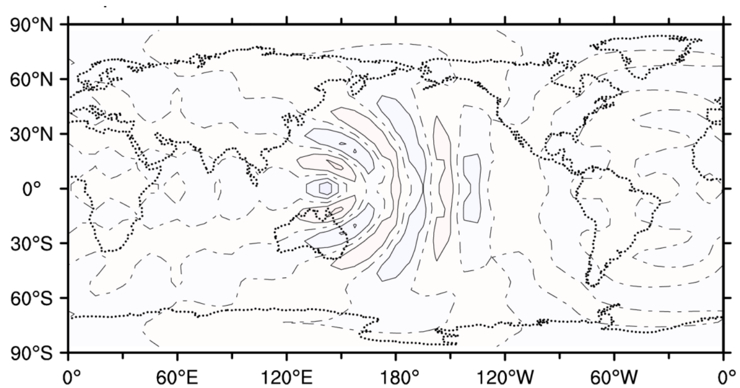
day 1



day 3

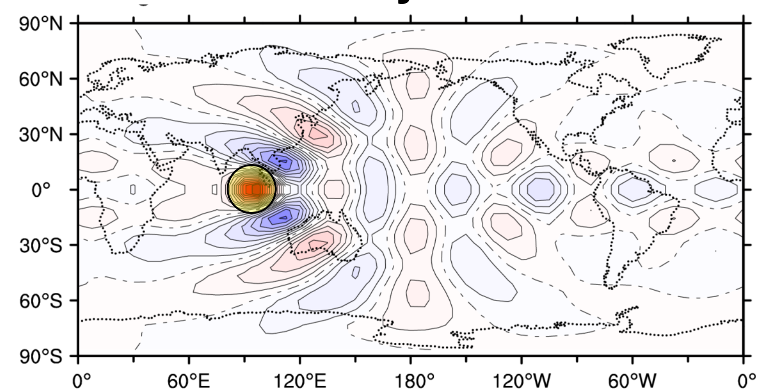


day 7

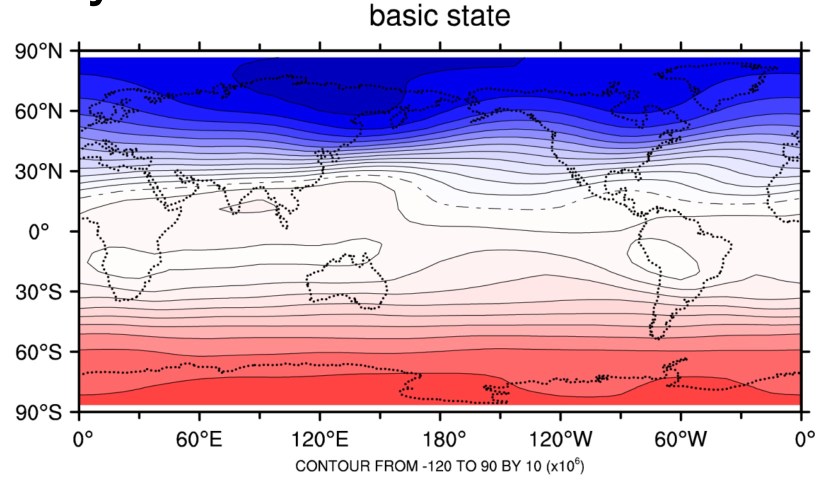


(vorticity)

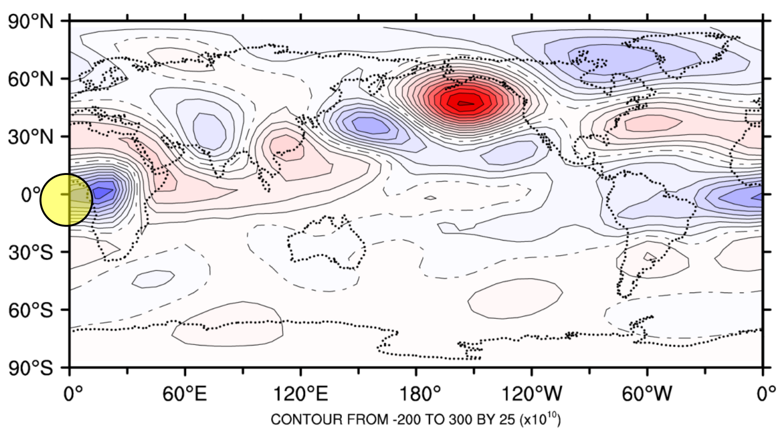
Linear response to steady source

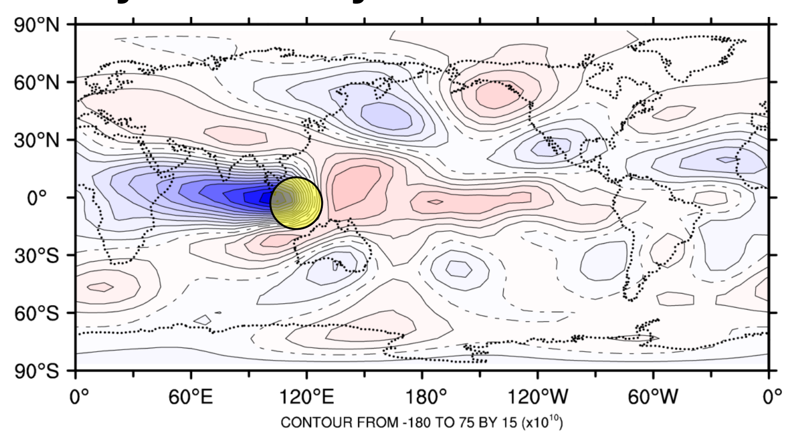


January mean 300hPa streamfunction



Linear response to steady vorticity source

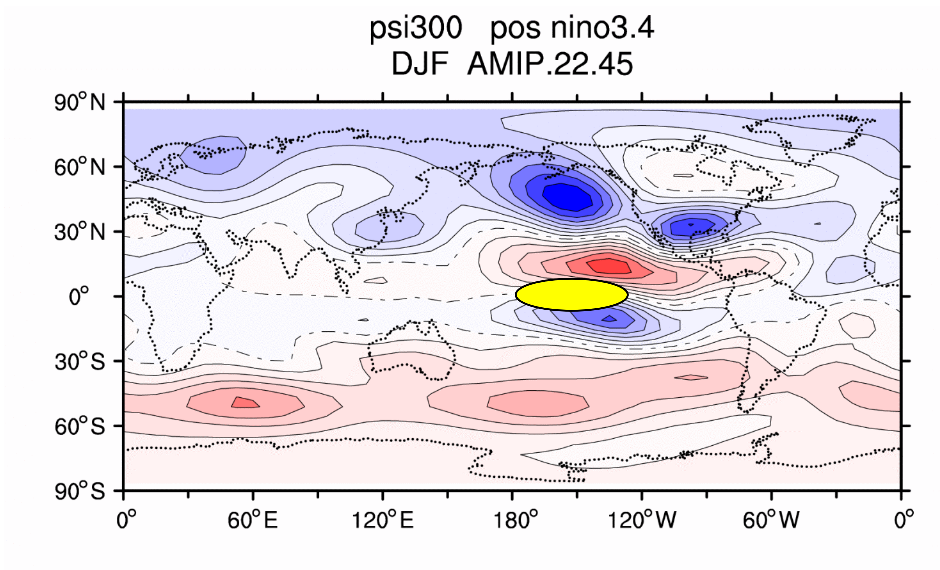




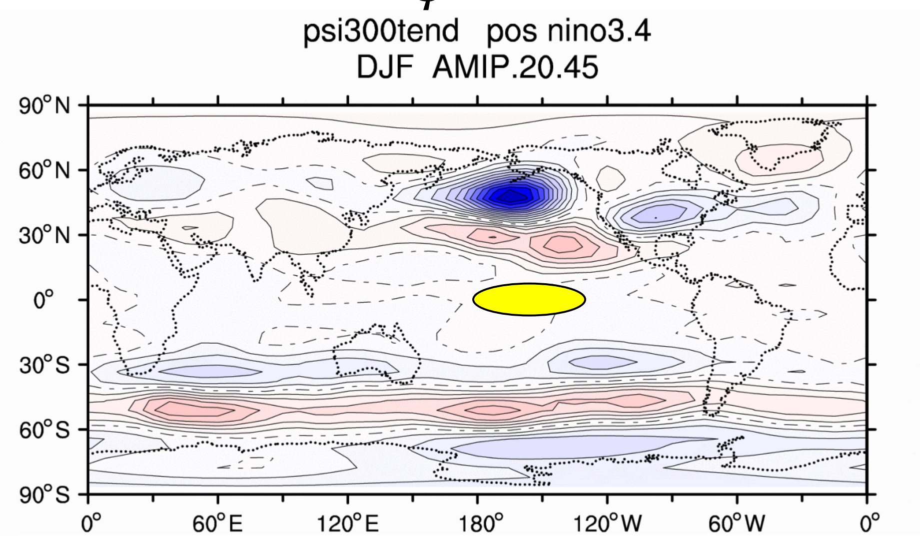
(streamfunction)

GCM response to El Nino SST

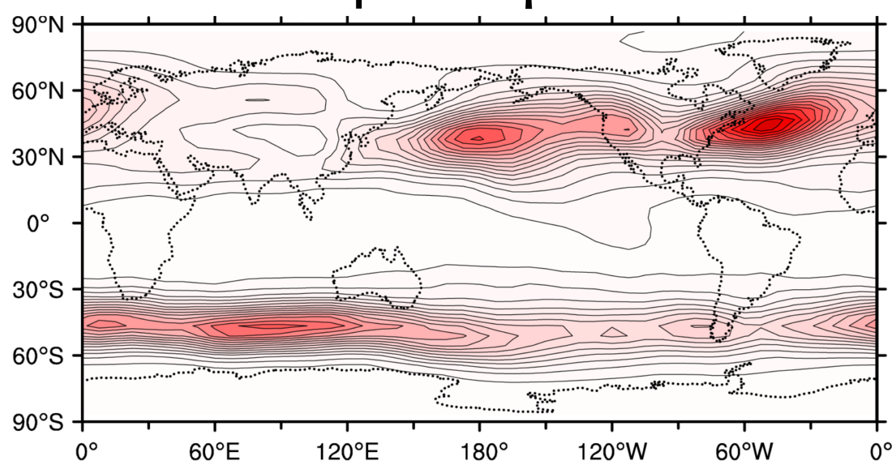
$$\hat{\psi}_{300}$$



$$-\overline{\nabla^{-2}(\vec{v}_{\psi}^{bp} \bullet \nabla \varsigma^{bp})}$$



2-7d bandpass ψ300 variance



The Atmospheric Response to Time-dependent Tropical Heating as Estimated from the Fluctuation Dissipation Theorem

Data compression & analysis through data driven modeling

Grant Branstator
National Center for Atmospheric Research

Andrey Gritsun, RAS; Andrew Majda, CIMS

Fluctuation Dissipation Theorem

(Leith, 1975)

Suppose have discretized dynamical system

$$\frac{d\phi}{dt} = F(\phi,\Lambda,f);\phi\big|_{t=0} = \phi_0;\phi,\phi_0 \in \Phi \qquad (\#)$$

Interested in

$$\langle A(\phi)\rangle = \int A(\phi)\rho(\phi)d\phi, \text{ for stationary PDF } \rho$$

Suppose f is changed by a small δf. Want

linear U] $\delta\langle A(\phi)\rangle = U\delta f$

If (*Deker & Haake, 1975; Risken, 1984*)

* (#) is assumed to include a small noise term so its PDF is not fractal
* (#) has a F - P equation with unique solution,

then

$$U_{ij}(t) = \int_0^t \left\langle A_i(\phi(t'+\tau)) \frac{\partial \ln \rho(\phi(t'))}{\partial \phi_j(t')} \right\rangle d\tau$$

Generalized FDT -- Simplifications

For a system like the earth's atmosphere

$$\rho \cong \rho_0 \exp\left\{ -(C^{-1}(0)\phi', \phi')/2 \right\}$$

So

$$U(t) \cong \int_0^t \left\langle A(\phi'(t'+\tau))(\phi'(t))^T \right\rangle C^{-1}(0)\,d\tau$$

Note if $A = I$,

$$U(t) = \int_0^t C(\tau)C^{-1}(0)\,d\tau$$

Majda, Abramov & Grote (2005) found third order accuracy for $A = I$ and second order accuracy for quadratic A.

Simplified FDT -- Incremental form

For quasiGaussian case with $A = I$,

the response at t to a steady forcing switched on at t_0 is

$$U(t,t_0)f = \int_{t_0}^{t} C(\tau)C^{-1}(0)d\tau f$$

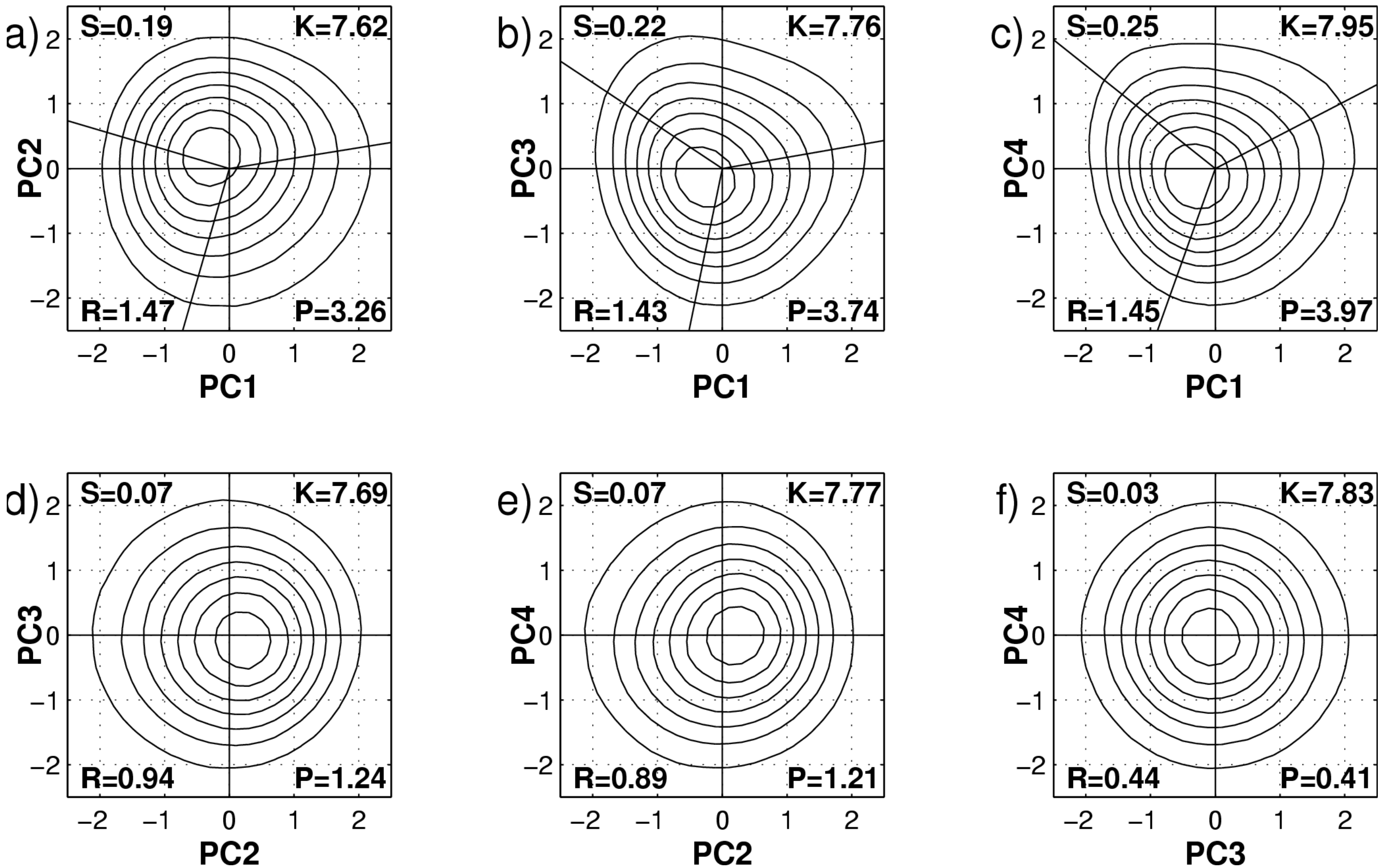
$\Rightarrow$

the operator that gives the response at t to a pulse forcing at t_0 is

$$\delta U(t,t_0) = C(t-t_0)C^{-1}(0)$$

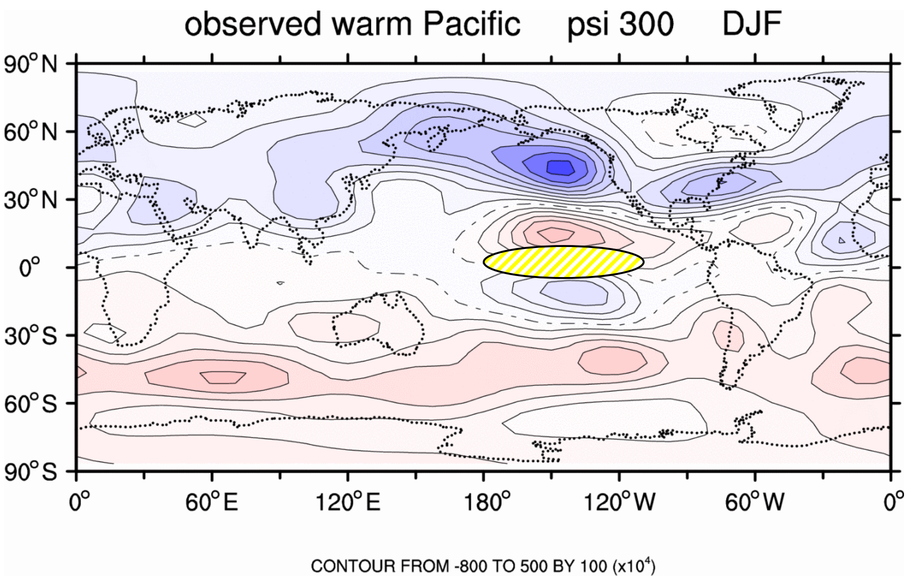
$\Rightarrow$

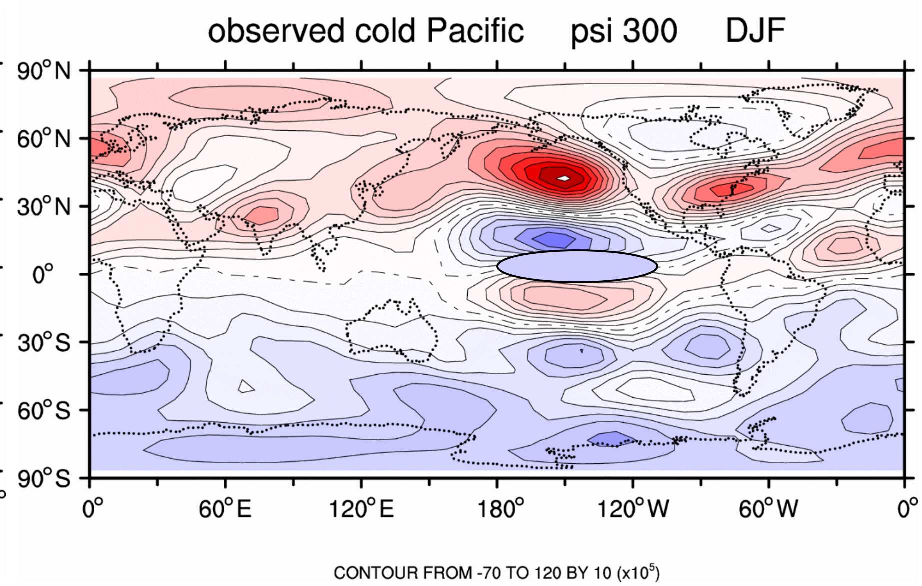
$$R(t) = \int_{t_0}^{t} C(t-\tau)C^{-1}(0)f(\tau)d\tau$$



Berner & Branstator (2006)

Nature's response to El Nino & La Nina





Test bed & application

Atmospheric general circulation model (NCAR's CCM0)

* Avoid sampling limitations when calculating lag covariances
* Can sample strictly intrinsic variability
* Enables rigorous testing of the resulting operator

Primitive equations, circa 1980 physical parameterizations

Perpetual January, fixed boundary conditions

R15
9 level } 18352 degrees of freedom

8 million 12hrly simulated states

Reduce Dimensionality

1. Pick fields from

   * ps
   * psi x 9
   * chi x 9
   * T   x 9
   * water vapor mixing ratio x 9

2. Truncate each field using EOFs

   * psi   100x9 (>90%)
   * T   496x9 (100%)

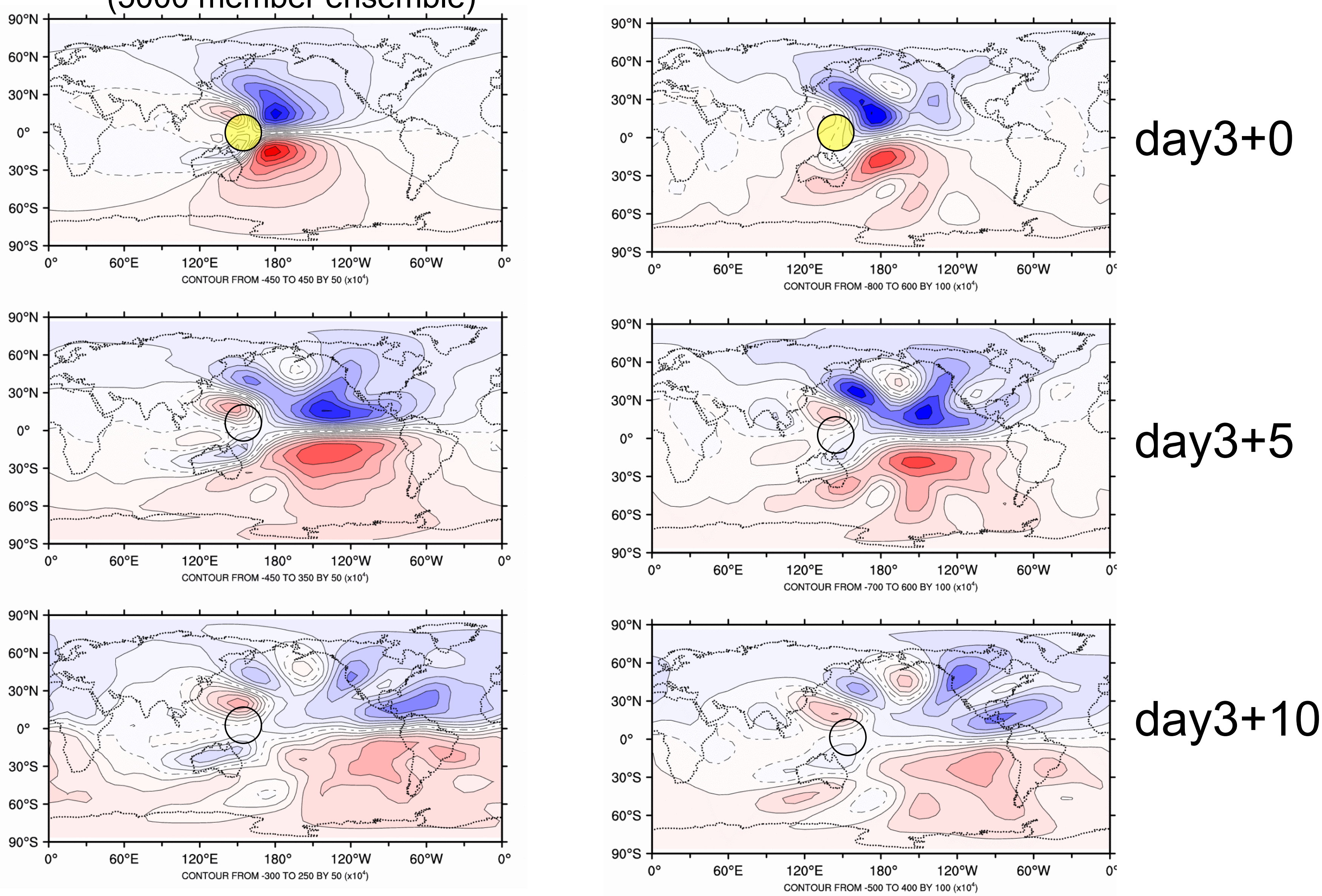
3. Form multivariate (truncated) fields,
   normalize by std dev & overweight T,
   calculate EOFs
   truncate (1800 EOFs, >95%)

Assume lag covariances vanish for $\tau > 30$d

3day pulse forcing

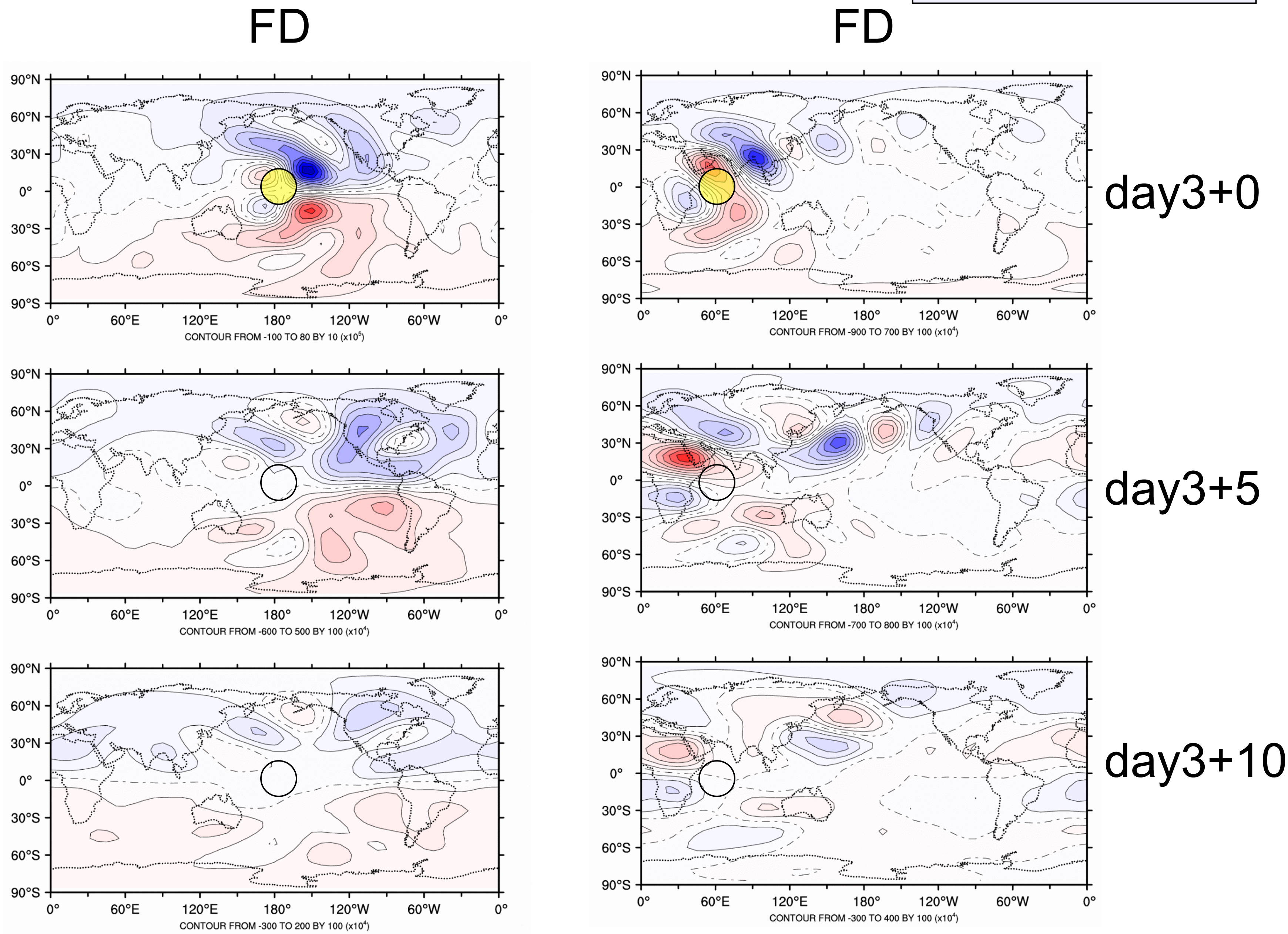
CCM0
(5000 member ensemble)

FD



3day pulse forcing

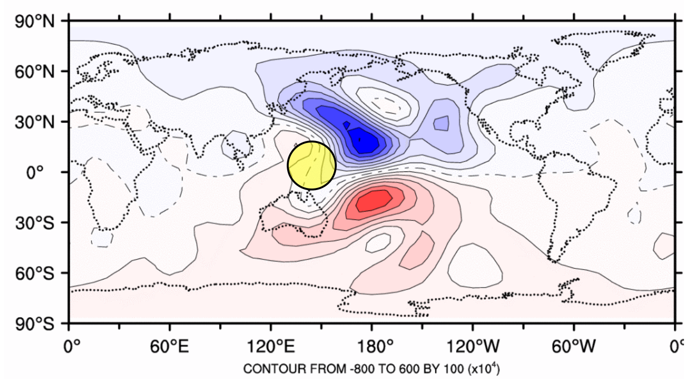
Exploration



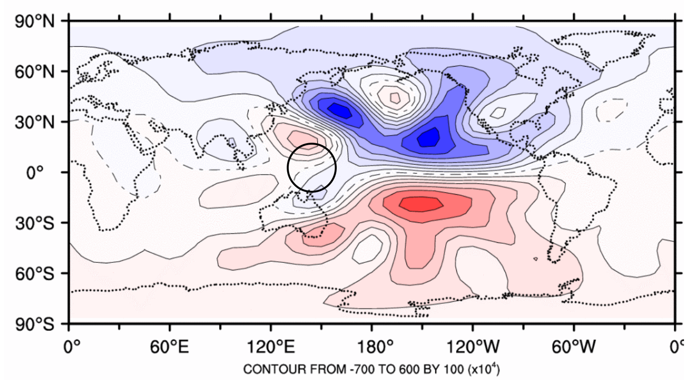
FD

3day pulse forcing

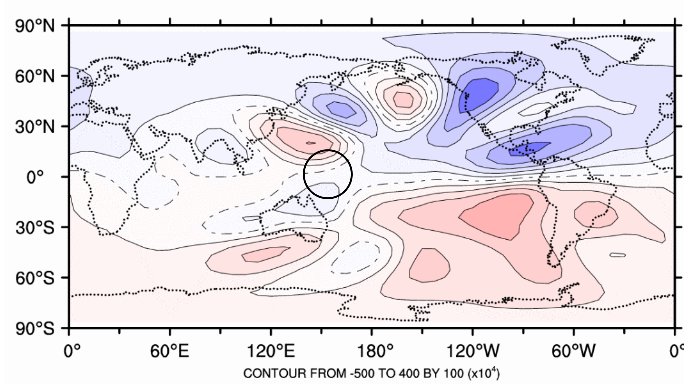
day3+0



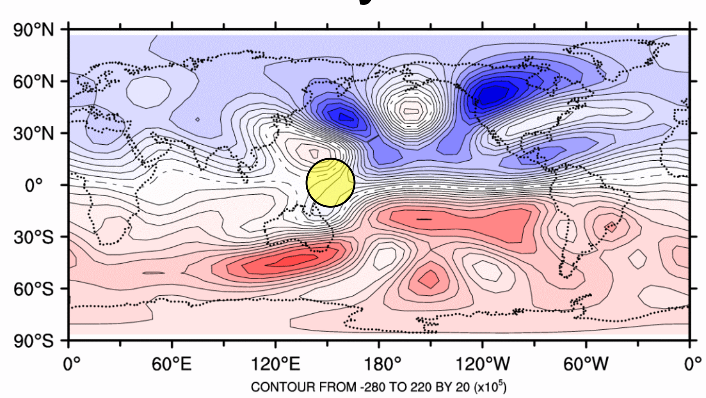
day3+5



day3+10



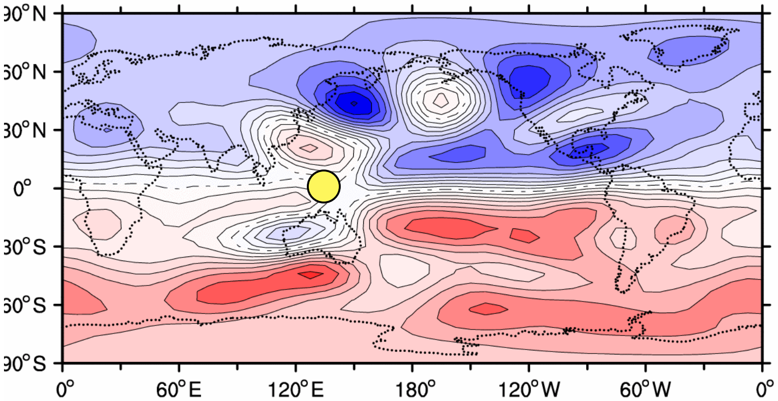
constant forcing day 30



CCM0

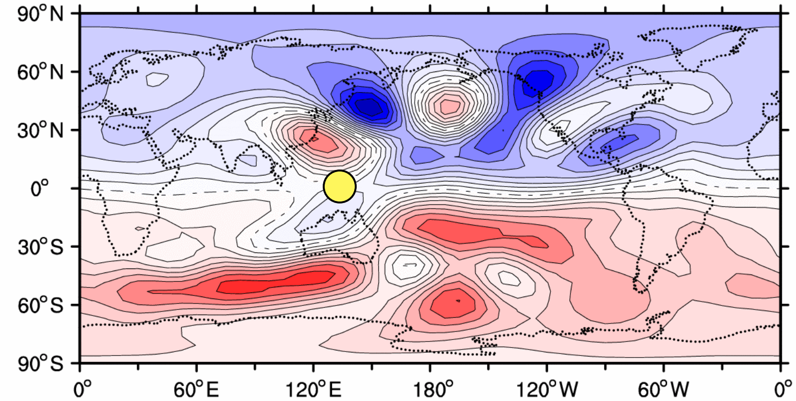
FDT

CCM0 strong forcing
psi336
(135.00, 0.00) 2.5C/day



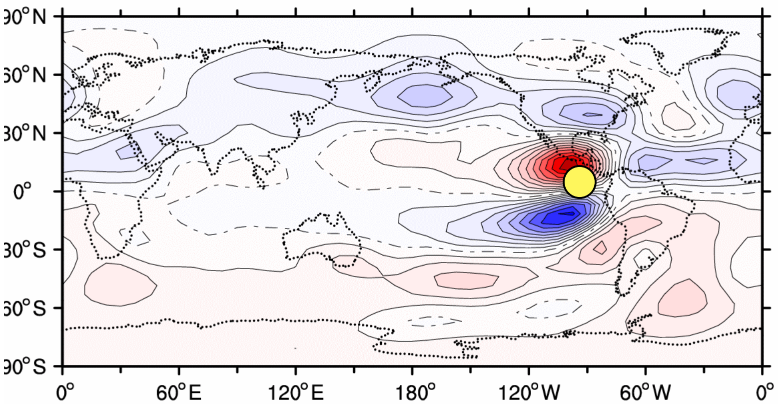
CONTOUR FROM -500 TO 400 BY 50 (x10^4)
FD vs CCM0 multifield cor= 0.81

FD
psi336
(135.00, 0.00) 2.5C/day



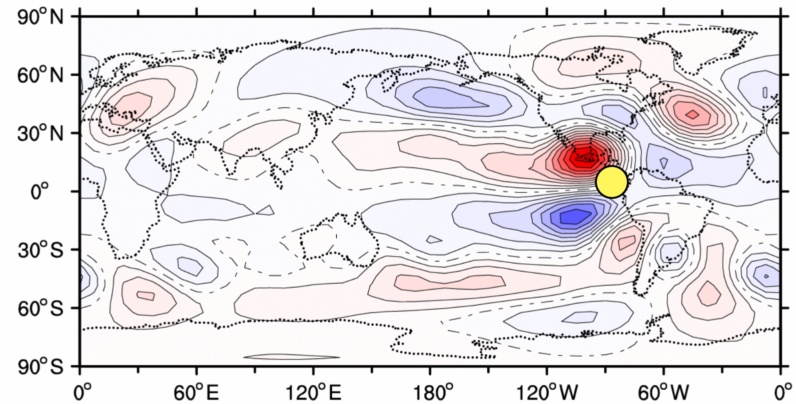
CONTOUR FROM -500 TO 400 BY 50 (x10^4)
FD vs CCM0 multifield cor= 0.81

CCM0 strong forcing
psi336
(-90.00, 0.00) 2.5C/day

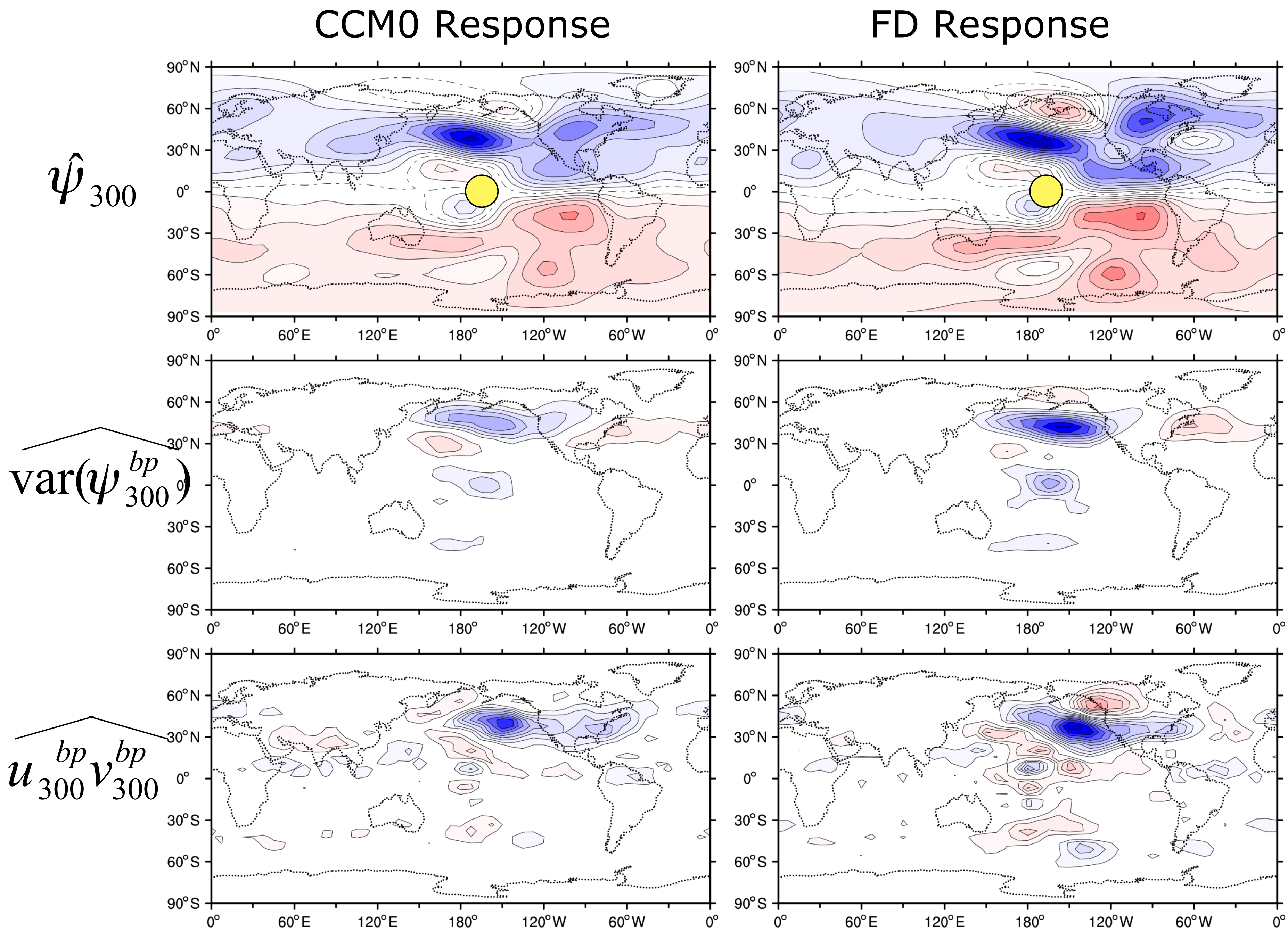


CONTOUR FROM -450 TO 500 BY 50 (x10^4)
FD vs CCM0 multifield cor= 0.77

FD
psi336
(-90.00, 0.00) 2.5C/day

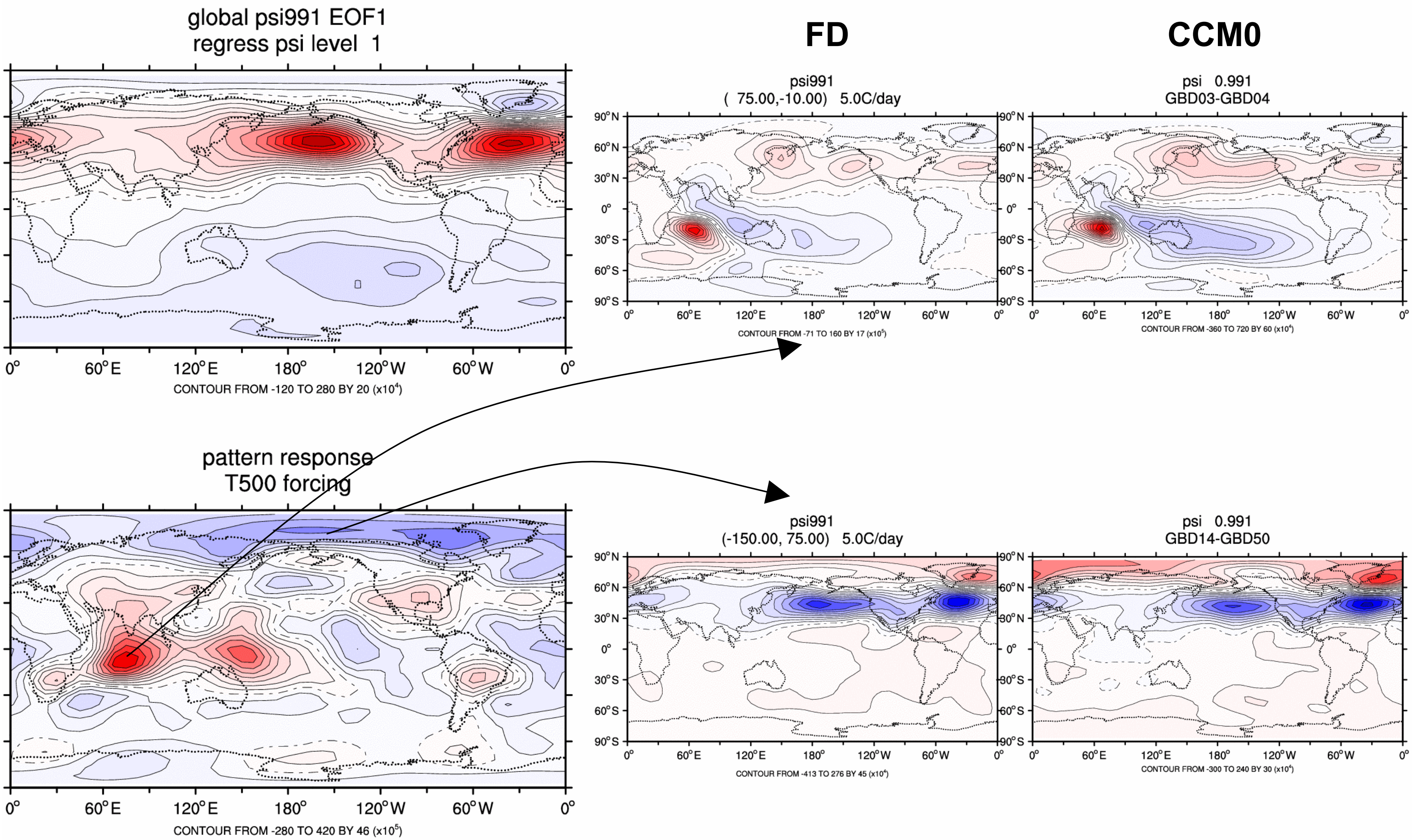


CONTOUR FROM -350 TO 500 BY 50 (x10^4)
FD vs CCM0 multifield cor= 0.77



CCM0 Response
FD Response
$\hat{\psi}_{300}$
$\widehat{\mathrm{var}(\psi_{300}^{bp})}$
$\widehat{u_{300}^{bp} v_{300}^{bp}}$
90°N
60°N
30°N
0°
30°S
60°S
90°S
0°
60°E
120°E
180°
120°W
60°W

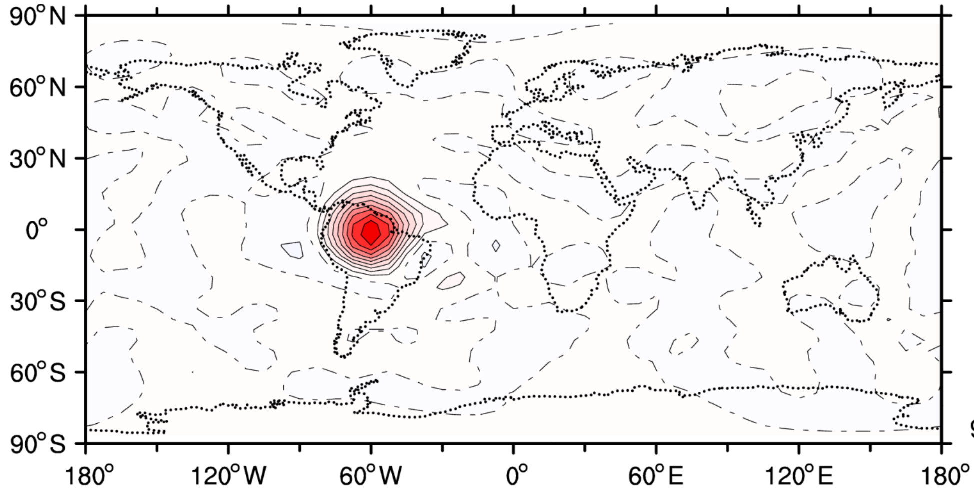
Control



global psi991 EOF1
regress psi level 1
CONTOUR FROM -120 TO 280 BY 20 (x10^4)
pattern response
T500 forcing
CONTOUR FROM -280 TO 420 BY 46 (x10^5)
FD
CCM0
psi991
(75.00,-10.00) 5.0C/day
psi 0.991
GBD03-GBD04
psi991
(-150.00, 75.00) 5.0C/day
psi 0.991
GBD14-GBD50
0°
60°E
120°E
180°
120°W
60°W
90°N
60°N
30°N
30°S
60°S
90°S

Attribution

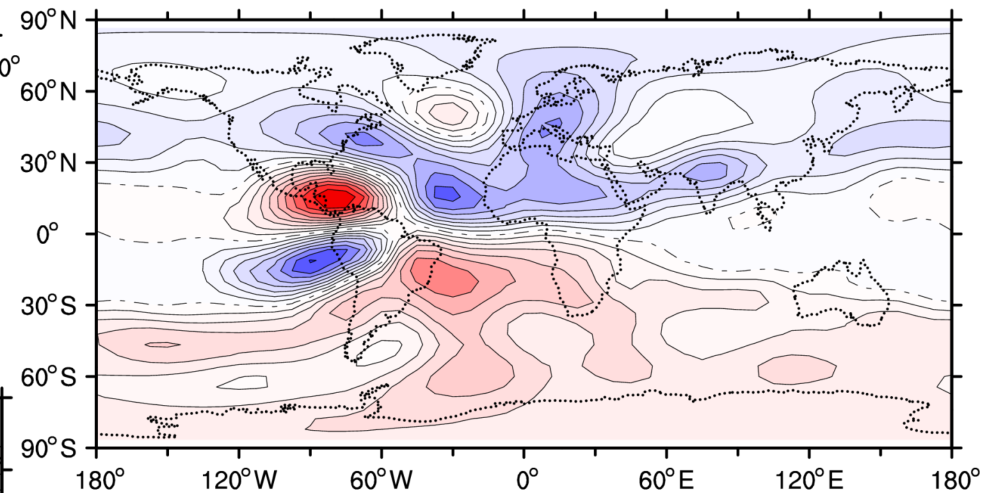
500mb heating



CONTOUR FROM -14 TO 127 BY 14 (x.001)

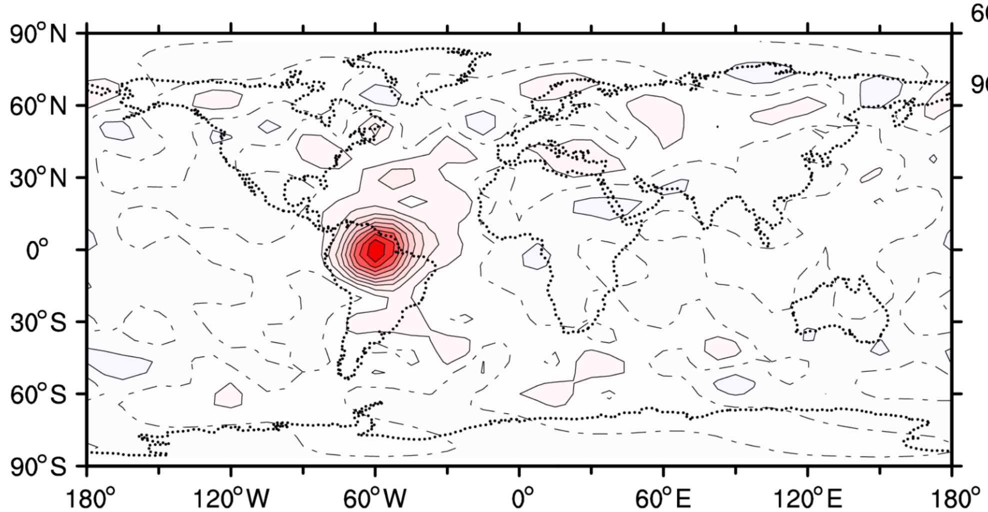
GCM

336mb streamfunction



CONTOUR FROM -178 TO 201 BY 22 ($x10^4$)

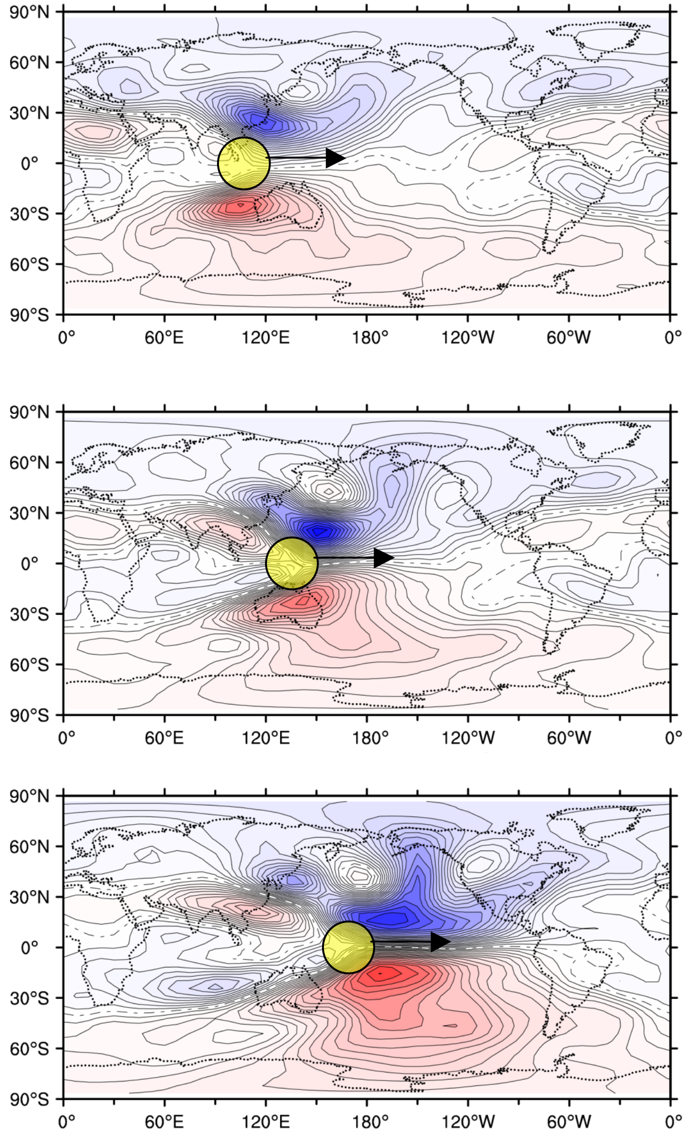
U^{-1}



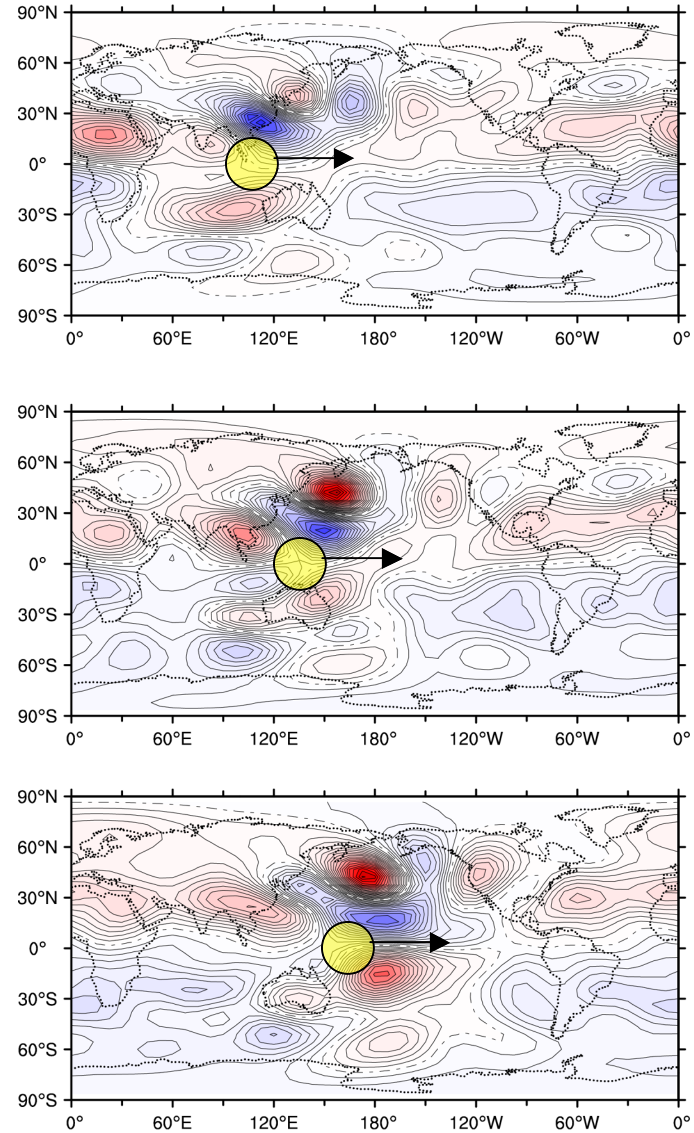
CONTOUR FROM -9 TO 88 BY 9 (x.001)

ψ_{300} response to 8deg/d heat source

GCM (15000 member ensemble)

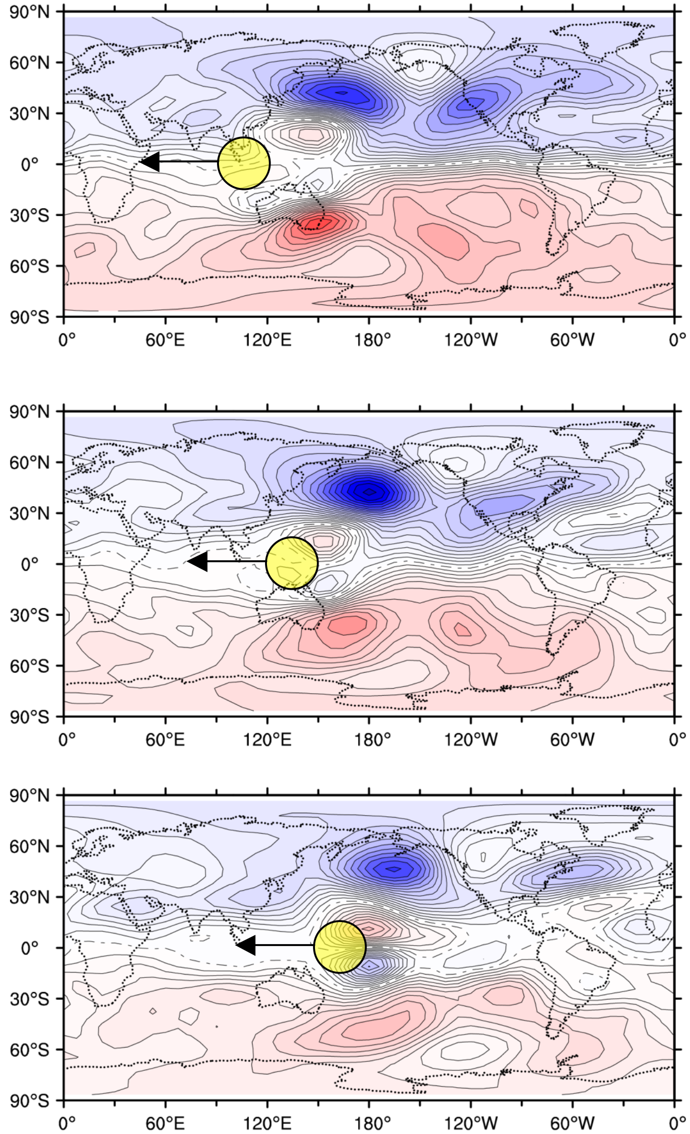


FDT

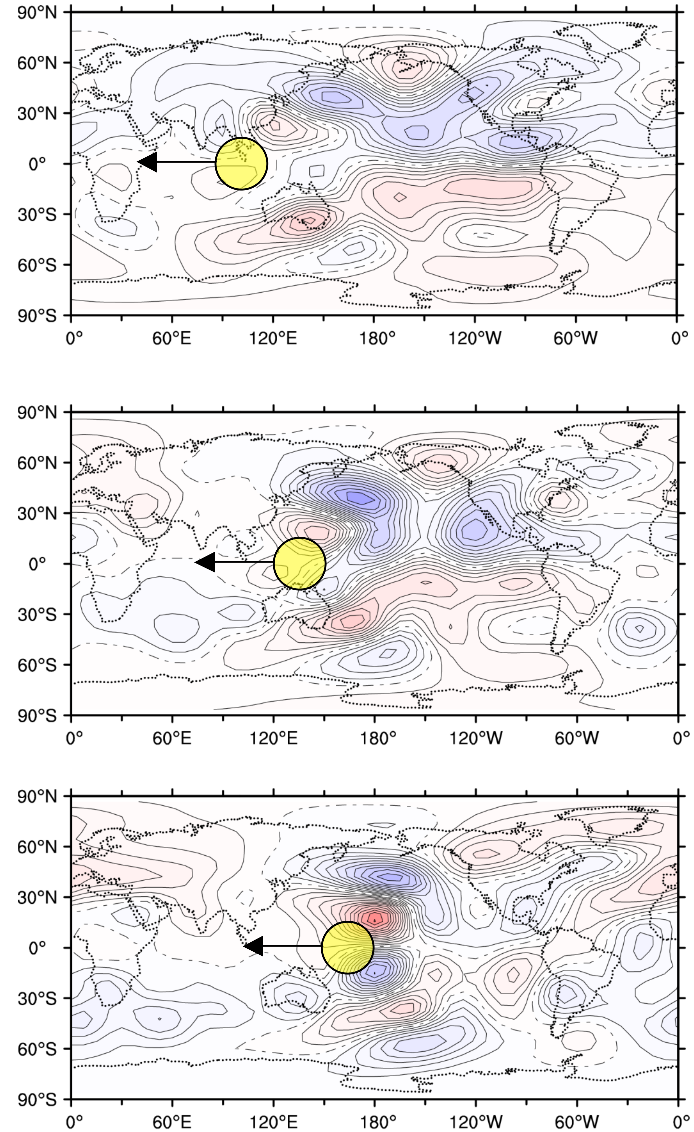


ψ300 response to -8deg/d heat source

GCM (15000 member ensemble)

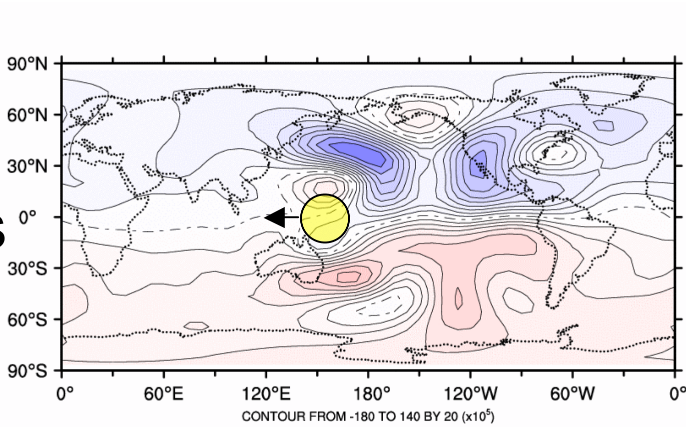


FDT

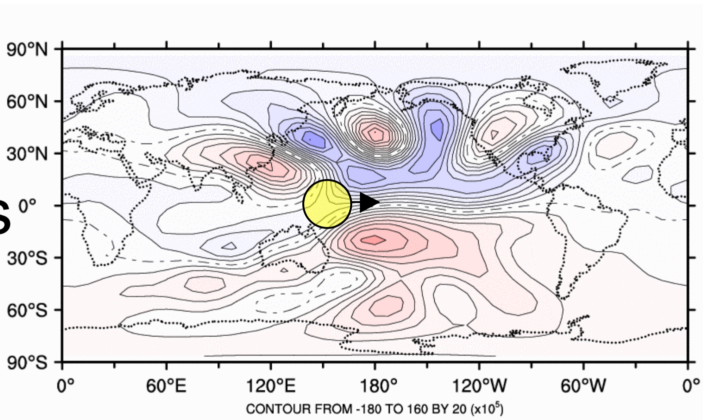


FD
moving source

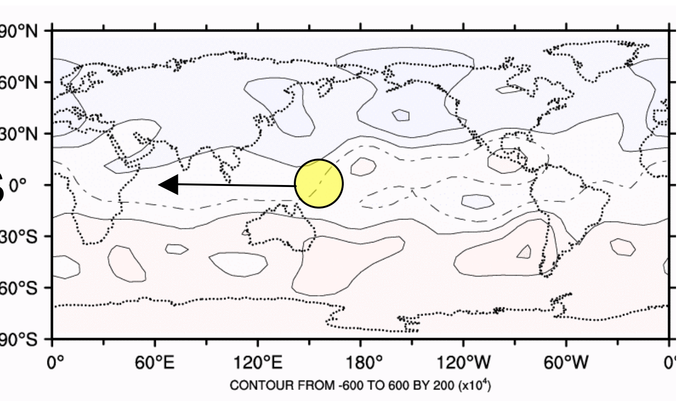
-6.4m/s



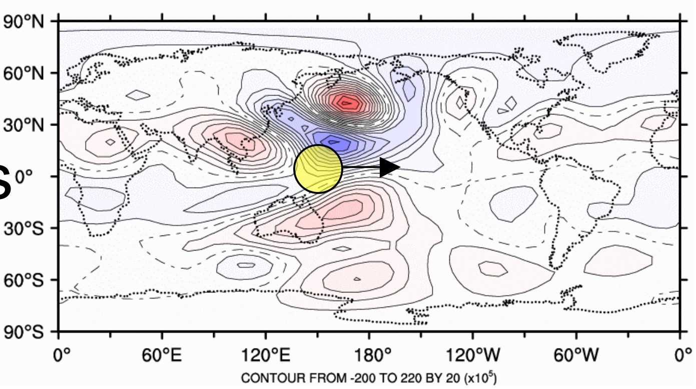
5m/s



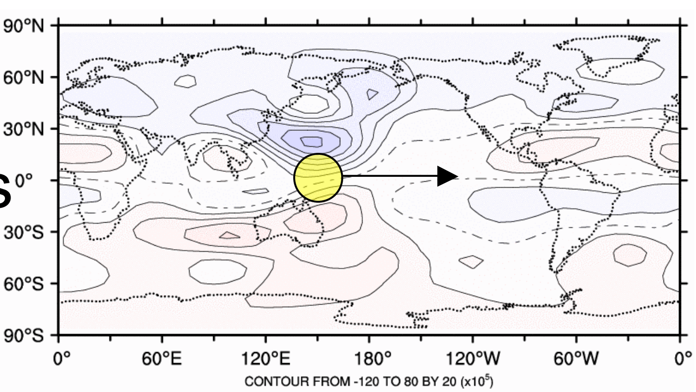
-26m/s



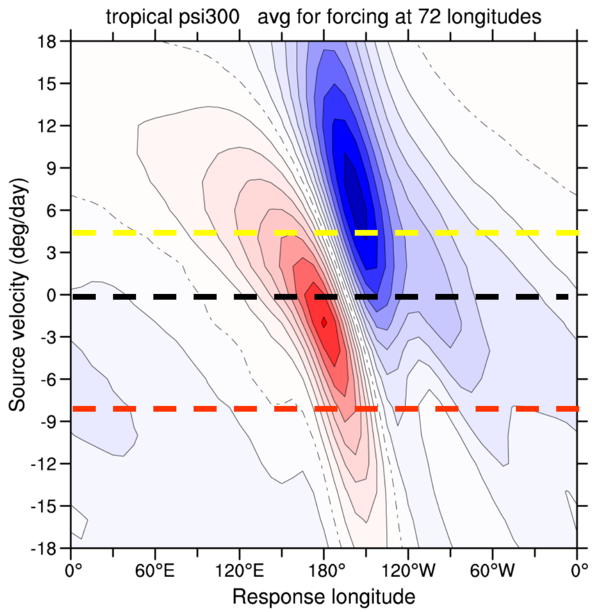
10m/s



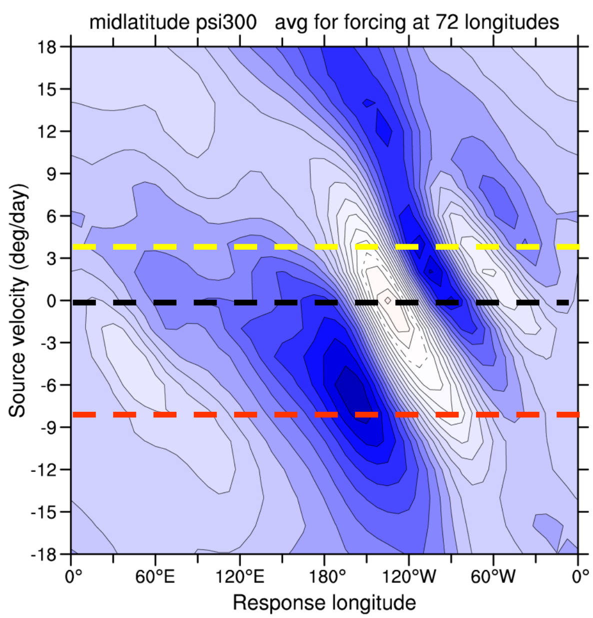
20m/s



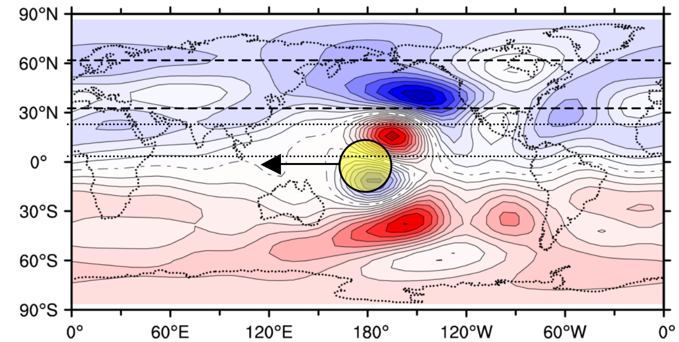
Response to moving eq heat source



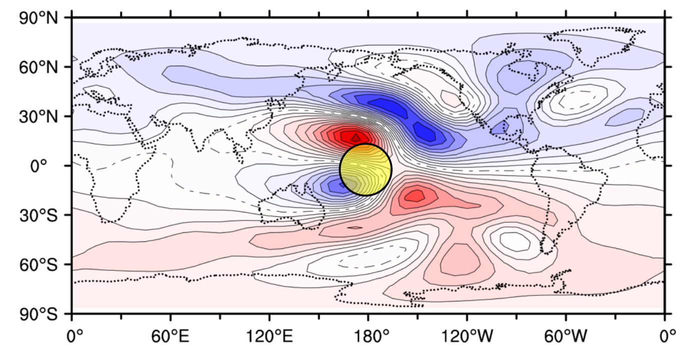
tropical ψ300



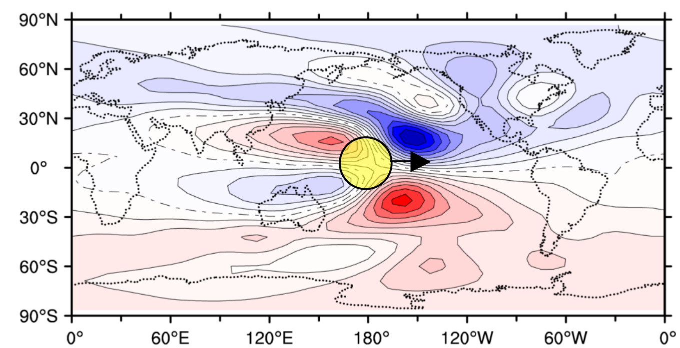
midlatitude ψ300



-8deg/d

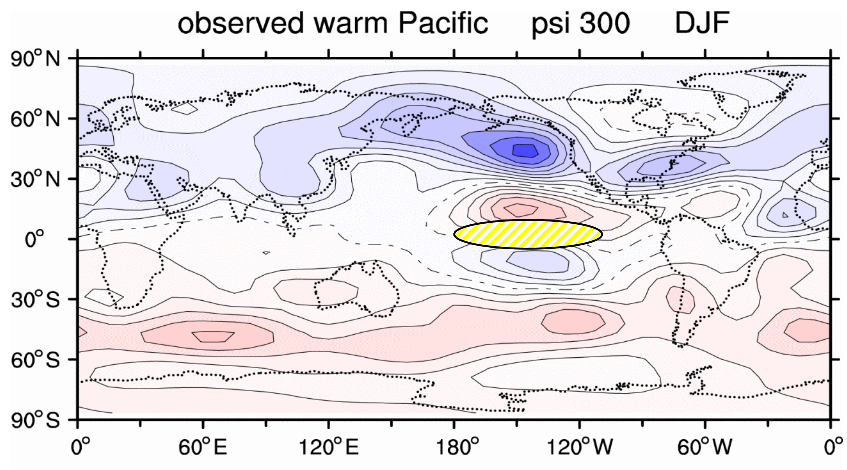


0deg/d

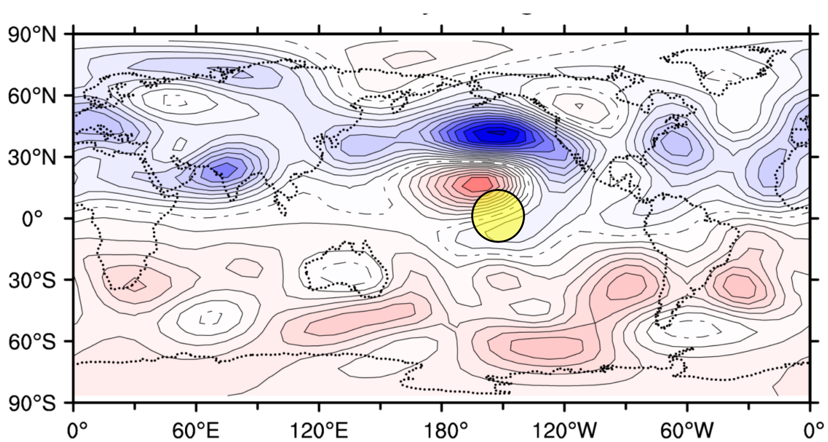


4deg/d

Response to El Nino in Nature



FDT response using operator from Nature



FDT from unfiltered data