Global Response to the Major Volcanic Eruptions in 9 Reanalysis Datasets

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Introduction

- Major volcanic eruptions are an important natural cause of climate change, e.g., for succeeding ~2 years [e.g., Robock, 2000]
- Recent major volcanic eruptions include:

Volcano	Country	Year	Month	QBO	Solar Cycle	Nino3.4
Mt. Agung	Indonesia	1963	March	Easterly	Min.	0 → +
El Chichón	Mexico	1982	Mar-Apr	Easterly	Max. →	0 → +
Mt. Pinatubo	Philippines	1991	June	Easterly	Max. →	0 → +

- Evaluation of their effects are important for evaluating:
  - anthropogenic climate change
  - a geo-engineering option [e.g., Crutzen, 2006; Robock et al., 2013]
- Also need good evaluation of other natural causes of climate change at the same time (i.e., QBO, Solar Cycle, and ENSO) [e.g., Free and Lanzante, 2009]

- In recent years, several new global atmospheric "reanalysis" datasets became available
  - Potential for better quantification of climate change in the past
  - Need intercomparison, validation, and evaluation (e.g., SPARC Reanalysis Intercomparison Project, S-RIP)
- In this study, monthly-mean zonal-mean temperature data from 9 reanalyses are analyzed to investigate the three volcanic eruptions' effects

Available Global Atmospheric Reanalyses

Product	Centre	Period	Resolution and **Lid Height** of the Forecast Model	Contact for S-RIP
MERRA	NASA	1979 – present	(2/3)x(1/2) deg., L72, **0.01 hPa**	S. Pawson
ERA-Interim	ECMWF	1979 – present	T_L255 & N128 reduced Gaussian (79km), L60, **0.1 hPa**	D. Tan
ERA-40	ECMWF	1957.9 - 2002.8	T_L159 & N80 reduced Gaussian (125km), L60, **0.1 hPa**	D. Tan
NCEP-CFSR	NCEP	1979 – 2009 2010 - present	T382 (T574 for post 2010), L64, **0.266 hPa**	C. Long
JRA-55	JMA	1958 - 2012	T319, L60, **0.1 hPa**	K. Onogi
JRA-25/JCDAS	JMA and CRIEPI	1979 – present	T106, L40, **0.4 hPa**	K. Onogi
NCEP-2 (R-2)	NCEP and DOE AMIP-II	1979 – present	T62, L28, **3 hPa**	W. Ebisuzaki
NCEP-1 (R-1)	NCEP and NCAR	1948 – present	T62, L28, **3 hPa**	W. Ebisuzaki
NOAA-CIRES 20th Century Reanalysis (20CR_v2)(*)	NOAA/ESRL PSD	1871 – 2010	T62, L28, **2.511hPa**	G. Compo & J. S. Whitaker

(*) 20CR assimilates only surface pressure reports and uses observed monthly sea-surface temperature and sea-ice distributions as boundary conditions.

- Analysis Period: *<u>1979-2009 (31 years)</u>*, 8 RAs (all except for ERA-40)
  - 2 eruptions: El Chichón (March-April 1982) and Mt. Pinatubo (June 1991)
- Analysis Period: *<u>1958-2001 (44 years)</u>*, 4 RAs (JRA-55, ERA-40, NCEP1, and 20CR)
  - 3 eruptions: Mt. Agung (March 1963), El Chichón, and Mt. Pinatubo

(NOTE: In 20CR and NCEP-CFSR, annual averages of the time-varying global mean CO_2 concentration, volcanic aerosols, and incoming solar radiation were specified in the forecast model.)

Method

- **<u>Multiple Linear Regression Analysis</u>** [e.g., Randel and Cobb, 1994; Akiyoshi et al., 2009]:

  $Y(t) = \alpha \cdot t + C_0(t) + \beta \cdot QBO30(t) + \gamma \cdot QBO50(t) + \delta \cdot SLR(t) + \varepsilon \cdot ENSO(t\text{-}4) + R(t)$

  where α, $C_0(t)$, *index(t)*

  $= A_1 + A_2 \cos\omega t + A_3 \sin\omega t + A_4 \cos 2\omega t + A_5 \sin 2\omega t + A_6 \cos 3\omega t + A_7 \sin 3\omega t \quad (\omega = 2\pi/12)$

Index	
QBO30	Zonal wind at 30 hPa at Canton, Gan, Singapore (F. U. Berlin)
QBO50	Zonal wind at 50 hPa at Canton, Gan, Singapore (F. U. Berlin)
SLR	Solar cycle index using the 10.7 cm flux
ENSO	Nino3.4 sea surface temperature (4-month lag considered)

  – Statistical test (for QBO etc.): 95% confidence interval

- **<u>Definition of the Volcanic Signals</u>** [e.g., Free and Lanzante, 2009] :

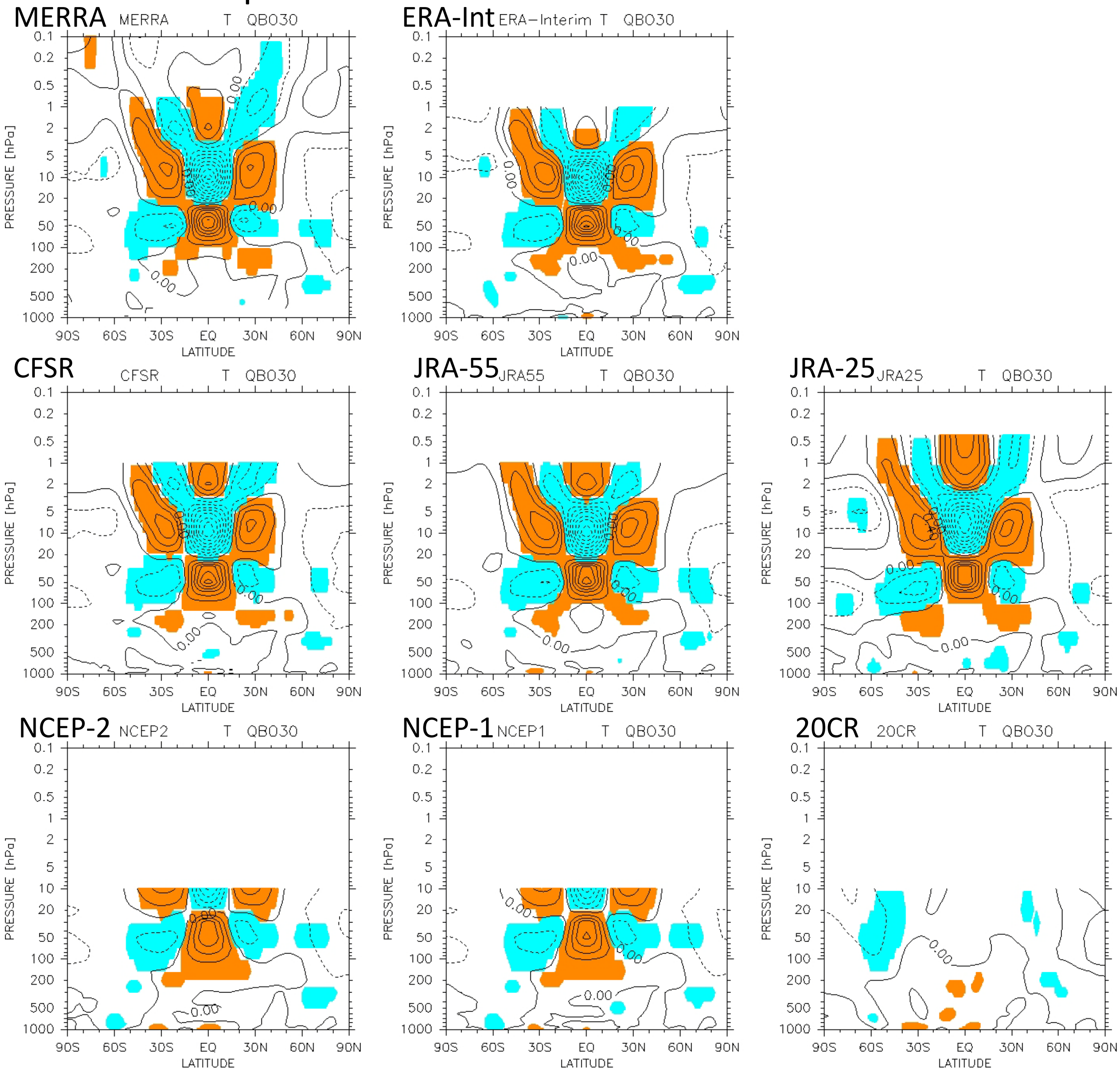
  R(t) is assumed to contain mainly the volcanic signals plus random variations

  (Volcanic anomaly) = (2-year (24-mon) averaged *R(t)* after each eruption)
  – (2-year (24-mon) averaged *R(t)* before each eruption)

  – Statistically significant signals are defined by following Randel [2010].

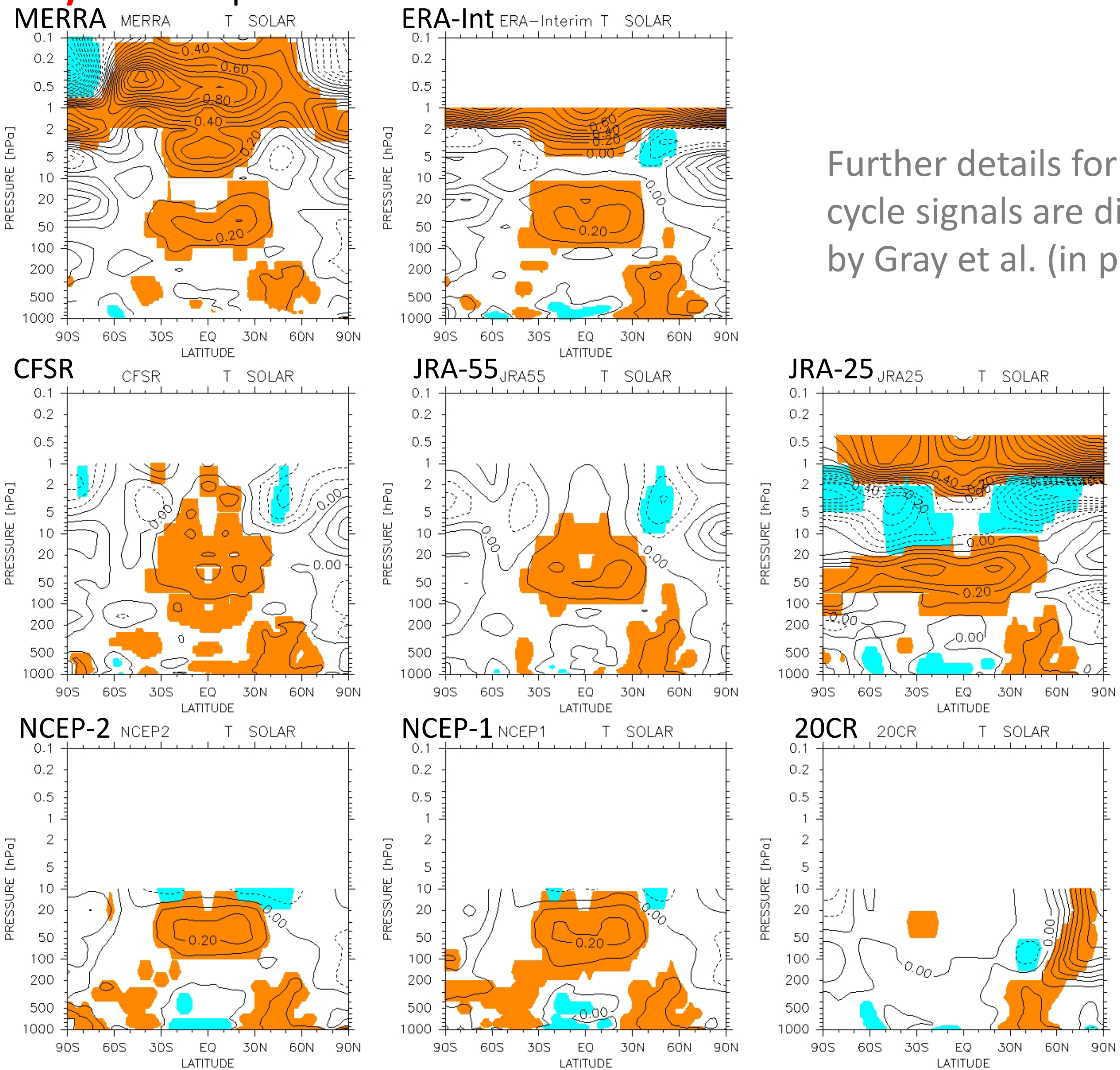
Results 1.
QBO, Solar Cycle, and ENSO from the 1979-2009 Analysis

QBO 30hPa. Temperature. Contour interval is 0.2 K



Note: Clear QBO features in the tropics. Subtropical out-of-phase response is also statistically significant.
20CR has no QBO (but some similarity in the response in the lower troposphere (500-1000 hPa)???).

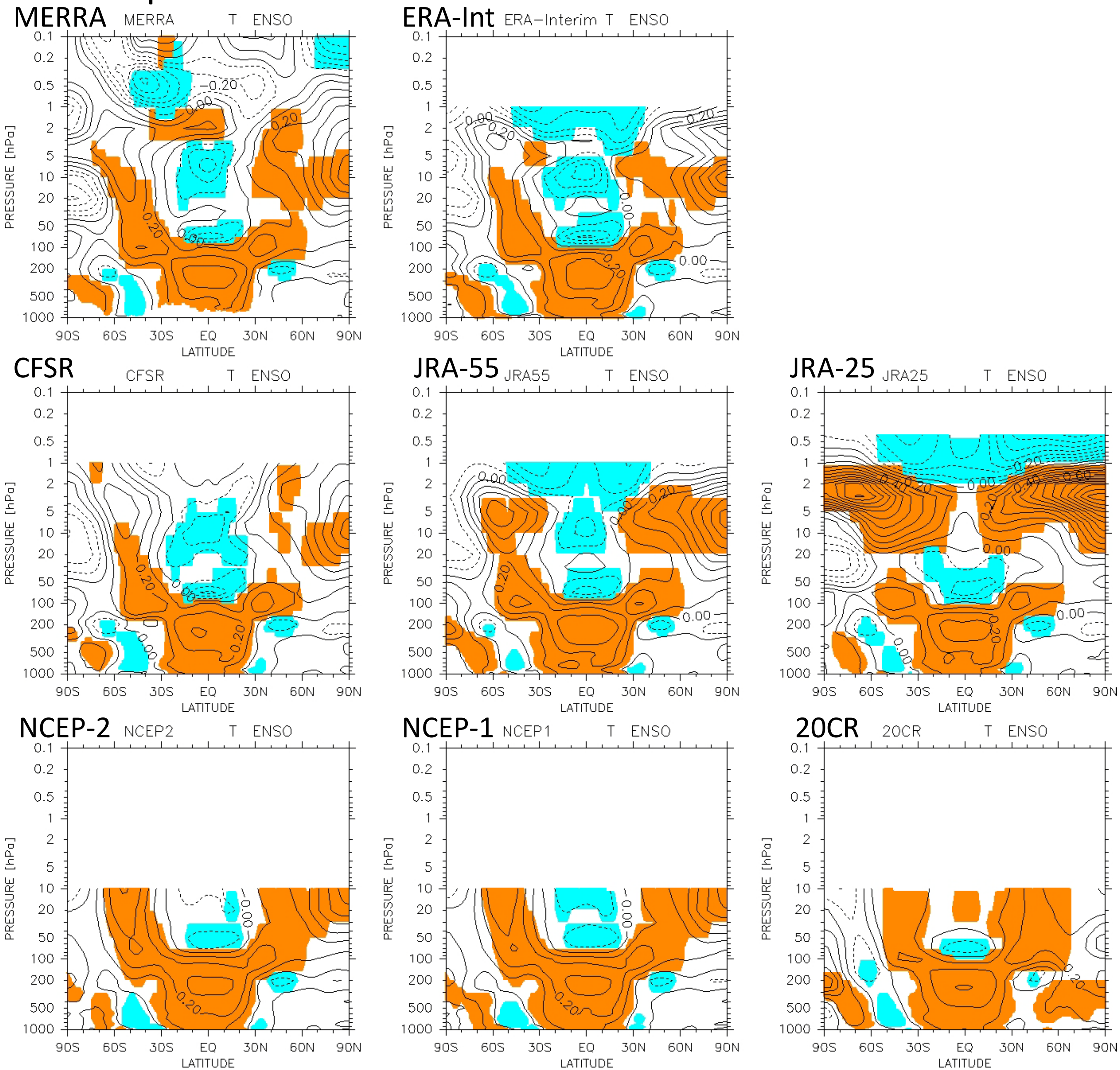
Solar Cycle. Temperature. Contour interval is 0.1 K



Further details for the solar cycle signals are discussed by Gray et al. (in prep.)

Note: Tropical lower stratospheric warming is robust, except for 20CR. (Note that JRA-25 has an issue around 30 hPa.)

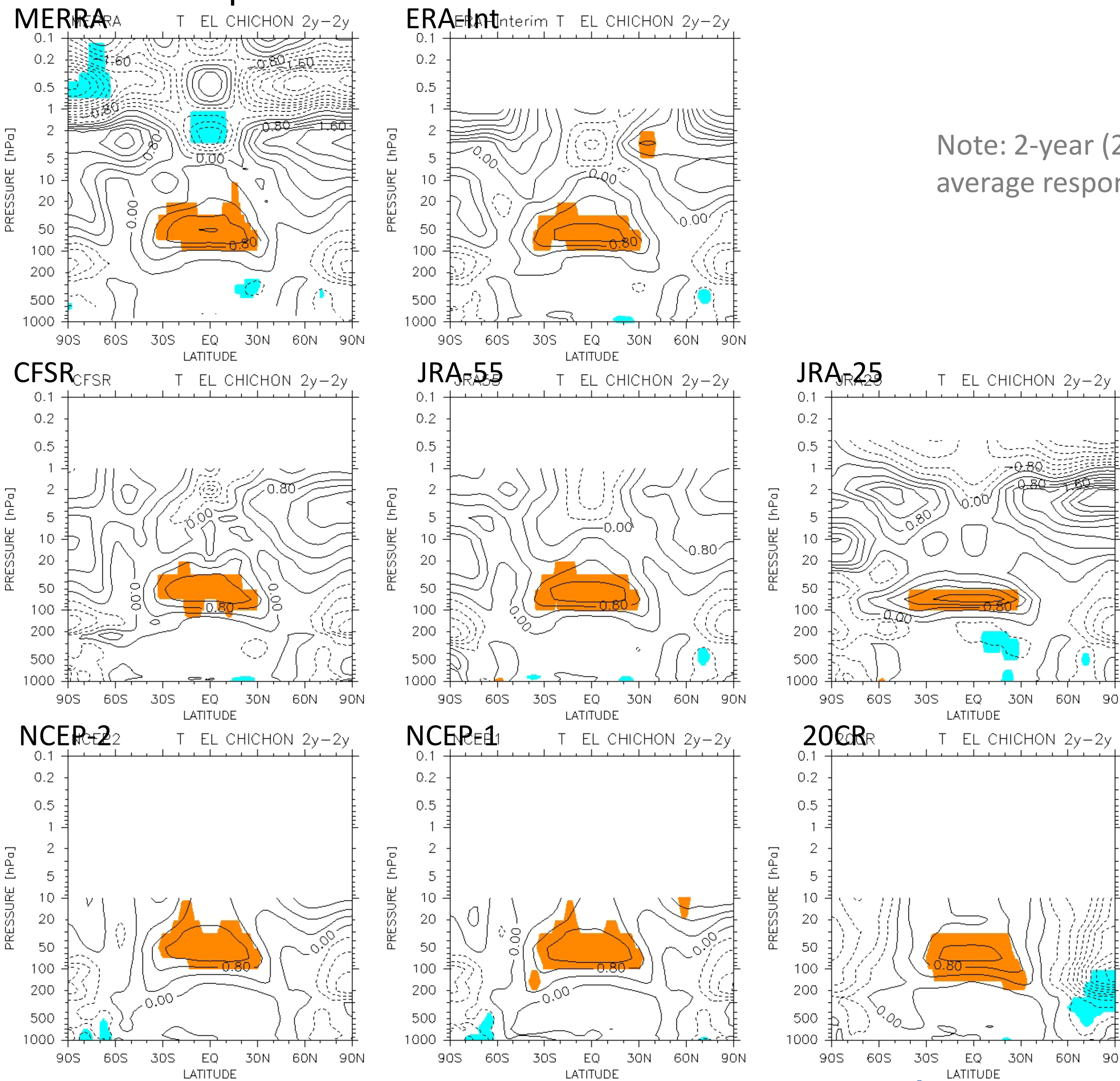
ENSO. Temperature. Contour interval is 0.1 K



Note: Positive signals in the tropical tropo. and midlatitude LS, and negative signals in the tropical LS

Results 2.
El Chichón & Mt. Pinatubo
from the 1979-2009 Analysis

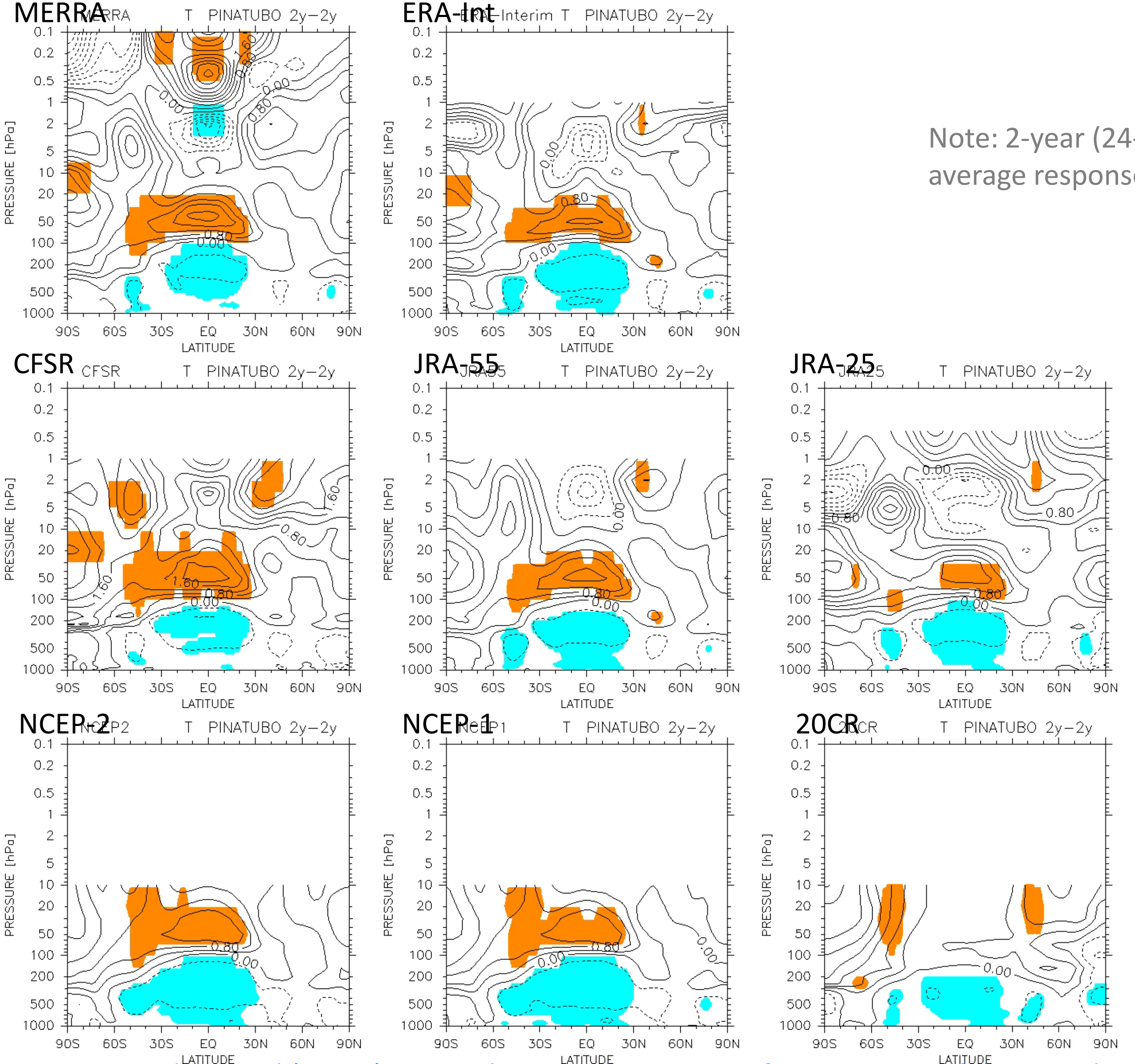
El Chichón. Temperature. Contour interval is 0.4 K



Note: 2-year (24-mon) average response

Note: Tropical lower stratospheric warming is significant in all the 9 reanalyses. (20CR→forcing in the forecast model)
Troposphere is not cooling (not significant).

Mt. Pinatubo. Temperature. Contour interval is 0.4 K



Note: 2-year (24-mon) average response

Note: Tropical LS warming and tropical (upper) tropospheric cooling are significant in most of the reanalyses.

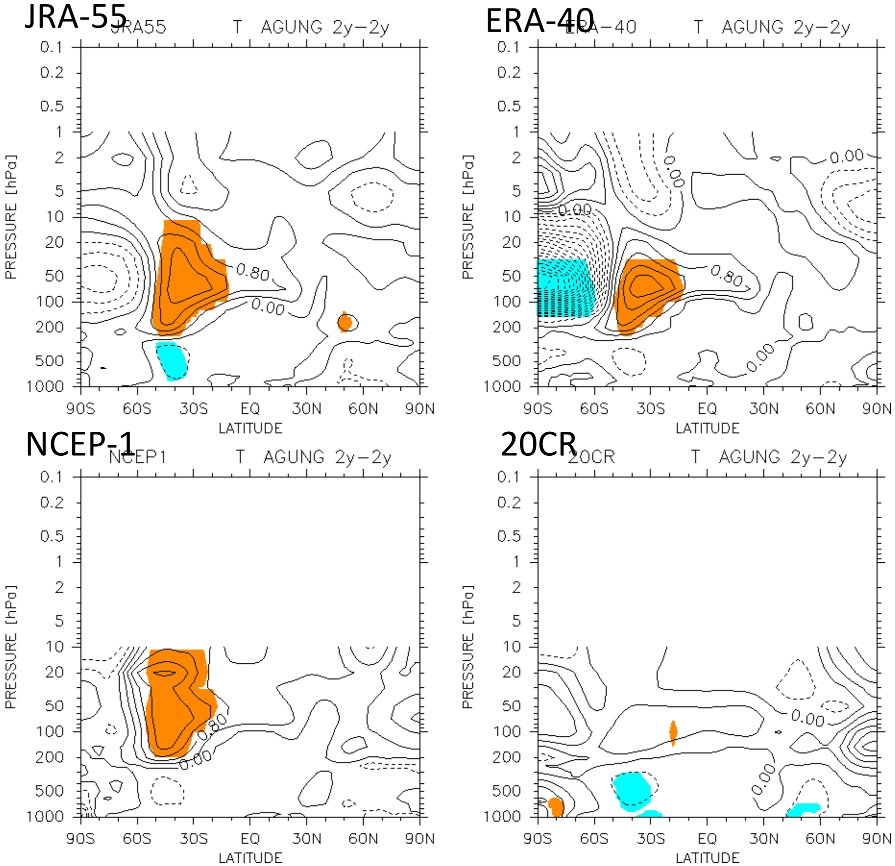
Results 3. Mt. Agung from the 1958-2001 Analysis

Some notes:

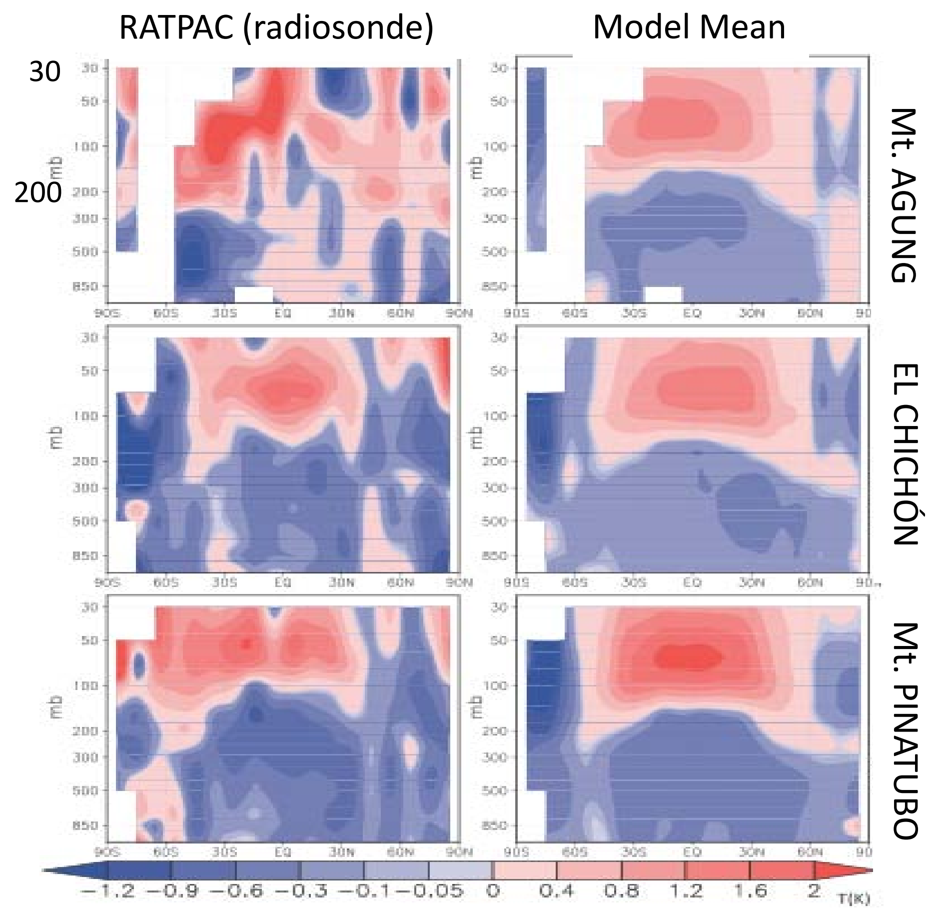
- JRA-55, ERA-40, NCEP-1, 20CR are analyzed
- QBO and ENSO signals are similar to the 1979-2009 analysis results for JRA-55, NCEP-1, and 20CR
- Solar signals are similar for JRA-55 and NCEP-1 in the stratosphere
- El Chichón and Mt. Pinatubo signals are similar particularly for JRA-55 and NCEP-1

Mt. Agung.

Temperature. Contour interval is 0.4 K



Free and Lanzante (JCLIM, 2009)



HadAT2 (another radiosonde dataset) showed similar results

6 Models: GFDL-CM2.0 & 2.1, GISS-ER, GISS-EH, HadGEM, NCAR-PCM

See also: Sato et al., Stratospheric Aerosol Optical Depths, 1850-1990, JGR, 1993 (Figure 2)

Note: Positive signals in SH midlatitude UTLS; asymmetric about the equator; different from the two other cases. This is consistent with radiosonde data analysis by Free and Lanzante (JCLIM, 2009).

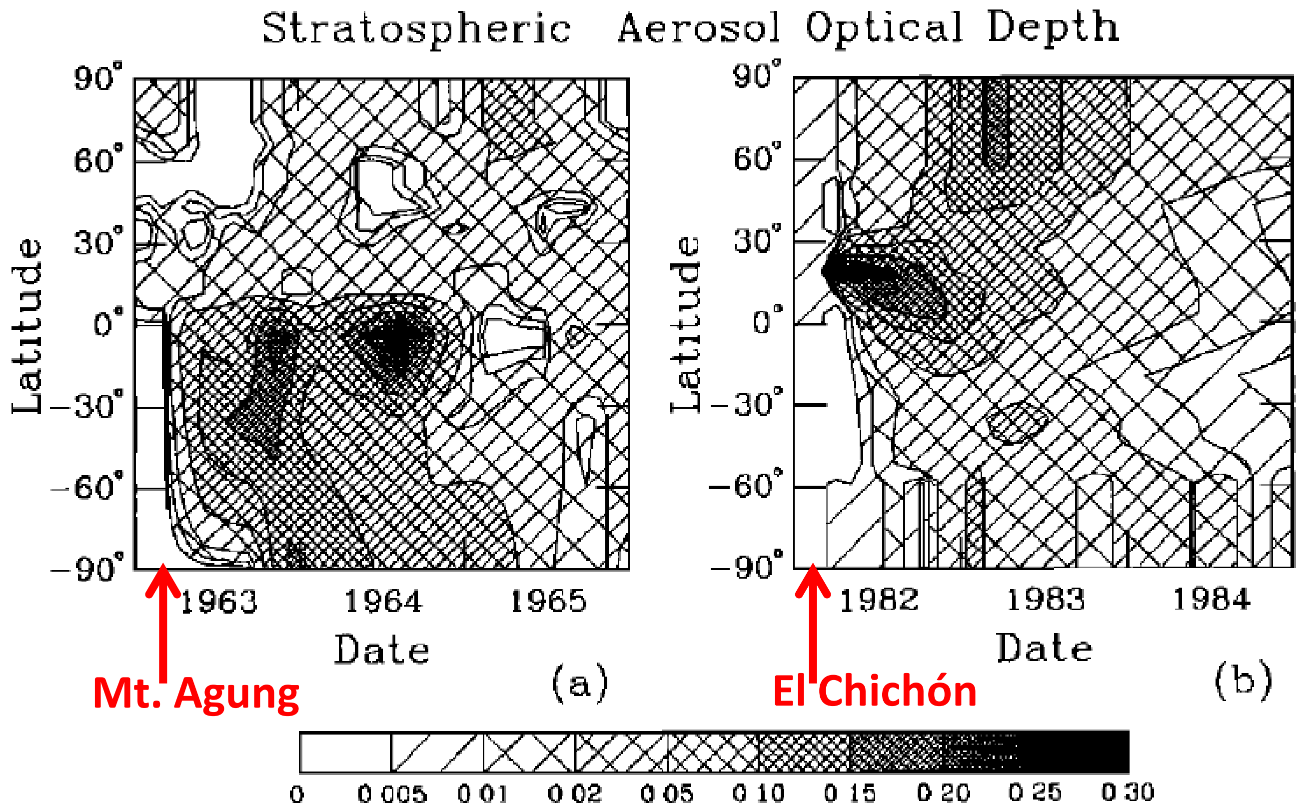


Fig. 2. Estimated stratospheric aerosol optical depth at $\lambda = 0.55$ μm as a function of latitude and time: (*a*) period after Agung and (*b*) period after El Chichon.

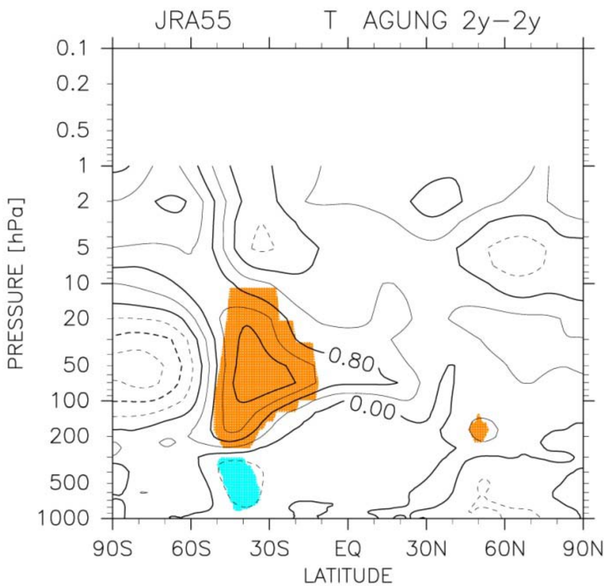
Sato et al., Stratospheric Aerosol Optical Depths, 1850-1990, JGR, 1993

For the period 1960-1978, measurements of atmospheric extinction were obtained at sites in both hemispheres Around 1963, they rely especially on the astronomical extinction observations. Coarser information is provided by analysis of lunar eclipses throughout this period.

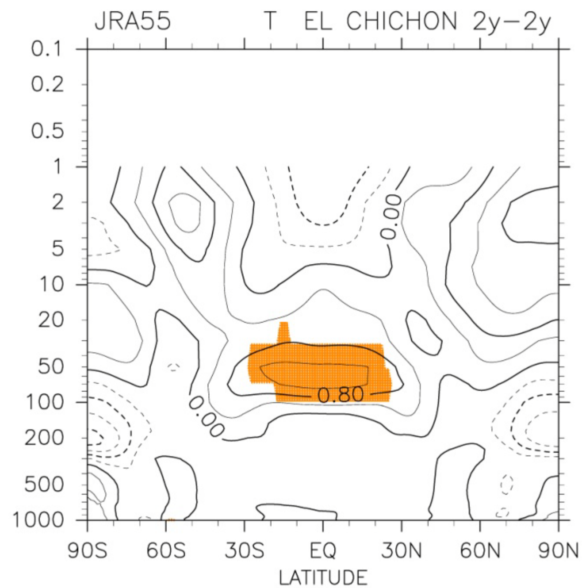
For the period 1979-1990, extensive satellite data begin with stratospheric aerosol monitor (SAM) II on the Nimbus 7 satellite launched in late 1978.

JRA-55 from the 1958-2001 analysis

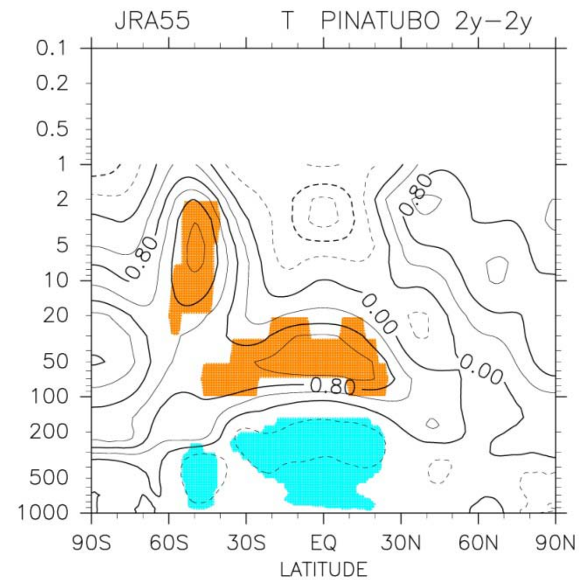
Mt. Agung



El Chichón



Mt. Pinatubo



Temperature. Contour interval is 0.4 K

Note: 2-year (24-mon) average response

Conclusions

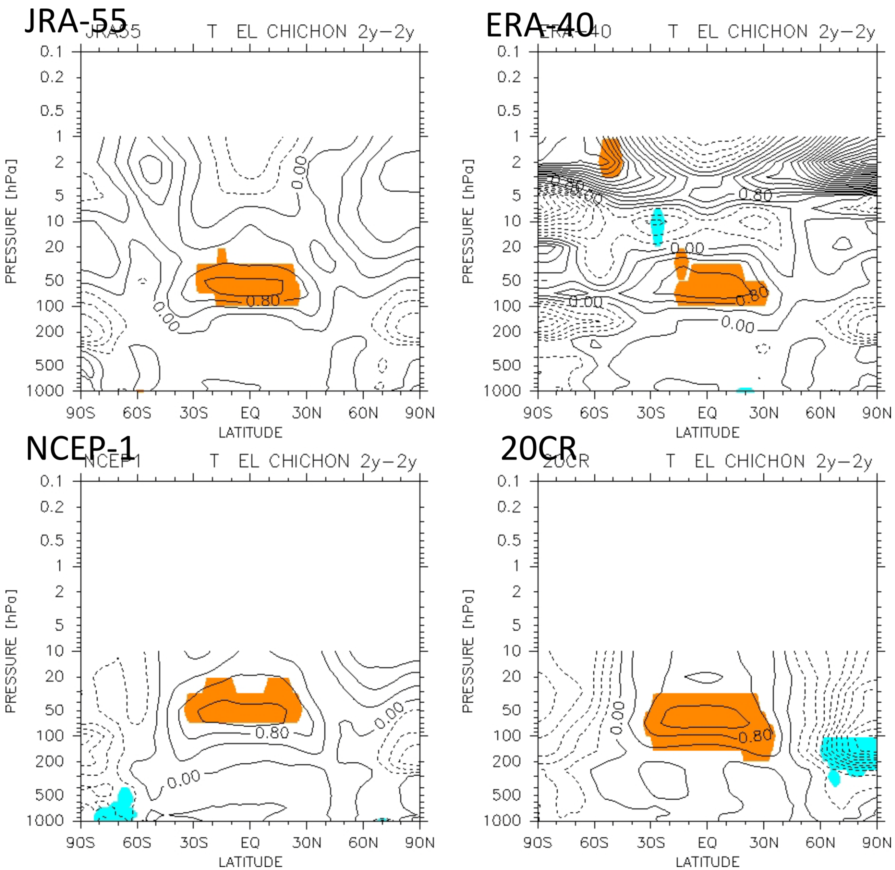
- Temperature data from 9 reanalyses are analyzed, for 1979-2009 (31 years) and for 1958-2001 (44 years)
  - multiple linear regression is used to evaluate trend, seasonal-cycle, QBO, Solar Cycle and ENSO components
  - time difference (2-year before and 2-year after each eruption) is used to evaluate the effects of each volcanic eruption

- QBO, Solar Cycle, and ENSO signals are qualitatively similar among reanalyses (except for 20CR)
- Mt. Agung (1963) : SH midlatitude UTLS warming, asymmetric about the equator (consistent with radiosonde and extinction measurements)
- El Chichón (1982): Tropical LS warming, no significant tropospheric cooling
- Mt. Pinatubo (1991): Tropical LS waming and tropical (upper) tropospheric cooling

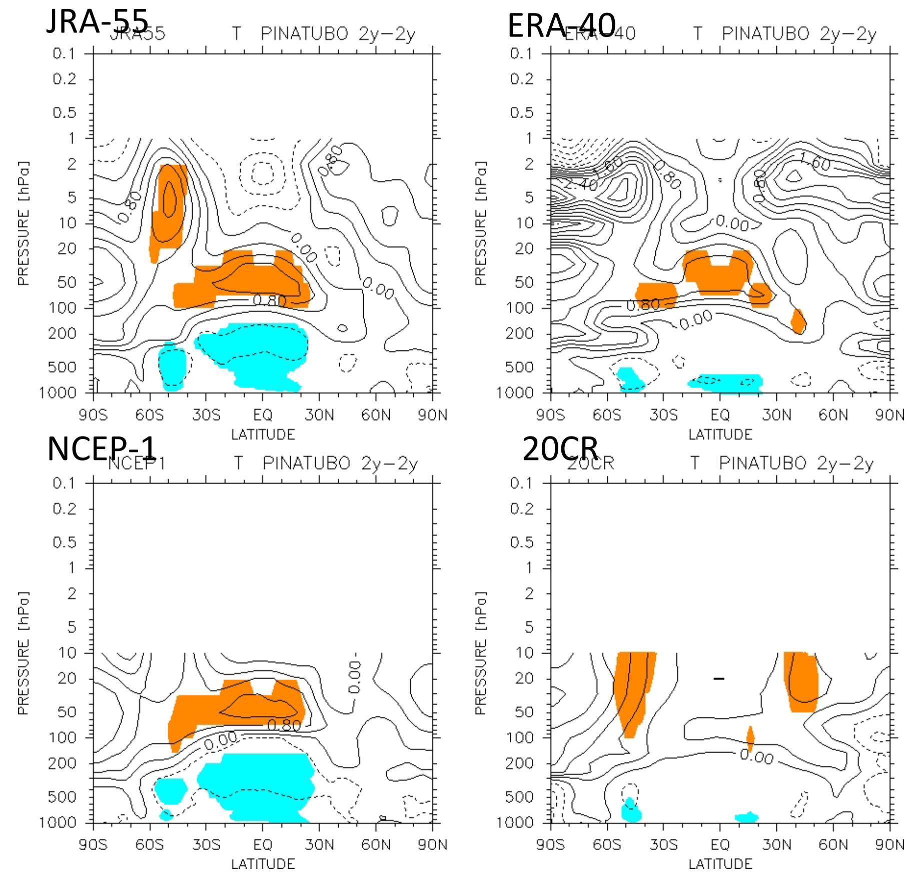
- Reanalysis intercomparison for this case gave us some more confidence on QBO/Solar Cycle/ENSO/volcanic effects, although there are several known issues (e.g., inhomogeneity in time) in reanalysis temperature data (see Craig Long's poster in Poster Session C)
- As a geo-engineering option . . . these three eruptions caused different effects, and Mt. Pinatubo is the only one that cooled the troposphere (but ENSO evaluation is very critical here)

(From the 1958-2001 analysis)

El Chichón



Mt. Pinatobo



Temperature. Contour interval is 0.4 K

Note: Similar to the 1979-2009 analysis results, particularly for JRA-55 and NCEP-1.

Method

- Multiple linear regression analysis [e.g., Randel and Cobb, 1994; Akiyoshi et al., 2009]:
  $Y(t) = \alpha \cdot t + C_0(t) + \beta \cdot QBO30(t) + \gamma \cdot QBO50(t) + \delta \cdot SLR(t) + \varepsilon \cdot ENSO(t\text{-}4) + R(t)$
  where α, $C_0(t)$, $index(t) = A_1 + A_2 \cos\omega t + A_3 \sin\omega t + A_4 \cos 2\omega t + A_5 \sin 2\omega t + A_6 \cos 3\omega t + A_7 \sin 3\omega t$
  ($\omega = 2\pi/12$)

Index	
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SLR	Solar cycle index using the 10.7 cm flux
ENSO	Nino3.4 sea surface temperature (4-month lag considered)

- Statistical test: 95% confidence interval (i.e., *1.96 · SE, where SE is standard error*)

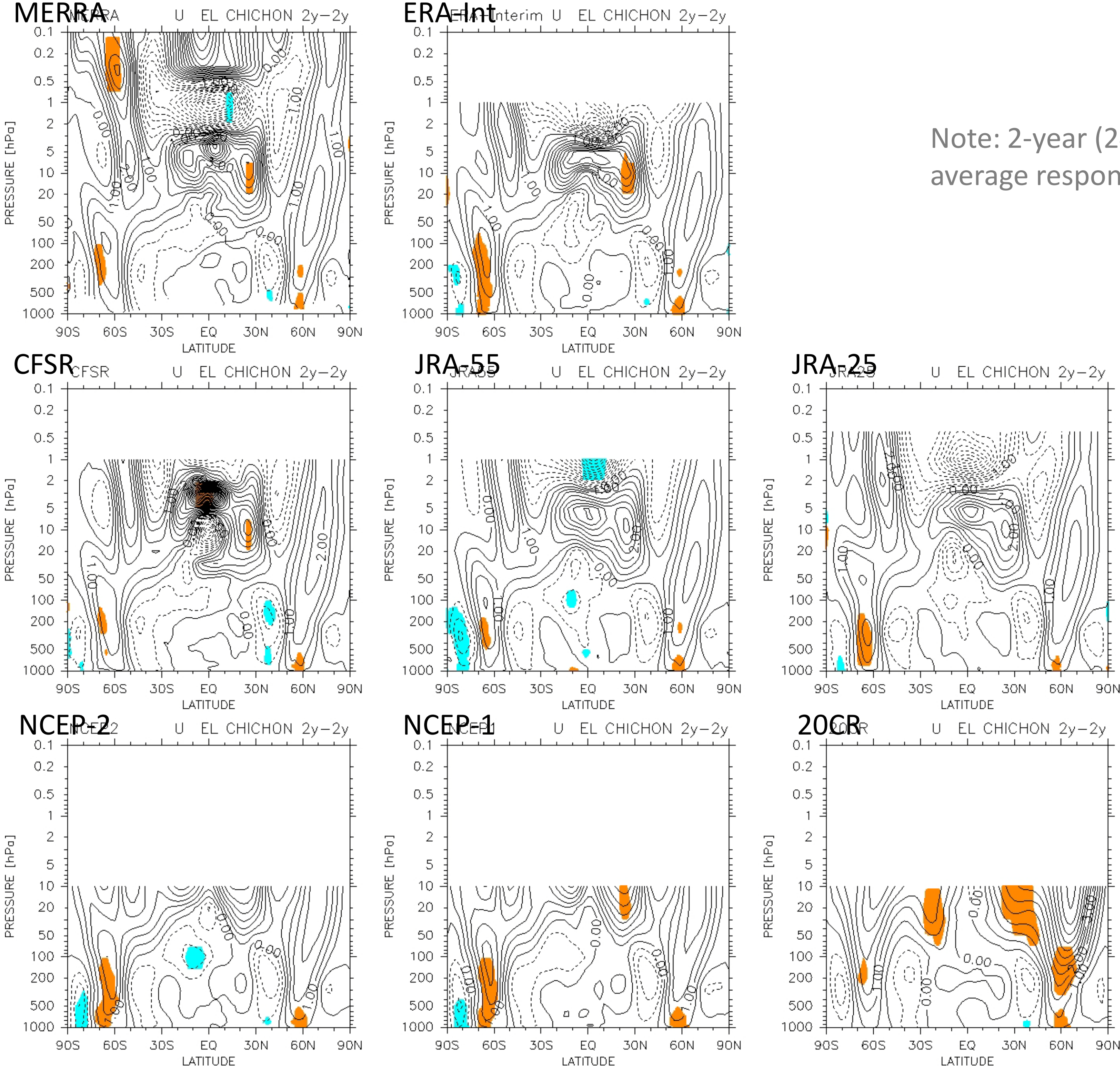
$$SE = \sqrt{\frac{S_e^2}{\sum (x_t - \bar{x})}}, \ (x_t\text{: index time series}) \qquad S_e^2 = \frac{\sum R^2(t)}{n - k - 1}, \ (n = \text{number of month}; k = 43)$$

- Definition of the **Volcanic Signals** [e.g., Free and Lanzante, 2009] :
  R(t) is assumed to contain mainly the volcanic signals plus random variations

  (Volcanic anomaly) = (2-year averaged *R(t)* after each eruption) – (2-year averaged *R(t)* before each eruption)

  Statistically significant signals are defined as those anomalies being greater than twice the standard deviation of annual mean *R(t)* at each latitude-pressure point [e.g., Randel , 2010].

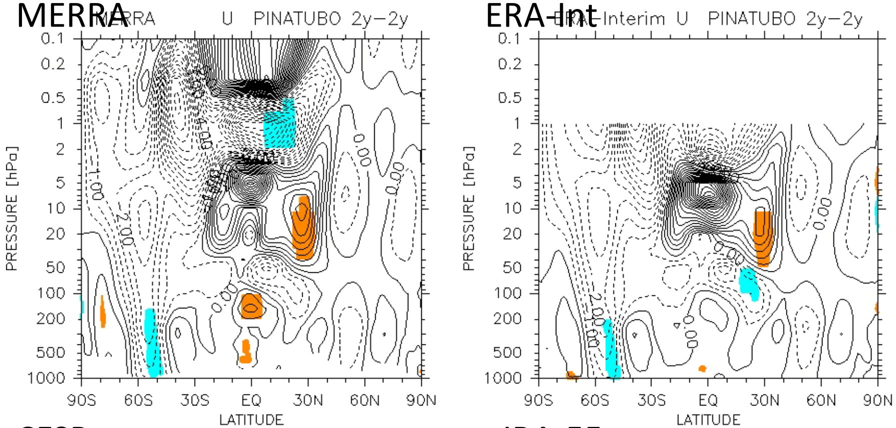
El Chichón.   Zonal Wind.   Contour interval is 0.5 m/s



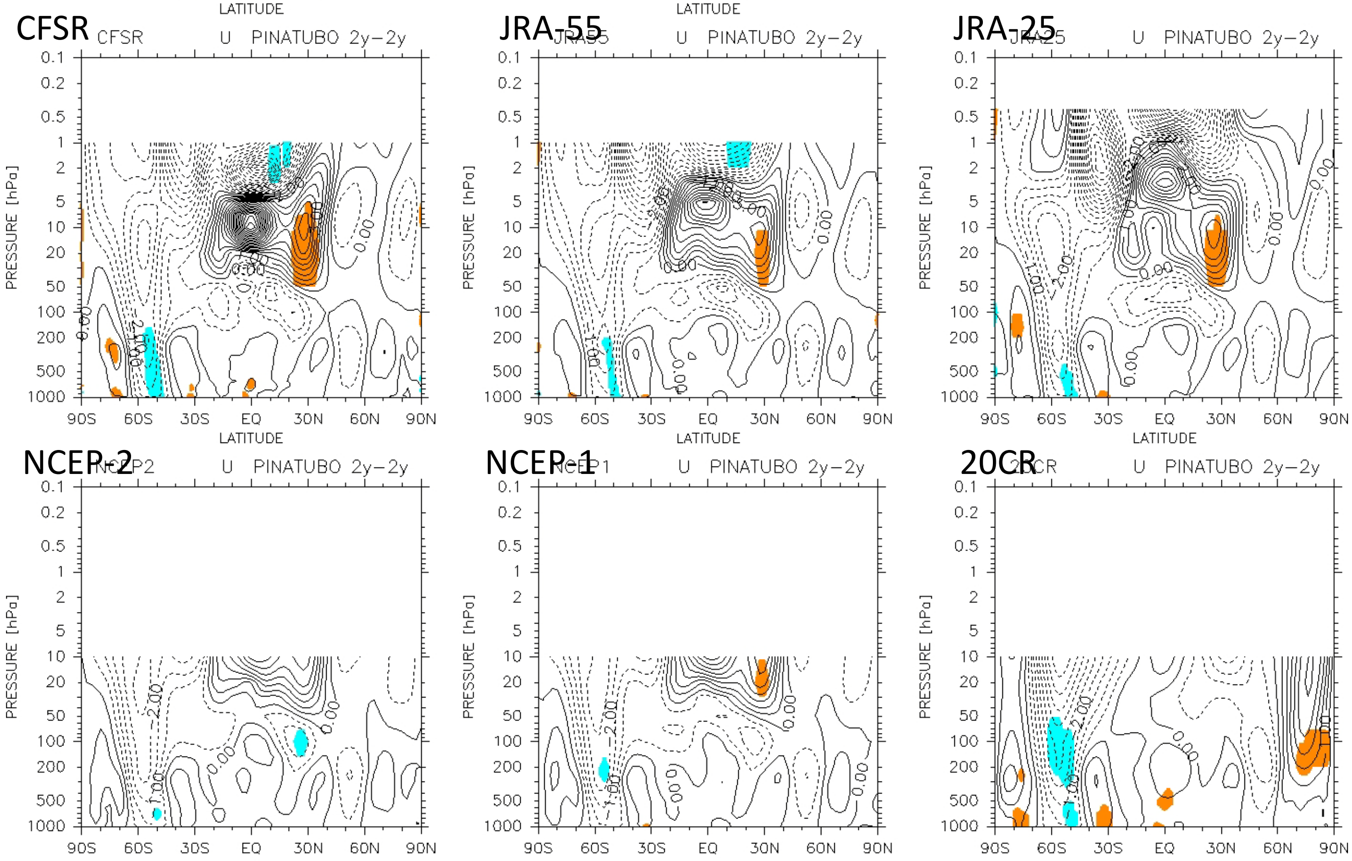
Note: 2-year (24-mon) average response

Note: Though mostly statistically insignificant, all RAs show quite similar extratropical tropospheric patterns (e.g., positive signals at 60S and 60N).

Mount Pinatubo. Zonal Wind. Contour interval is 0.5 m/s



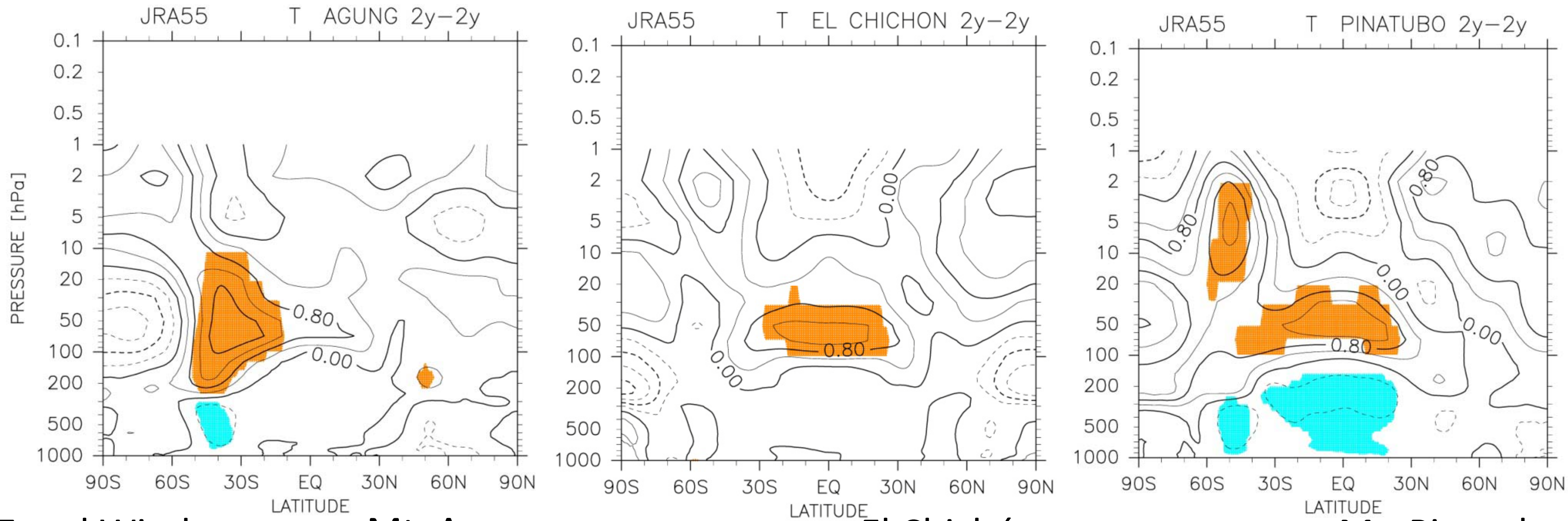
Note: 2-year (24-mon) average response



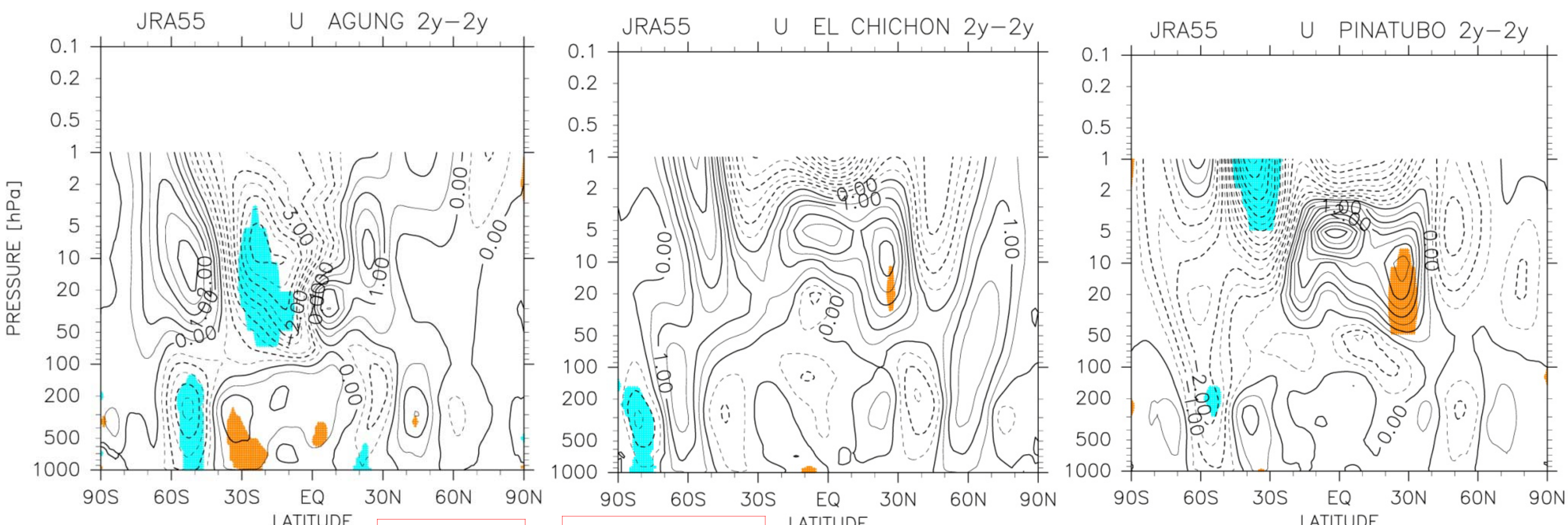
Note: Though mostly statistically insignificant, all RAs show quite similar extratropical tropospheric patterns (e.g., a negative signal at 60 S). (And, they are opposite in sign from those for El Chichón.)

JRA-55 **from the 1958-2001 analysis**

Temperature Mt. Agung El Chichón Mt. Pinatubo



Zonal Wind Mt. Agung El Chichón Mt. Pinatubo



$$\frac{\partial u}{\partial z} \simeq -\frac{g}{fT}\frac{\partial T}{\partial y}$$

$$\frac{\partial u}{\partial z} \simeq -\frac{g}{\beta T}\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)$$

Note: 2-year (24-mon) average response