Tropical and Extratropical Connections Associated with QBO and ENSO

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I will discuss several issues in two parts:
(1) QBO variations, (2) NH/SH changes with QBO/ENSO

Outline

■ Part 1: QBO variations and dynamics:

Stalling feature

Annual synchronization

ENSO modulation

■ Part 2: NH and SH changes with QBO and ENSO:

MSSW frequency in NH winter

Stationary wave structure in SH spring

Ref.: None

Part 1
QBO variations

Part 1 discusses issues of QBO variations that are long or recently known

Outline for QBO part

■ Basics (stalling events)

How do these occur?

■ Annual synchronization

How does this occur? (Taguchi and Shibata 2013)

■ ENSO modulation

Does QBO modulates with ENSO? (Taguchi 2010)

* I exclude other effects of solar cycle, volcanic eruptions, and global warming (trend), etc.

Ref.: I will mention other relevant references below.

Part 1
Data and method

We use 3 kinds of data to discuss QBO variations in Part 1

Data

■Equatorial zonal wind data (cf. Naujokat 1986)
Complied from radiosonde obs., and archived at FUB
Monthly data from 1953 to 2008 (1953 to 2012 in places)
Available at 7 levels from 70 to 10 hPa

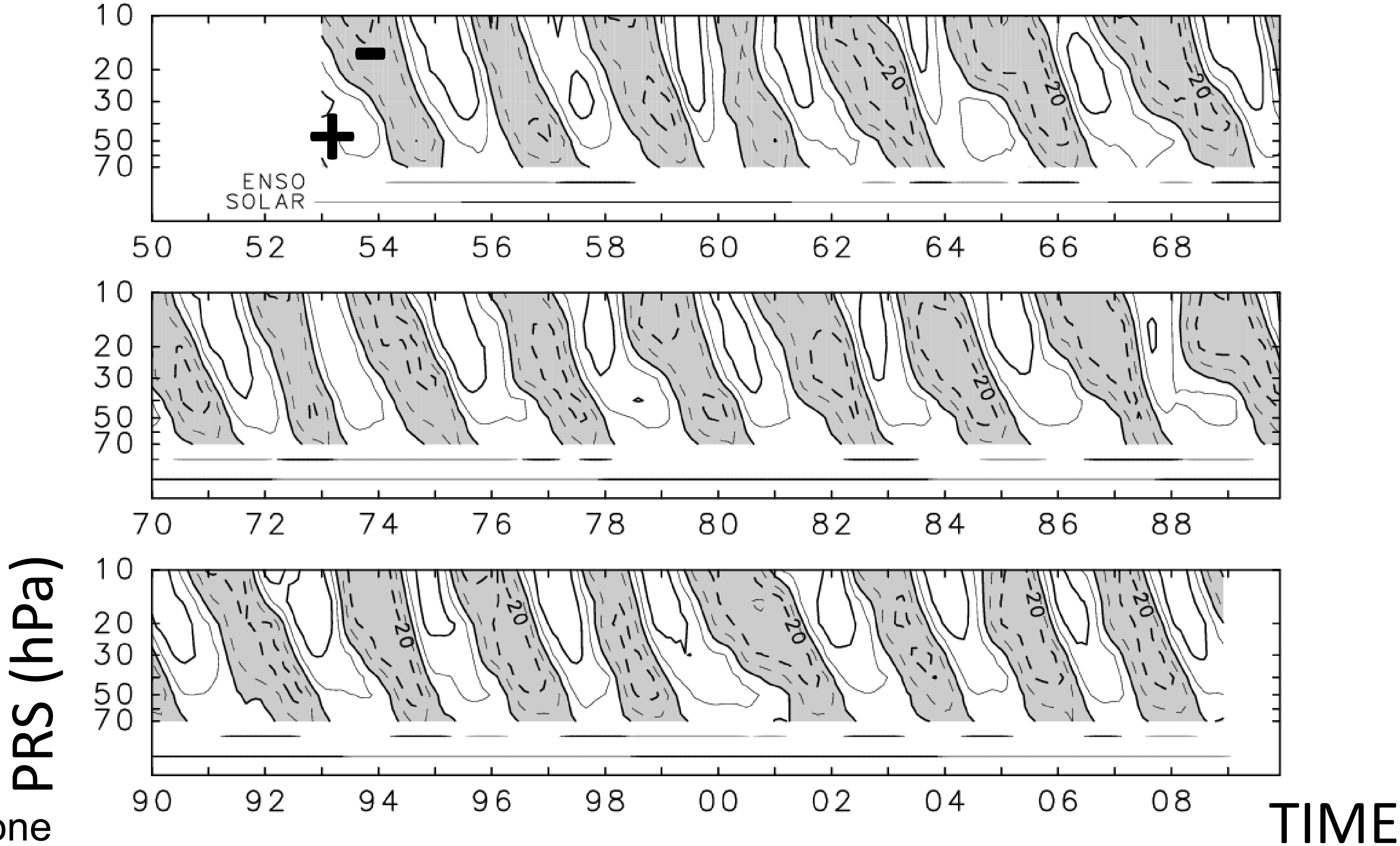
■JRA-25/JCDAS reanalysis data (Onogi et al. 2007)
1979-2008, 2.5x2.5, L23
Use daily mean data to get monthly mean data:
[U], [T], [V]res, [W]res, EPFD, etc.

■MRI CCM simulations (Shibata and Deushi 2005, 2008)
REF-1: 5 runs x 25 years (1980 to 2004) forced with obs. SST

Ref.: None

We extract QBO signals/anomalies (A') by removing clim. seasonal cycle and apply 5-mo. running mean

Time-height sections of FUB U' (m/s)



Ref.: None

We use the TEM zonal momentum equation to diagnose the budget of QBO variations

Diagnosis

■Governing equation (TEM zonal momentum equation)

T = M +V +D +X

- T: tendency of mean zonal wind
- M, V: meridional and vertical advection
- D: resolved wave driving
- X: all other effects (including effects of unresolved waves)

■TEM diagnosis using JRA-25 data

◇Use JRA-25 monthly mean data to calculate all terms, except for X
X is calculated as a residual of all other terms

◇Examine stalling feature and annual synchronization

Ref.: Andrews et al. (1987), Monier and Weare (2011)

Part 1
Observations
Basics (stalling feature)

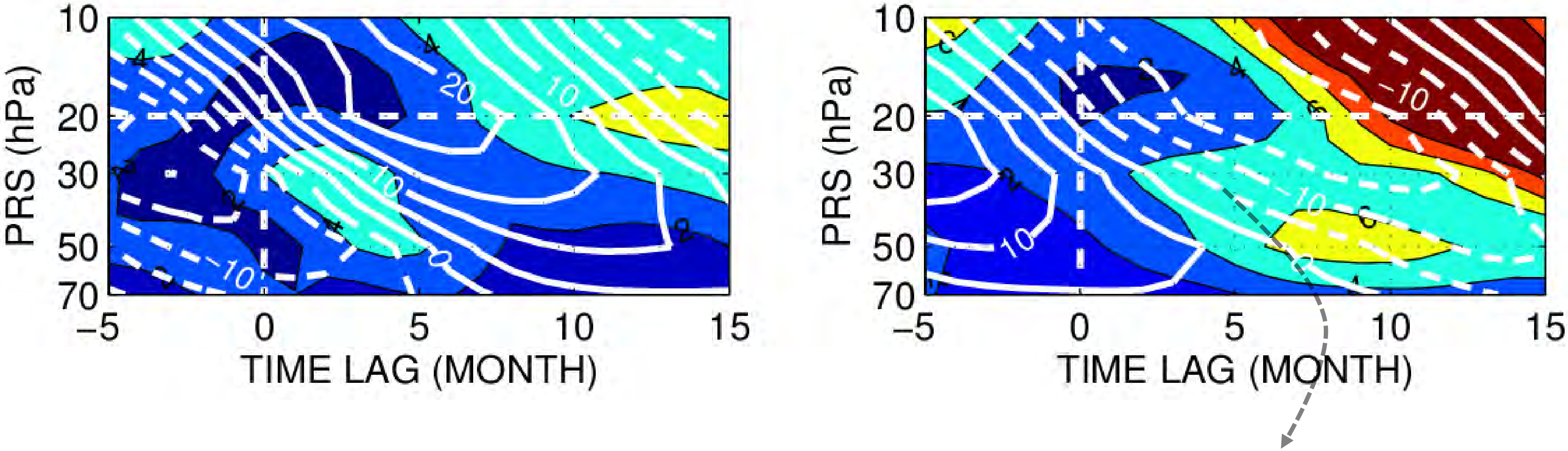
QBO is characterized by more irregular propagation of ELY shear zones (stalling events); how do these occur?

Intro for stalling

Composite U’ (white) and variability (colors)

WLY onset at 20hPa

ELY onset at 20hPa



Larger variability

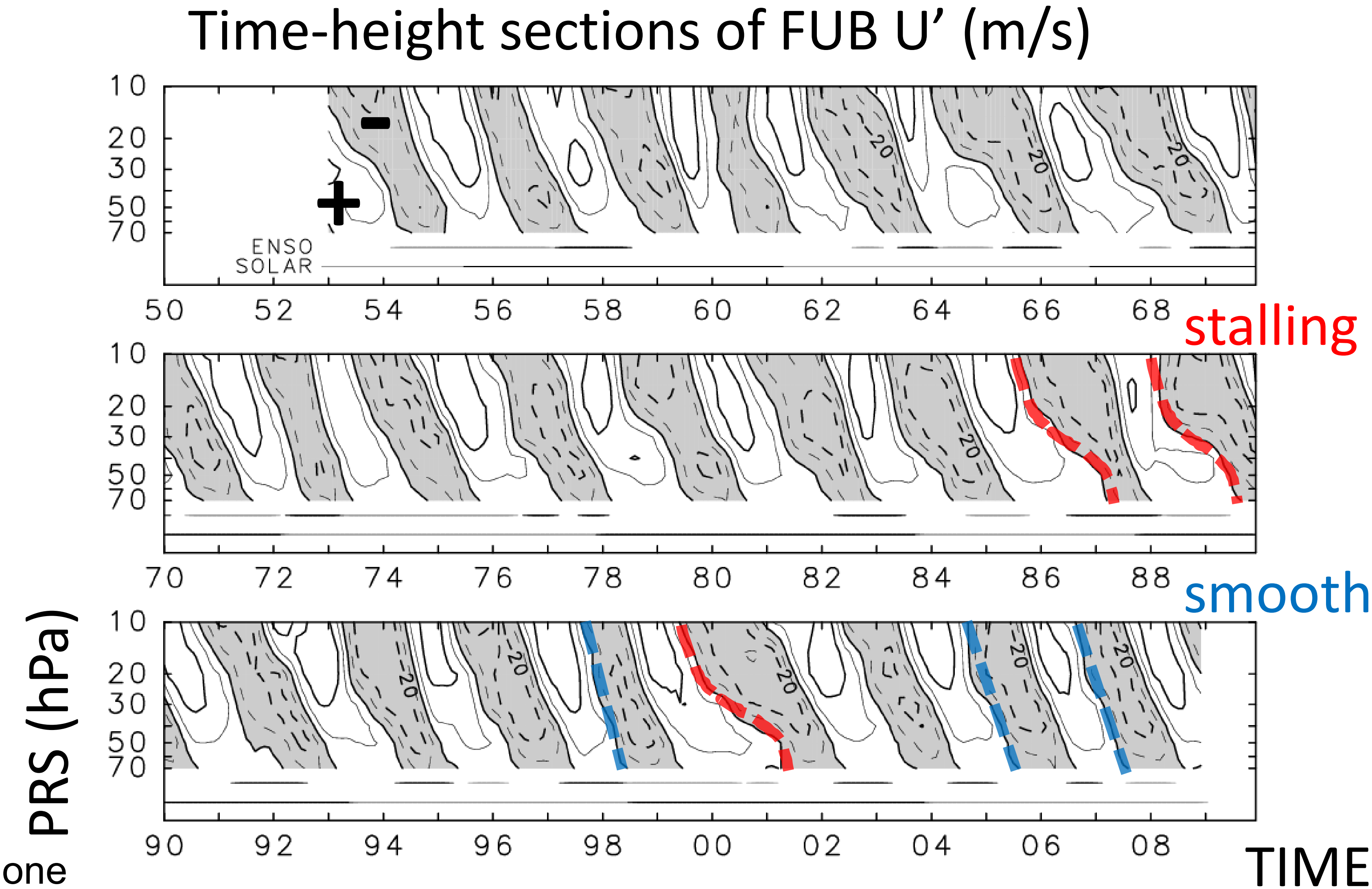
Additional questions:

◇How/why is the variability in WLY shear zones smaller w/o stalling?

◇How/why is the variability in amplitude much smaller?

Ref.: Cf. Baldwin et al. (2001)

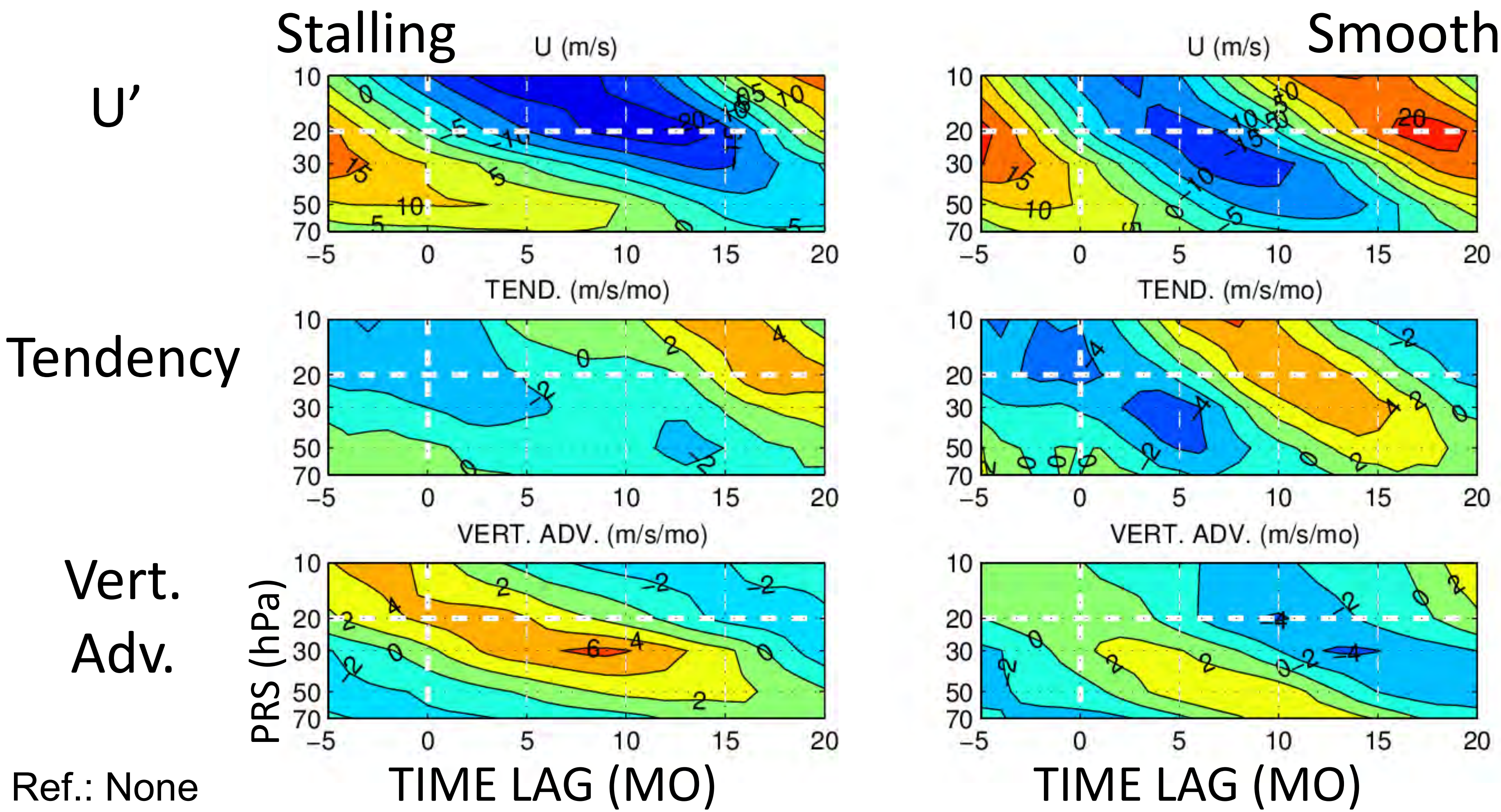
We compare "stalling" and "smooth" groups: each consists of 3 cases of descending ELY



Ref.: None

Stalling cases have weakly negative tendency, contributed by vertical advection

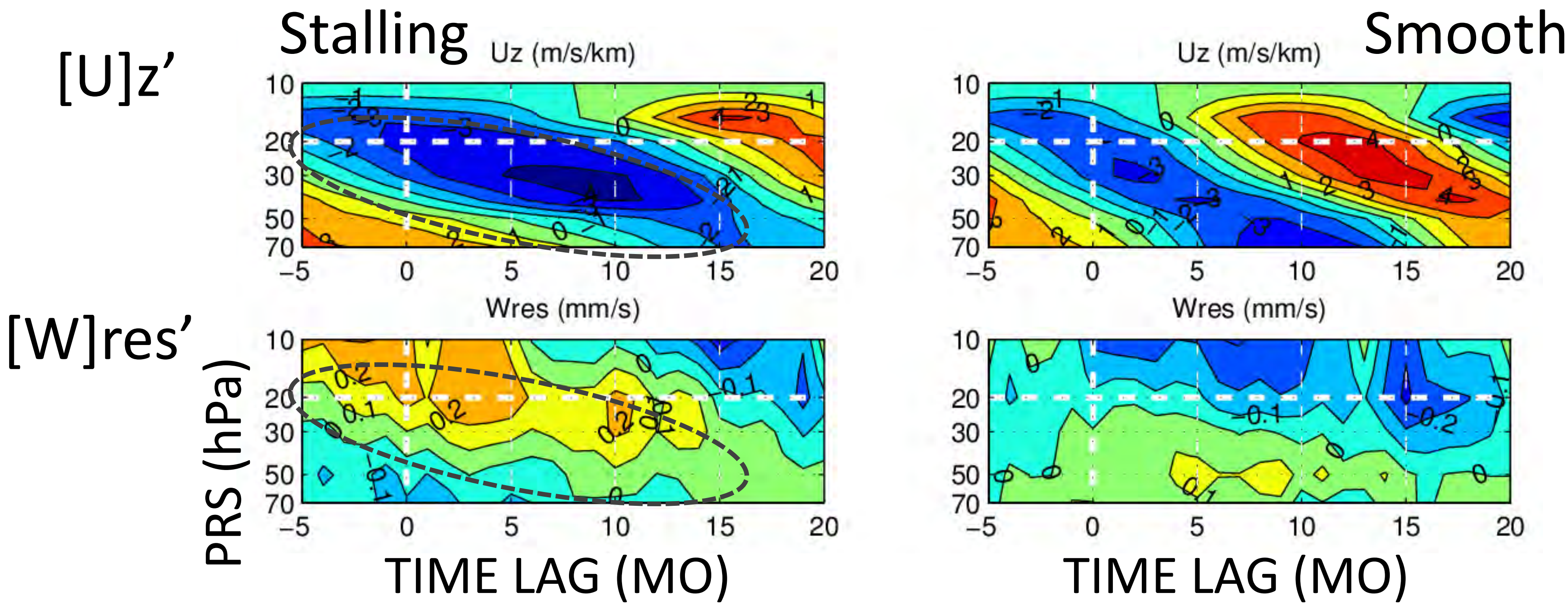
QBO U’, tendency, and vert. adv. in 5N/S wrt 20hPa ELY onset



Ref.: None

Vertical wind shear and upwelling show consistent differences even at upper levels for negative lag

QBO $[U]_z$’ and [W]res’ in 5N/S wrt 20hPa ELY onset



The stronger vertical advection for stalling
Is contributed by combinations of:

◇QBO [U]z’ and time-constant [W]res

◇time-constant [U]z and QBO [W]res’

Ref.: None

Stronger QBO signal preceding at upper levels will make the processes operate stronger for stalling near 30 hPa

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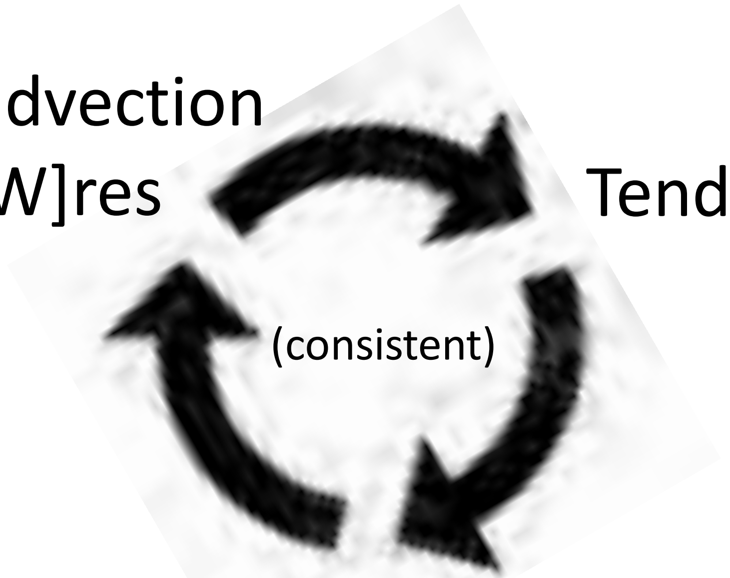
Speculation for stalling of ELY



Ref.: None

We will examine whether/how the annual cycle of the upwelling plays a role

■ Conventional view

Stronger upwelling for NH winter plays a role

■ We will examine the role in the momentum budget

Vertical advection = - [U]z [W]res

$[U]z = [U]z^{LTM} + [U]z^{annual} + [U]z^{QBO}$

$[W]res = [W]res^{LTM} + [W]res^{annual} + [W]res^{QBO}$

*LTM: long time mean (time-constant)

Differences in vert. adv. are contributed

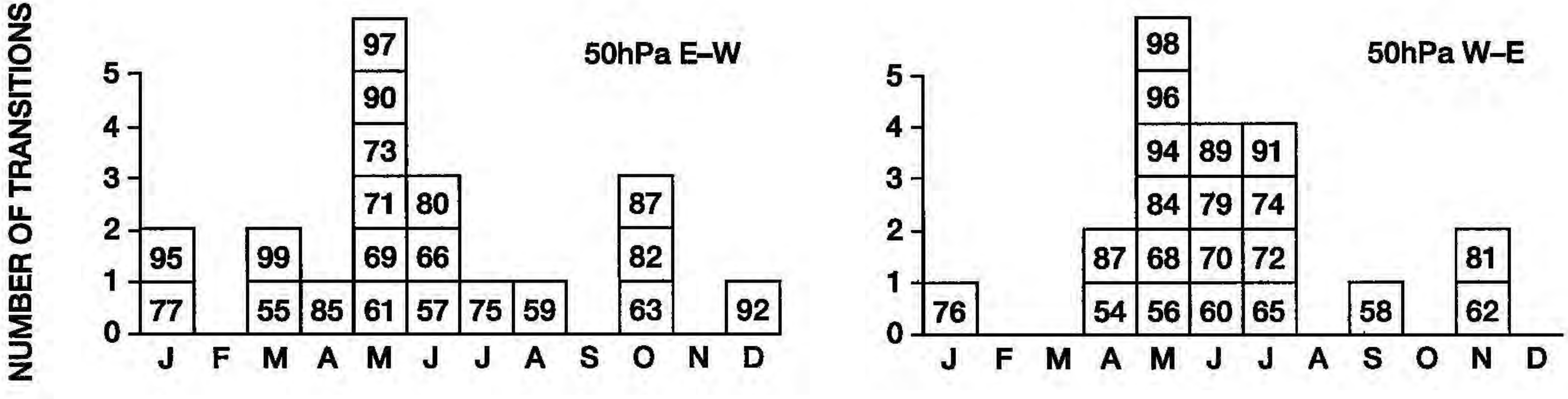
by QBO signal and LTM field in JRA-25 data

Ref.: None

Part 1
Observations
Annual Synchronization

It’s long known that QBO is somewhat synchronized with annual cycle; how does this occur?

Seasonal distributions of U reversals at 50hPa



(Pawson et al. 1993; Baldwin et al. 2001)

- Existing studies examine the mechanism using idealized models

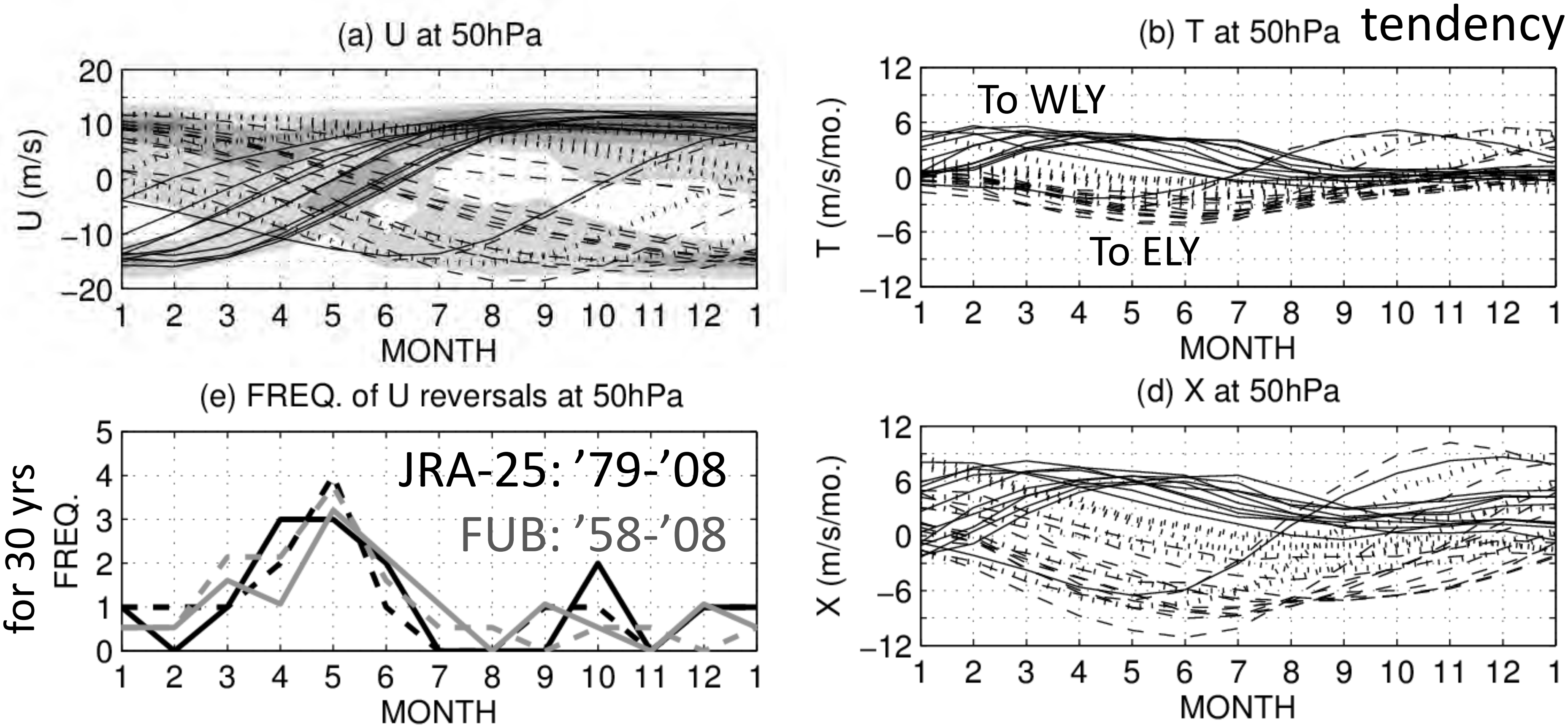
  Dunkerton (1990), Kinnersley and Pawson (1996), Hampson and Haynes (2004)

- We re-examine this feature thru a diagnostic analysis of the JRA-25 and CCM data

Ref.: None

Zonal wind reversals (for NH spring/summer) tend to accompany large tendencies and residual

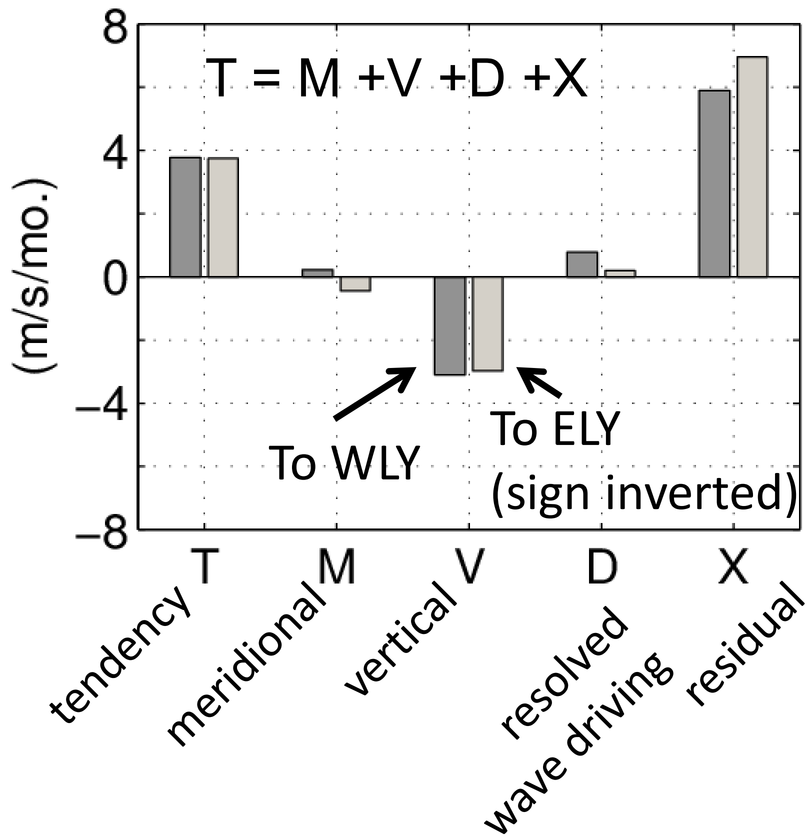
[U]'and tendency in 5N/S, 50hPa for '79-'08



Ref.: Shades in (a) show frequencies above 10%, with 10% increment.

The tendencies T for the annual synchronization largely balances with X

Bar chart for TEM diagnosis when tendency is large from April to June (top/btm 30 %)



5N/S, 50hPa

Suggest role of unresolved, small scale waves in annual synchronization

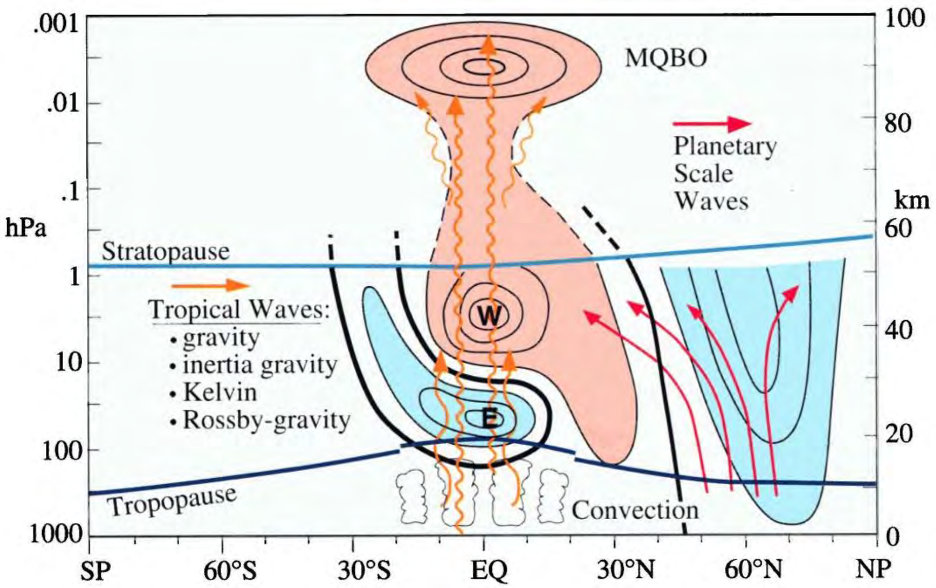
*I'll mention other effects in examining CCM data

Ref.: None

Part 1
Observations
ENSO-modulation

It was long hypothesized that QBO modulates with ENSO, but existing results seemed inconclusive

QBO-related processes



Baldwin et al. (2001)

■Hypothesis

ENSO (SST variations)

→Convection

→equatorial wave activity

（→BD circulation)

→QBO

■Existing studies

◇Many seemed inconclusive

◇These seem more relevant:

Geller et al. (1997)

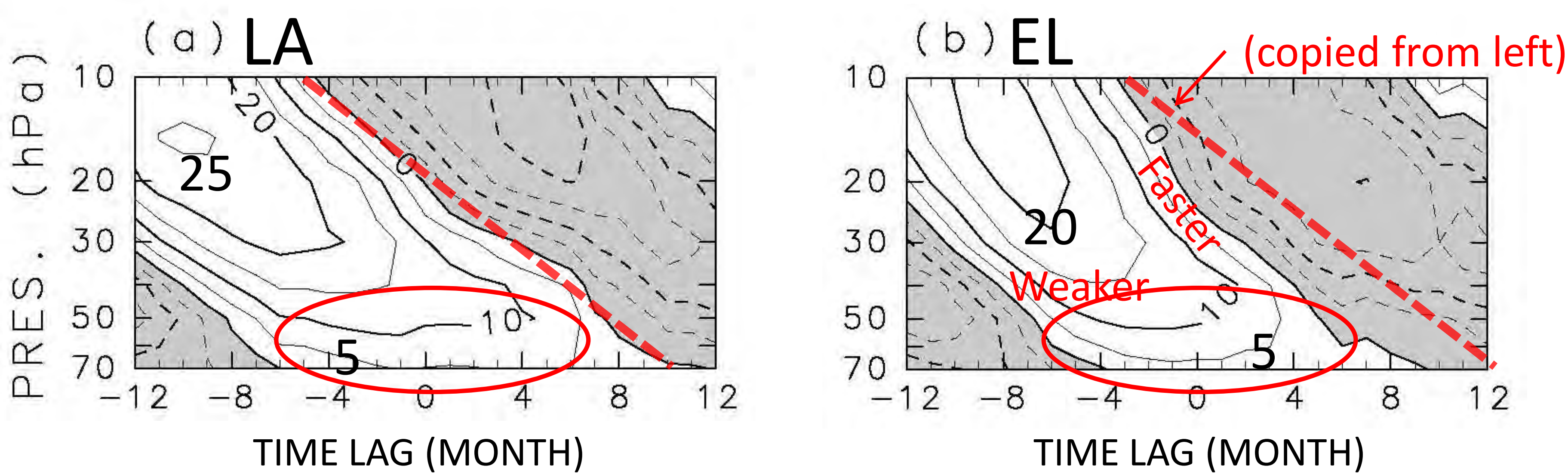
Maruyama and Tsuneoka (1988)

Ref.: None

Composite analysis shows weaker amplitude and faster phase propagation of QBO for EL

Modulation by ENSO

FUB composite U' wrt WLY peak at 50hPa



Generally robust regardless of : season and QBO phase

Ref.: LA/EL are based on cold/warm episodes by NOAA/CPC.
About bottom or top 25% samples are LA/EL.
Composites are wrt Ψ=116 deg., center of W group. Taguchi (2010,JGR)

How does the ENSO-modulation of QBO occur? we can speculate about role of wave driving

■ENSO-modulation of QBO

Faster phase progression (and weaker amplitude) for EL

■ENSO-modulation of BDC

BDC, or tropical upwelling is stronger for EL

(e.g., Randel et al. 2009; Taguchi 2010)

⇒We speculate:

wave driving for QBO must be stronger during EL

for the faster QBO progression under the stronger BDC

*Poster (D) by Prof. Marvin Geller

ENSO modulation of QBO changes with decadal or longer scales

ENSO-QBO connection affects tropical CPT temperatures

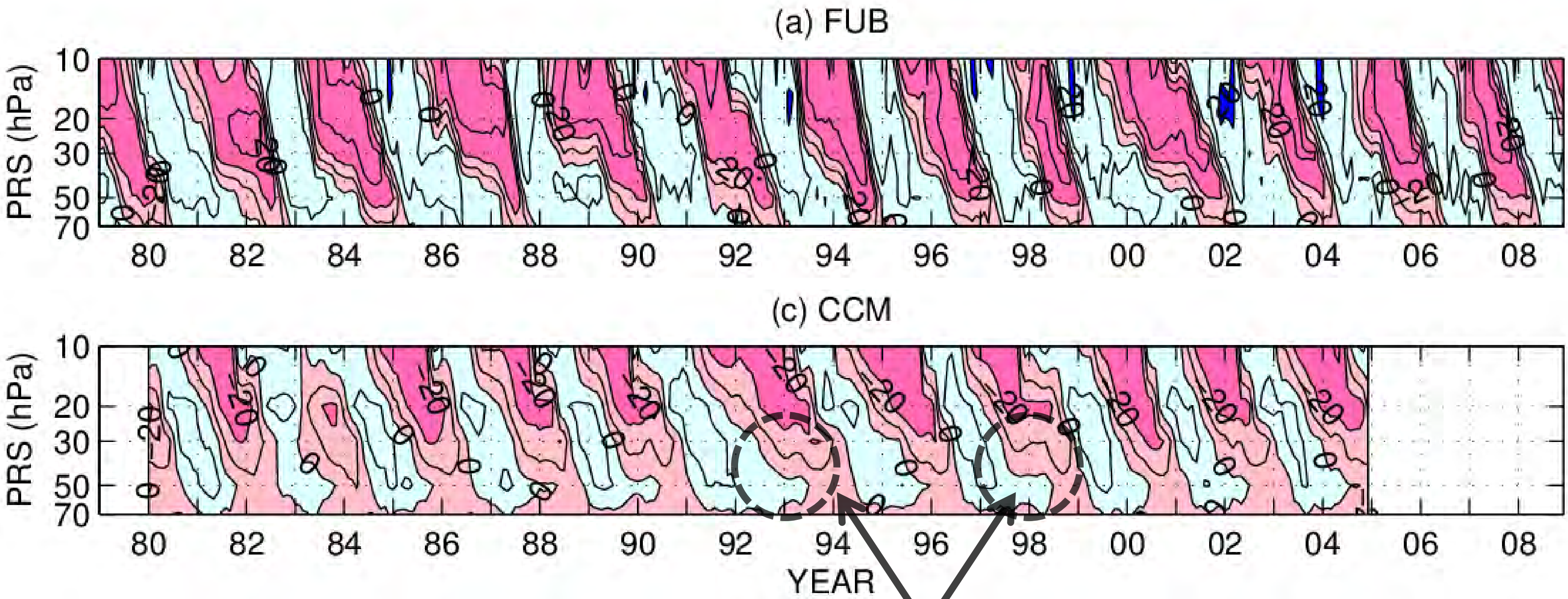
Ref.: None

Part 1
MRI CCM simulations

The MRI CCM (REF-1) reasonably simulates a QBO-like oscillation, with some differences

QBO in MRI CCM

Time-height sections of equatorial zonal wind (m/s)



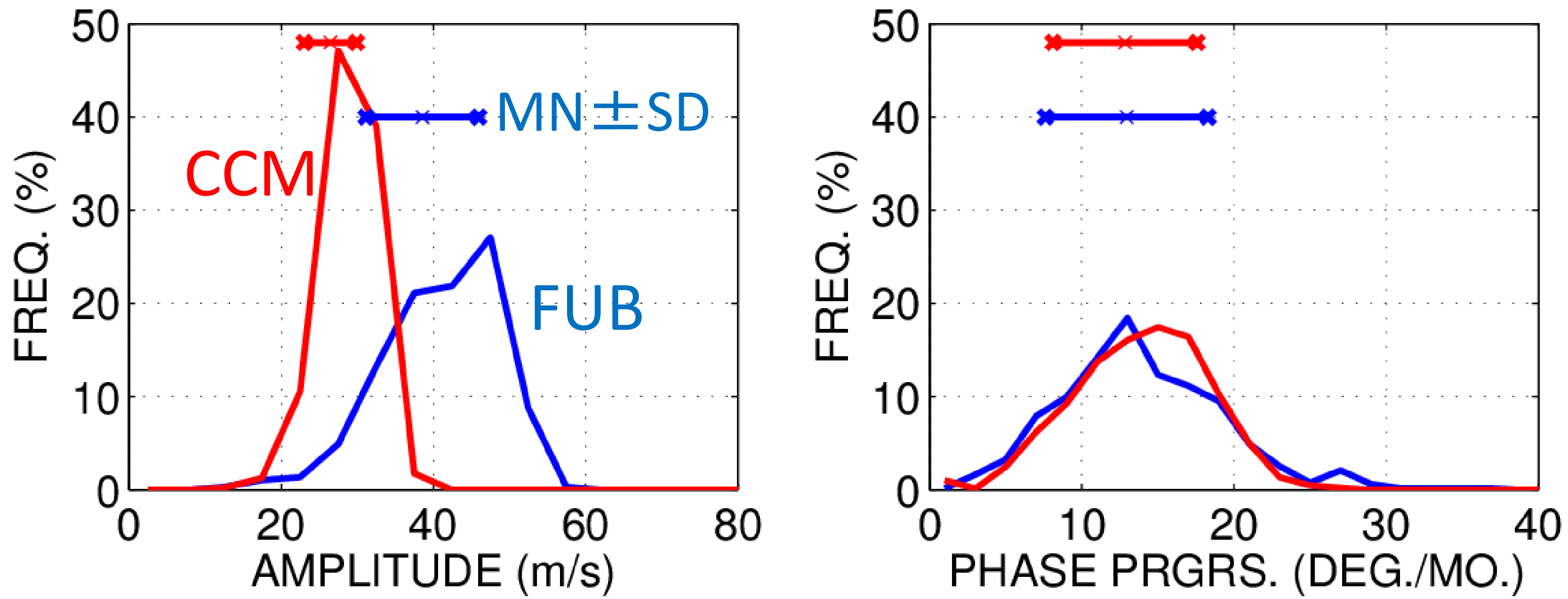
Stalling of ELY phase in simulation

Ref.: Shibata and Deushi (2005,2008)

Modeled QBO underestimates amplitude, while well reproducing phase progression rate

Basic properties of CCM QBO

PDFs of |ψ| and ψ’ for FUB and CCM data



(EOF based, dimensional)

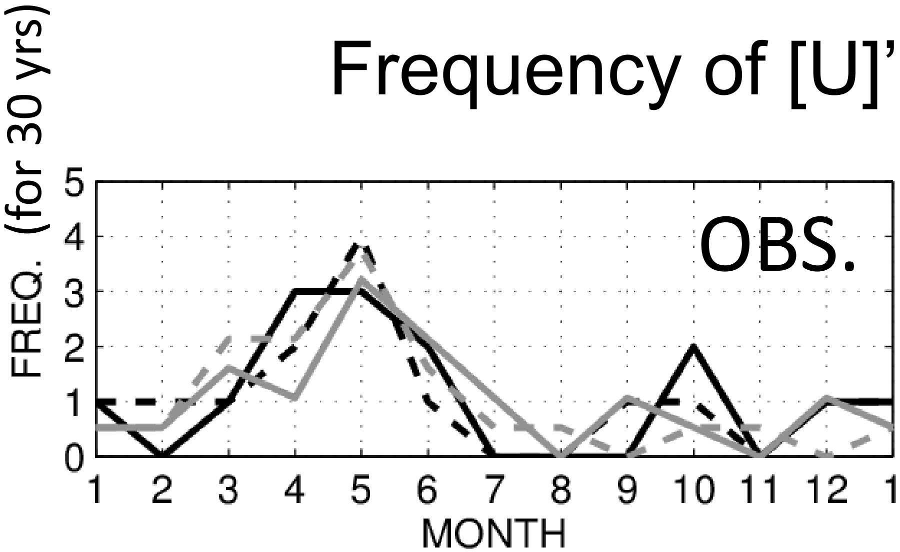
(EOF based measure of phase progression rate)

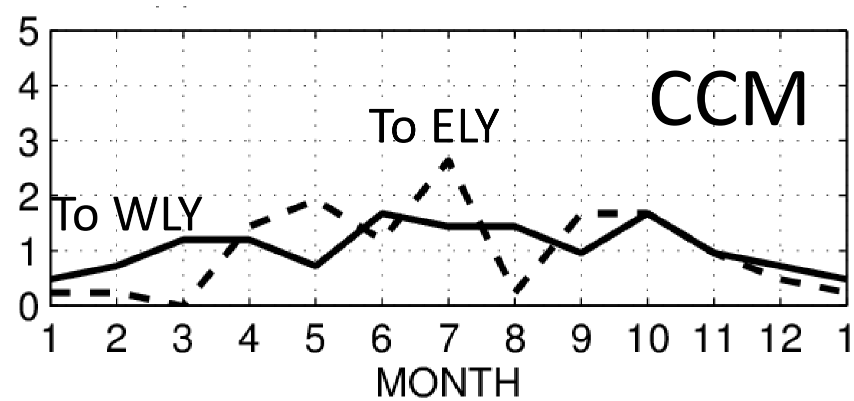
Ref.: None

Modeled QBO shows seasonally uniform distributions of wind reversals and NOGWF

Annual synchro. of CCM QBO

Frequency of [U]’ reversals at 50hPa

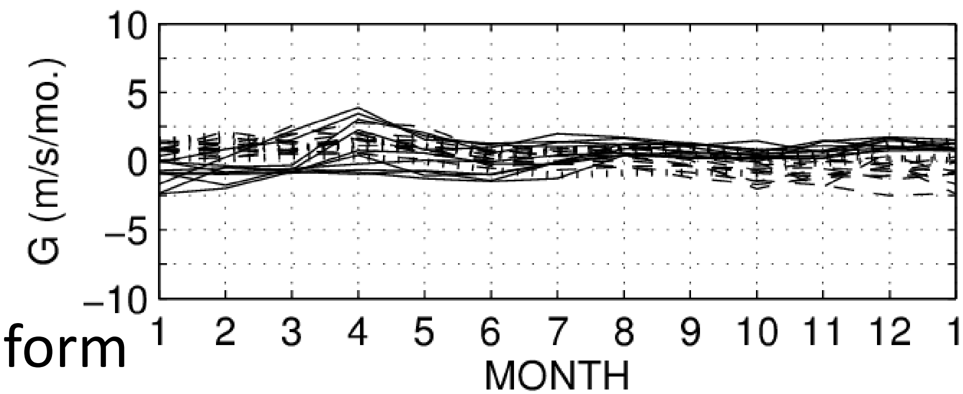




FUB 1958-2008

JRA-25 1979-2008

Hines NOGWF at 50hPa



Seasonally uniform

Ref.: None

The absence of annual synchro. may be due to time-constant NOGWF source or other factors

■MRI CCM simulations

Do not reproduce annual synchronization

Seems consistent with a time-constant source for NOGWF

⇒But, we will need to further examine other factors:

tropical tropospheric wind (filtering)

source level of NOGWF

SAO-QBO connection

⇔Poster (D) by Dr. Thomas Krismer

Role of SAO (and annual cycle of upwelling)

Annual synchro. reproduced in CCM using Hines scheme

Ref.: None

We have examined the three aspects of QBO: stalling, annual synchro., and ENSO modulation

Summary: QBO part

■Results and speculations

wave driving and vert. adv. play roles depending on the aspect of interest

◇Basics, stalling of ELY phase

feedback among zonal wind, tendency, vertical advection
triggered by stronger QBO signals at upper levels

◇Annual synchronization

role of small scale waves (GWs)

◇ENSO modulation

weaker amplitude and faster propagation for EL
role of wave driving

■Future plan

We will seek to better organize the results into a clear, firm picture

Ref.: None

Part 2
NH/SH changes
with QBO and ENSO

Part 2 discusses changes in NH winter/ SH spring stratosphere with QBO and ENSO

Outline for extratropical part

■NH, DJF in obs. and MRI CCM

◇Seasonal (DJF) mean states

Existing studies have shown nonlinear changes

◇Variability, or MSSWs

How does MSSW frequency change with the two factors?

How does a CCM simulate the NH winter changes?

■SH, SON in obs.

◇Seasonal (SON) mean states

Does the SH also change nonlinearly with NINO3 and QBO?

Ref.: I'll mention relevant studies below.

Part 2
Data

We use NCEP/NCAR reanalysis data etc. for real world, and MRI CCM simulation for comparison

Data

■Observations: 1957/58-2012/13

◇NCEP/NCAR reanalysis data

◇QBO index: equatorial zonal wind (FUB)

50 hPa for NH, 20 hPa for SH

◇ENSO indices: NINO3.4 or NINO3 SST (CPC/NOAA)

■MRI CCM simulation

REF-B1 run for present climate, 1960-2006

Ref.: None

Part 2
NH winter

Existing studies leave a question about changes in MSSW frequency with ENSO

Background: NH winter

■Seasonal-mean states

Nonlinear changes with QBO and ENSO

(Garfinkel and Hartmann 2007; Wei et al. 2007)

■Variability, or frequency of MSSWs

A question exists for MSSW frequency changes with ENSO

◇Obs. (Butler and Polvani 2011)

MSSW freq. increases for LA and EL than for NT

◇Model (Taguchi and Hartmann 2006)

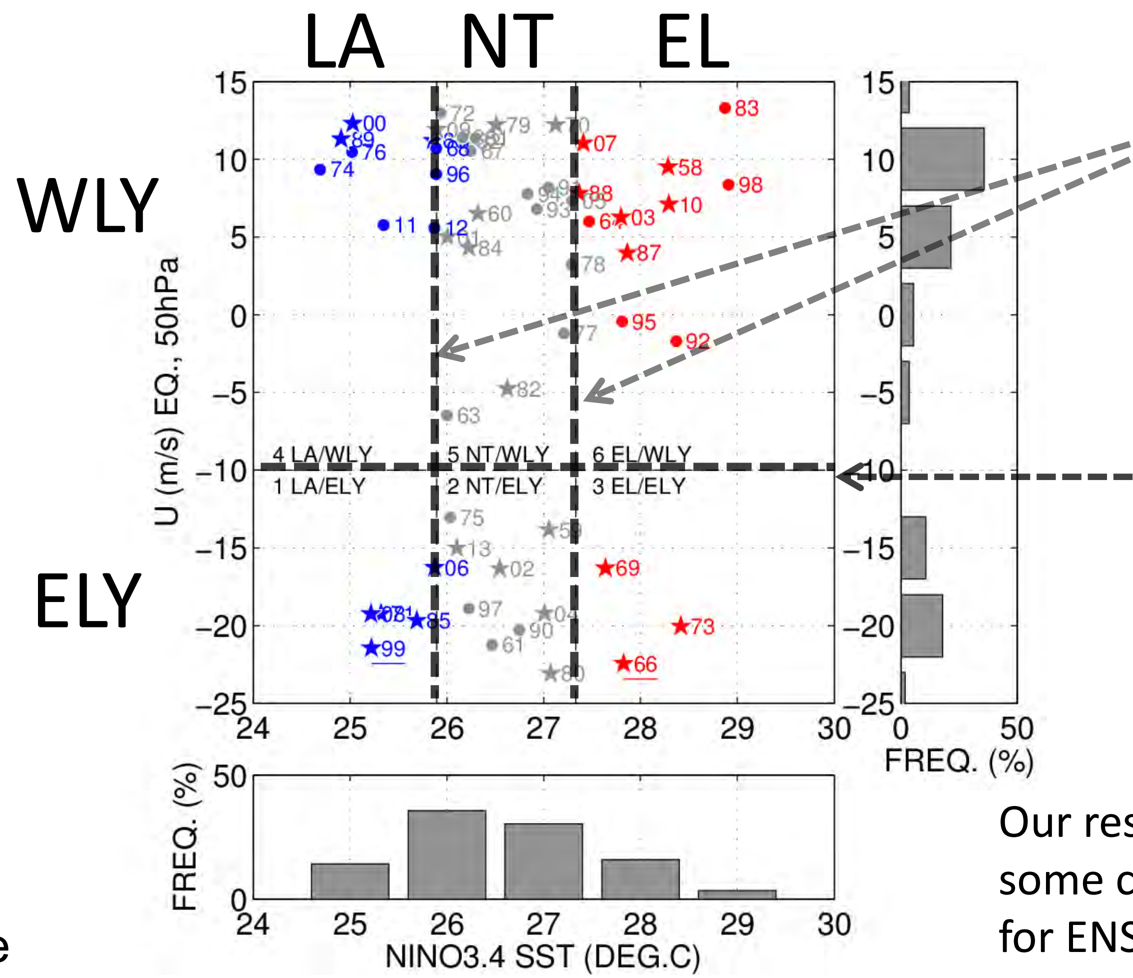
MSSW freq. increases for EL than for LA

⇒**How can we understand MSSW changes with ENSO?**

Ref.: None

We classify 56 years (’57/’58-’12/’13) into 6 groups defined by 3 ENSO and 2 QBO conditions

Scatter plot of ENSO and QBO indices for DJF



ENSO threshold: 25% top/bottom (0.72K anom. SST, or 0.70 std. dev.)

QBO threshold: U=-10m/s

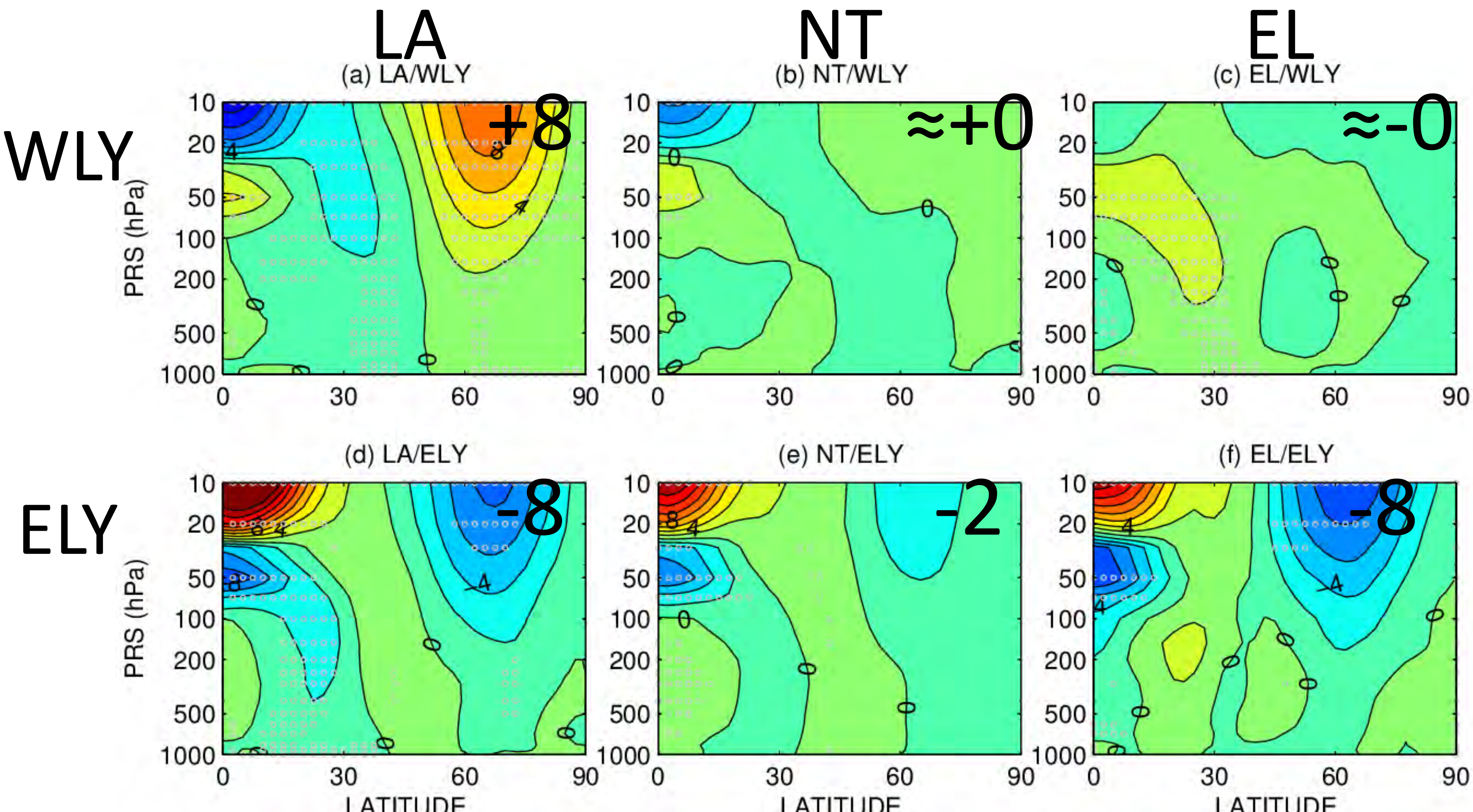
Clear bimodality, without values around -10 m/s.

Our results are insensitive to some changes in the thresholds for ENSO/QBO.

Ref.: None

Our results reproduce known nonlinear changes in seasonal (DJF) mean states

DJF composite [U] diffs. (m/s) from climatology

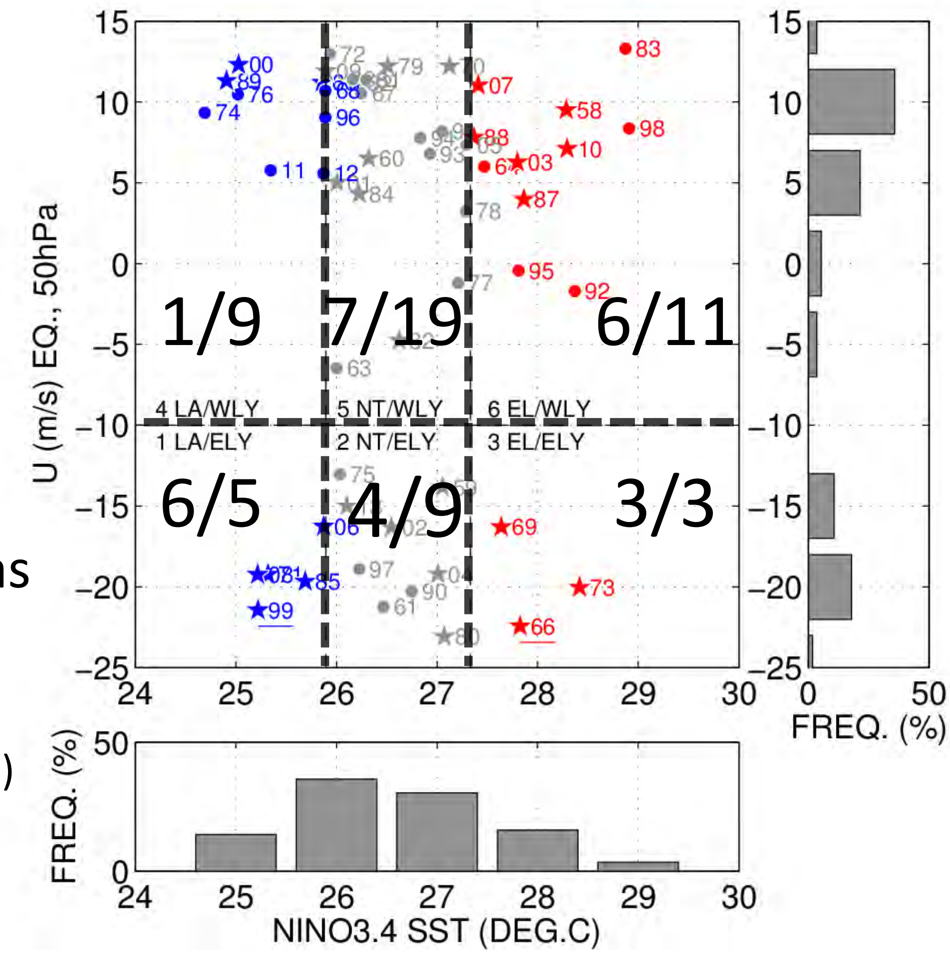


Ref.: Gray dots denote 90 % significance.

MSSW frequency/probability shows nonlinear changes with ENSO and QBO

MSSW probability for 6 groups

of MSSWs / # of winters

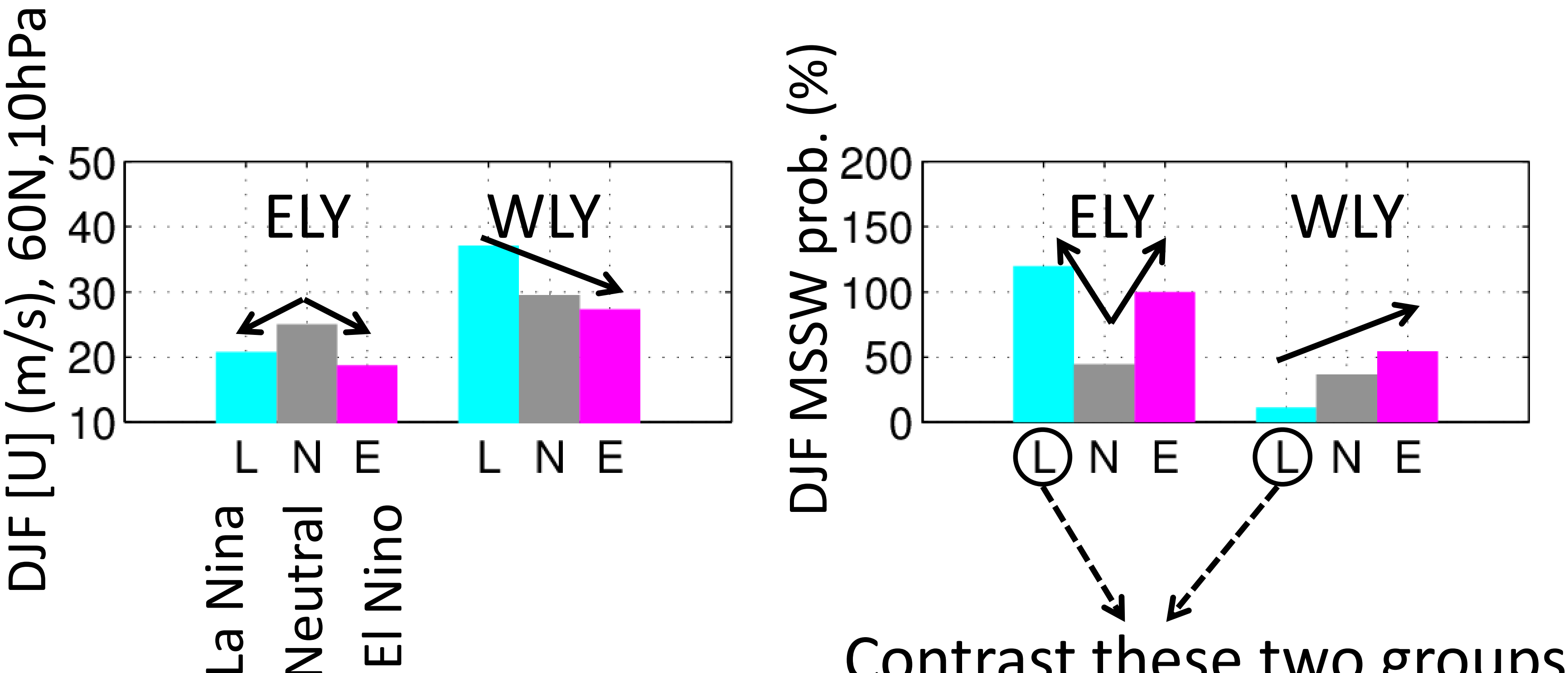


MSSWs are defined as [U] reversals at 60N, 10hPa (Charlton and Polvani 2007)

Ref.: None

Seasonal mean [U] and MSSW probability show consistent changes for DJF

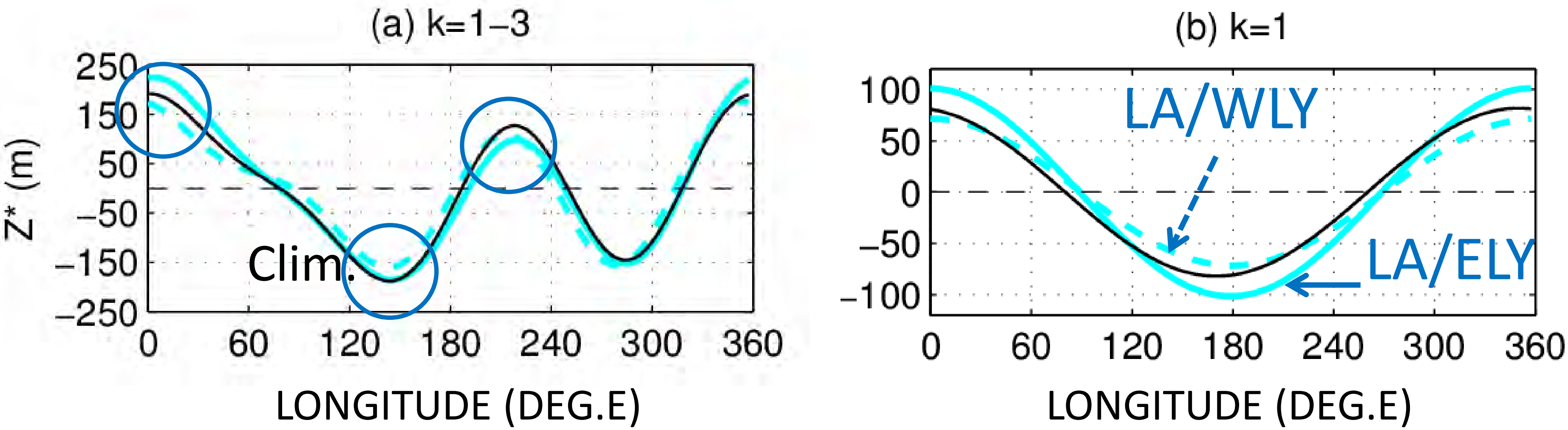
Bar charts for seasonal mean [U] (m/s) and MSSW probability (%) for DJF



Ref.: None

The high MSSW probability for LA/ELY winters is consistent w/ strengthened stationary wave 1

DJF stationary waves at 60N, 300hPa



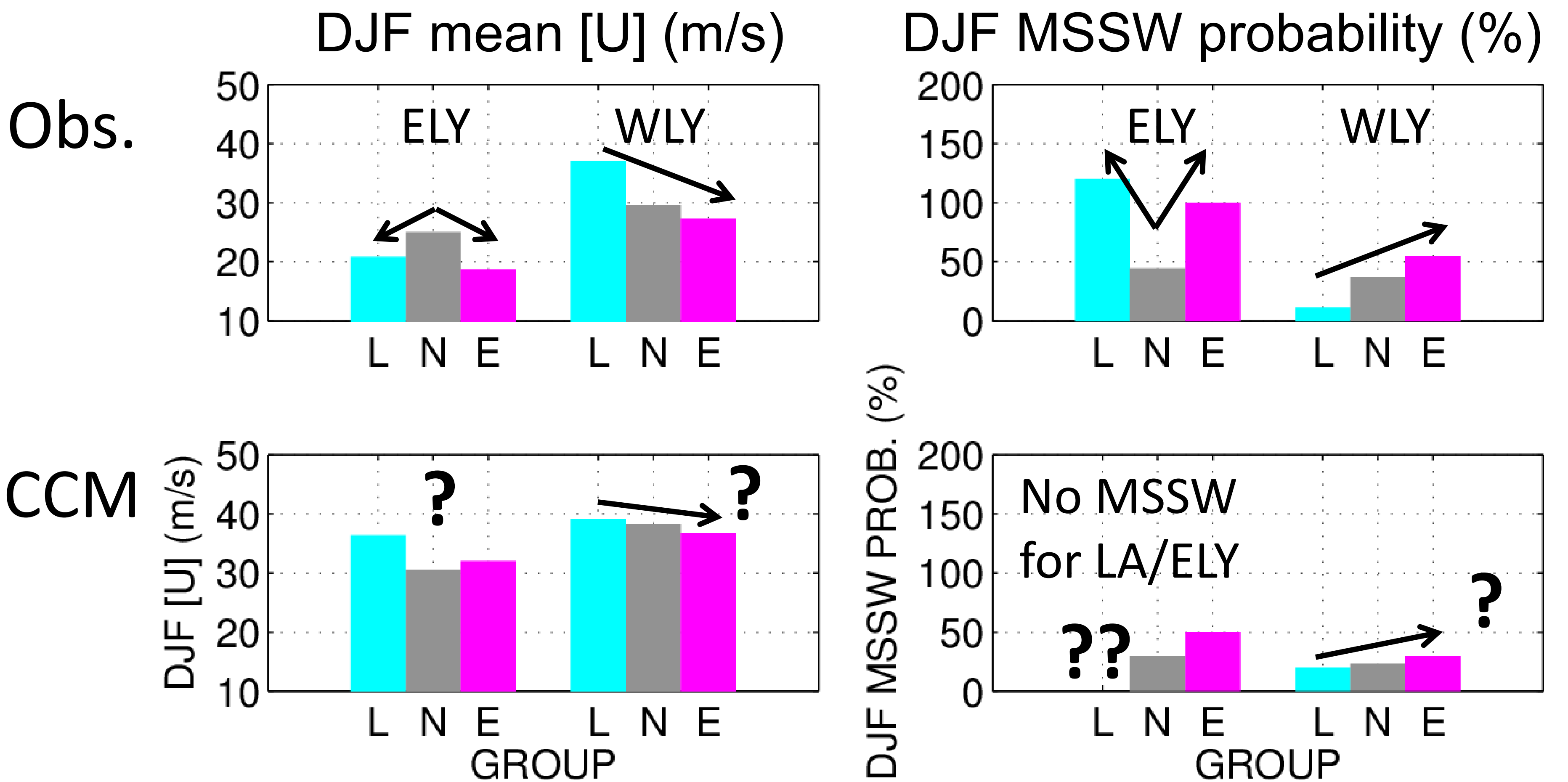
LA/ELY winters show
◇decreased ridge near clim. trough
◇increased ridge near clim. ridge

Two groups show different stationary wave responses:
◇different mean wind (basic state)
◇similar heating (precip.) anomalies

Ref.: None

The MRI CCM does not simulate obs. changes in seasonal mean state or MSSW probability

MRI CCM REF-B1 for NH winter



Ref.: None

Part 2
SH spring

Existing studies examined SH changes with each or both of QBO and ENSO

Background: SH spring

■Changes with each factor (QBO or ENSO)

◇SH stratosphere is sensitive to QBO at higher levels, e.g., 25 hPa (Baldwin and Dunkerton 1998; Naito 2002)

◇La Nina- or CP El Nino-like SSTs lead to enhanced PW activity (Lin et al. 2012)

■Nonlinear changes with both factors (Hurwitz et al. 2011)

◇PW activity response to CP El Nino is stronger during QBO ELY

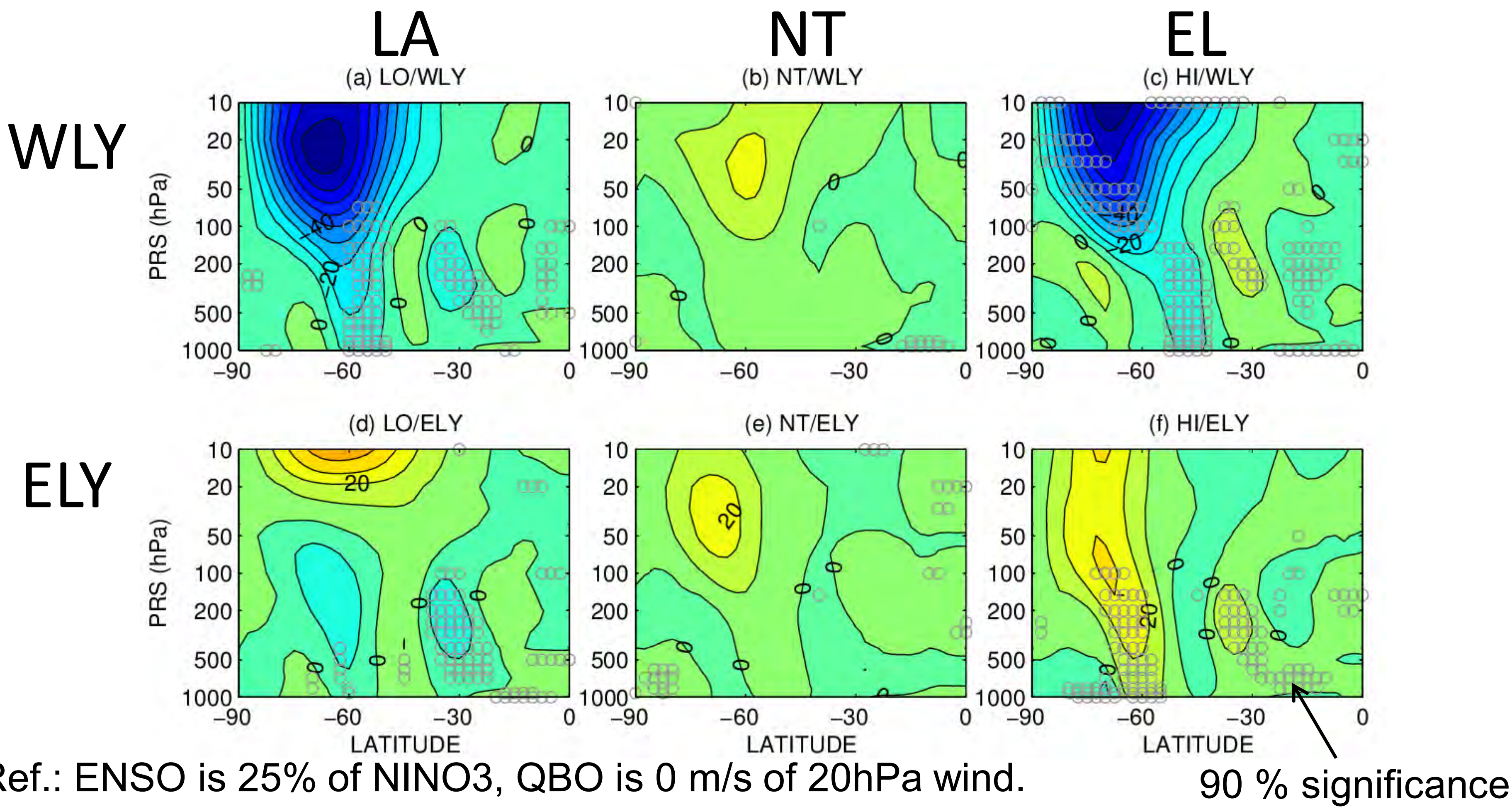
◇SH stratosphere may be insensitive to conventional El Nino

Does the SH also change nonlinearly with NINO3 and QBO?

Ref.: None

Composite analysis shows significant changes in wave 1 amplitude

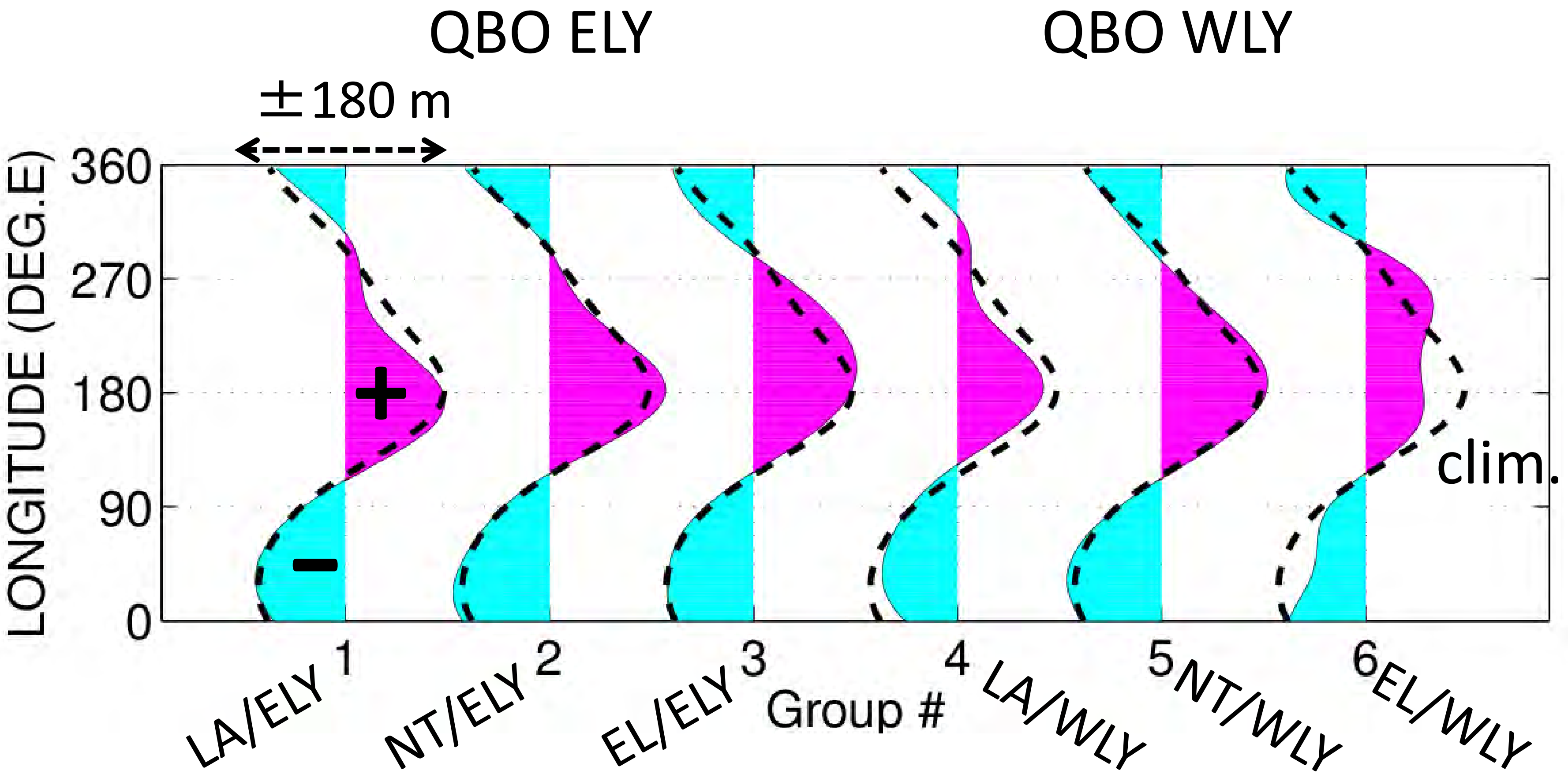
SON stationary wave 1 amp. diff. (m) from clim.



Ref.: ENSO is 25% of NINO3, QBO is 0 m/s of 20hPa wind.

Composite analysis suggests interesting changes in stationary wave structure

SON stationary waves 1-3: 50-70S, 100hPa



Ref.: ENSO is 25% of NINO3, QBO is 0 m/s of 20hPa wind.

We examined NH and SH changes w/ QBO and ENSO; we will further explore the mechanisms for the changes

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Summary:
Extratropical part

■NH winter

◇Obs. (Taguchi 2014, submitted to JC)

MSSW probability changes nonlinearly as in seasonal mean states

◇MRI CCM simulation

It may be still difficult to model these changes

■SH spring

◇Obs.

SH spring is also likely to experience nonlinear changes

e.g., stationary wave pattern changes with NINO3

Ref.: None

Summary

This talk has discussed (1) QBO variations, and (2) NH/SH changes with QBO and ENSO

Summary

■ We have detected (and diagnosed) various signals:

◇QBO variations

Stalling, annual synchronization, ENSO modulation

◇Nonlinear changes in both NH/SH with QBO and ENSO

NH winter: MSSW probability

SH spring: stationary wave pattern

■ We will seek to strengthen and expand the analyses

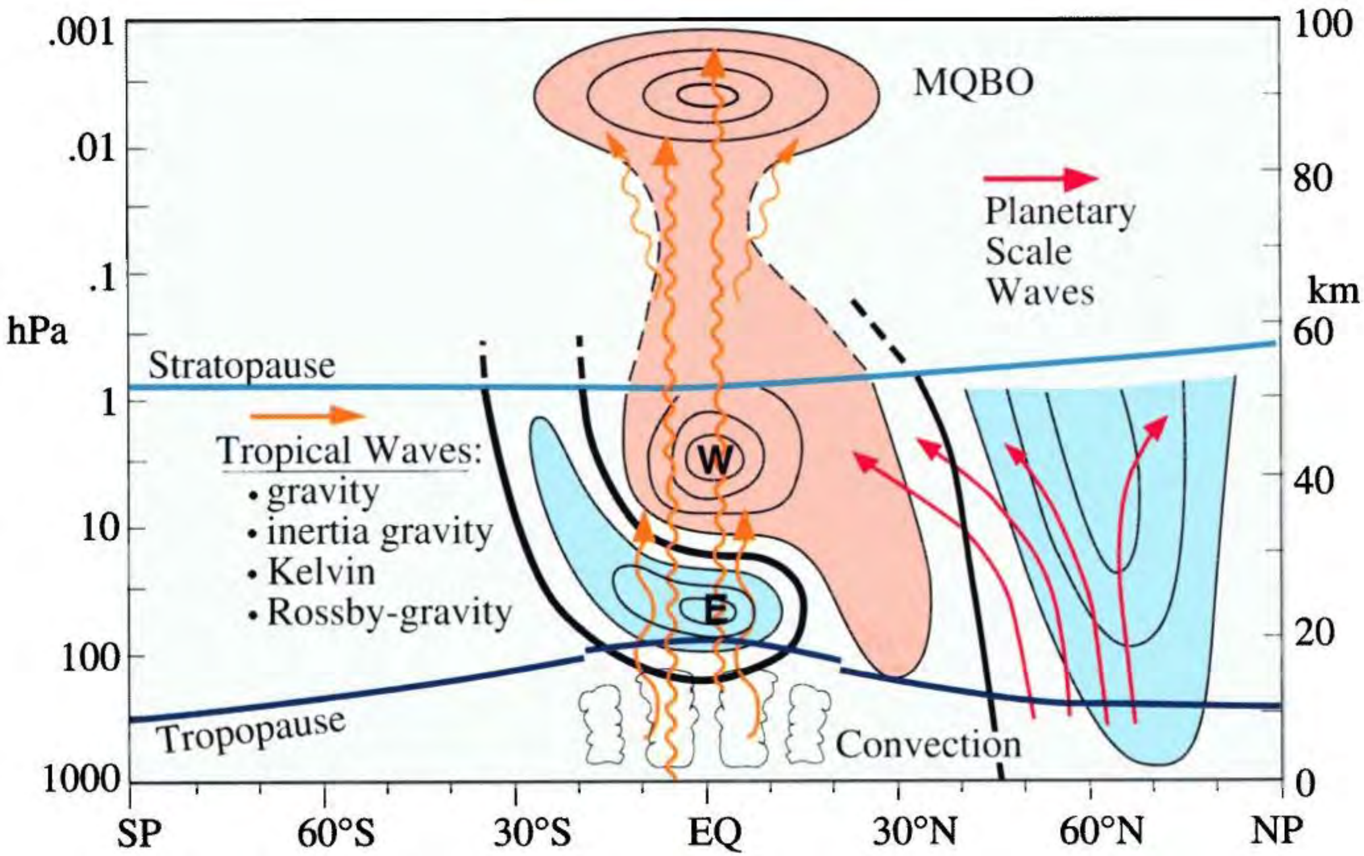
the analyses lead to further issues as mentined in places

Ref.: None

Back-ups

The mechanism of QBO is the interaction of mean zonal flow with various equatorial waves

Schematic of QBO-related processes



Ref.: Baldwin et al. (2001)

We extract QBO signals/anomalies as follows

Method

1. Extract QBO signals/anomalies (denoted as A')
   remove climatological seasonal cycle
   apply 5-month running mean

2. Perform EOF analysis
   apply EOF to U' in 10-70 hPa (or other regions)
   obtain EOF1,2 and PC1,2
   obtain amplitude, phase progression rate, etc.
   ＊*Focusing on zero wind lines will be sensitive to data and analysis procedures*

Ref.: None

The basic, momentum budget of QBO is among tendency, vertical advection, and wave driving

■ TEM

T = M +V +D +X

■ Basic budget of QBO component

T’ ≈ V’ + WD’

(WD: wave driving of various scales)

i.e.,

$[U]_t' \approx (-[U]_z [W]res)' + WD'$

Ref.: None

The basic, momentum budget of QBO is:
$[U]_t \approx - [U]_z [W]res + WD$

■ For ELY shear zones, the momentum budget is:

<-> = <+> + <-->

Vertical advection of QBO component is roughly:

$- ([U]z^{BG} [W]res^{QBO} + [U]z^{QBO} [W]res^{BG})$,

($[U]z^{BG}$: <->; $[W]res^{BG}$: <+>)

where A^{BG} represents LTM (time-constant) background

■ For ELY shear zones, the vertical advection is:

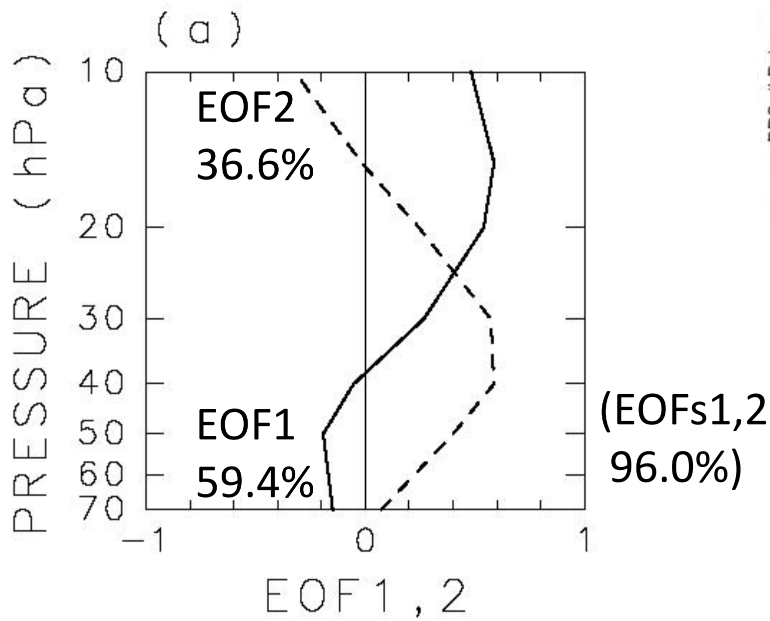
<+> = - (<-><+> + <-><+>)

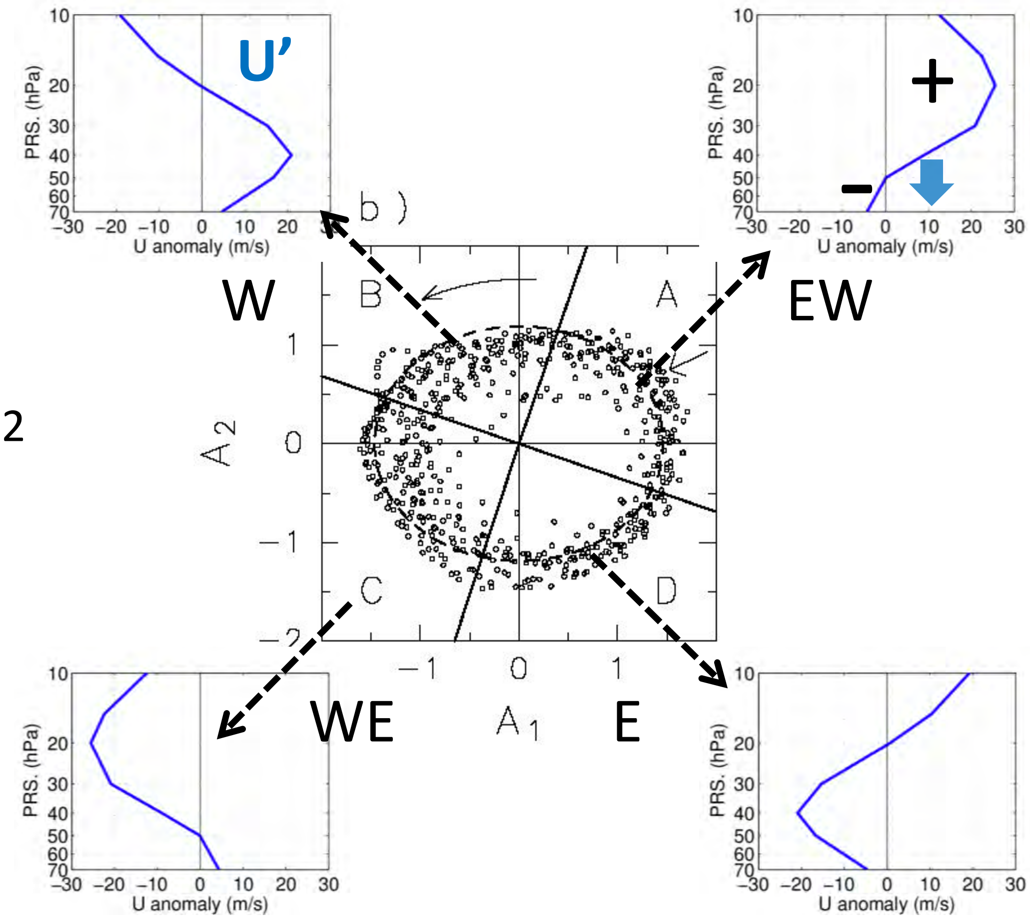
Ref.: None

The EOF analysis can well capture the phase propagation of the QBO.

EOF results

EOF1,2 structures, and PC1,2 distribution





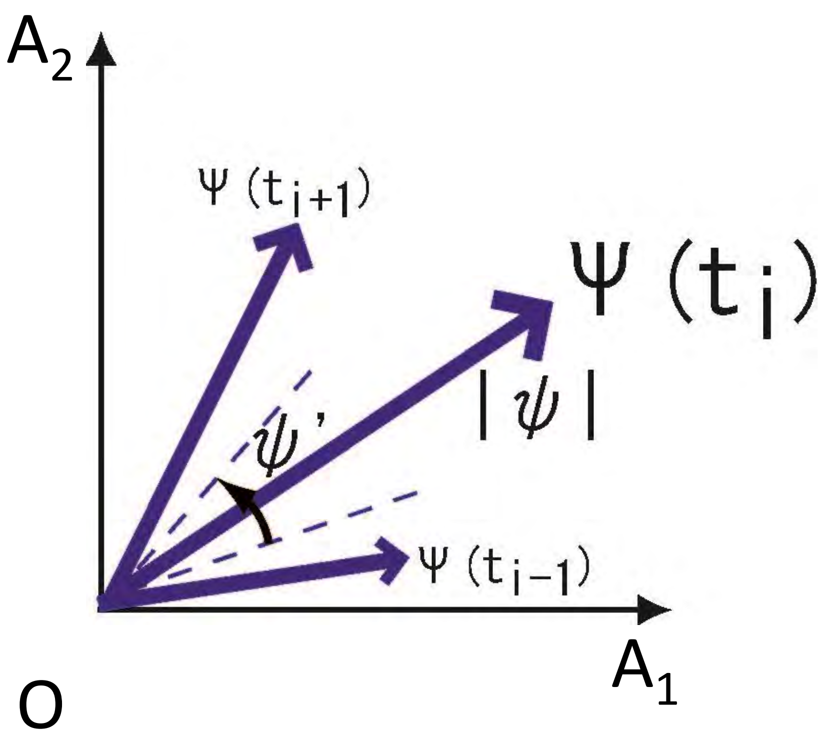
$$U' \approx PC_1(t)\mathbf{e}_1(z) + PC_2(t)\mathbf{e}_2(z)$$
$$= \sigma_{PC1}\,[A_1(t)\mathbf{e}_1 + A_2(t)\mathbf{e}_2]$$

Ref.: Wallace et al. (1993)

We get amplitude and phase progression rate using the trajectory of PC1,2

Definition of |ψ| and ψ'

Schematic for amplitude and phase progression rate



Amplitude: |**ψ**|
distance from origin
(non-dimensional)

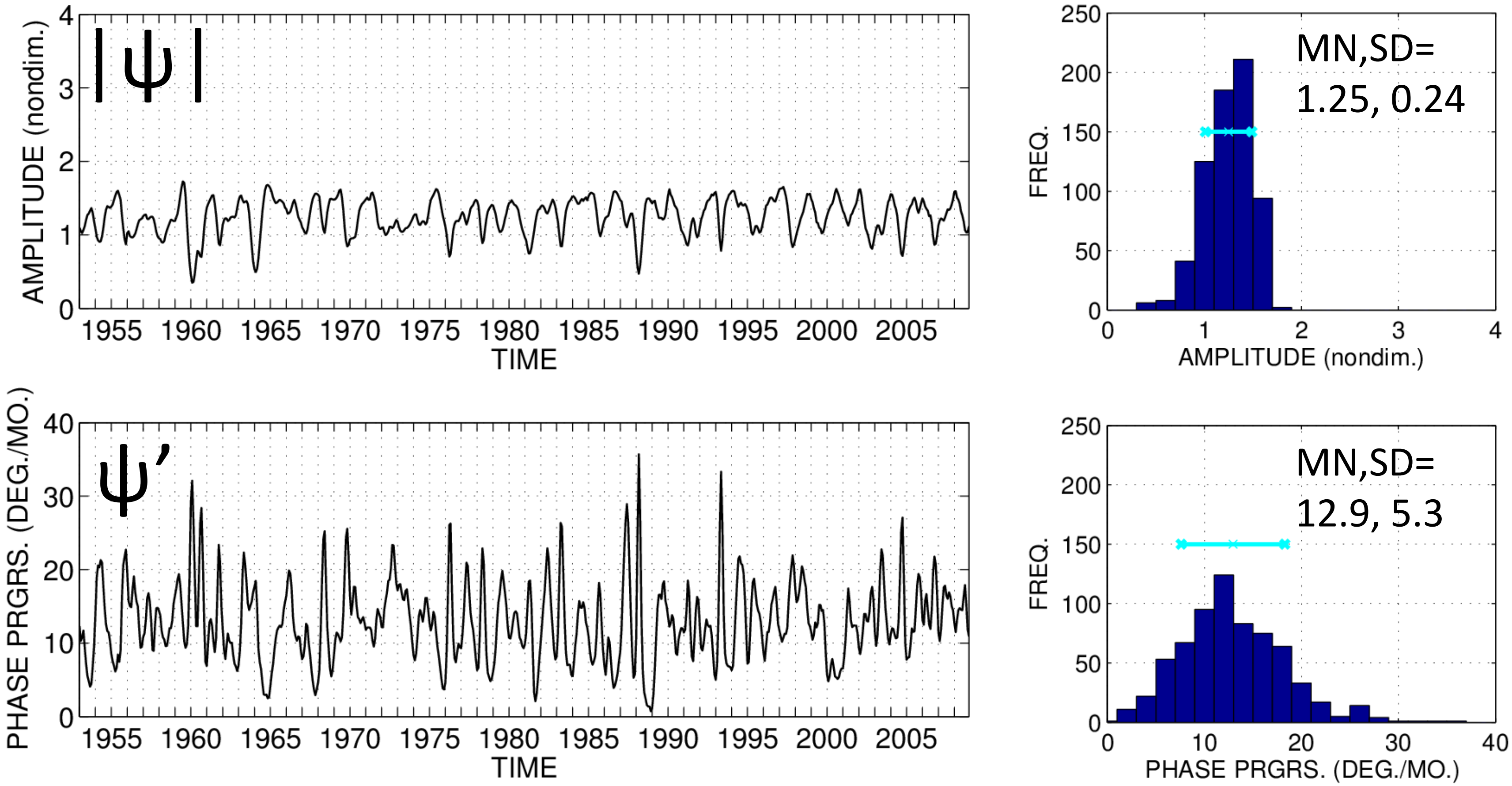
Phase progression rate: **ψ**'
time change in argument
(deg./mo.)

Each data point accompanies
info of month (season) and quadrant.

Ref.: This definition of amplitude here is different from that of Kawatani.

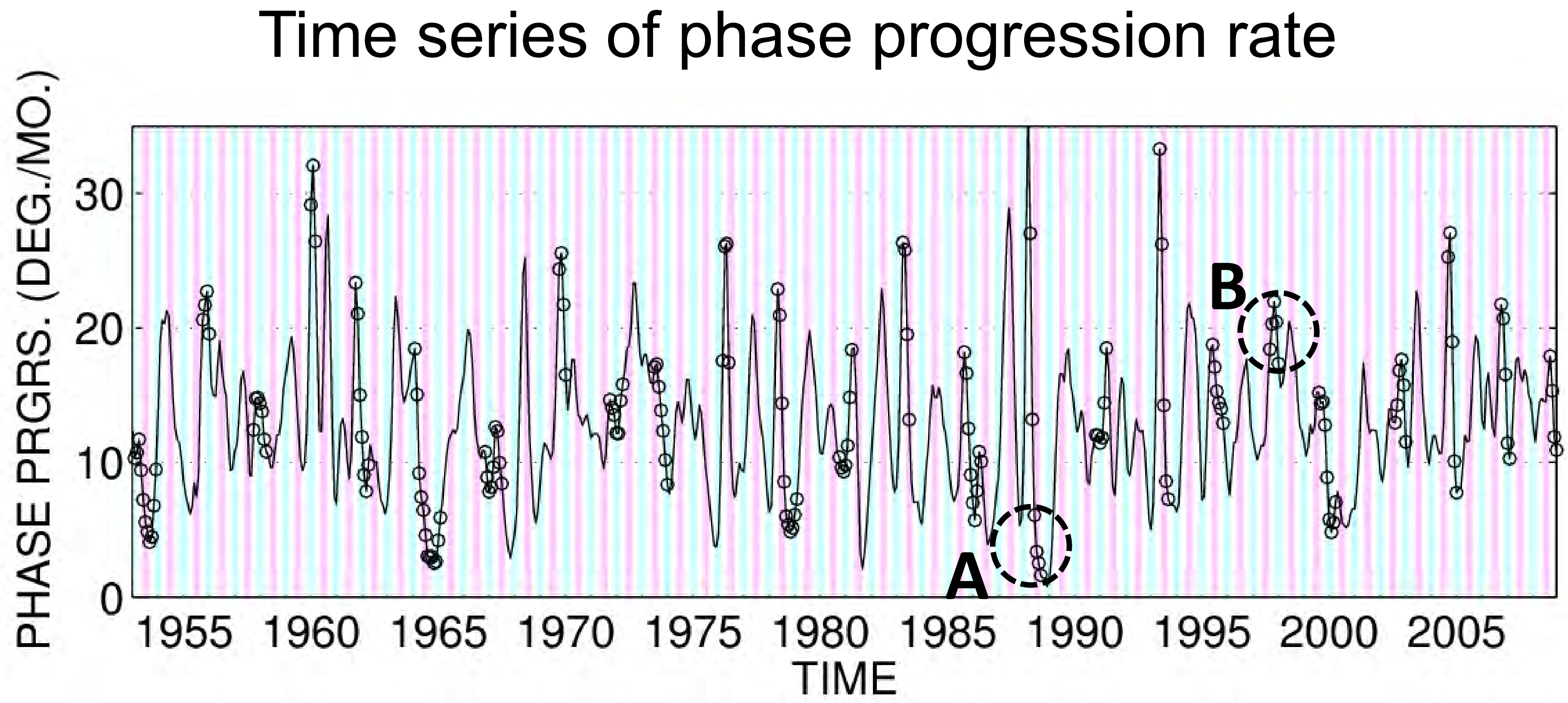
Phase progression rate shows larger variability (i.e., VAR/MN ratio) than amplitude

Time series and PDFs of |ψ| and ψ’



Ref.: None

The time series of phase progression rate sometimes have small values.



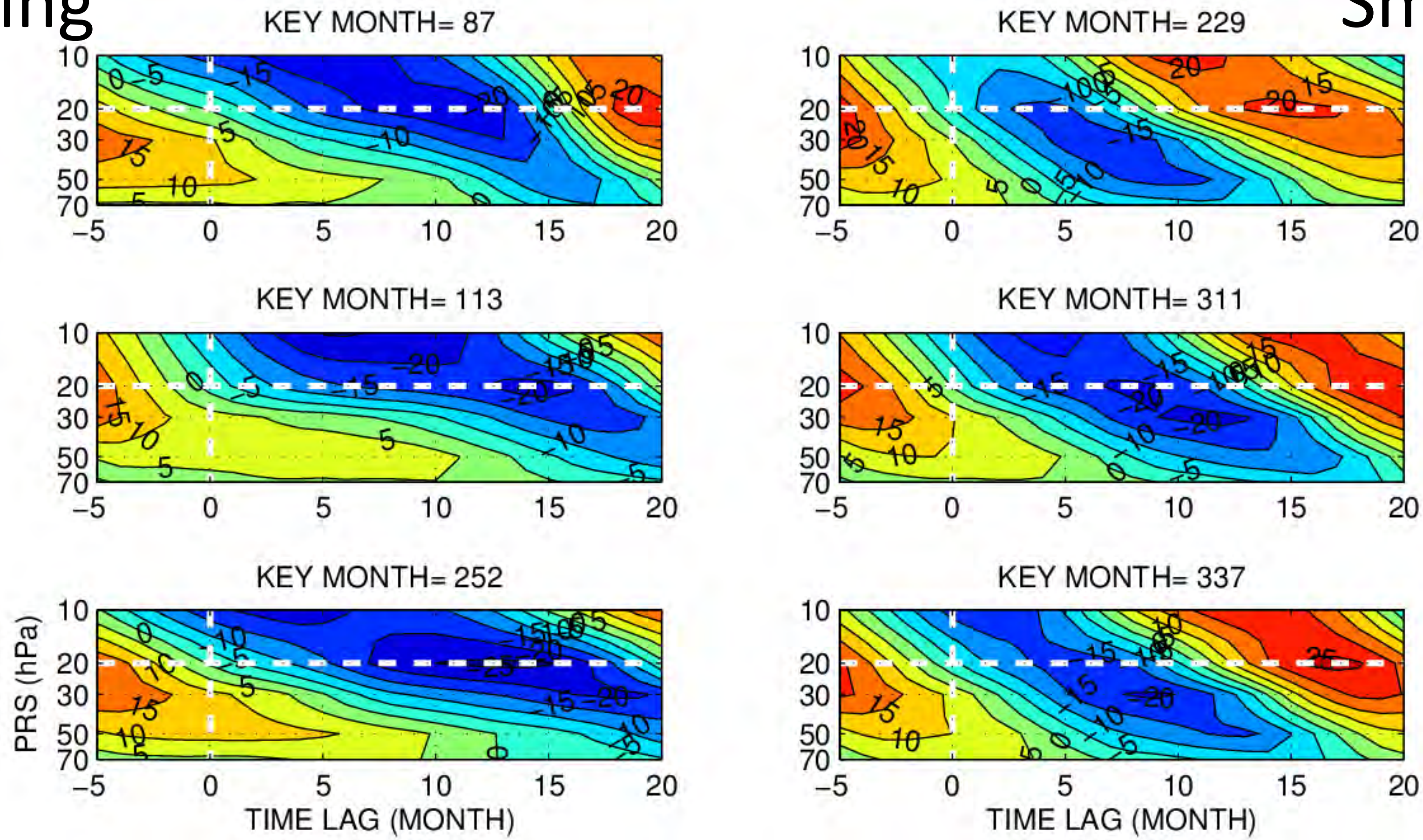
Ref.: Cyan for DJF
Magenta for JJA
Circles for W group (WLY peak near 50 hPa)

We contrast two groups of 3 cases: stalling cases vs. smooth propagation cases

U anomalies (m/s) for 6 cases

Stalling

Smooth



Ref.: Key month is counted wrt for Jan., 1979.

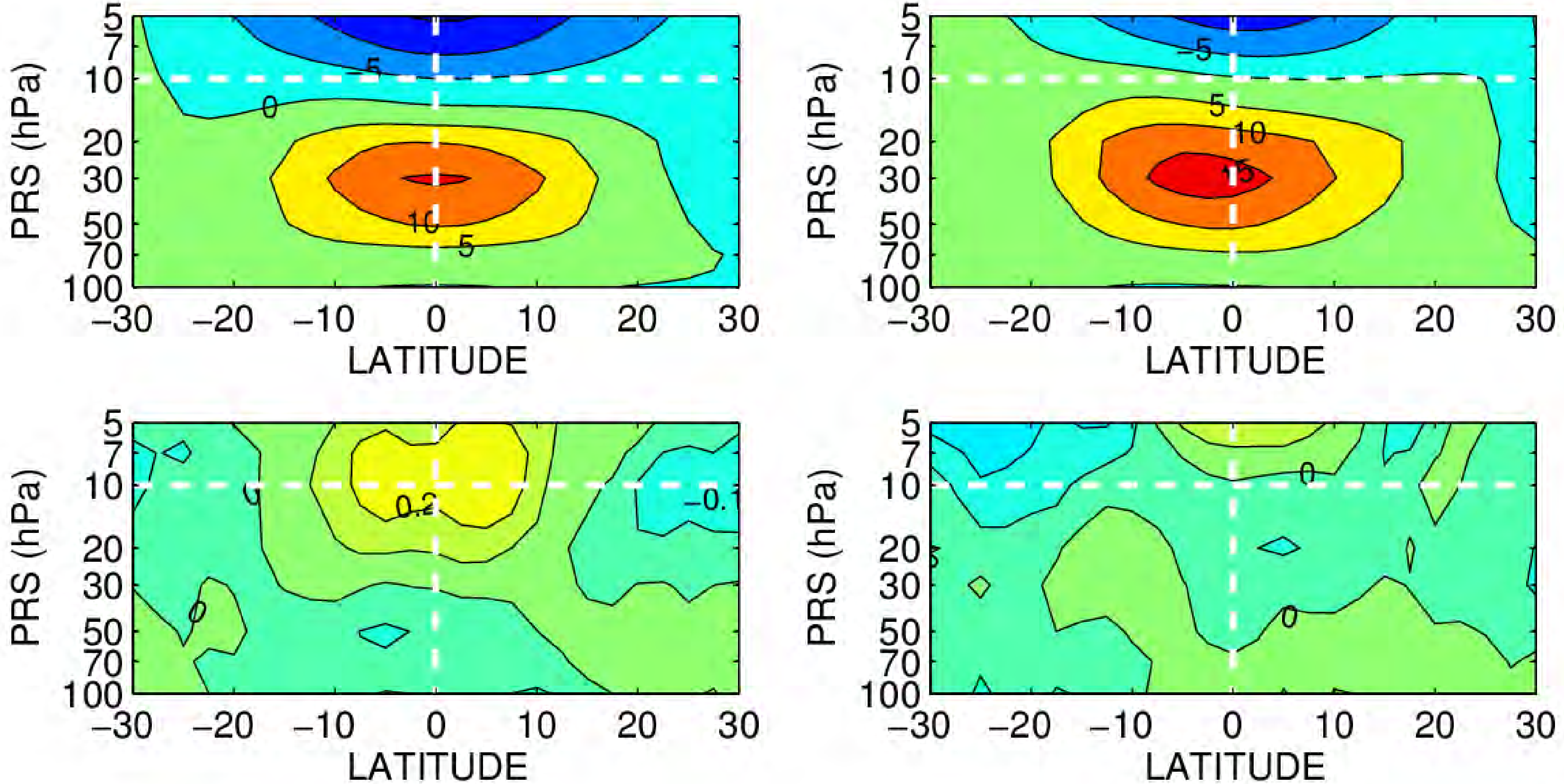
Stalling cases show stronger QBO signal (in upwelling) around 10hPa

[U]’ and [W]res’ before ELY onset at 20hPa

Stalling | Smooth

[U]’ (m/s)

[W]res’ (mm/s)

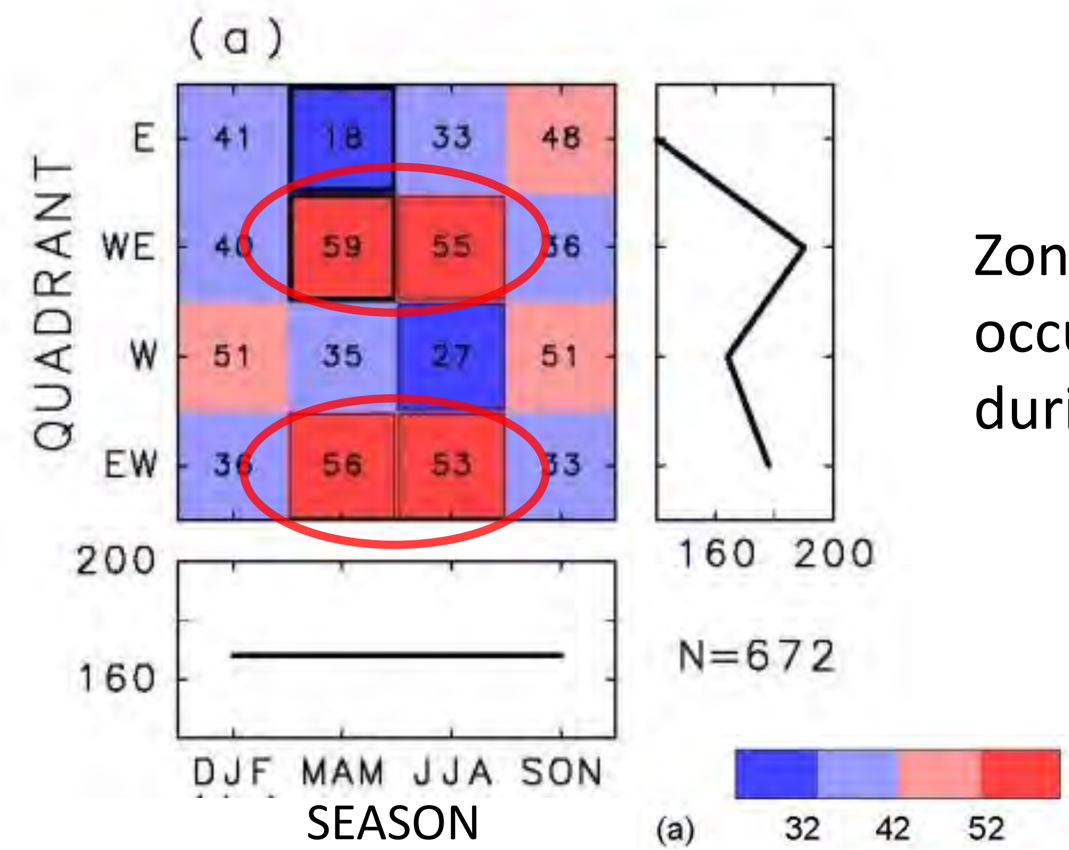


Ref.: Time means are taken for lag= -5 to -1 months

2D sorting reproduces the annual synchronization feature

Modulation by season

Number of samples for each of 16 groups



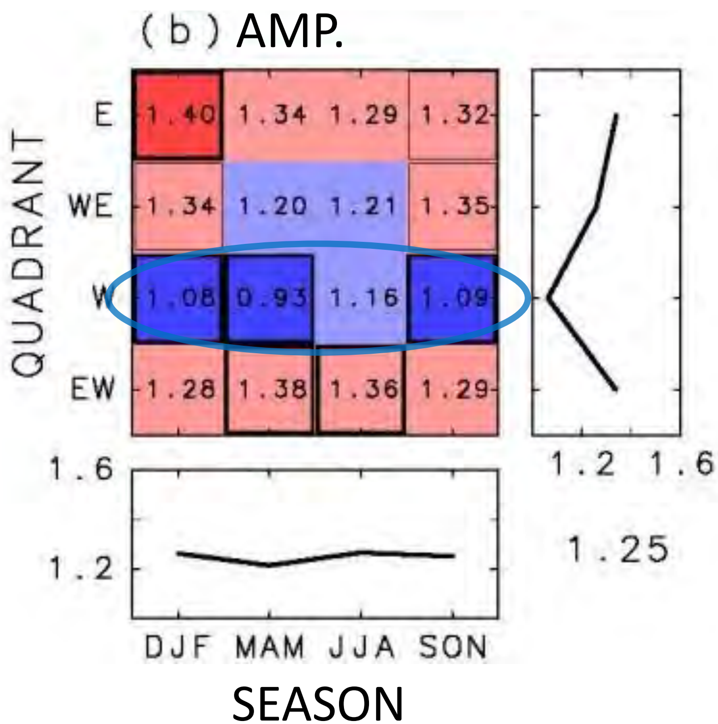
Zonal wind reversals at 50 hPa occur frequently during NH spring and summer

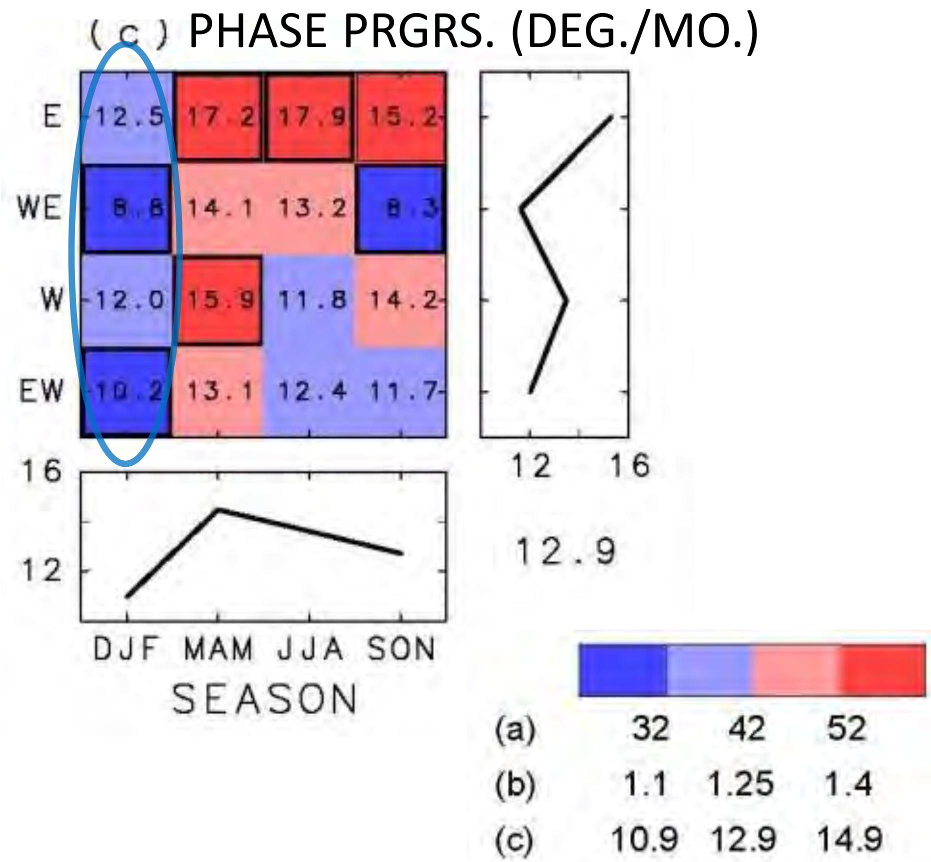
Ref.: Taguchi (2010,JGR)

2D sorting shows variations in |ψ| and ψ' with season and phase

Modulation by season

Amplitude, and phase progression rate



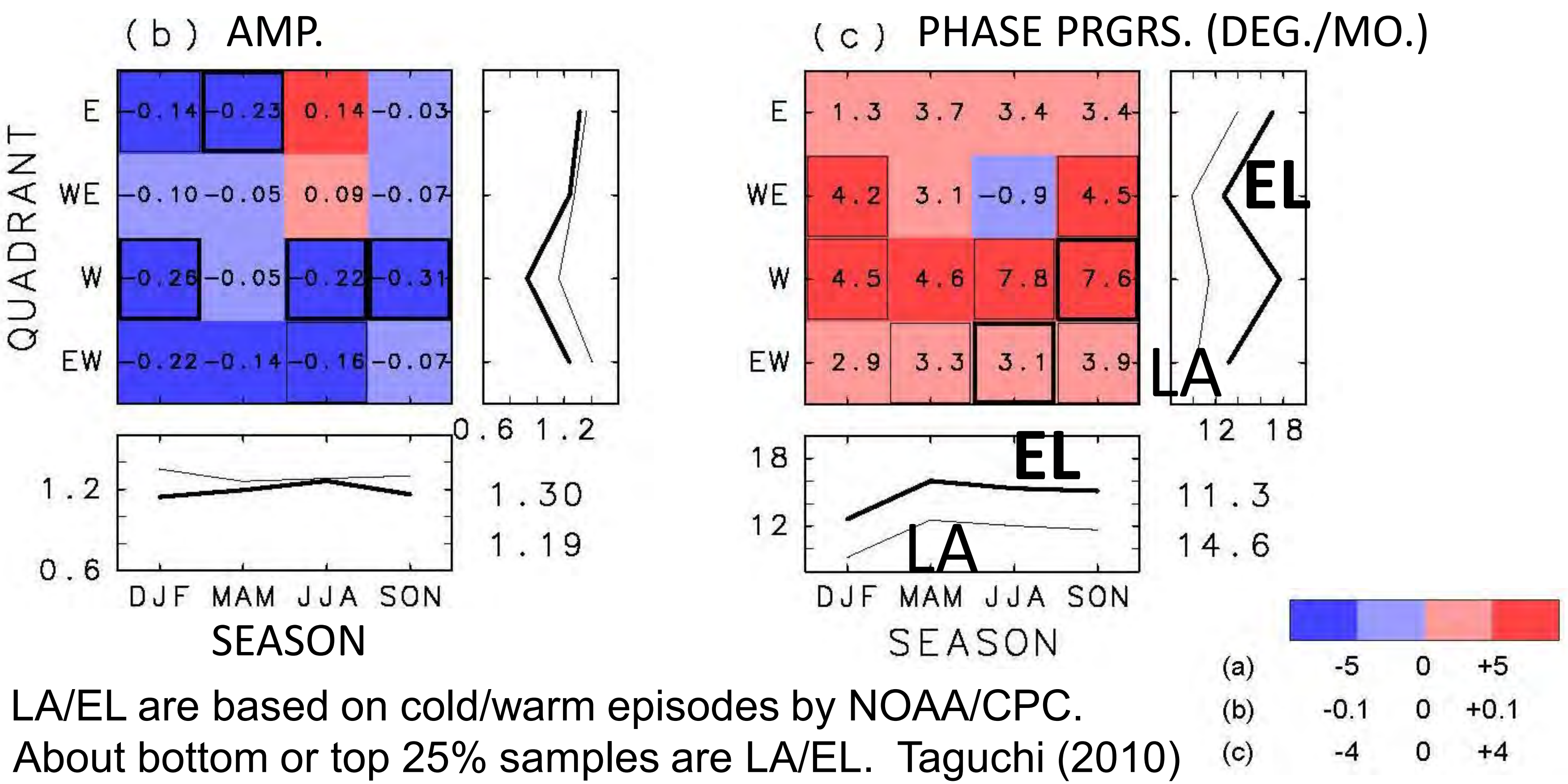


Ref.: Taguchi (2010)

Such features are generally robust regardless of season and QBO phase

Modulation by ENSO

Composite differences, EL minus LA

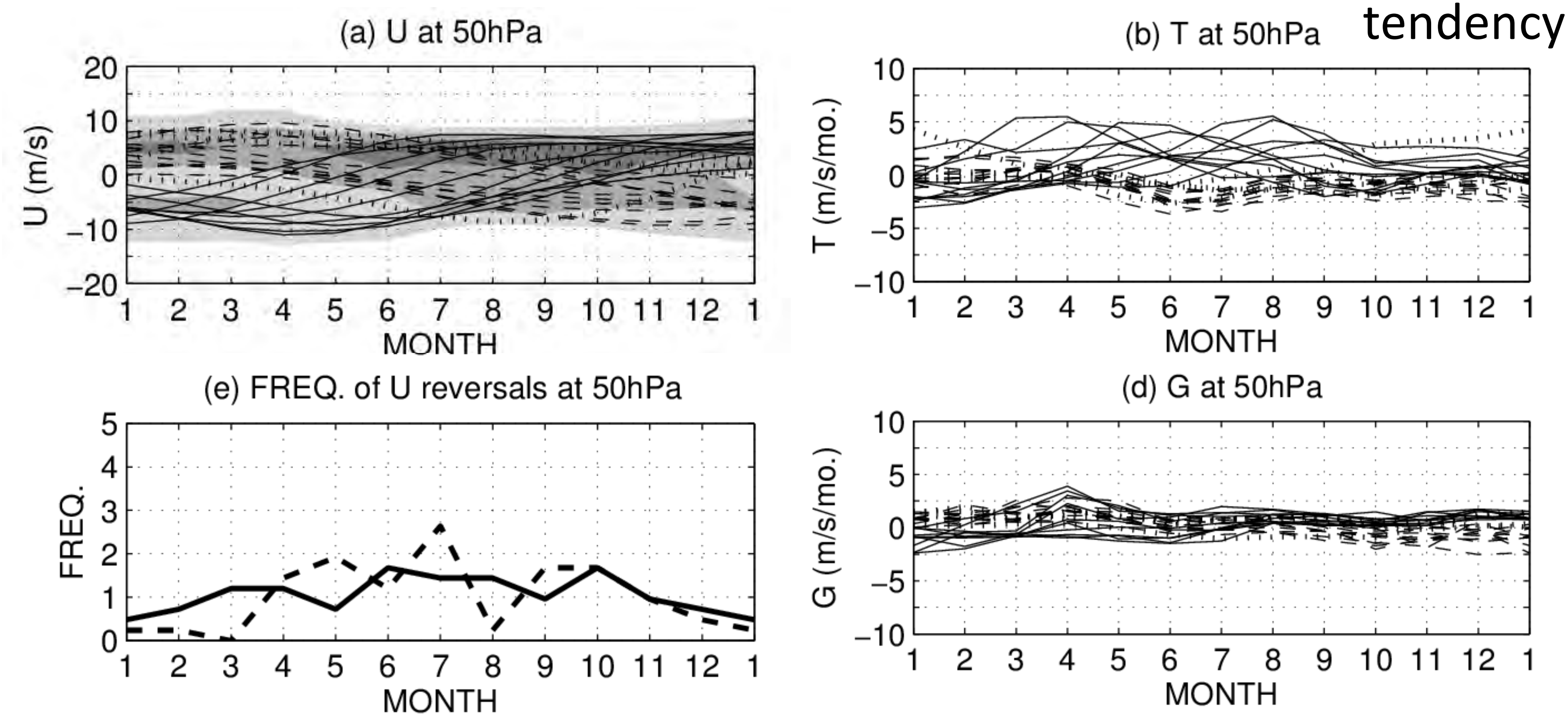


Ref.: LA/EL are based on cold/warm episodes by NOAA/CPC.
About bottom or top 25% samples are LA/EL. Taguchi (2010)

The absence of annual synchro. from CCM corresponds to roughly uniform G term (in time)

MRI CCM

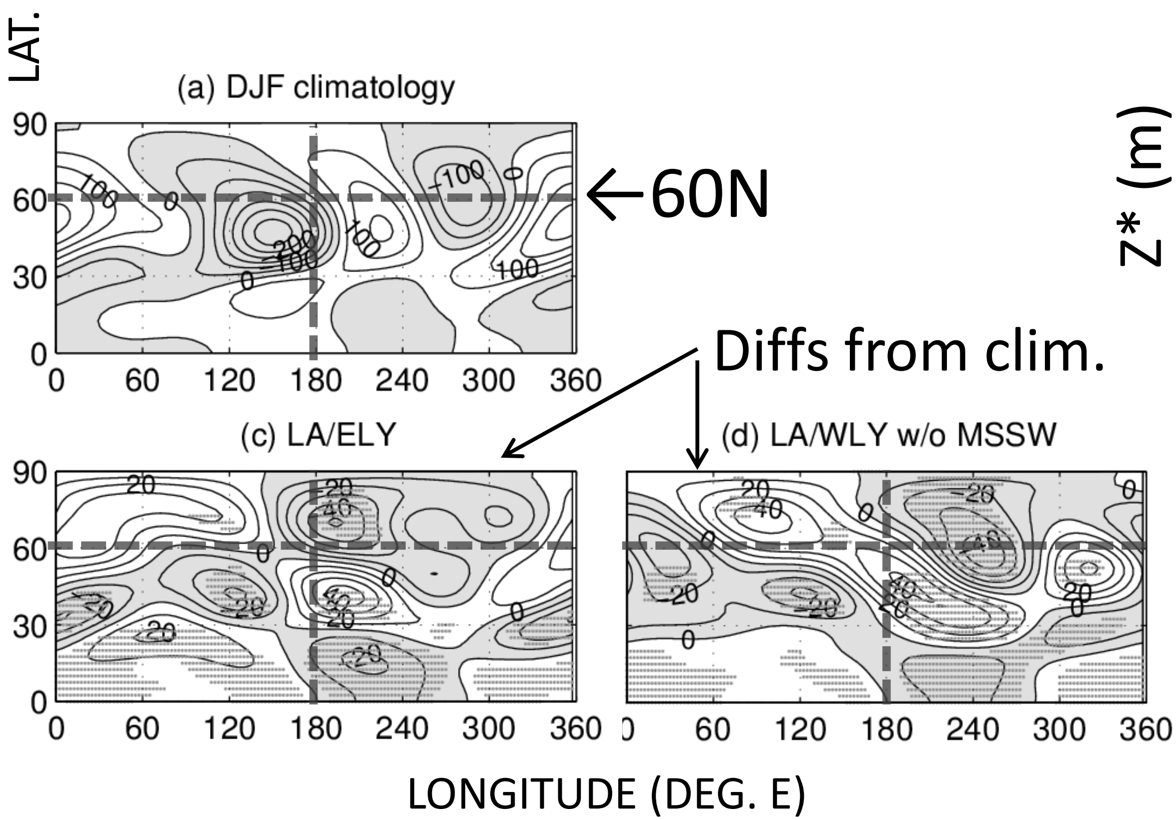
[U] anomalies and tendency in MRI CCM data

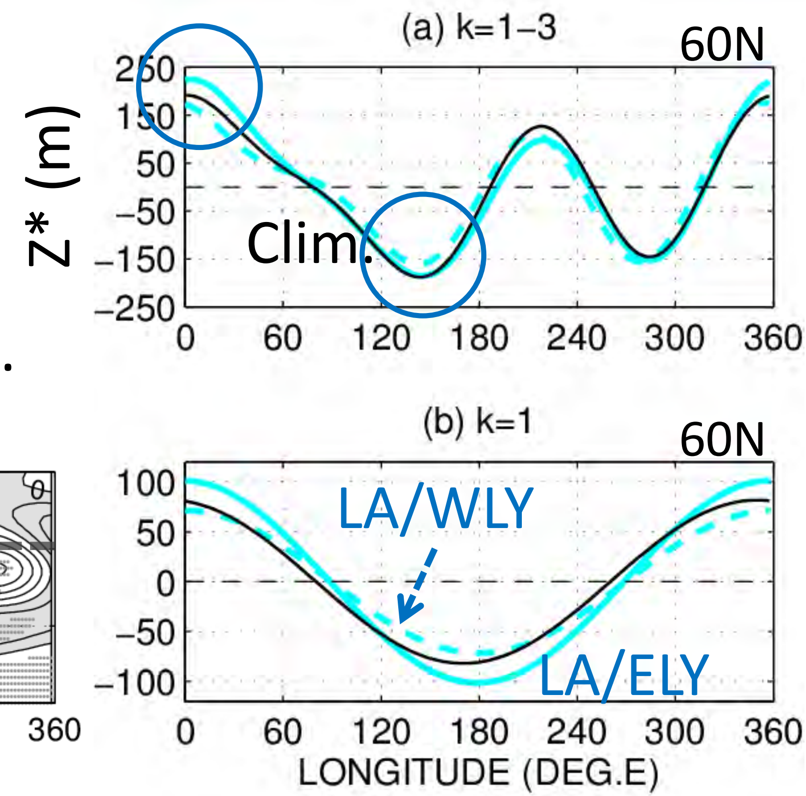


Ref.: None

The high MSSW probability for LA/ELY winters is consistent w/ strengthened stationary wave 1

300hPa stationary waves
for LA/ELY (highest prob.) vs. LA/WLY (lowest)

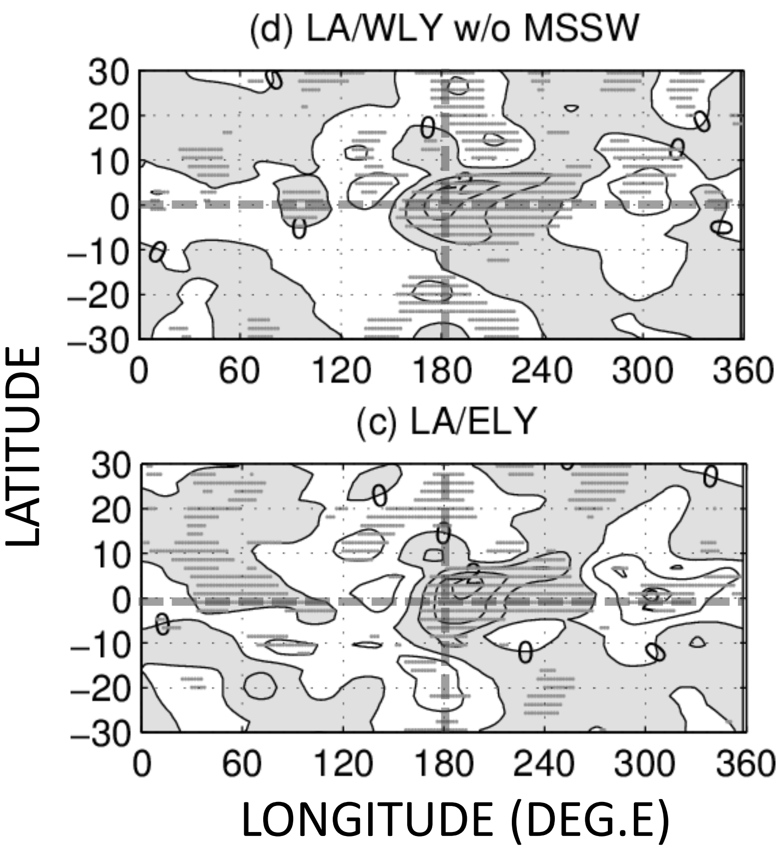


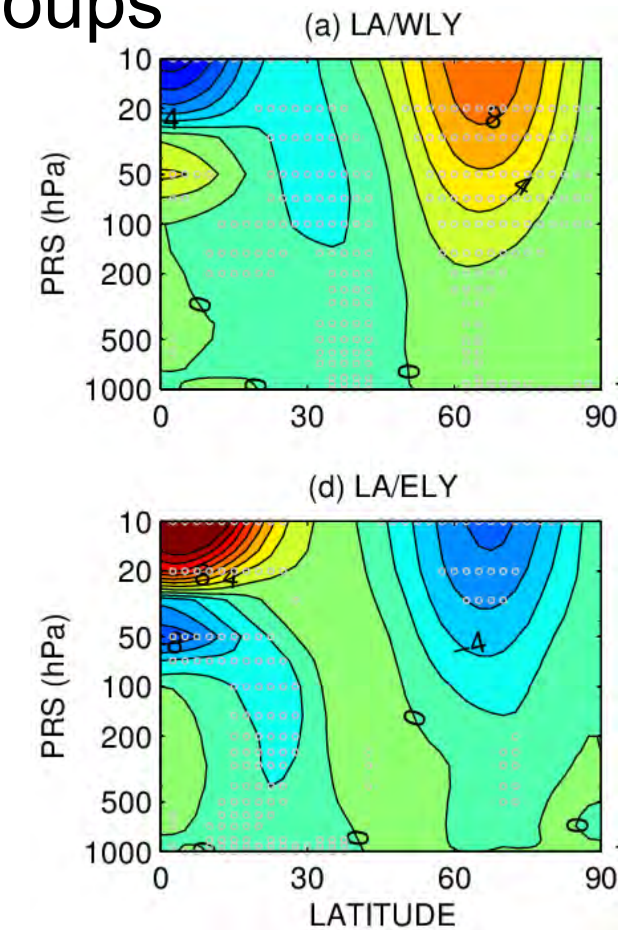


Ref.: None

We speculate that the stationary wave responses are affected by zonal wind profiles

Precip. (kg/m^2/day) and zonal wind (m/s) anomalies for the two groups

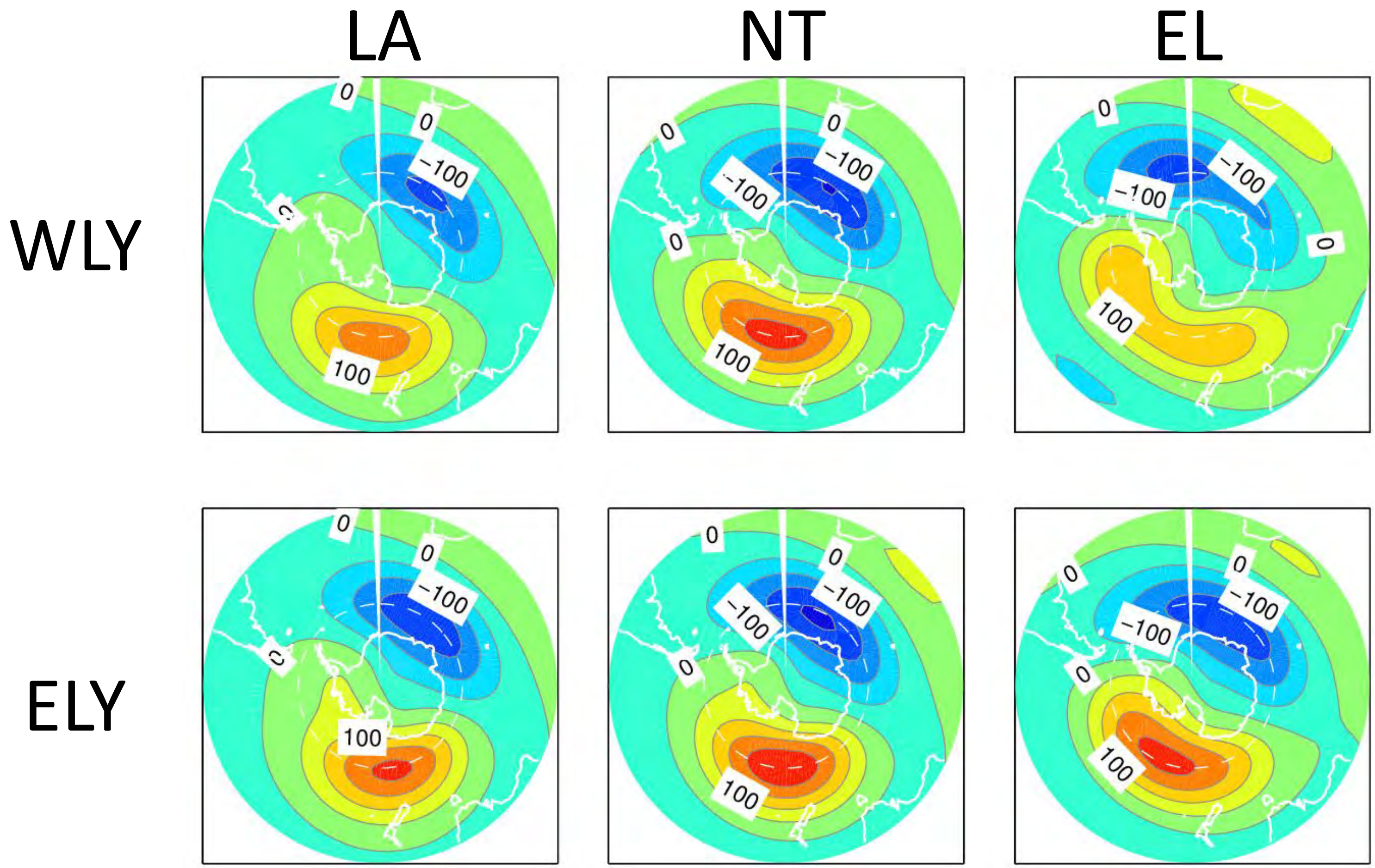




Ref.: Gray dots are 90% significant differences from climatology.

Composite analysis suggest nonlinear changes in stationary waves

SON stationary waves 1-3 at 100hPa

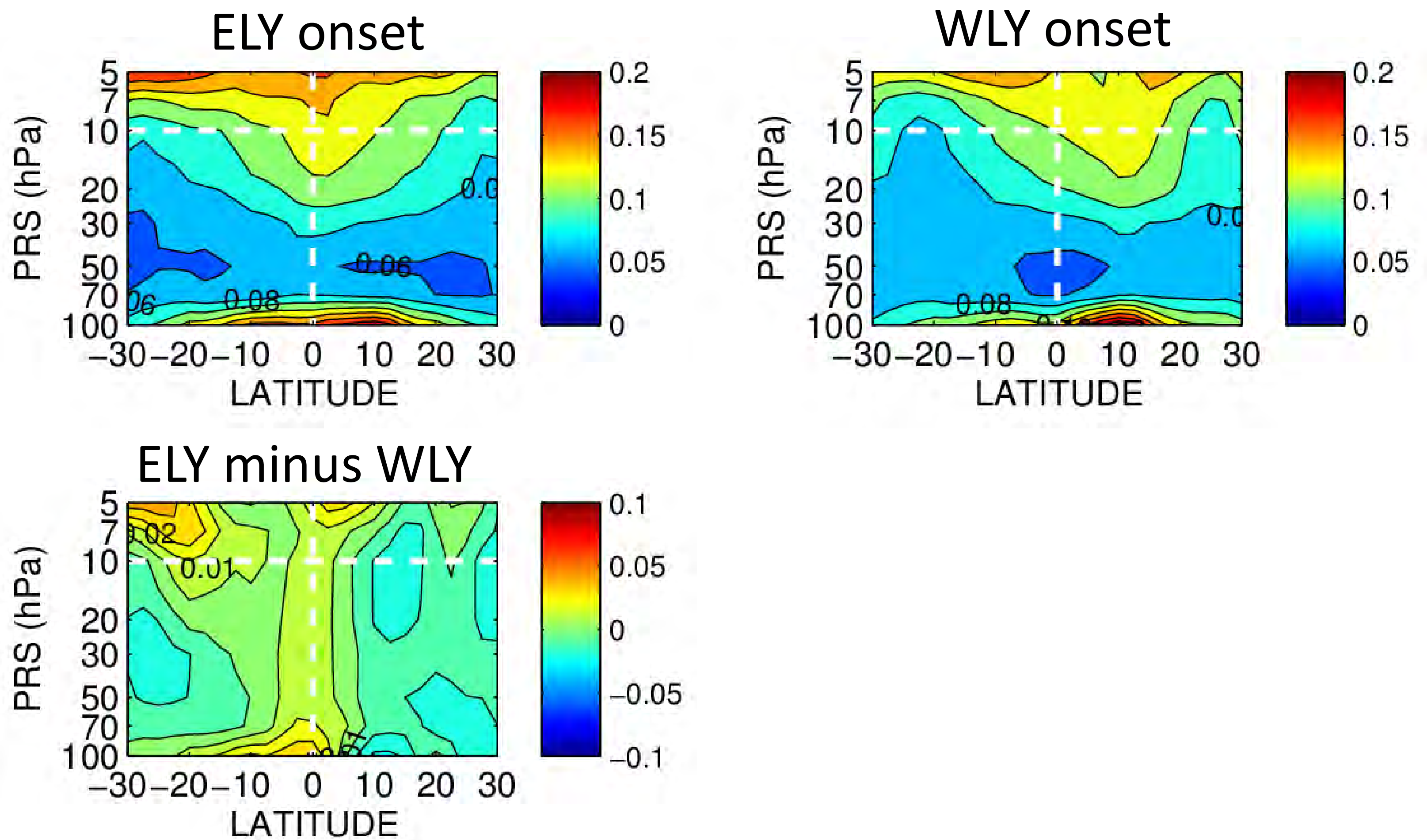


Ref.: ENSO is 25% of NINO3, QBO is 0 m/s of 20hPa wind. CI is 50 m. Mark 60S.

Secondary Back-ups

ELY onset cases show larger variability in QBO upwelling at upper levels (≲10 hPa)

Std. dev. of [W]res’ (mm/s)



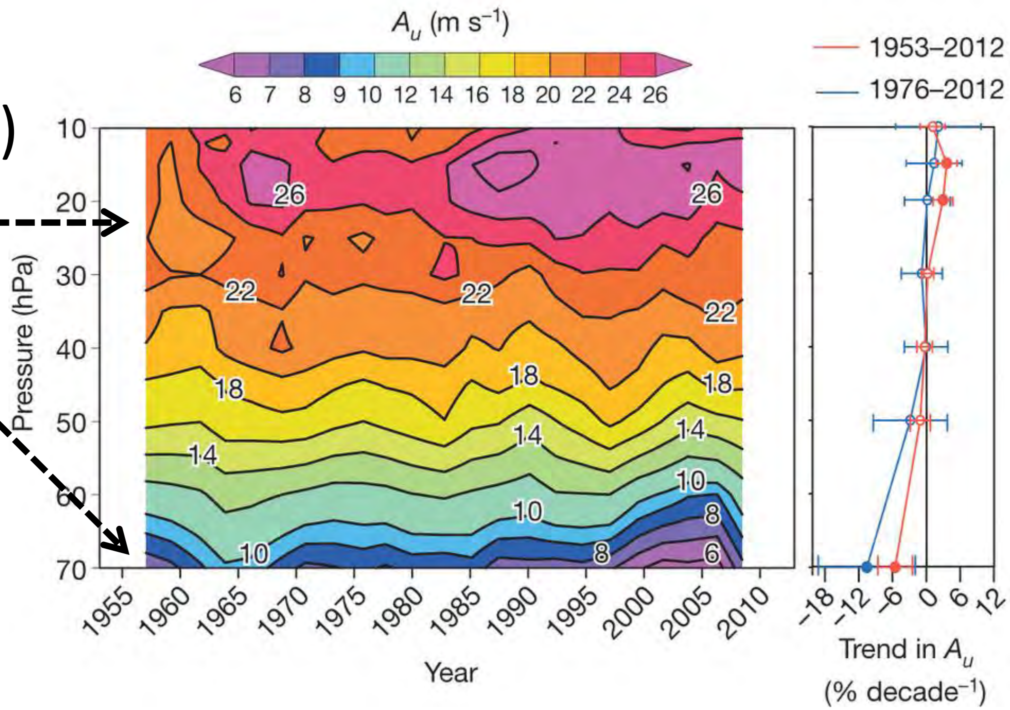
Ref.: Time means are taken for lag= -5 to -1 months

Kawatani and Hamilton show trend in QBO amp., while it is difficult to find trend in QBO period.

Trend

Three-cycle mean amplitude of QBO
for each time (month) and level

■Amplitude
(Kawatani and Hamilton 2013)
Increase at upper levels
Decrease at lower levels



■Other properties, such as period and phase progression rate
Difficult to find due to large variability

Ref.: None

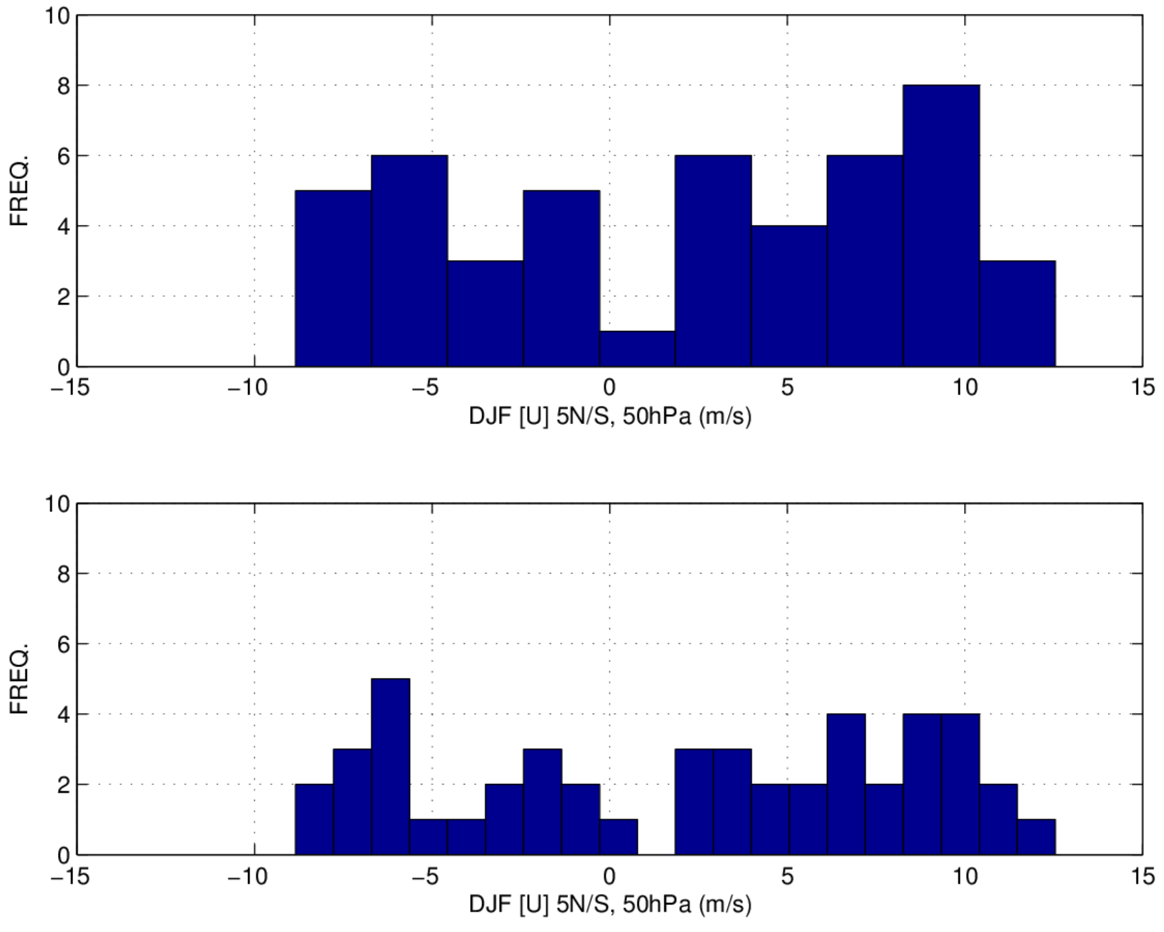
QBO index in the MRI CCM run shows a node of PDF around 0 m/s.

MRI

PDFs of DJF [U] in 5N/S, 50hPa

Nbin=10

Nbin=20

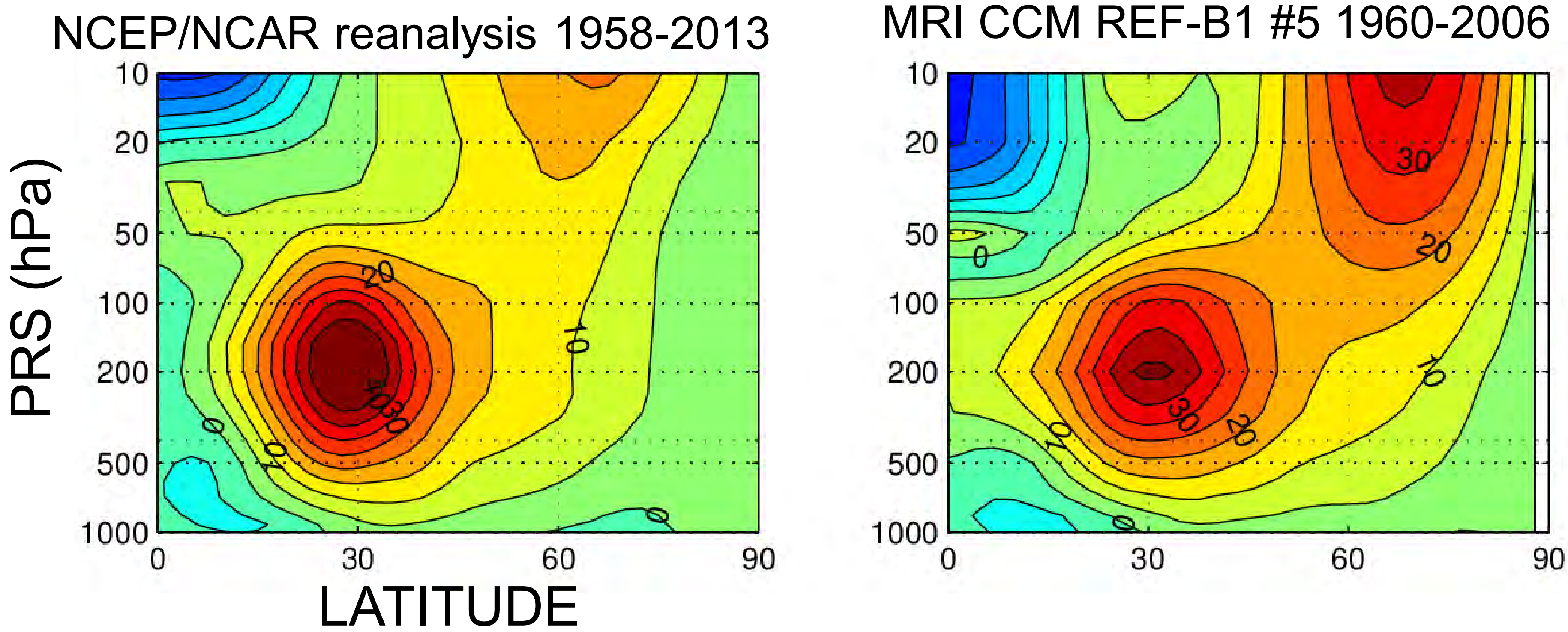


Ref.: None

MRI CCM run shows too strong polar vortex in NH winter stratosphere

MRI

DJF climatology of [U] (m/s)

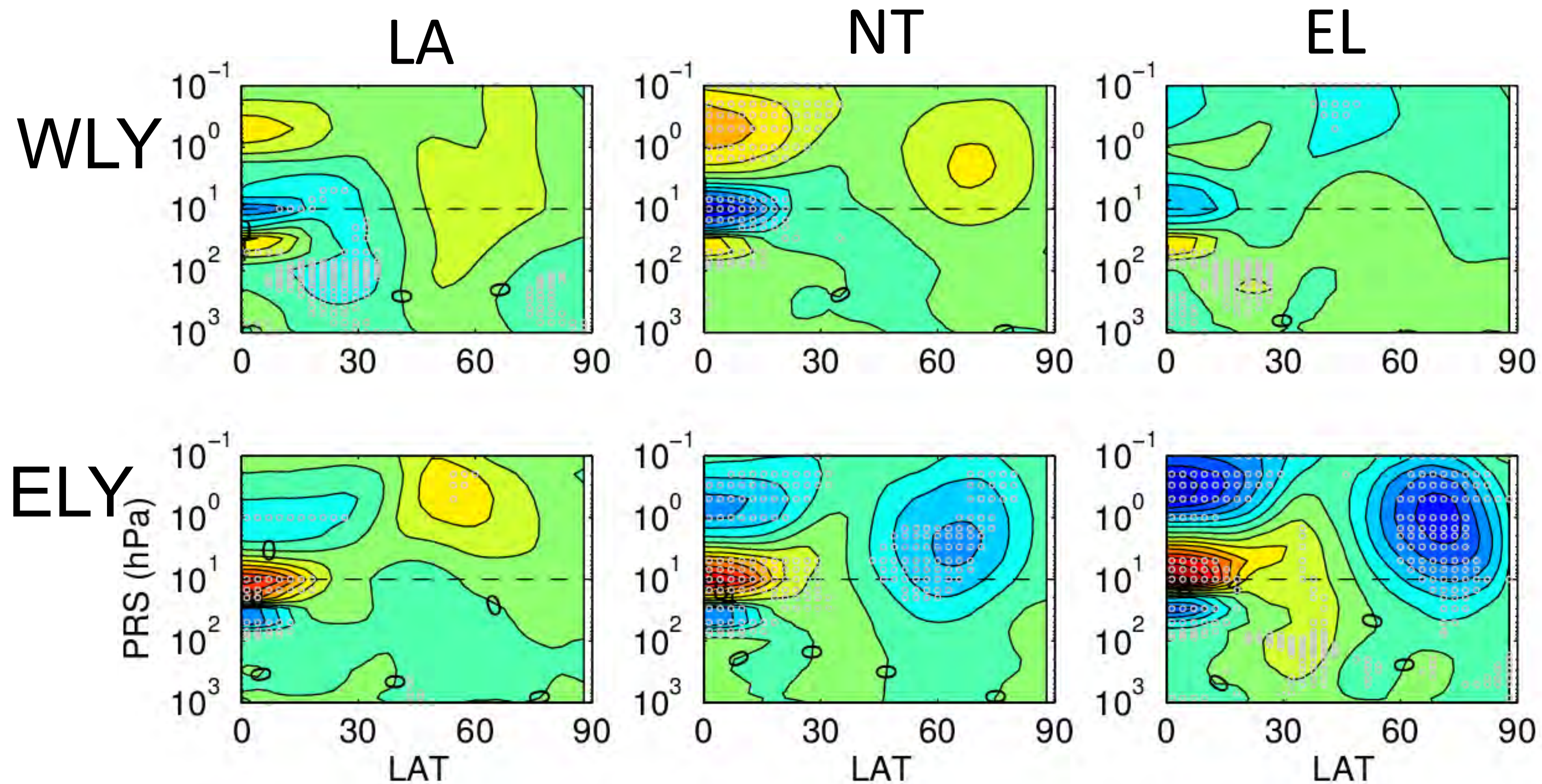


Ref.: None

MRI CCM run (REF-B1) does not reproduce mean wind changes with ENSO and QBO.

MRI CCM

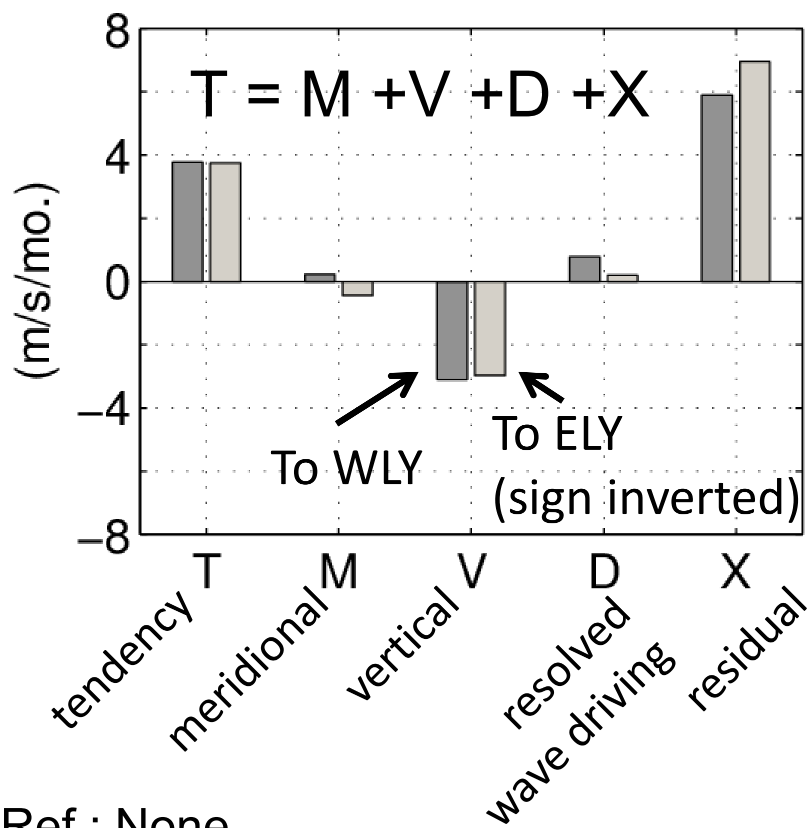
DJF [U] diffs (m/s) from climatology



Ref.: LA/EL are bottom/top 25 % of observed NINO3.4. QBO threshold is 0 m/s wind at 5N/S, 50hPa.
CI is 2 m/s. Gray dots denote statistical significance at 90 % level.

The tendencies T for the annual synchronization largely balances with X

Bar chart for TEM diagnosis in 5N/S, 50hPa when tendency is large from April to June (top/btm 30 %)



Suggest role of unresolved, small-scale waves in annual synchronization

*Poster (D) by Dr. Thomas Krismer

◇SAO
determines seasonality of QBO

◇Annual cycle of [W]res in LS
allows downward propagation
when it becomes weak

Ref.: None