QBO/Solar Modulation of the Madden-Julian Short-Term Climate Oscillation: Mechanisms and Comparisons with Models

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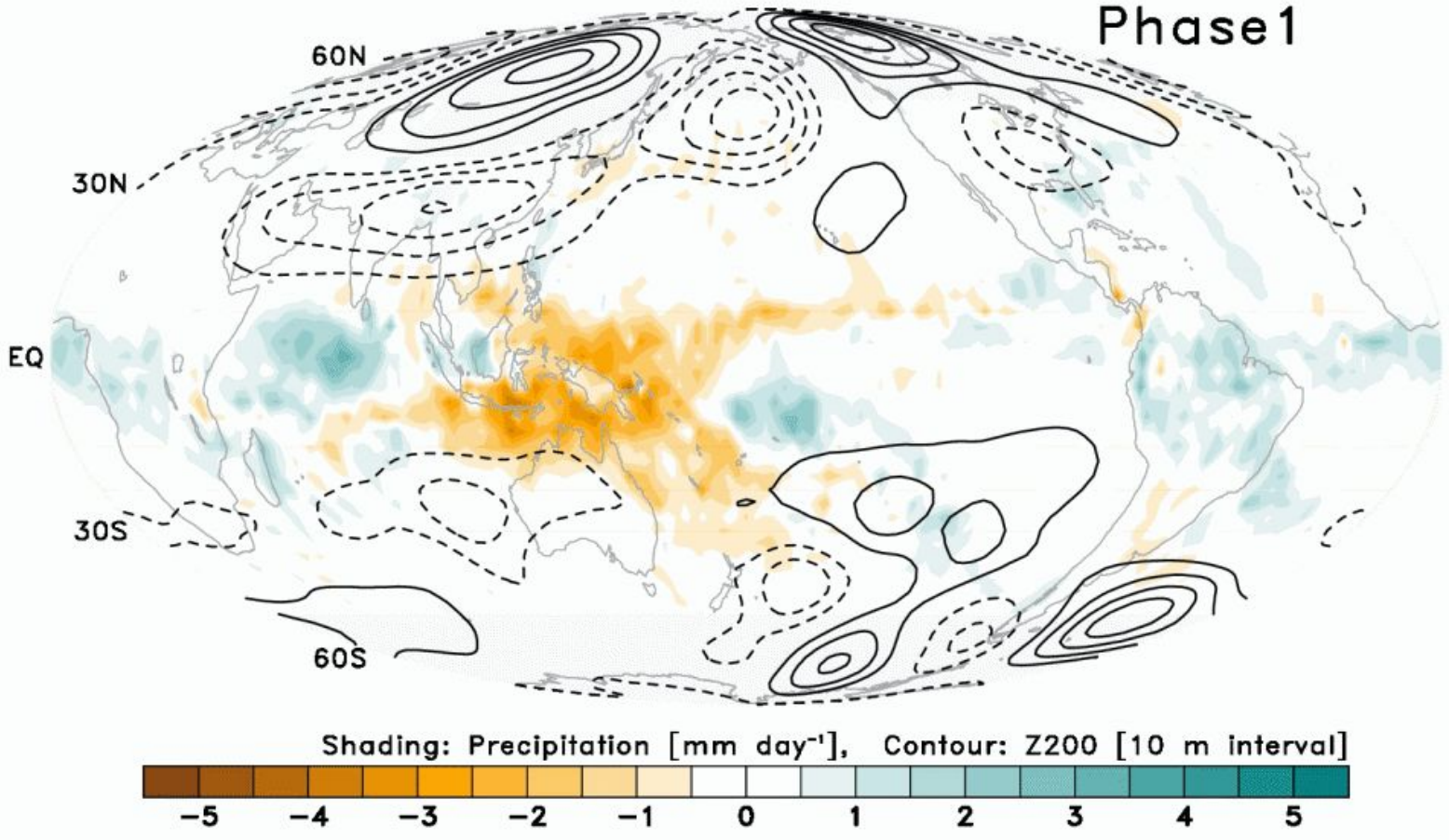
- *The Madden-Julian Oscillation (MJO), also known as the 30 to 60 day oscillation, is a an eastward propagating pattern of alternately intense and weak tropical convection and precipitation primarily in the Indo-Pacific region.*
- *It is the strongest of the subseasonal climate oscillations and has important effects on extratropical circulation and subseasonal climate, including effects on extreme rainfall in the U.S.*



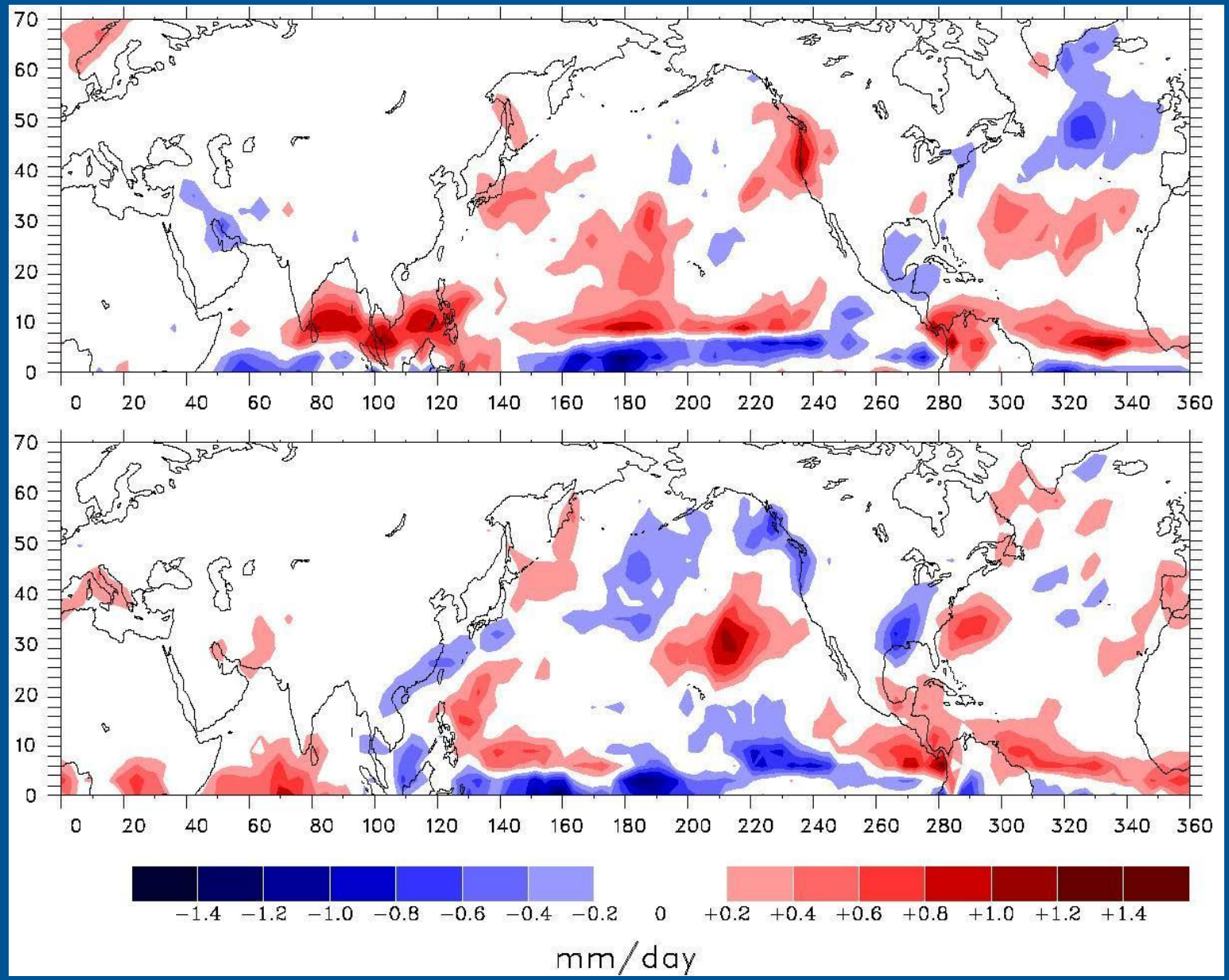
20-100-day filtered variables
Shading: Precipitation
Contour: GPH200 (solid: +, dashed: -)

Video kindly provided by
Dr. Min-Seop Ahn, Univ. of Washington

Effect on Precipitation of a Weak MJO Event (Amp. ~ 1 s.d.)

MJO Phases 3 to 6:

MJO Phases 1,2,7,8:

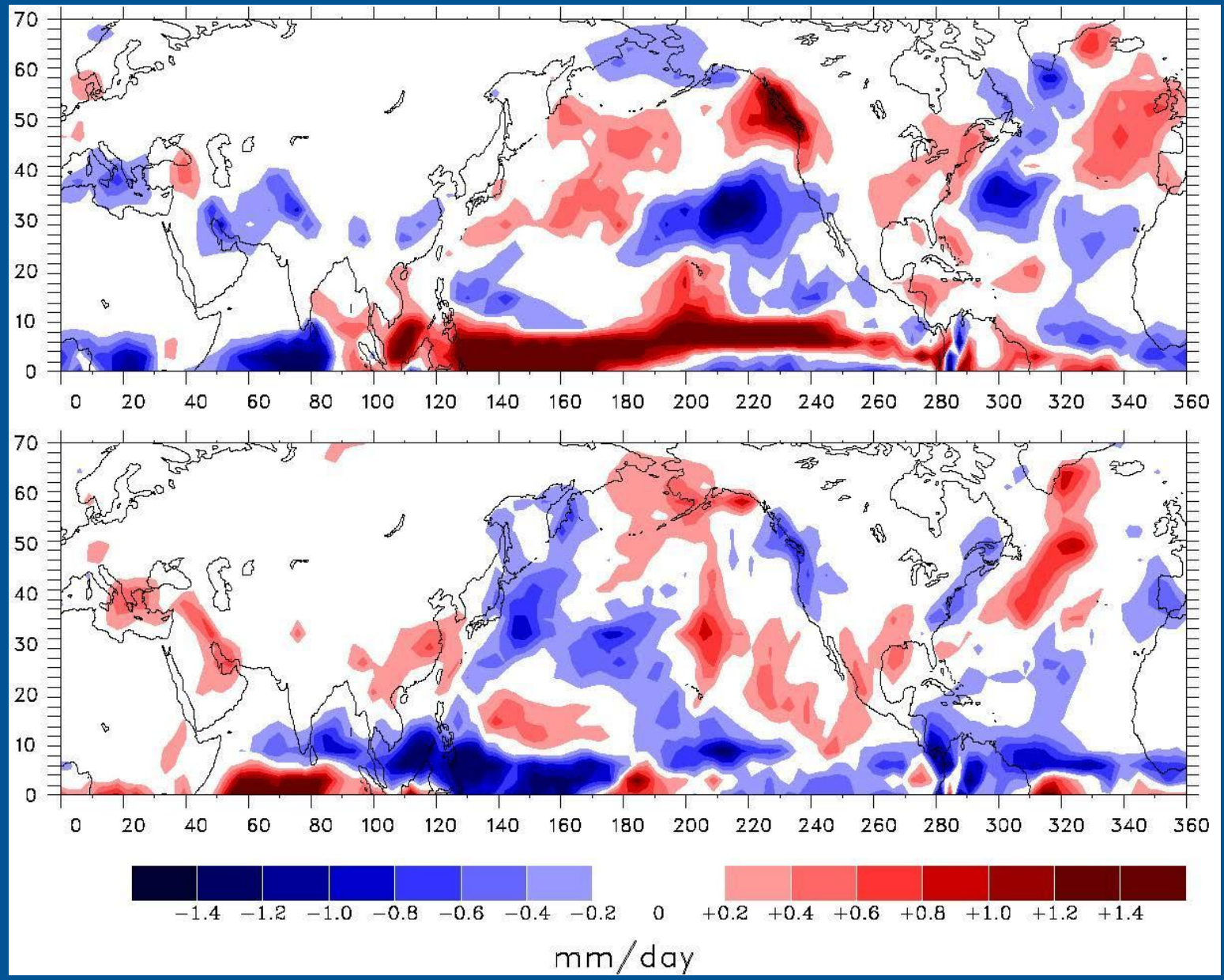


ERA Interim Reanalysis Data

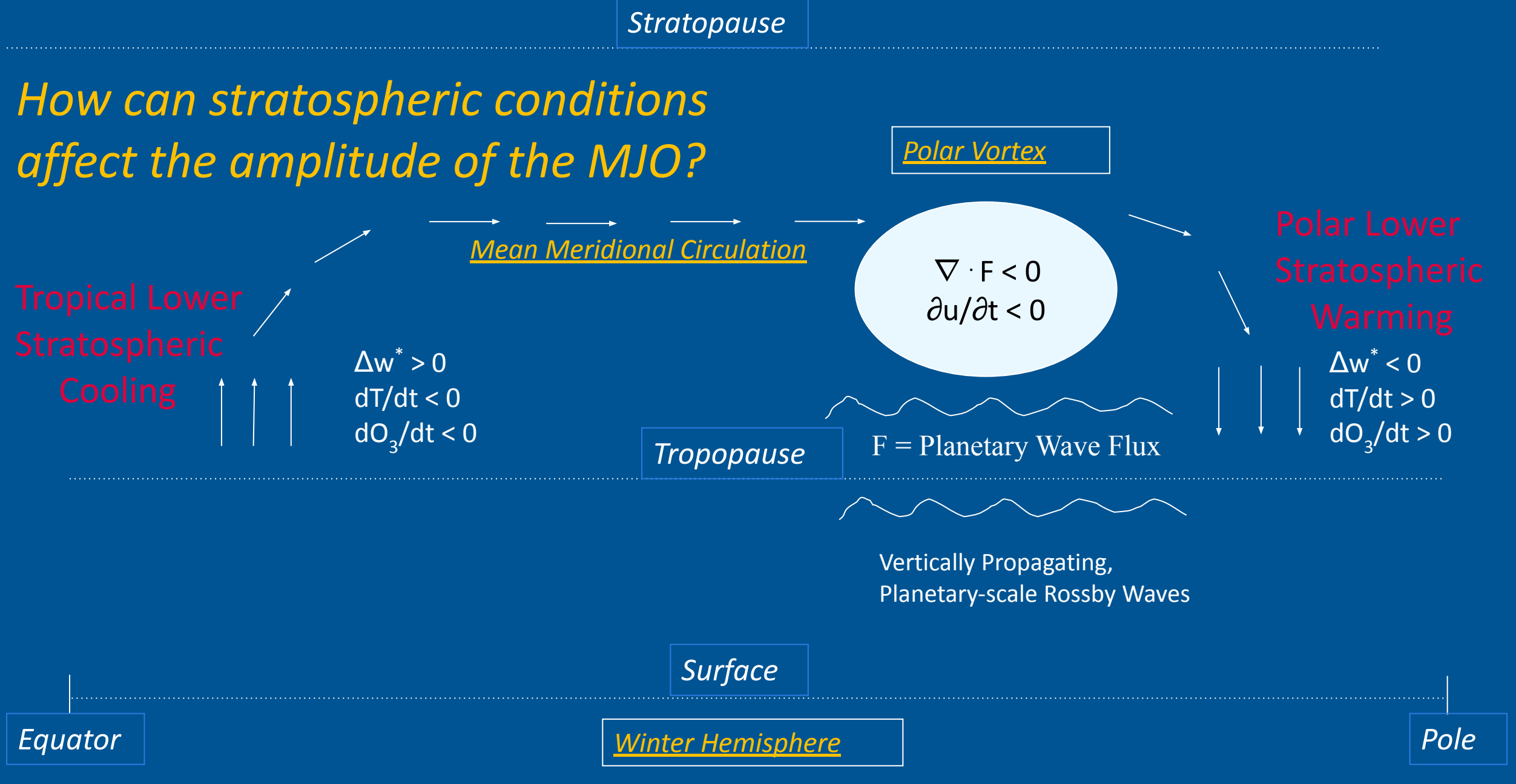
Effect on Precipitation of a Strong MJO Event (Amp. ~ 2 s.d.)

MJO Phases 3 to 6:

MJO Phases 1,2,7,8:



ERA Interim Reanalysis Data


Stratopause
How can stratospheric conditions affect the amplitude of the MJO?
Polar Vortex
Mean Meridional Circulation
Tropical Lower Stratospheric Cooling
$\Delta w^* > 0$
$dT/dt < 0$
$dO_3/dt < 0$
$\nabla \cdot F < 0$
$\partial u/\partial t < 0$
Polar Lower Stratospheric Warming
$\Delta w^* < 0$
$dT/dt > 0$
$dO_3/dt > 0$
Tropopause
F = Planetary Wave Flux
Vertically Propagating,
Planetary-scale Rossby Waves
Surface
Equator
Winter Hemisphere
Pole

Stratopause

How can stratospheric conditions affect the amplitude of the MJO?

Polar Vortex

Mean Meridional Circulation

$\nabla \cdot F < 0$
$\partial u/\partial t < 0$

Reduced Static Stability

$\Delta w^* > 0$
$dT/dt < 0$
$dO_3/dt < 0$

Polar Lower Stratospheric Warming

$\Delta w^* < 0$
$dT/dt > 0$
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Tropopause

F = Planetary Wave Flux

Increased Convection and Precipitation

Vertically Propagating, Planetary-scale Rossby Waves

Surface

Equator

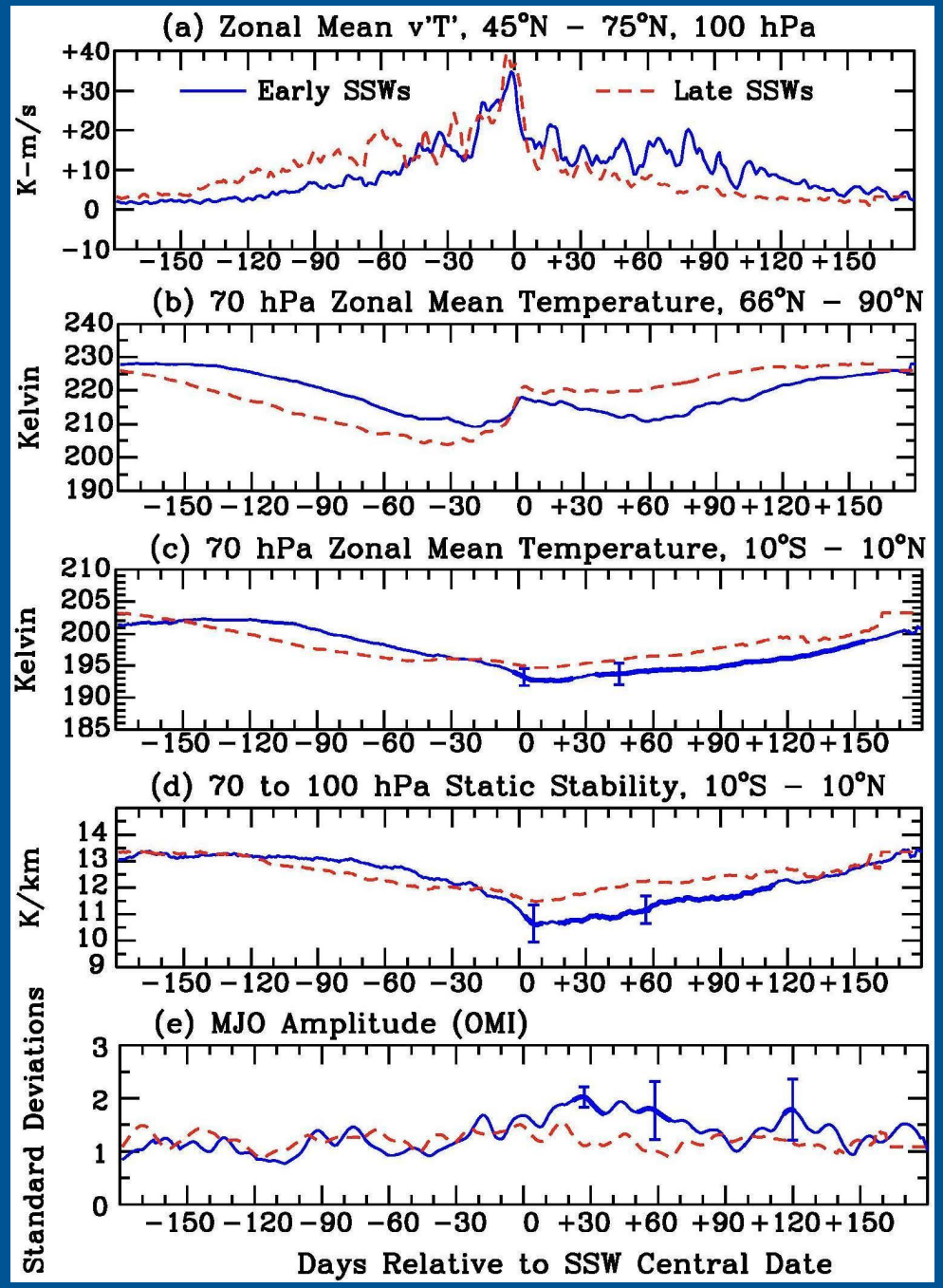
Winter Hemisphere

Pole

Is there statistically significant evidence that stratospheric conditions can influence the MJO?

In the case of large wave forcing events (e.g., those that produce sudden stratospheric warmings, SSWs) happening in late fall and early winter, the answer appears to be YES.

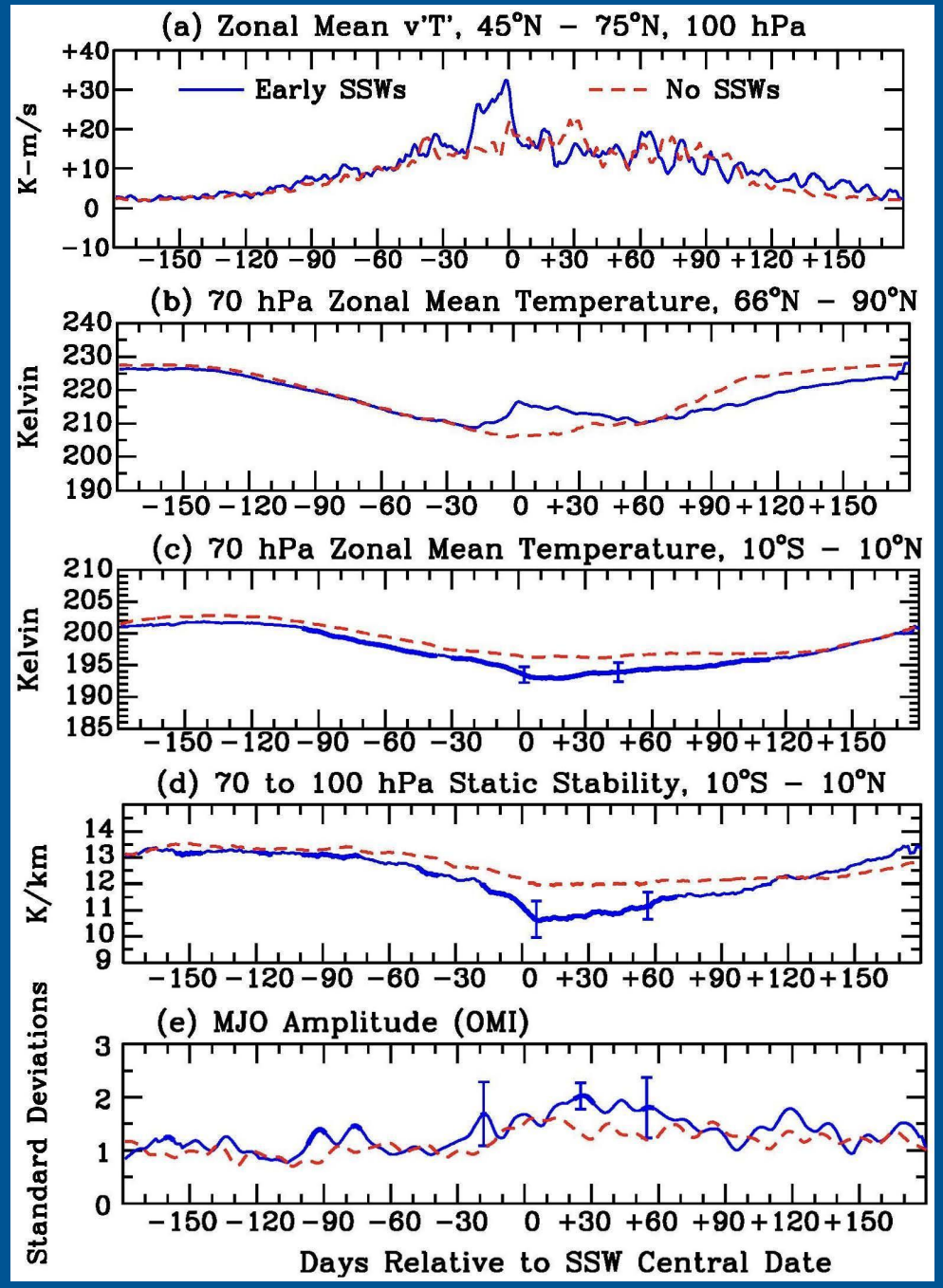
Years with early winter SSWs vs. years with late winter SSWs.



Is there statistically significant evidence that stratospheric conditions can influence the MJO?

In the case of large wave forcing events (e.g., those that produce sudden stratospheric warmings, SSWs) happening in late fall and early winter, the answer appears to be YES.

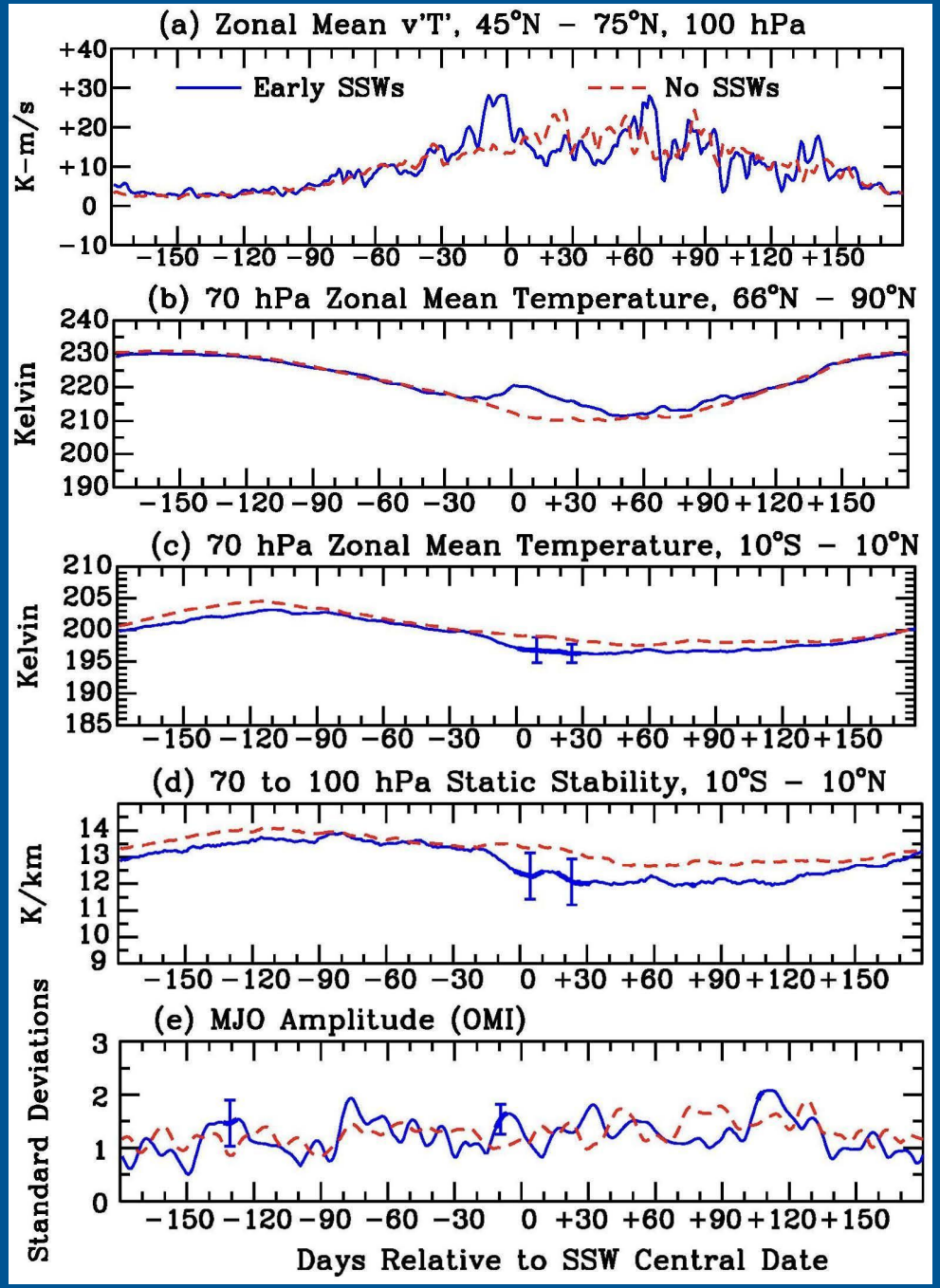
Years with early winter SSWs vs. years with no SSWs.



Are Existing Coupled Climate Models Able to Simulate Stratospheric Influences on the MJO?

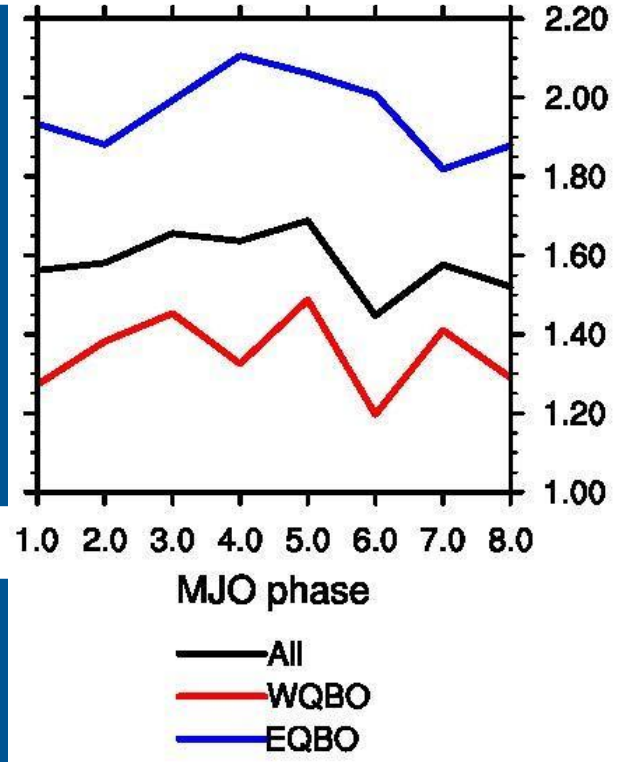
<u>Probably not yet</u>. We have found one model so far that comes close (MRI-ESM2-0). It simulates a reduction of static stability after early winter SSWs. However, the climatological tropical static stability is too high compared to observations so there is no effect on MJO amplitude.

<u>MRI model years with early winter SSWs vs. model years with no SSWs</u>.

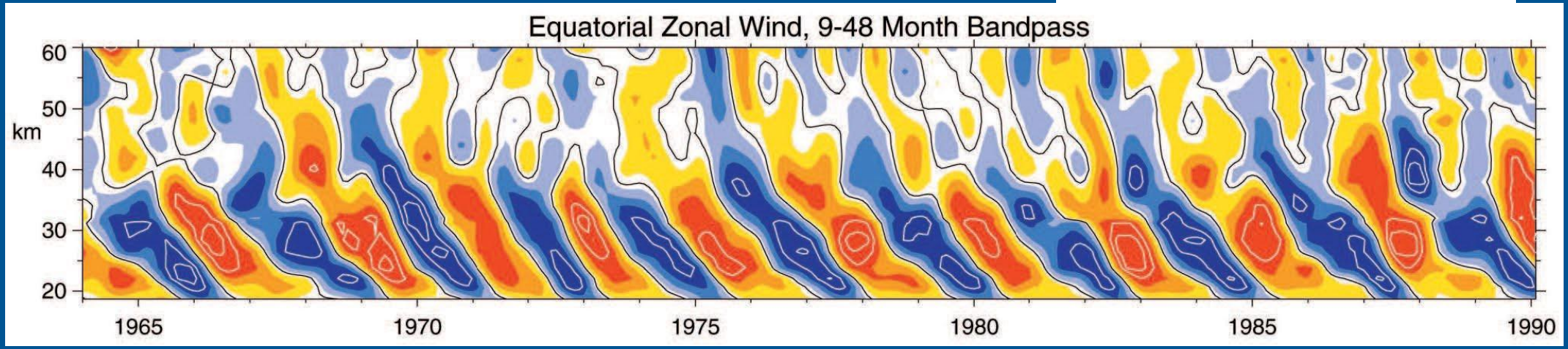


Beginning about 6 years ago, it was realized that the amplitude and occurrence rate of MJO events differs significantly depending on the phase of the stratospheric quasi-biennial oscillation during boreal winter (DJF).

MJO Amplitude, Standard Deviations:



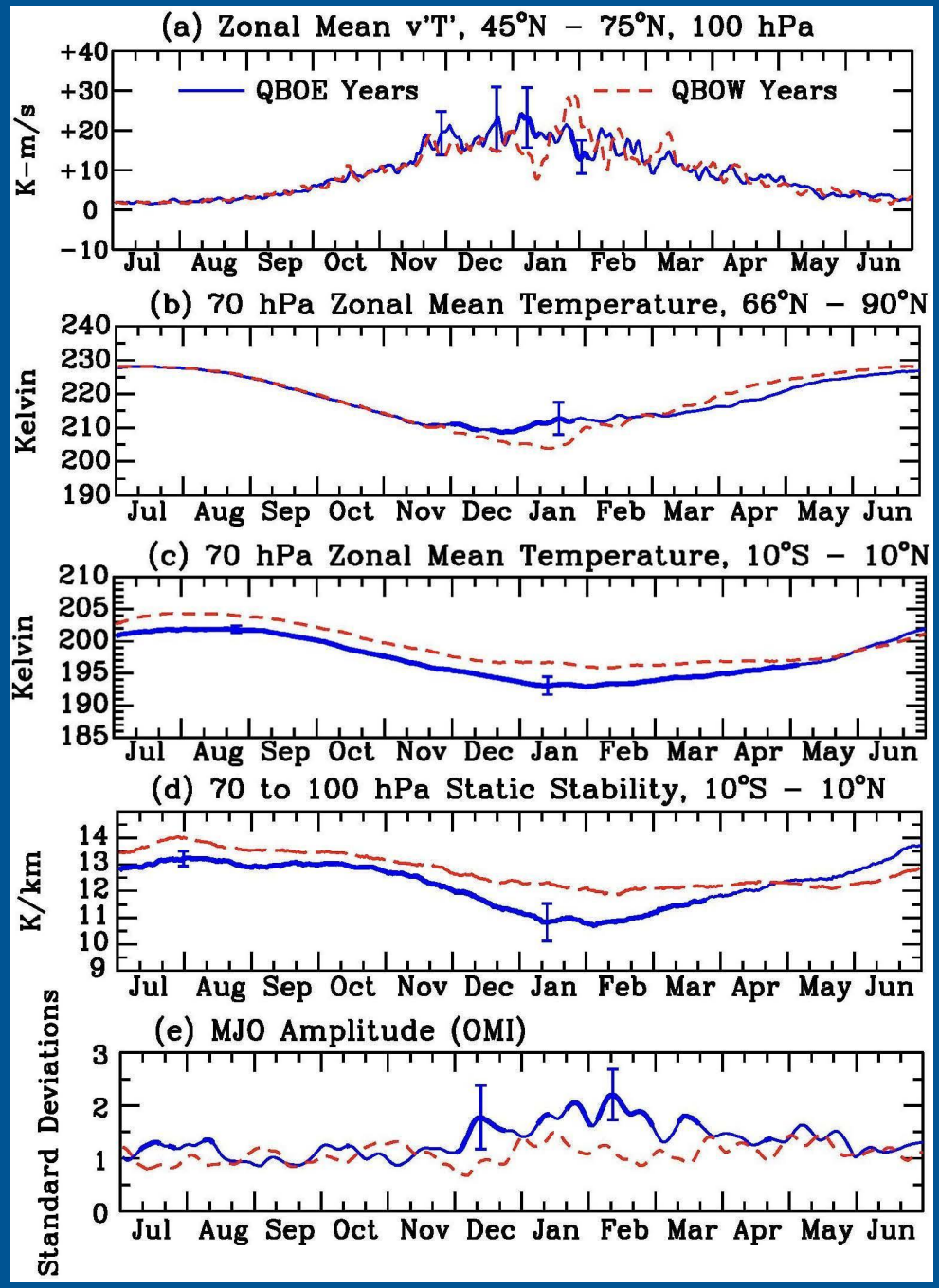
Yoo and Son, GRL, 2016:



Credit: Baldwin et al. 2001

Is there statistically significant evidence that stratospheric conditions can influence the MJO?

In the case of the QBO, the answer appears to be YES. Note the larger upward wave fluxes (a) in early winter during QBOE.



QBOE years vs. QBOW years

Hypothesized Mechanism:

Stratopause

Holton & Tan, 1980

Poleward Displacement of the Zero Wind Line Produces Enhanced Poleward Wave Propagation

QBOE:

$\bar{u} < 0$

$\bar{u} = 0$

Mean Meridional Circulation

Polar Vortex

$\nabla \cdot F > 0$

$\partial u/\partial t > 0$

Poleward Strengthening of the Mean Meridional Circulation

$\Delta w^* < 0$

$dT/dt > 0$

$dO_3/dt > 0$

Reduced Static Stability

$\Delta w^* > 0$

$dT/dt < 0$

$dO_3/dt < 0$

Tropopause

F = Planetary Wave Flux

Vertically Propagating, Planetary-scale Rossby Waves

Increased Convection and Precipitation

Surface

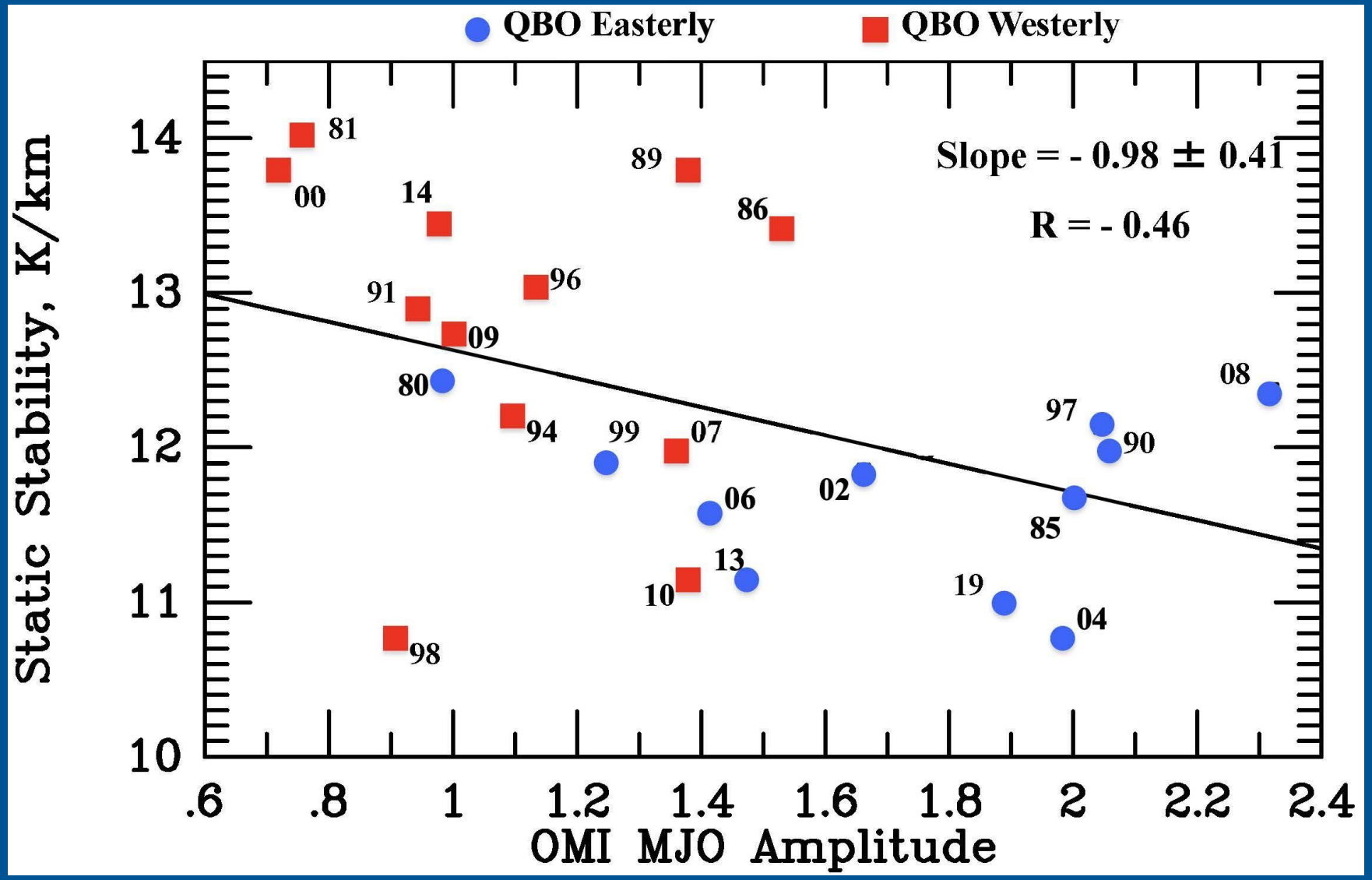
Equator

Late Fall and Early Winter

Pole

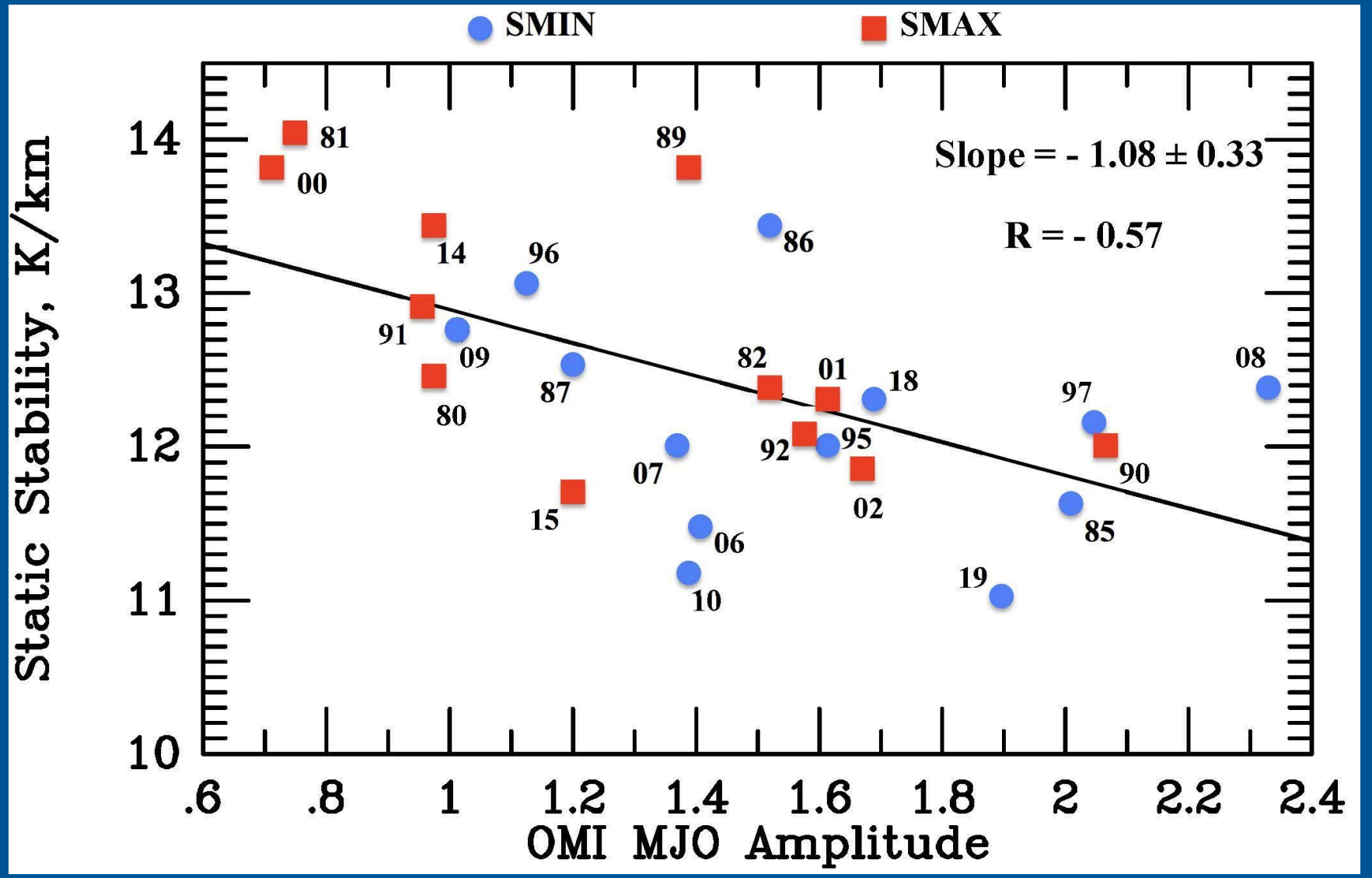
Tropical Lower Stratospheric Static Stability vs. MJO Amplitude (DJF):

QBOE and QBOW Winters



Tropical Lower Stratospheric Static Stability vs. MJO Amplitude (DJF):

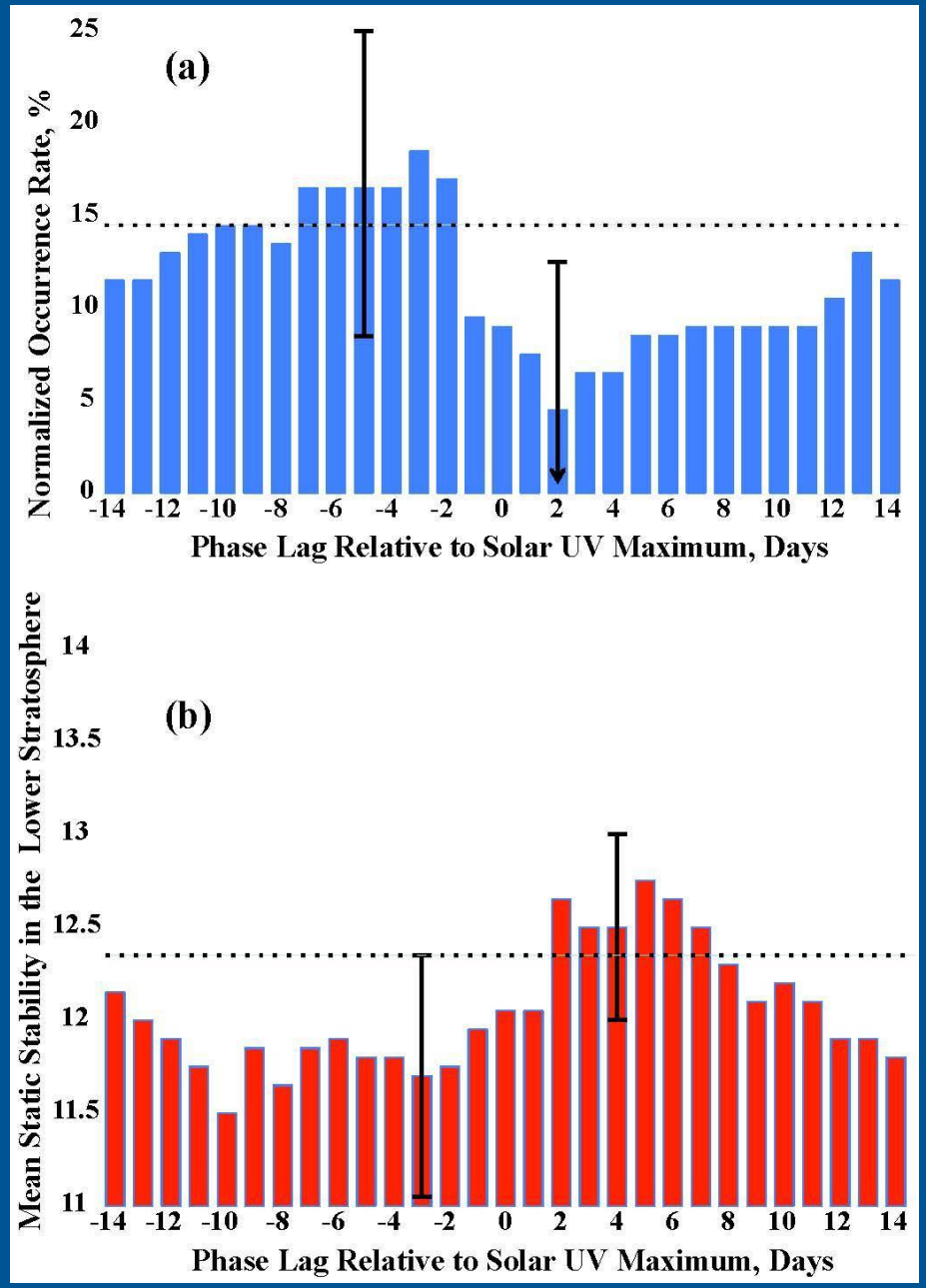
SMIN and SMAX Winters



Calculate Normalized Occurrence Rates of MJO events with amplitudes > 2.0 versus phase lag relative to 64-68 solar UV peaks. Only days in DJFMAM are considered.

Also, calculate corresponding mean static stabilities in the lower stratosphere (70 to 100 mb), averaged over the warm pool region where MJO amplitudes are largest.

A Significant Response



Hypothesized Mechanism:

Kodera & Kuroda, 2002

Direct Effects of Solar UV Increases On Ozone and Radiative Heating in the Tropical Upper Stratosphere

Positive Perturbation of Zonal Wind; Indirect Effects on Wave Absorption at Lower levels in the Extratropics

$\nabla \cdot F > 0$

$\partial u/\partial t > 0$

$\Delta w^* > 0$

F = Planetary Wave Flux

Vertically Propagating, Planetary-scale Rossby Waves

Increased Static Stability

$\Delta w^* < 0$

$dT/dt > 0$

$dO_3/dt > 0$

Reduced Convection and Latent Heat Release

Stratopause

Tropopause

Surface

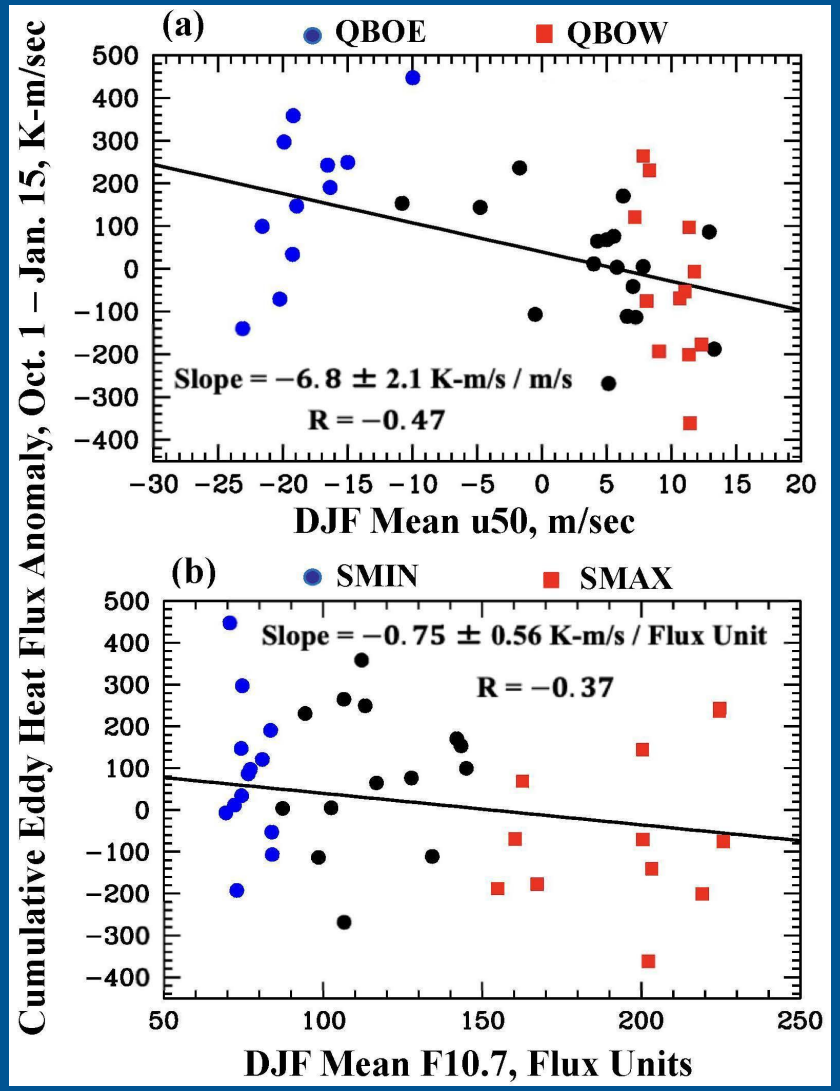
Equator

Winter Hemisphere

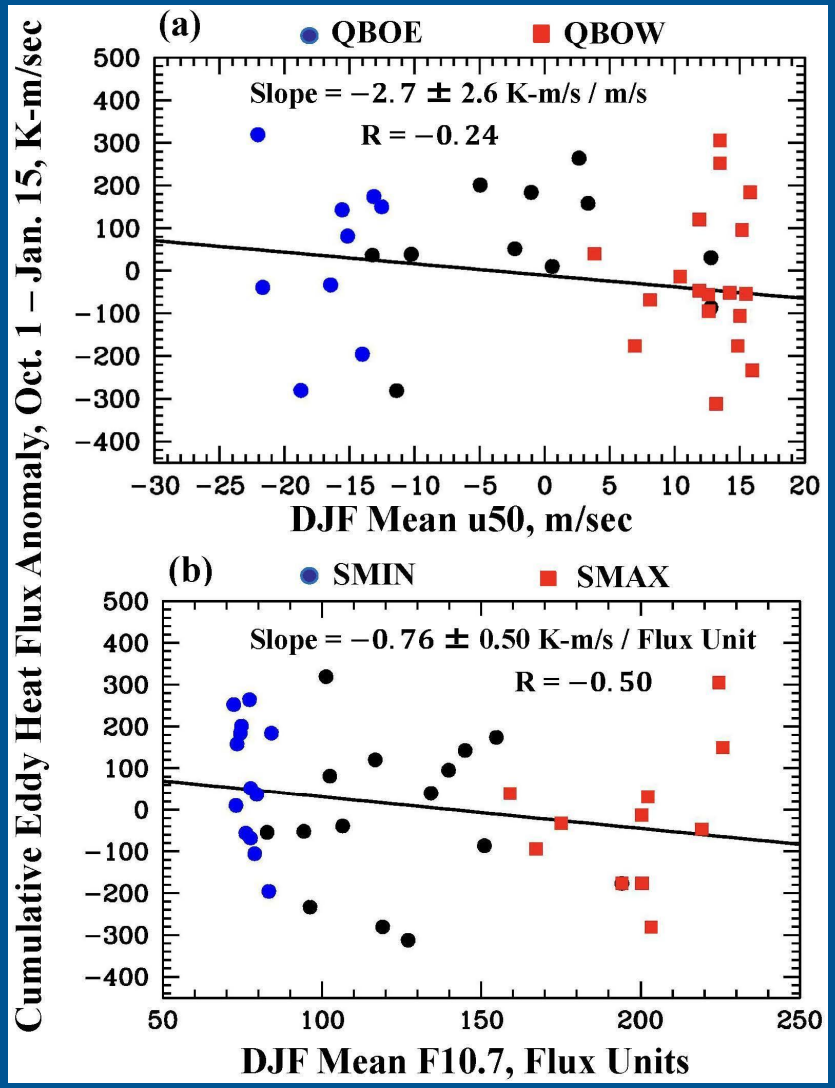
Pole

How well does the MRI model simulate the observed QBO and 11-yr solar influences on extratropical wave forcing in late fall / early winter?

ERA5 Data, 1979-2019



MRI CMIP6 Simulation, 1961-2000



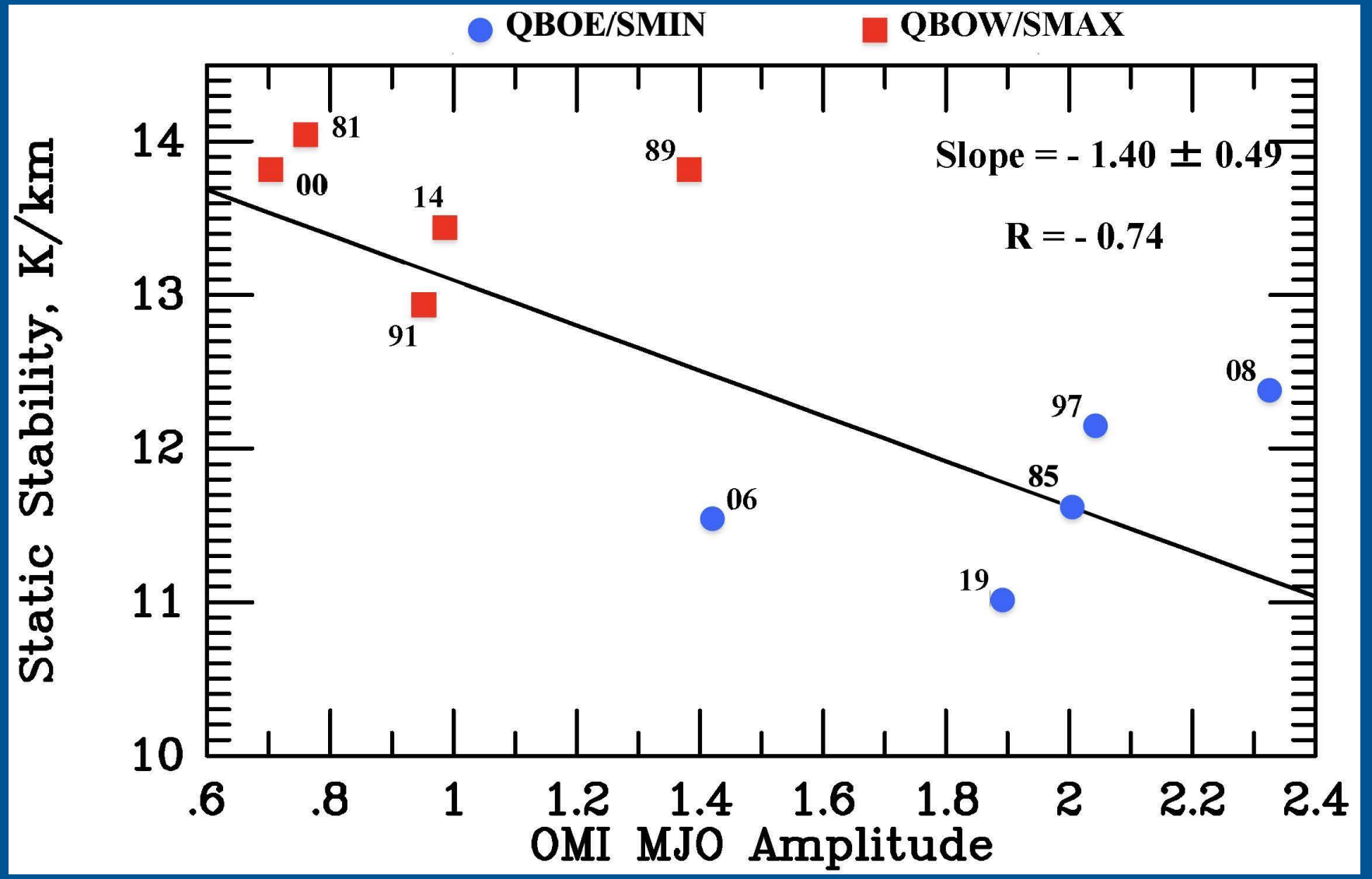
Conclusions

- Sudden stratospheric warmings (SSWs) in late fall and early winter (prior to mid-January) produce a statistically significant, lagged increase in MJO amplitude beginning about 20 days after the central date of the SSW.
- There is evidence for a secondary influence of the 11-year solar cycle (in addition to an influence of the stratospheric QBO) on the occurrence rate of relatively strong MJO events.
- At least one coupled model participating in CMIP6 (MRI-ESM2-0) simulates well the observed QBO and 11-yr solar influences on early winter wave forcing and comes close to simulating the early winter SSW effect on MJO amplitude. With some model improvements, it could potentially simulate the QBO/Solar-MJO connection.

Extra Slides

Tropical Lower Stratospheric Static Stability vs. MJO Amplitude (DJF):

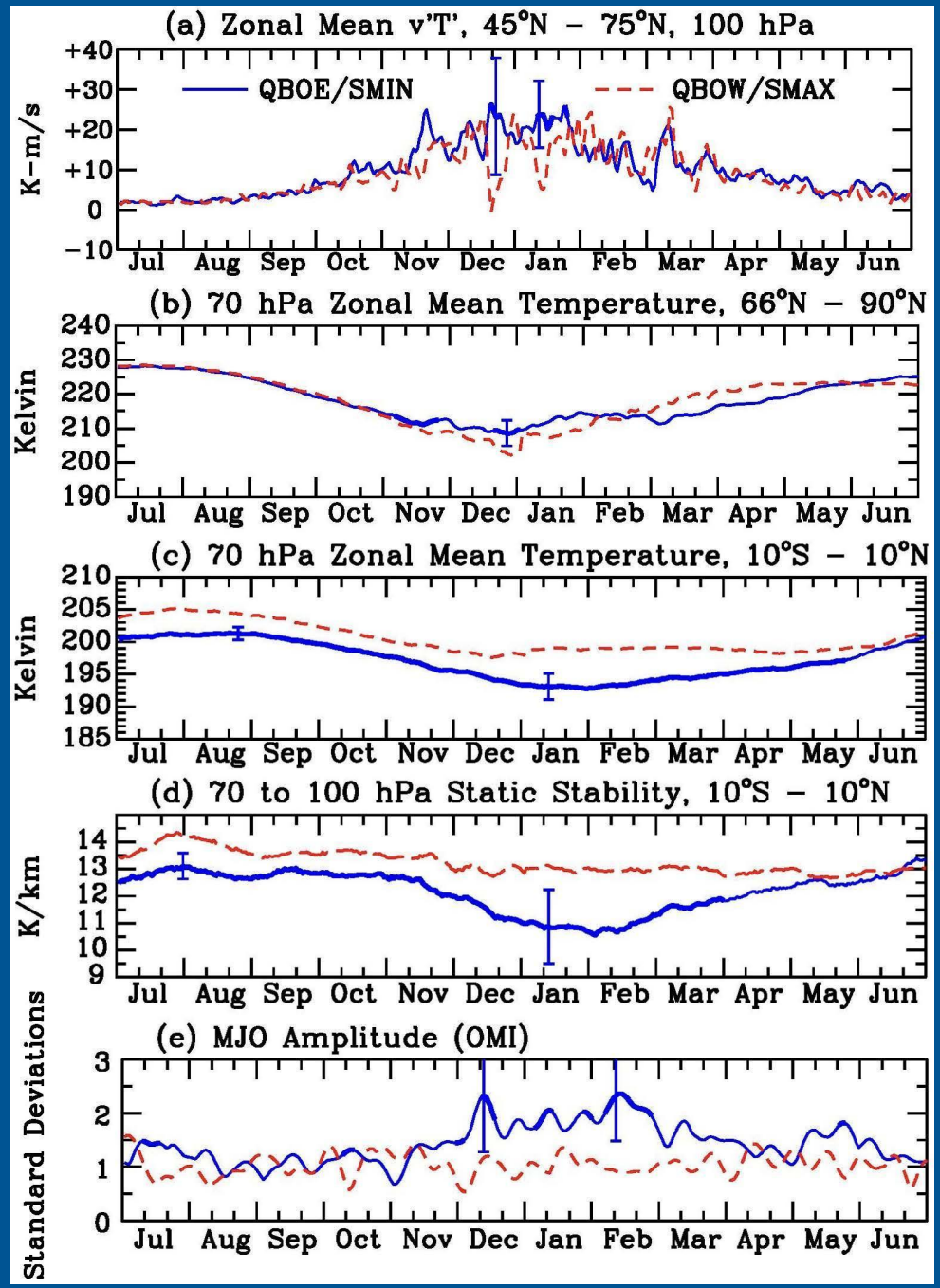
QBOE/SMIN & QBOW/SMAX Winters



Is there statistically significant evidence that stratospheric conditions can influence the MJO?

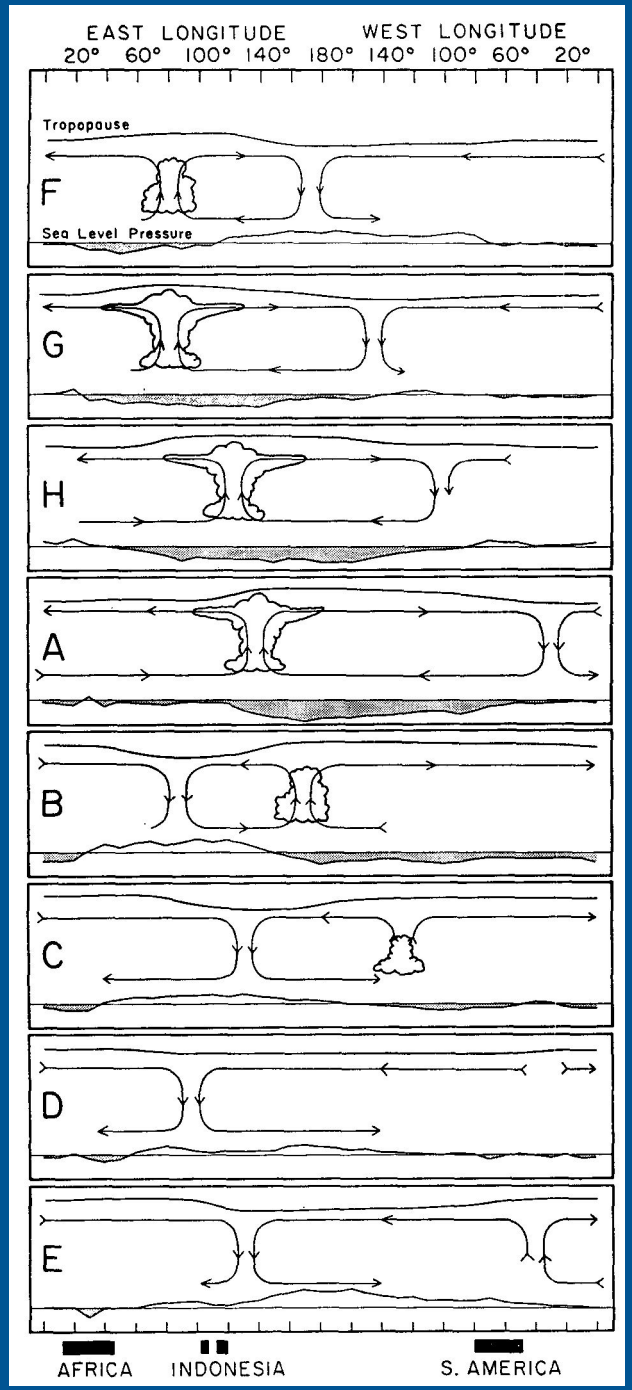
In the case of years when the QBO and solar cycle are working together, the answer appears to be YES.

QBOE/SMIN years vs. QBOW/SMAX years



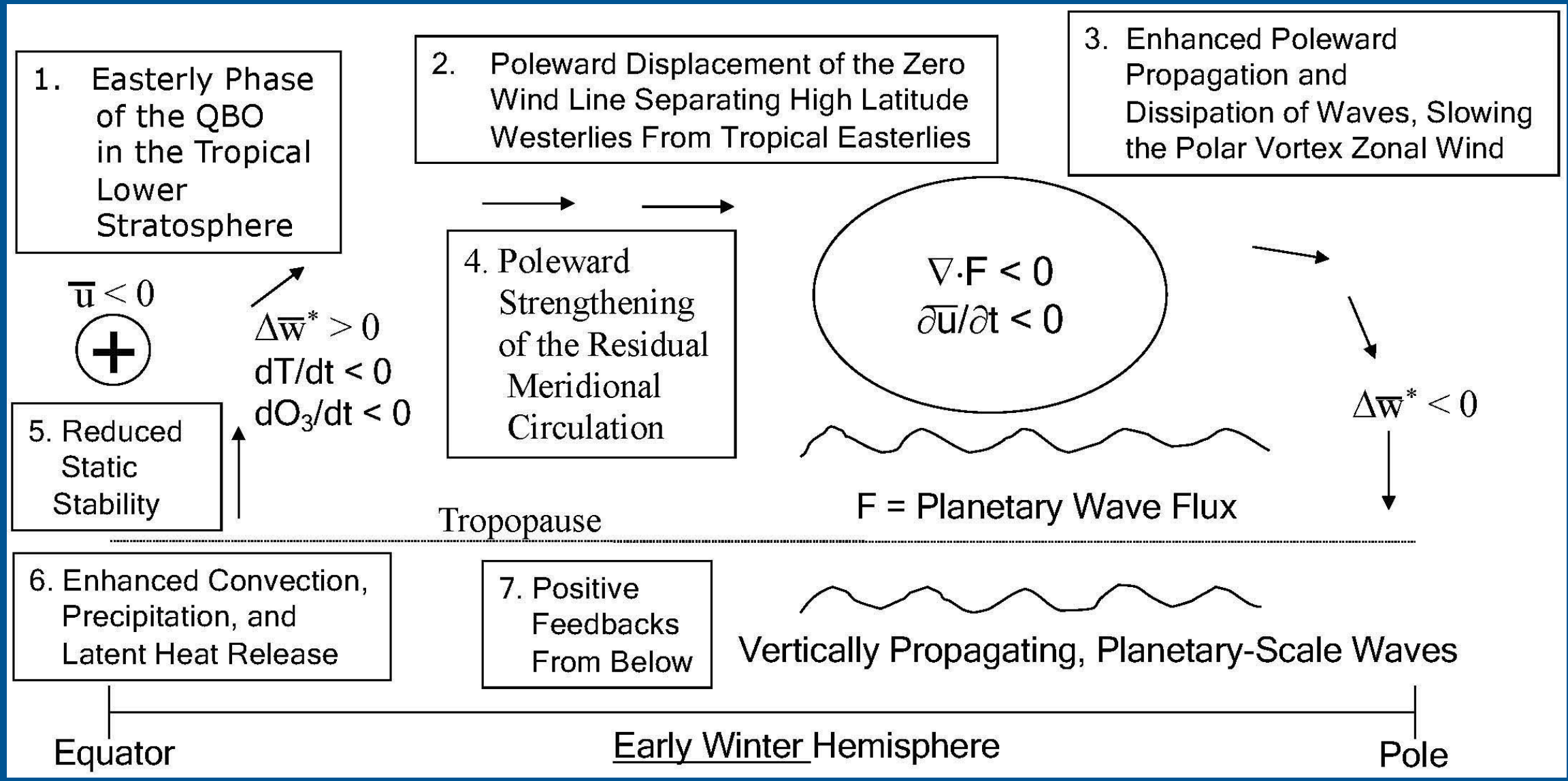
Why is MJO Convection Especially Sensitive to Conditions in the Tropical Lower Stratosphere?

Unlike normal tropical convection, the MJO extends vertically into the uppermost troposphere so it is possible that conditions at its upper boundary can affect its eastward propagation and intensity. An MJO event can potentially be amplified by favorable conditions (e.g., reduced static stability) in the lowermost stratosphere.

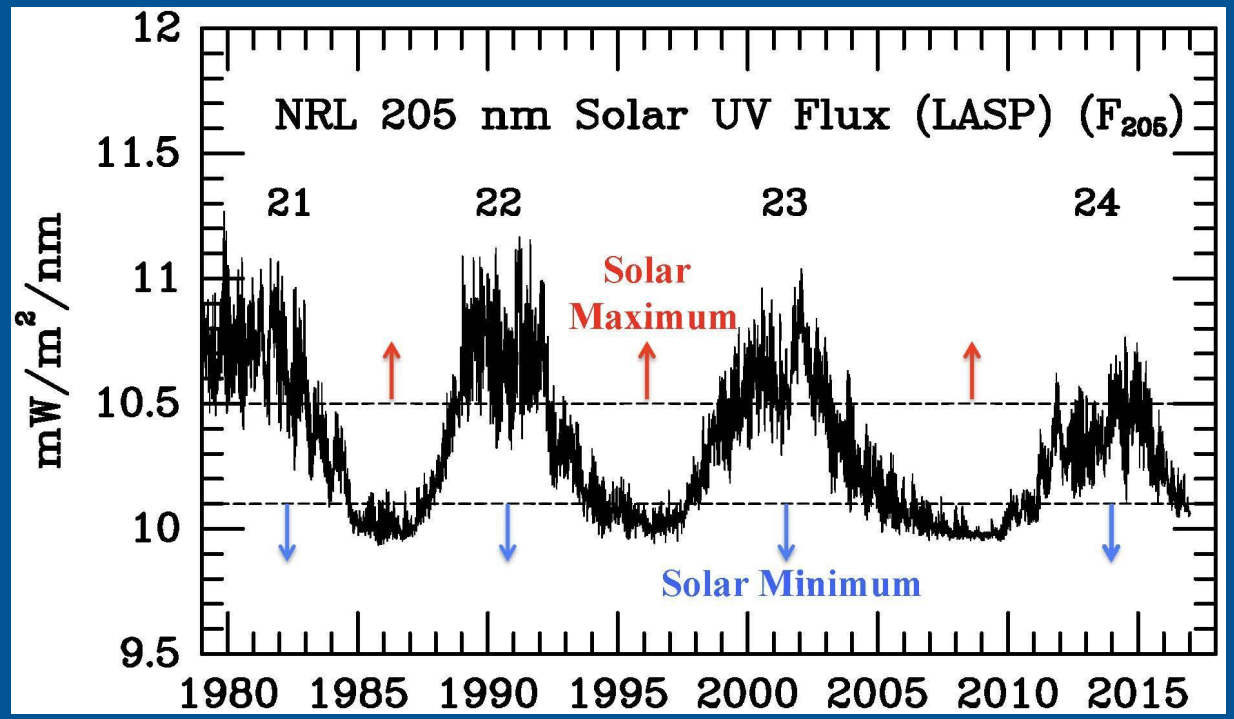


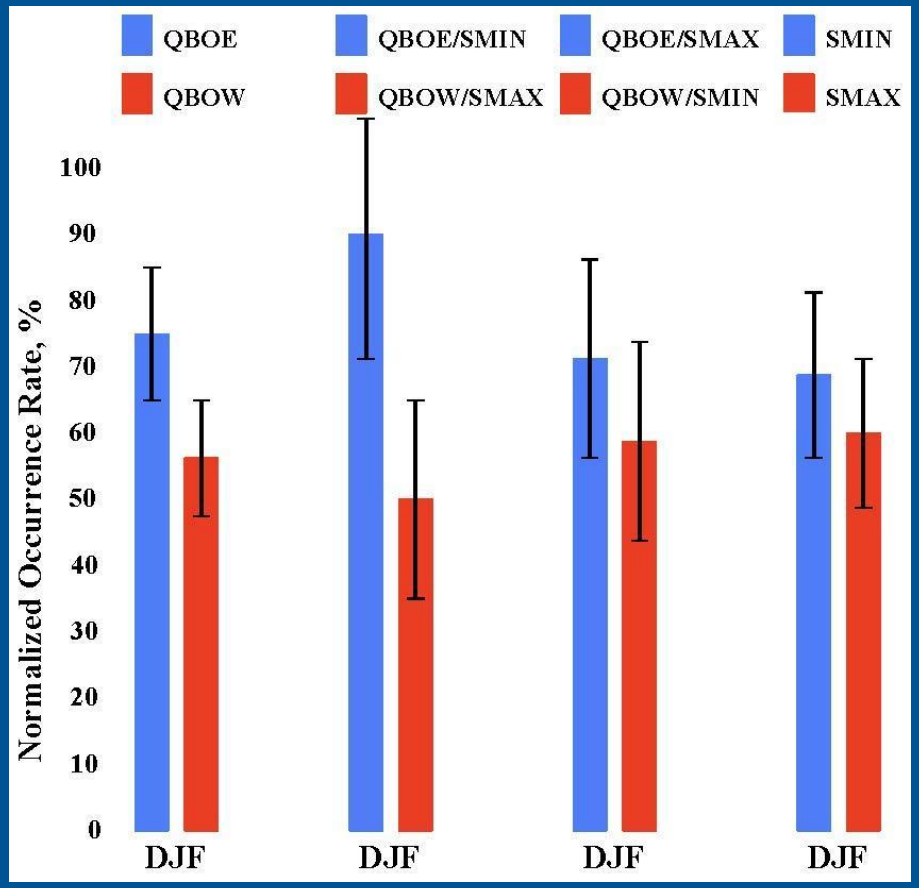
Credit: Madden & Julian, 1972

How does the Stratospheric QBO modulate the MJO?



A similar but less statistically significant dependence of the amplitude and occurrence rate of MJO events on the phase of the 11-yr solar cycle was also found.



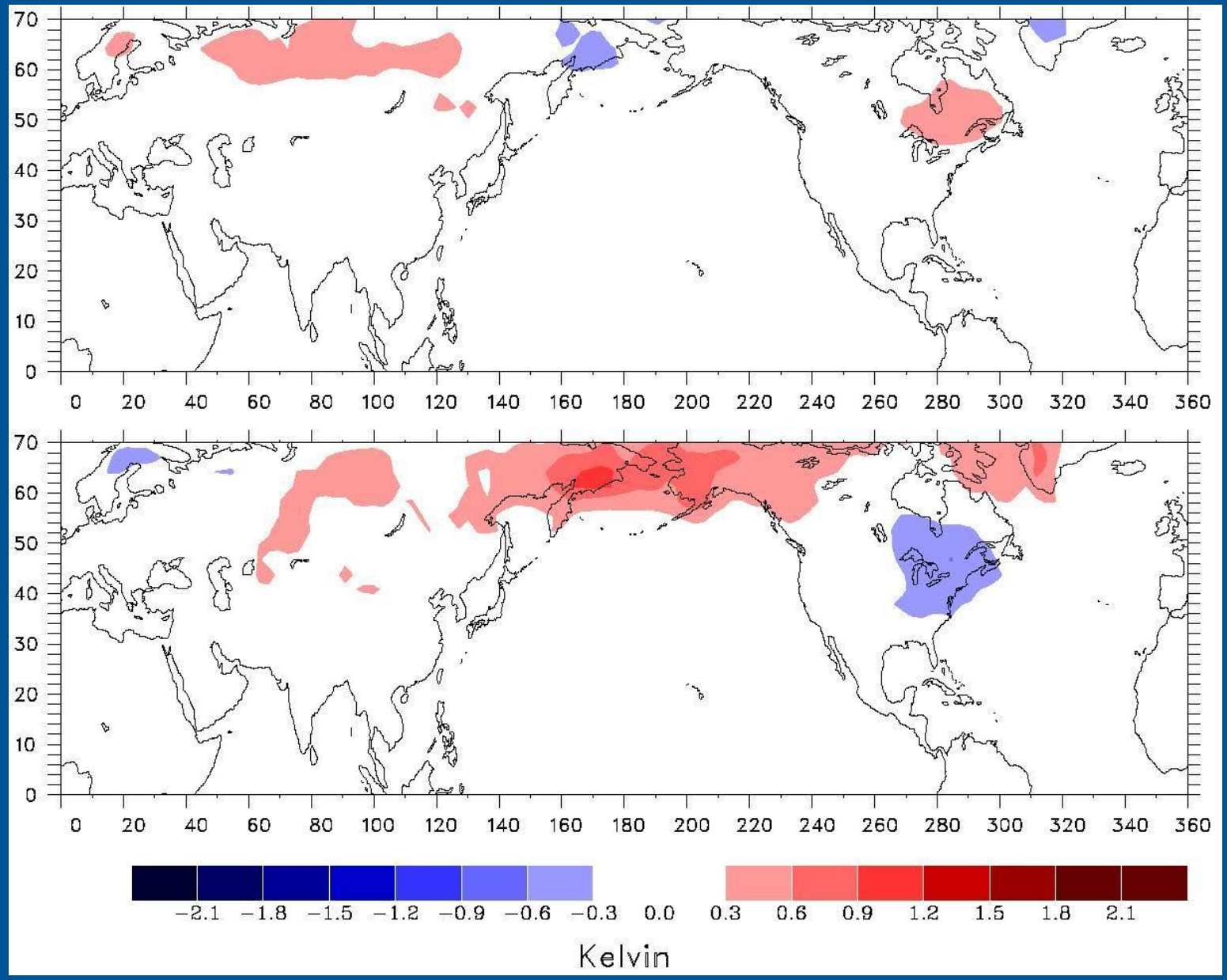


Hood, GRL, 2016:

Effect on Air Temp. of a Weak MJO Event (Amp. ~ 1 s.d.)

MJO Phases 3 to 6:

MJO Phases 1,2,7,8:

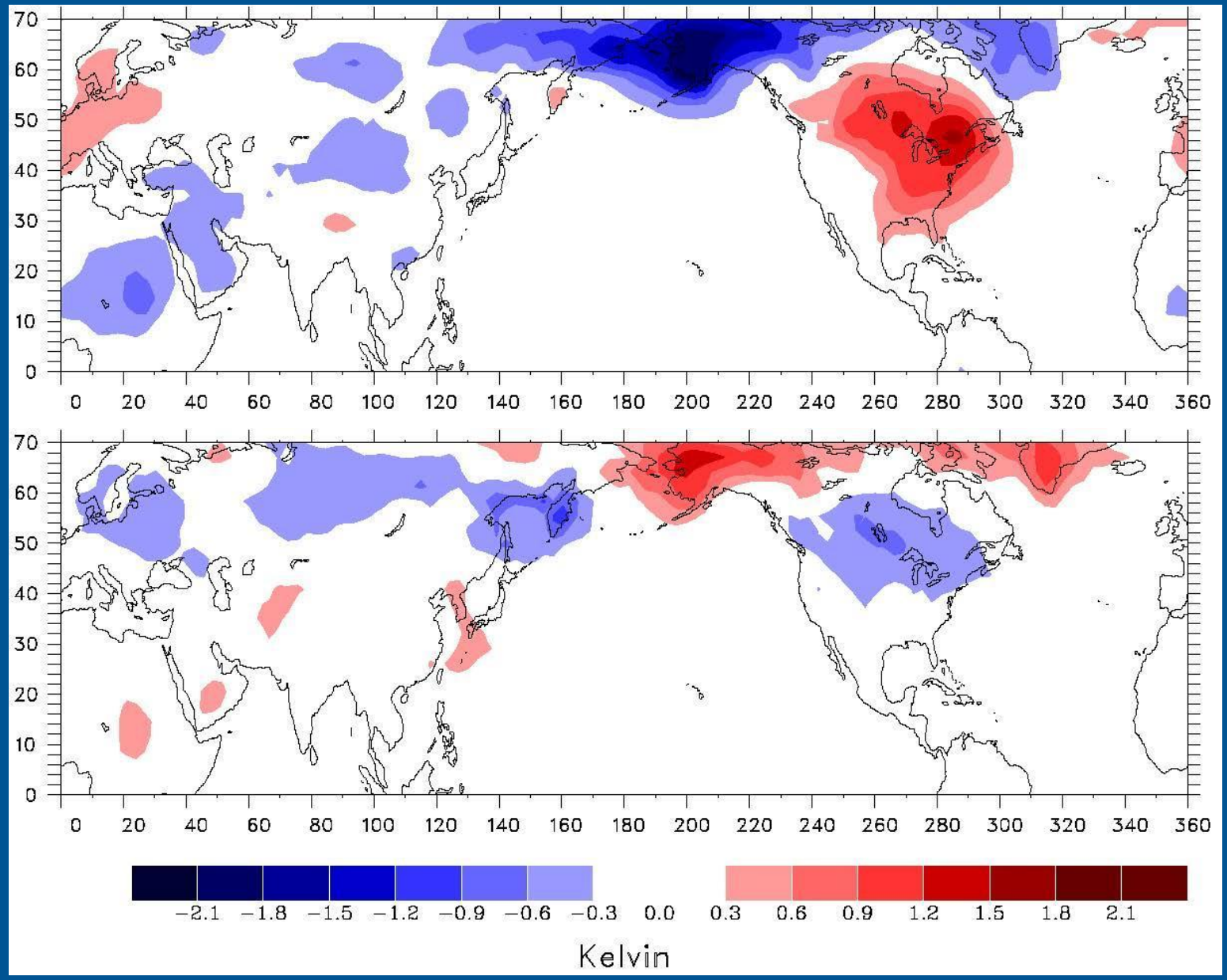


ERA Interim Reanalysis Data

Effect on Air Temp. of a Strong MJO Event (Amp. ~ 2 s.d.)

MJO Phases 3 to 6:

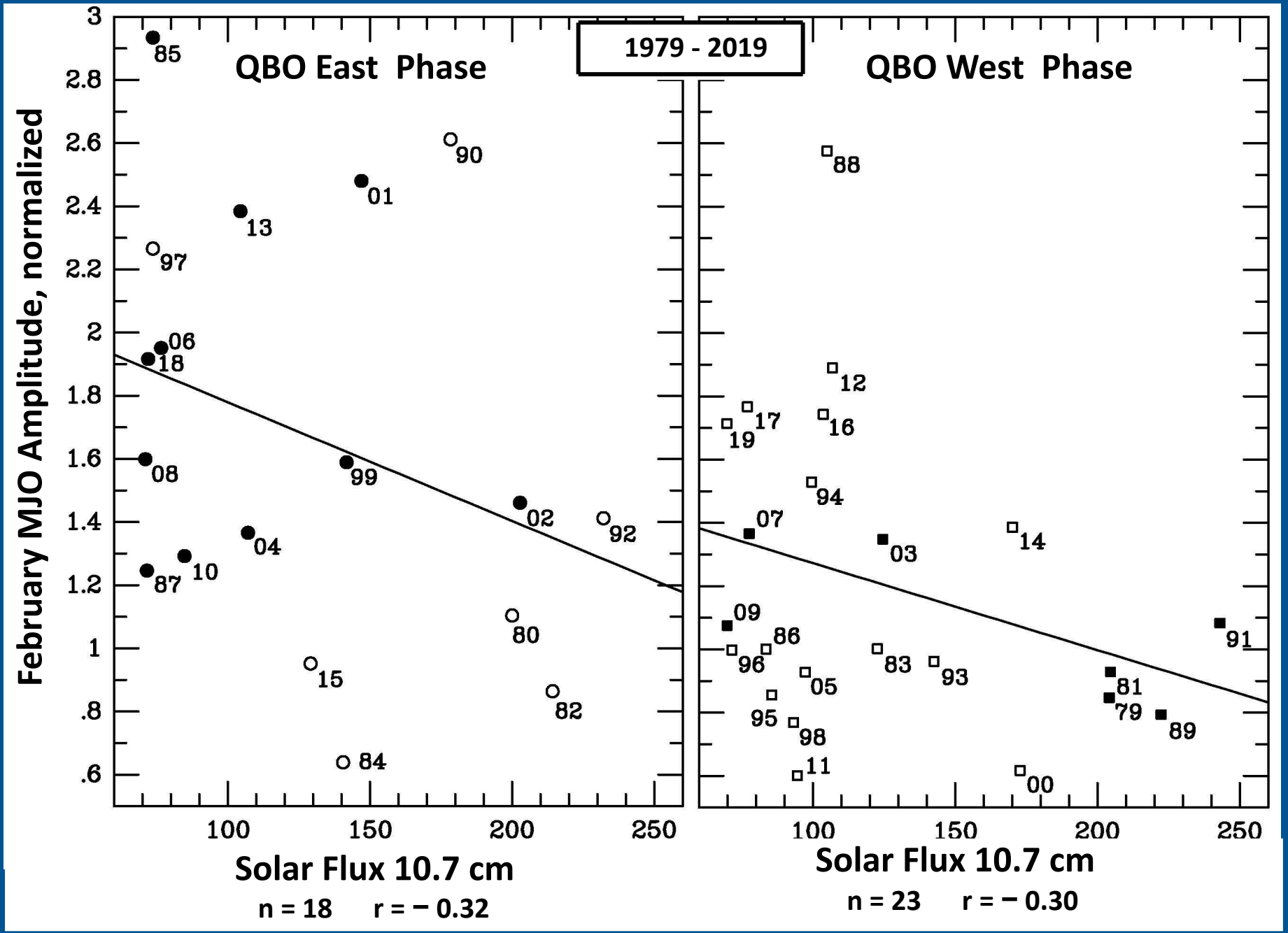
MJO Phases 1,2,7,8:



ERA Interim Reanalysis Data

Solar cycle dependence of the QBO modulation of the MJO in <u>February</u>; solid symbols indicate major midwinter warmings

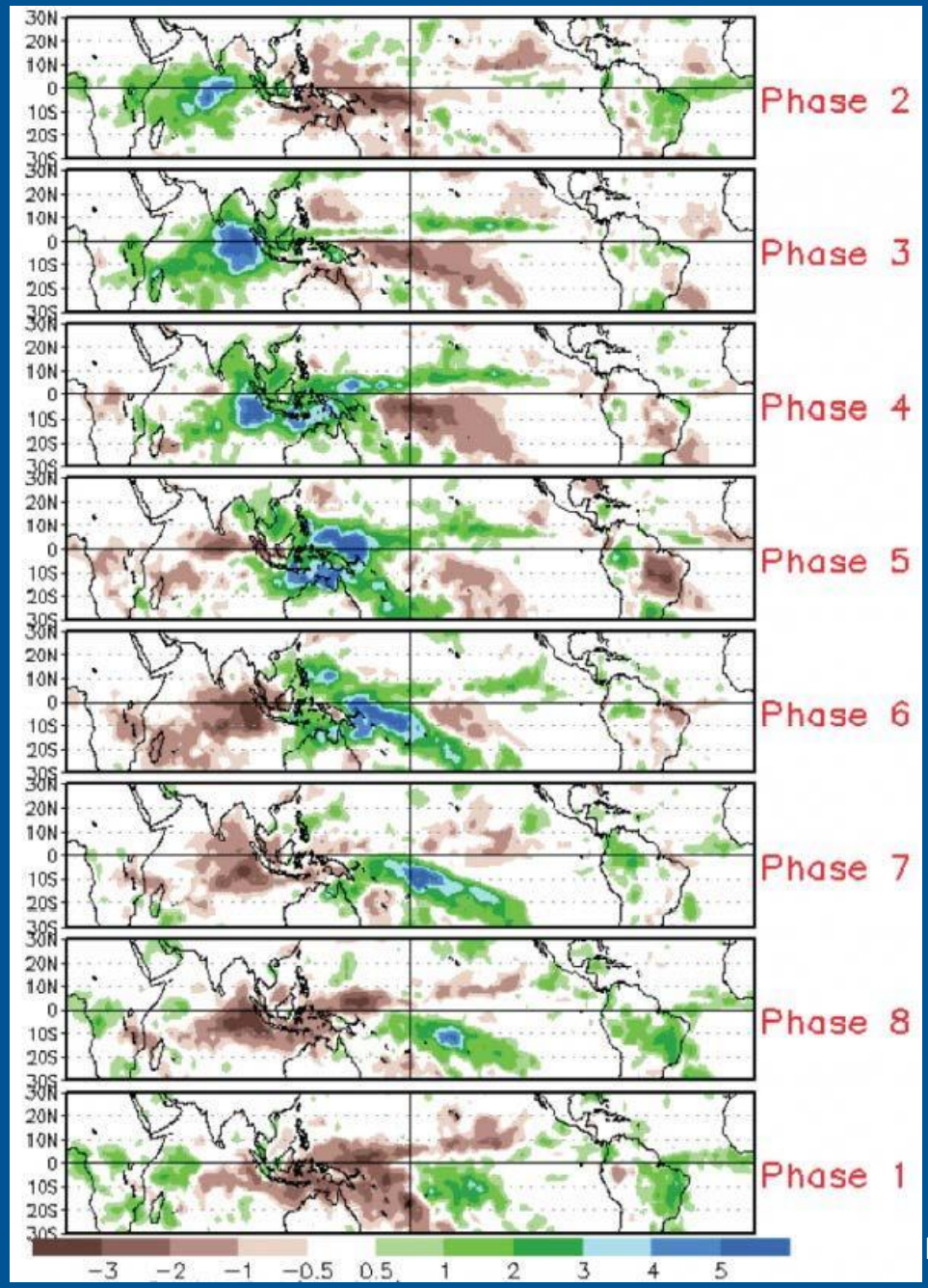
QBO phase is defined using 45 hPa equatorial winds in January and February



The MJO is characterized by an amplitude and phase. The amplitude can be derived from an EOF analysis of satellite outgoing longwave radiation (OLR) data. The phase is an indicator of the longitudinal location of the main convective center of the MJO.

Amplitude = $(EOF1^2 + EOF2^2)^{1/2}$

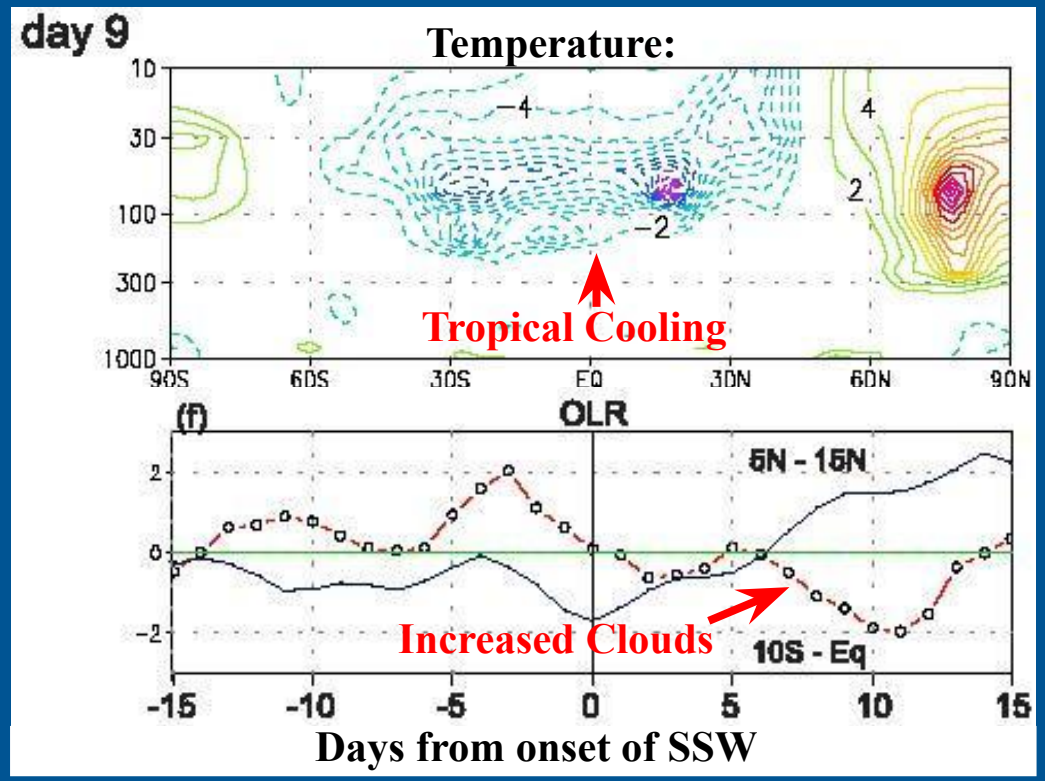
EOF1,EOF2 are derived from an EOF analysis of satellite Outgoing Longwave Radiation Data



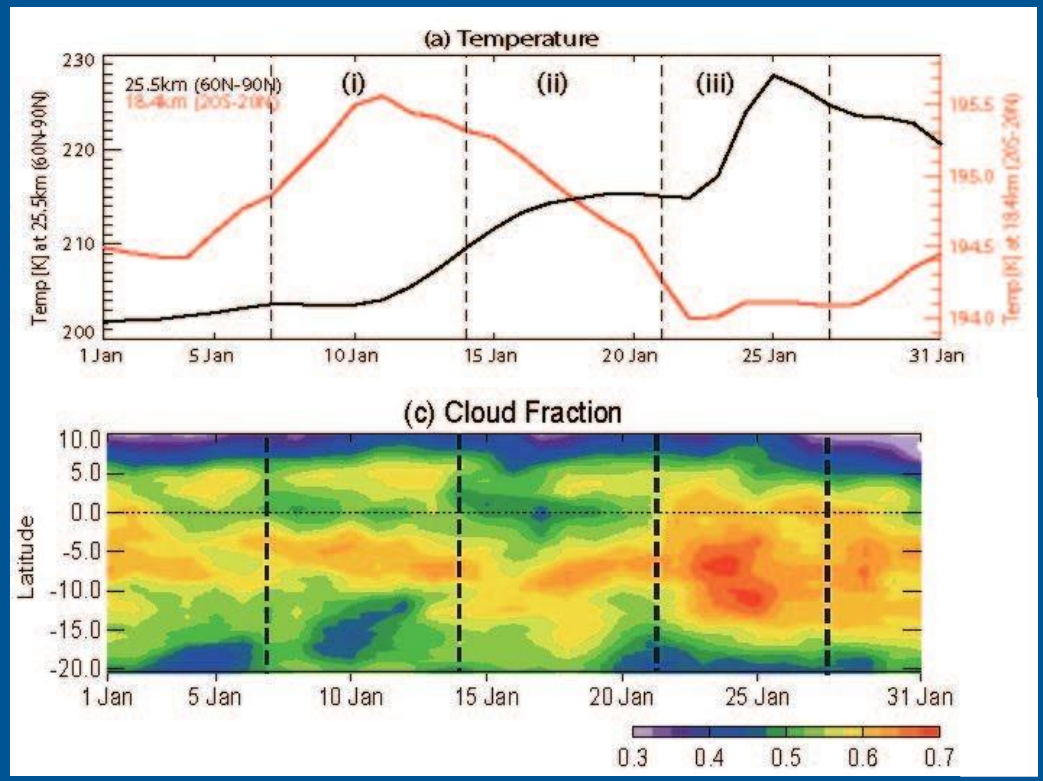
Credit: Jon Gottschalk

Evidence for a SSW influence on deep tropical convection:

Observations (Kodera, GRL, 2006);
Composite of 12 selected SSWs:

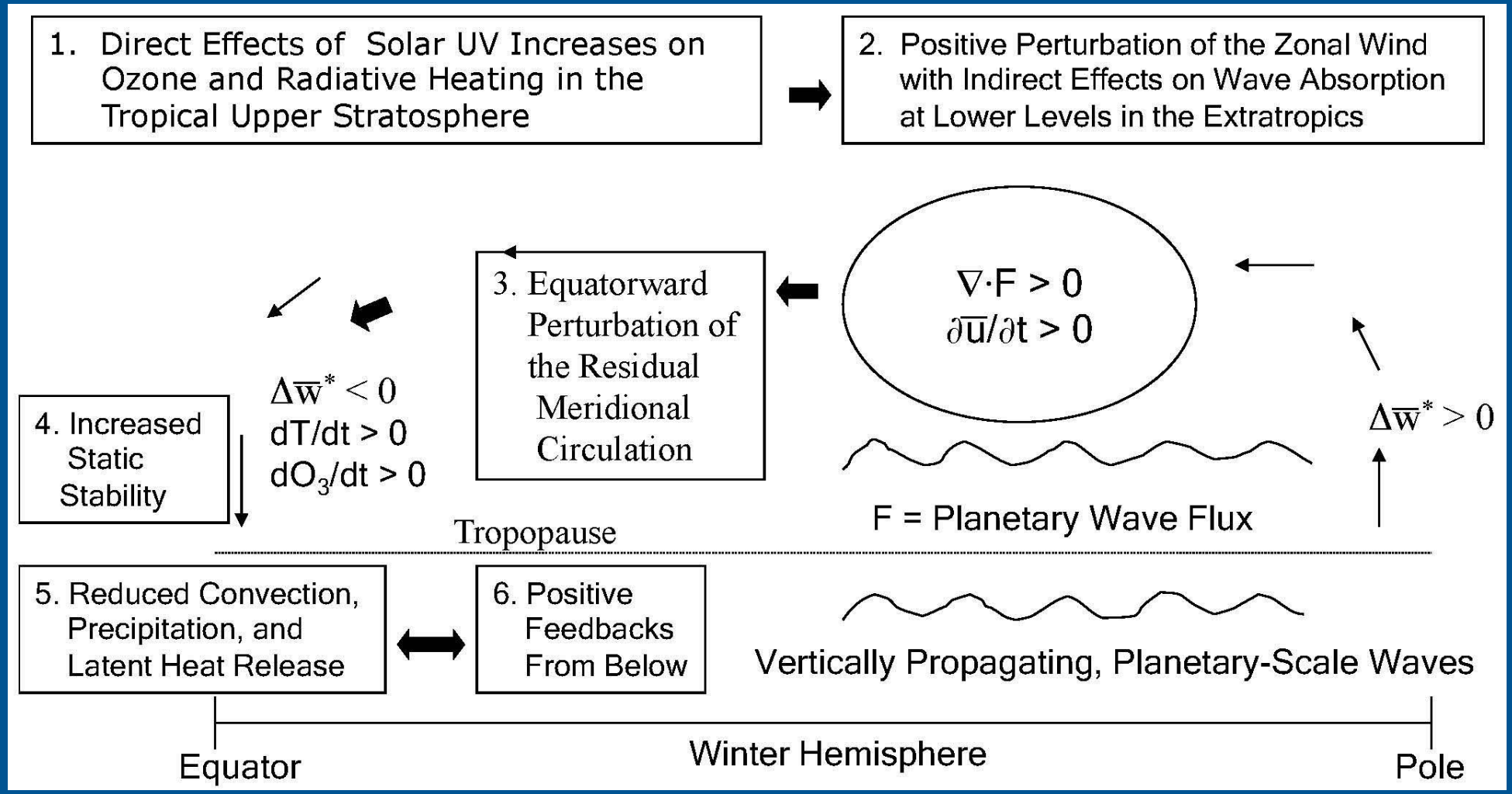


Model Simulation (Eguchi et al., ACP, 2015):
(See also Yoshida and Mizuta, IUGG, 2019)



Both observations and model simulations indicate an increase in convective cloud production just south of the equator following a SSW

Solar Variability can also affect static stability in the tropical lower stratosphere



Solar maximum conditions are shown. Opposite would be expected at solar minimum.

e.g., Kodera & Kuroda (2002); Hood (2018)