Arctic Sea Ice Loss, Long-Term Trends in Extratropical Wave Forcing, and the Emergence of the QBO/Solar-MJO Connection

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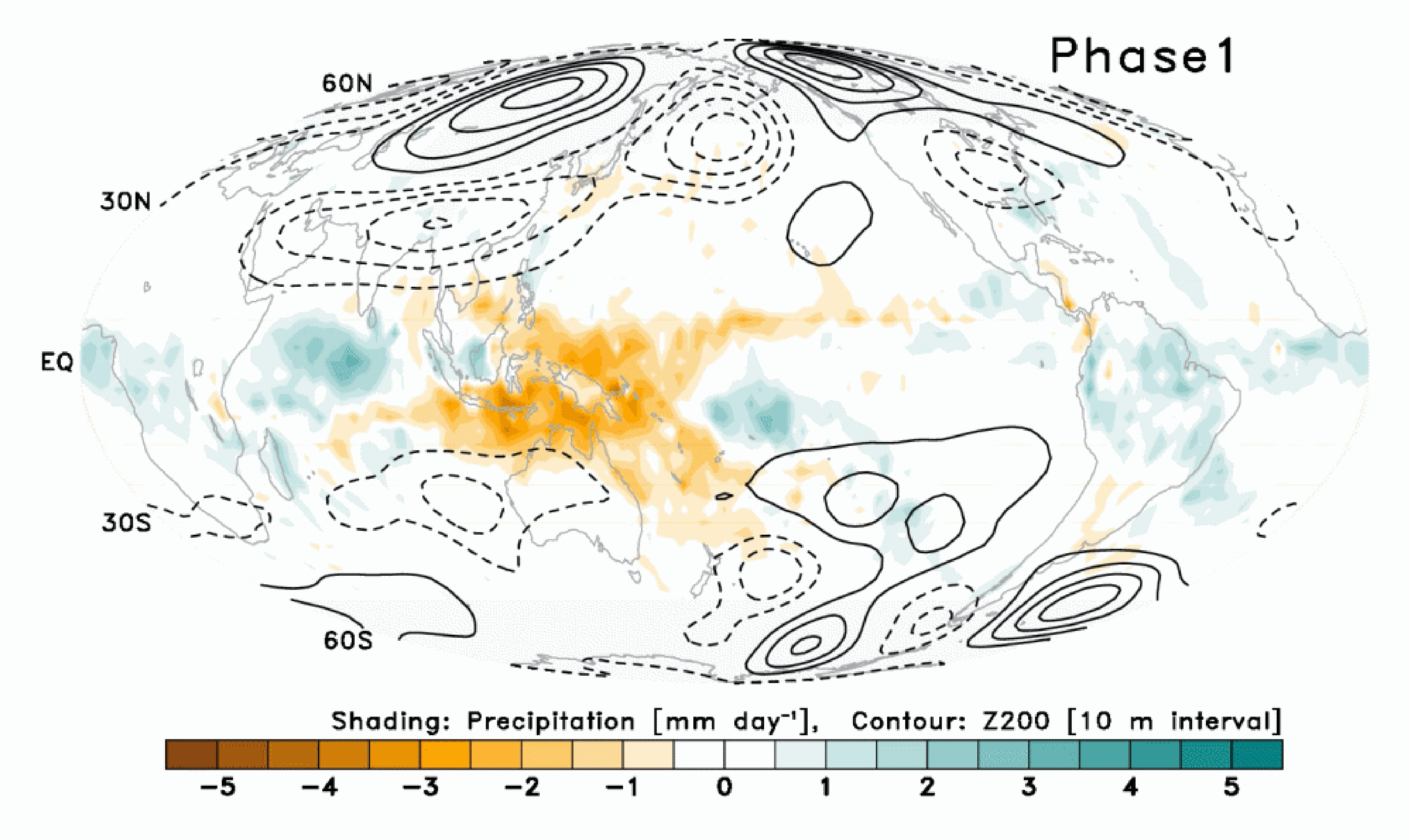
Acknowledgments: NASA LWS program, NSF Climate & Large-scale Dynamics program.

- *The Madden-Julian Oscillation (MJO), also known as the 30 to 50 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.*

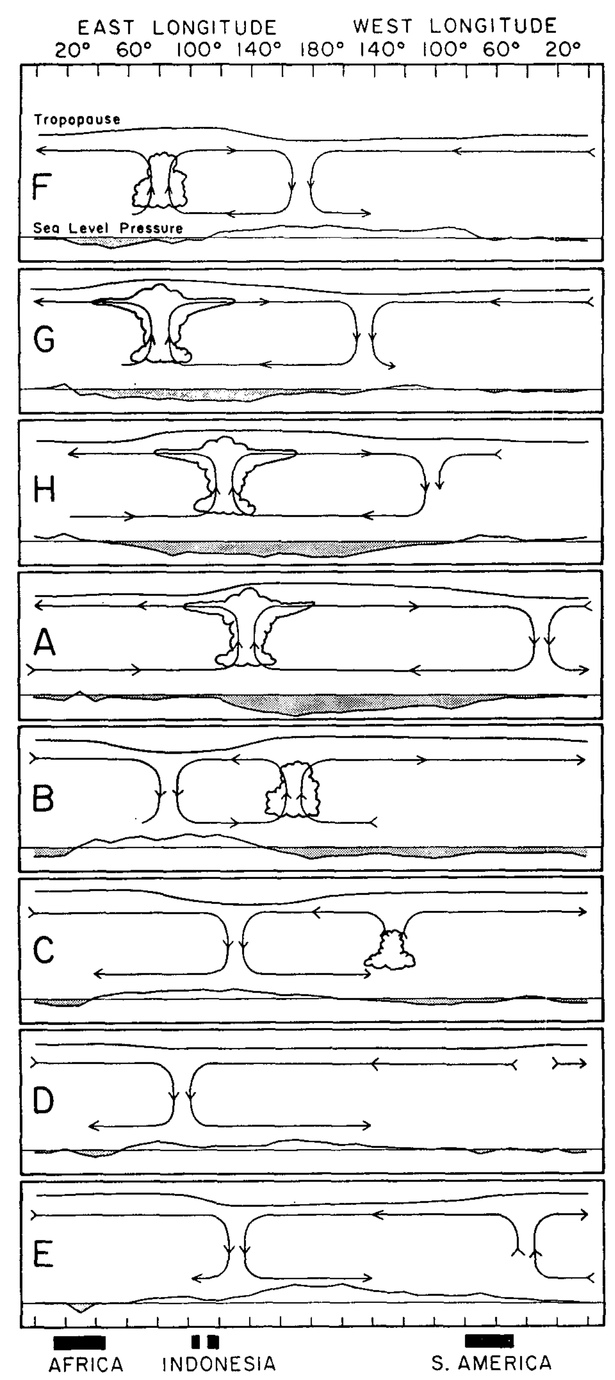


20-100-day filtered variables
Shading: Precipitation
Contour: GPH200 (solid: +, dashed: -)

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

MJO Convection Extends to Relatively High Altitudes, Making It More Susceptible to Stratospheric Influences

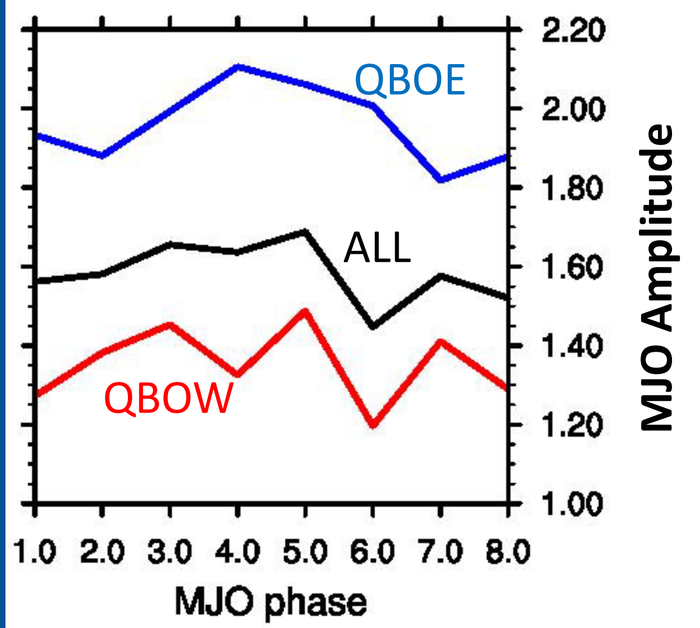
Unlike normal tropical convection, the MJO extends vertically into the uppermost troposphere so it is possible that conditions at its upper boundary can affect its eastward propagation and intensity. An MJO event can potentially be amplified by favorable conditions (e.g., reduced static stability) in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

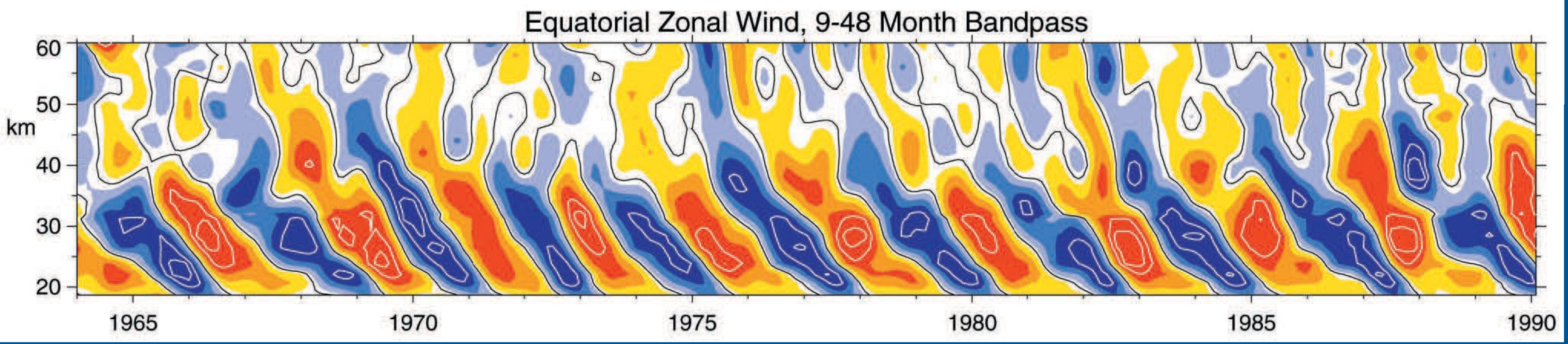


Credit: Madden & Julian, 1972

Beginning about 7 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).

Yoo and Son, GRL, 2016:

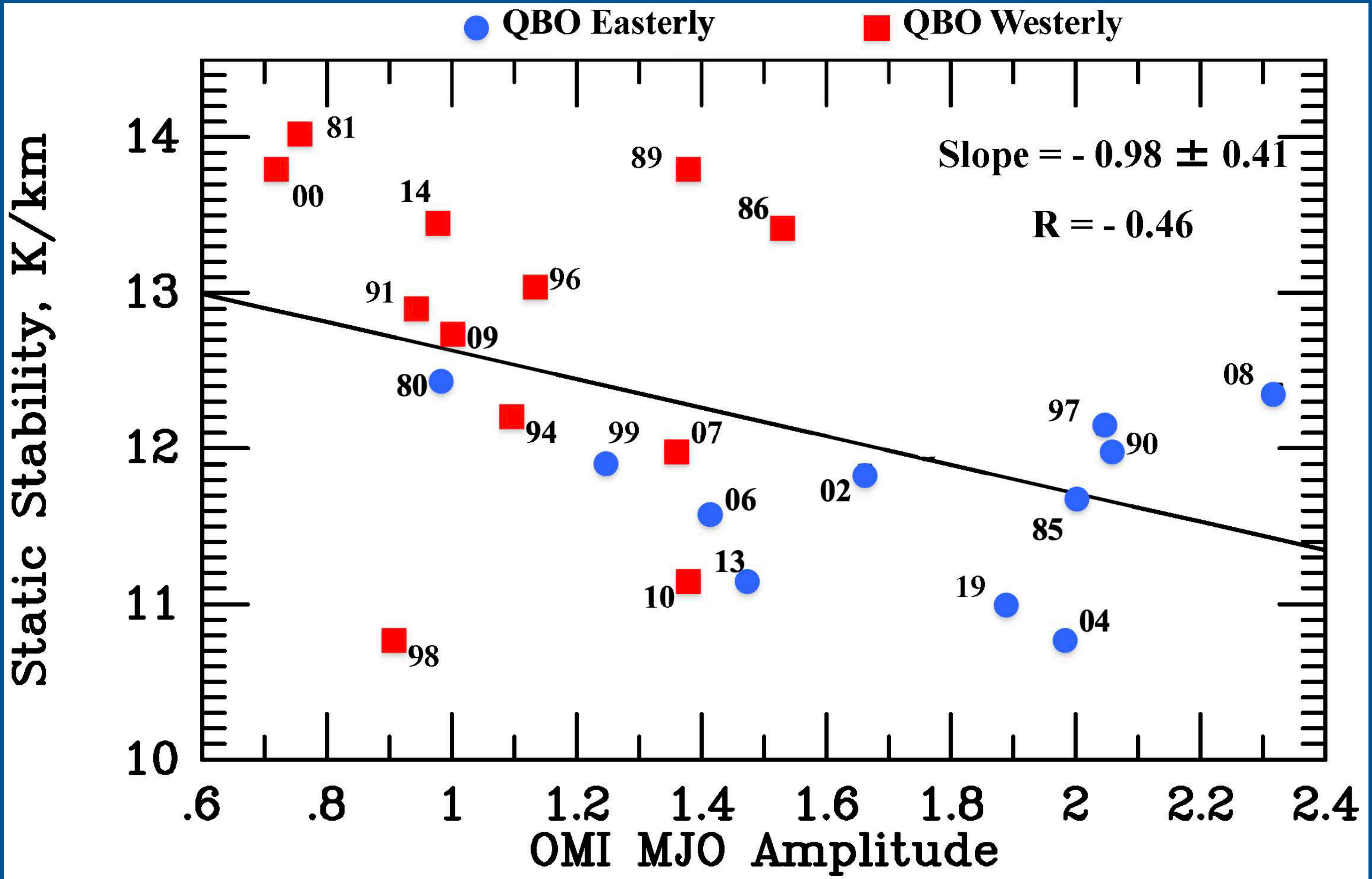




Credit: Baldwin et al. 2001

What is meant by the QBO-MJO connection?

QBOE and QBOW Winters

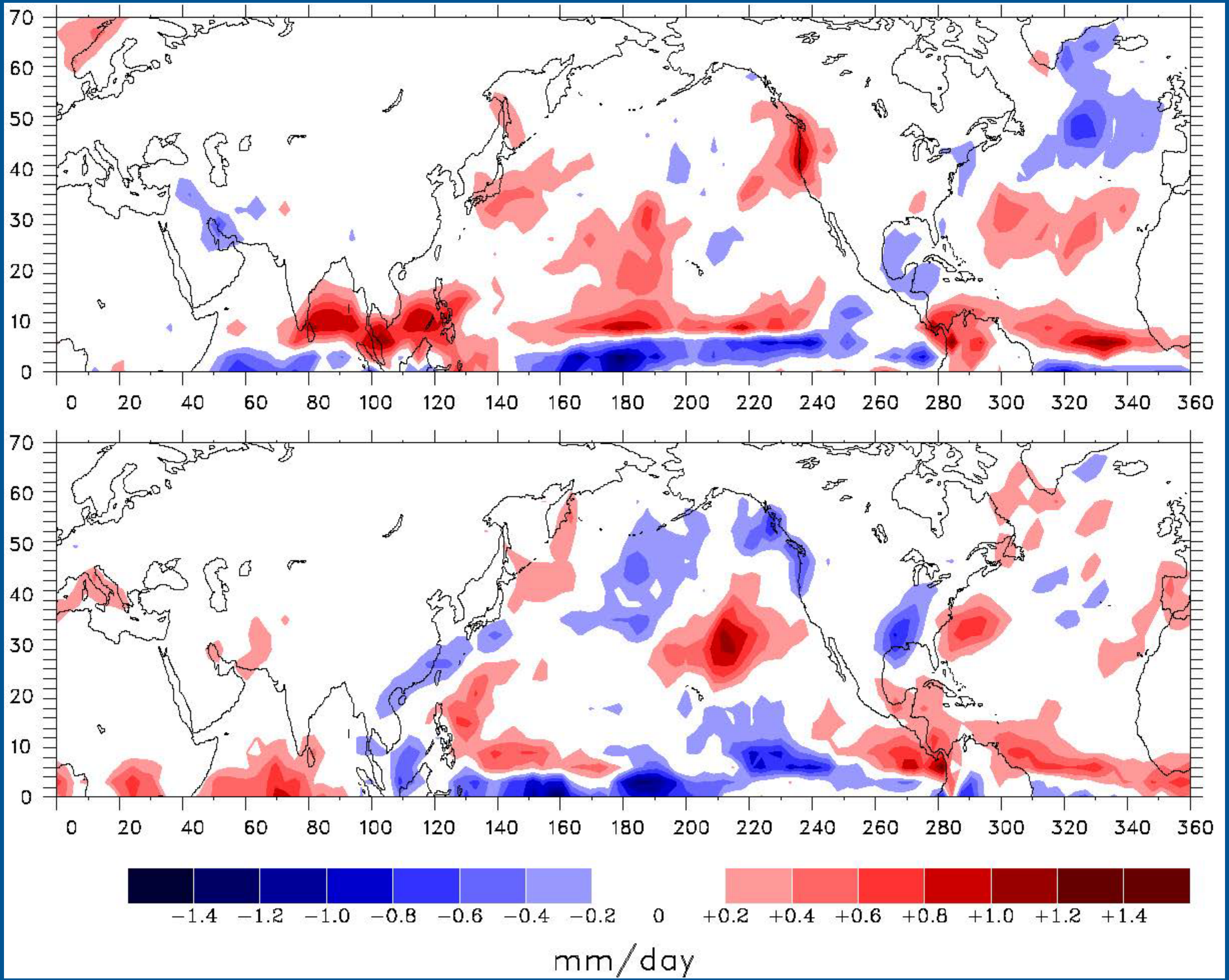


Tropical Lower Stratospheric Static Stability vs. MJO Amplitude (DJF):

Average Precipitation for an Amplitude ~1 MJO Winter

MJO Phases 3 to 6:

MJO Phases 1,2,7,8:

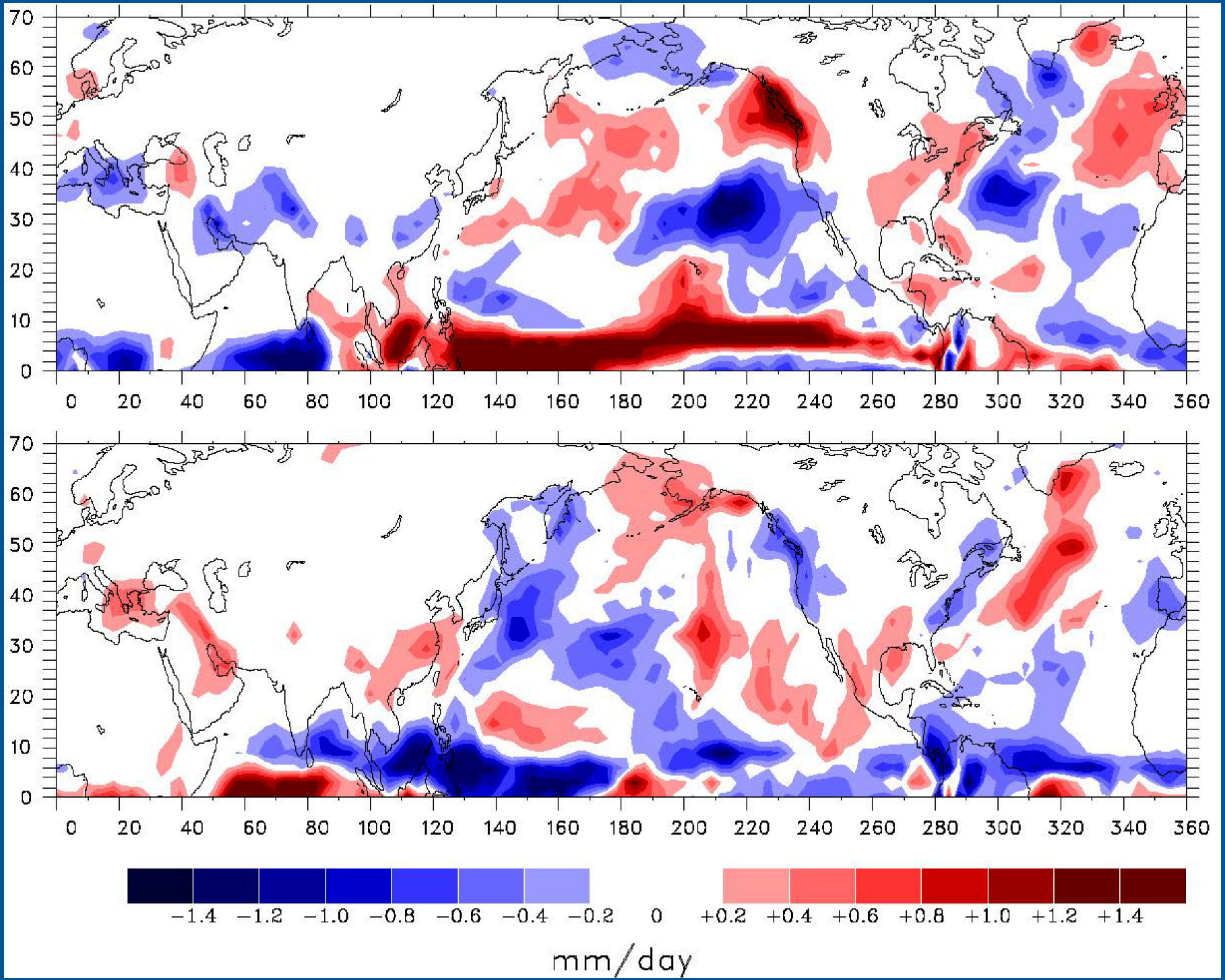


ERA Interim Reanalysis Data

Average Precipitation for an Amplitude ~2 MJO Winter

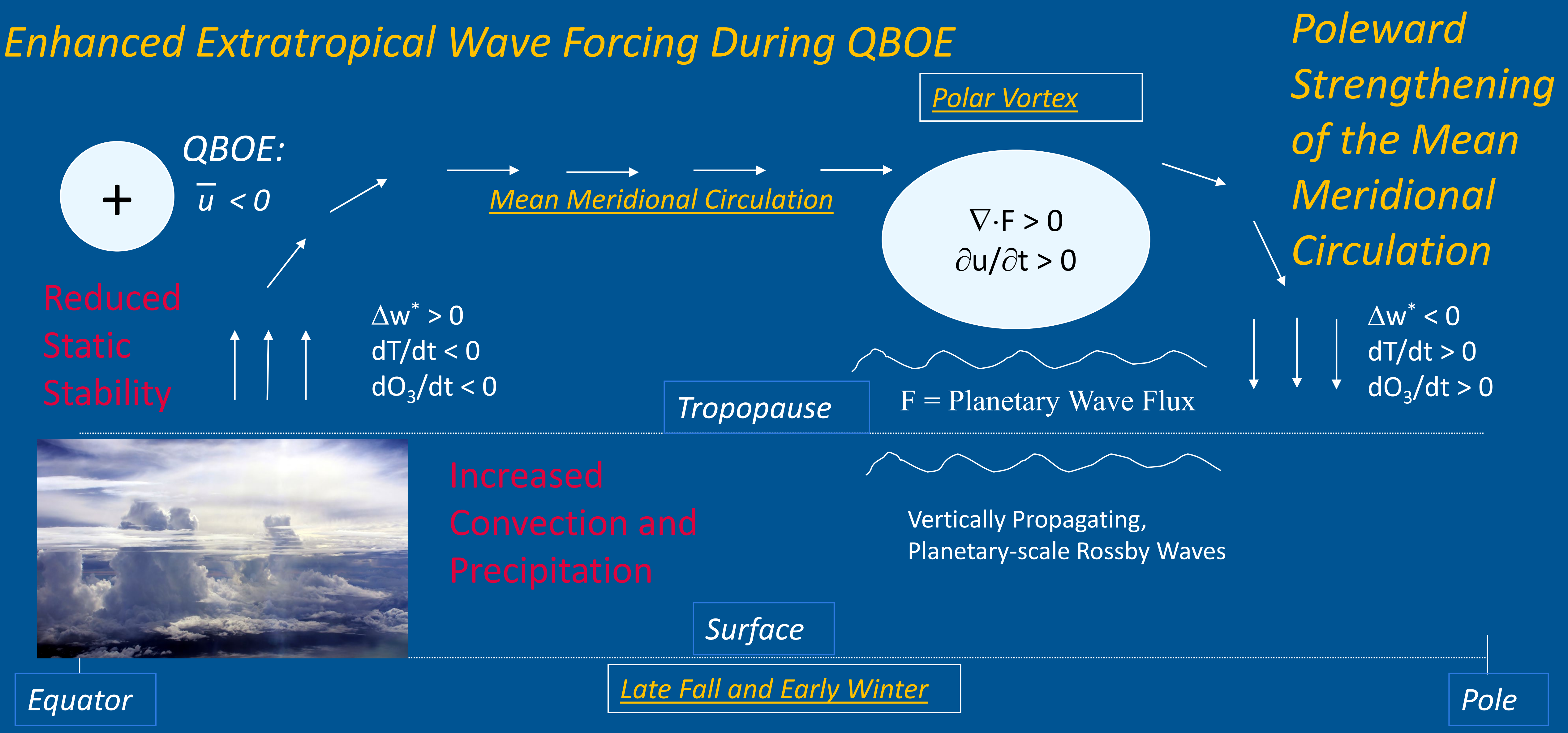
MJO Phases 3 to 6:

MJO Phases 1,2,7,8:

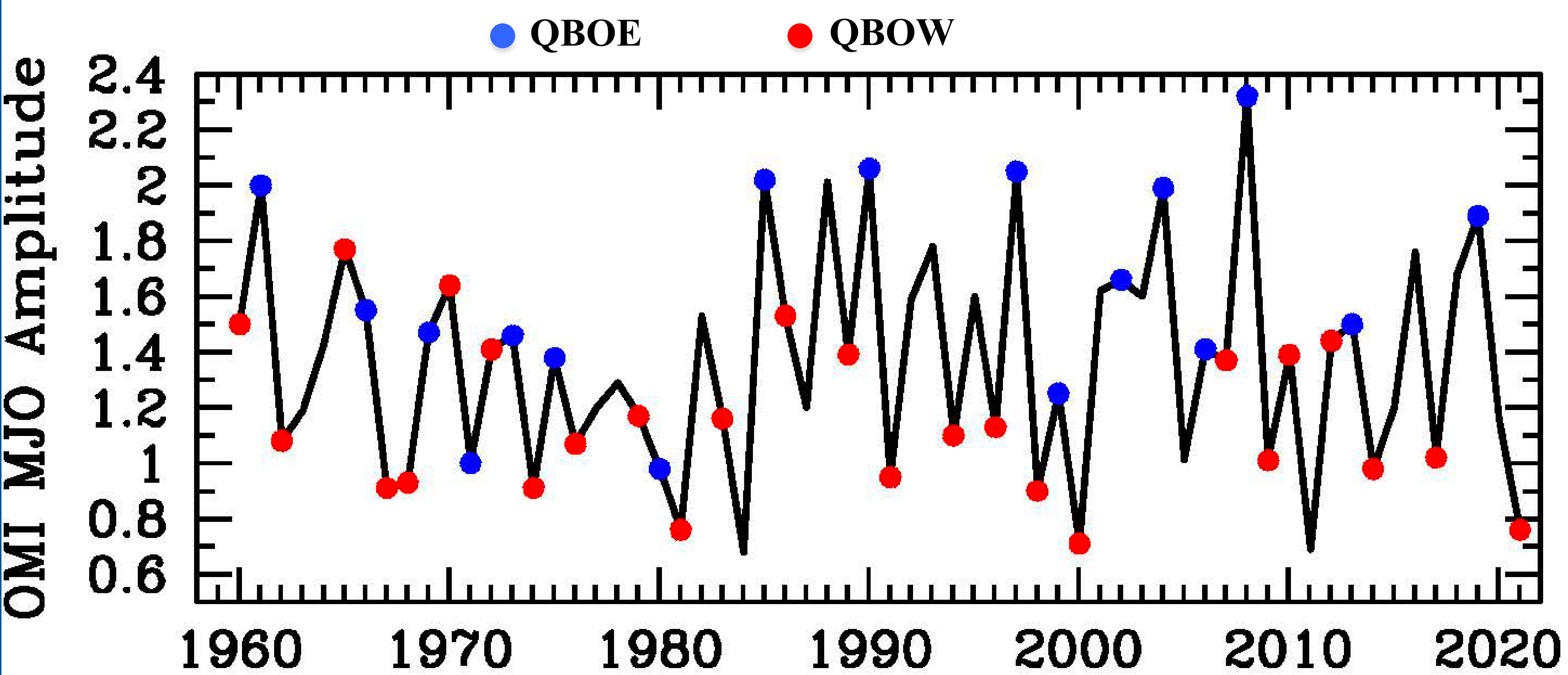


ERA Interim Reanalysis Data

Proposed Mechanism for QBO Influence on the MJO (Holton-Tan Effect)



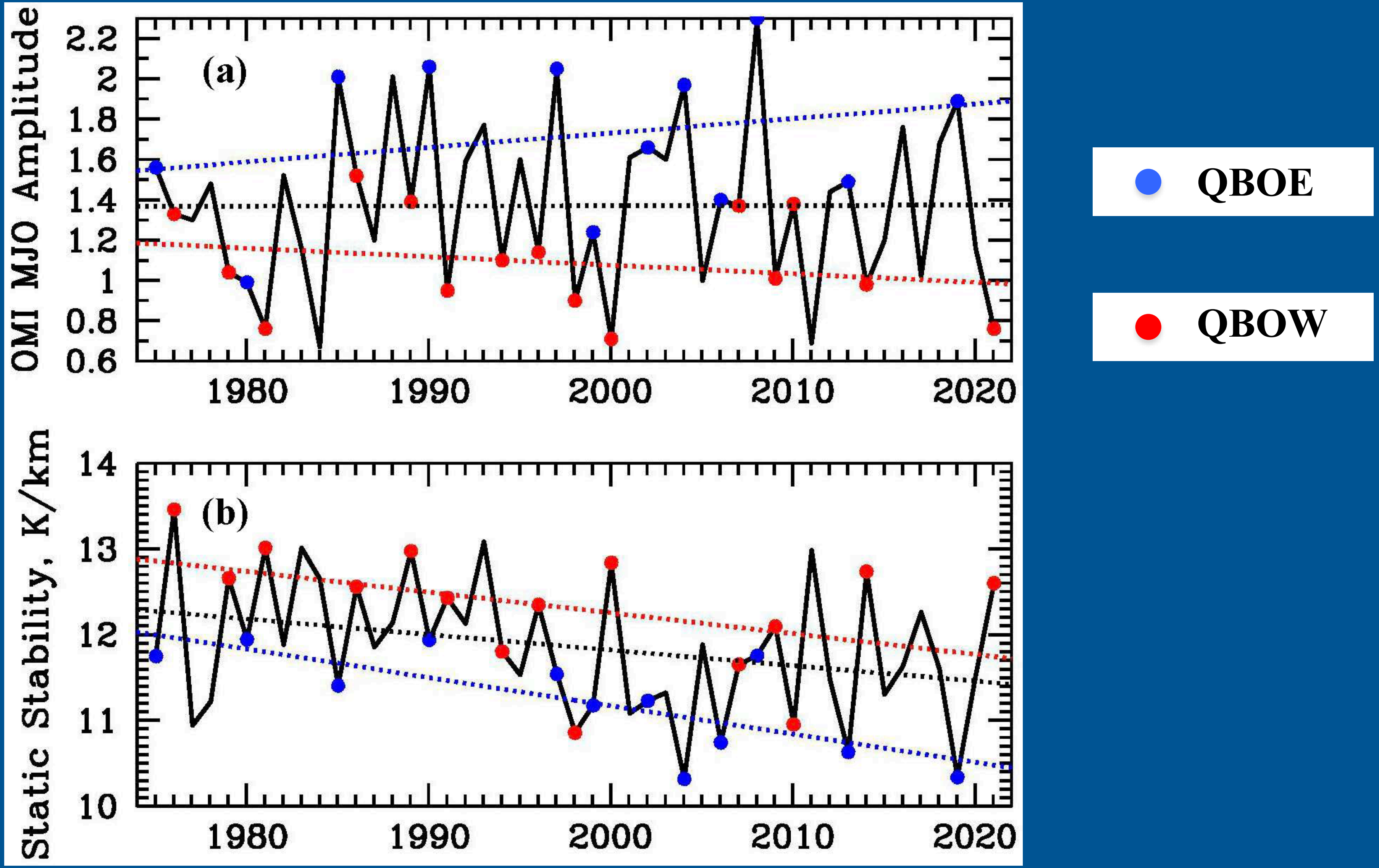
DJF Mean MJO Amplitude, 1959-2021



Data Sources: *1979-2021: NOAA; 1959-1978: Calculated from ERA5 reanalysis OLR data*

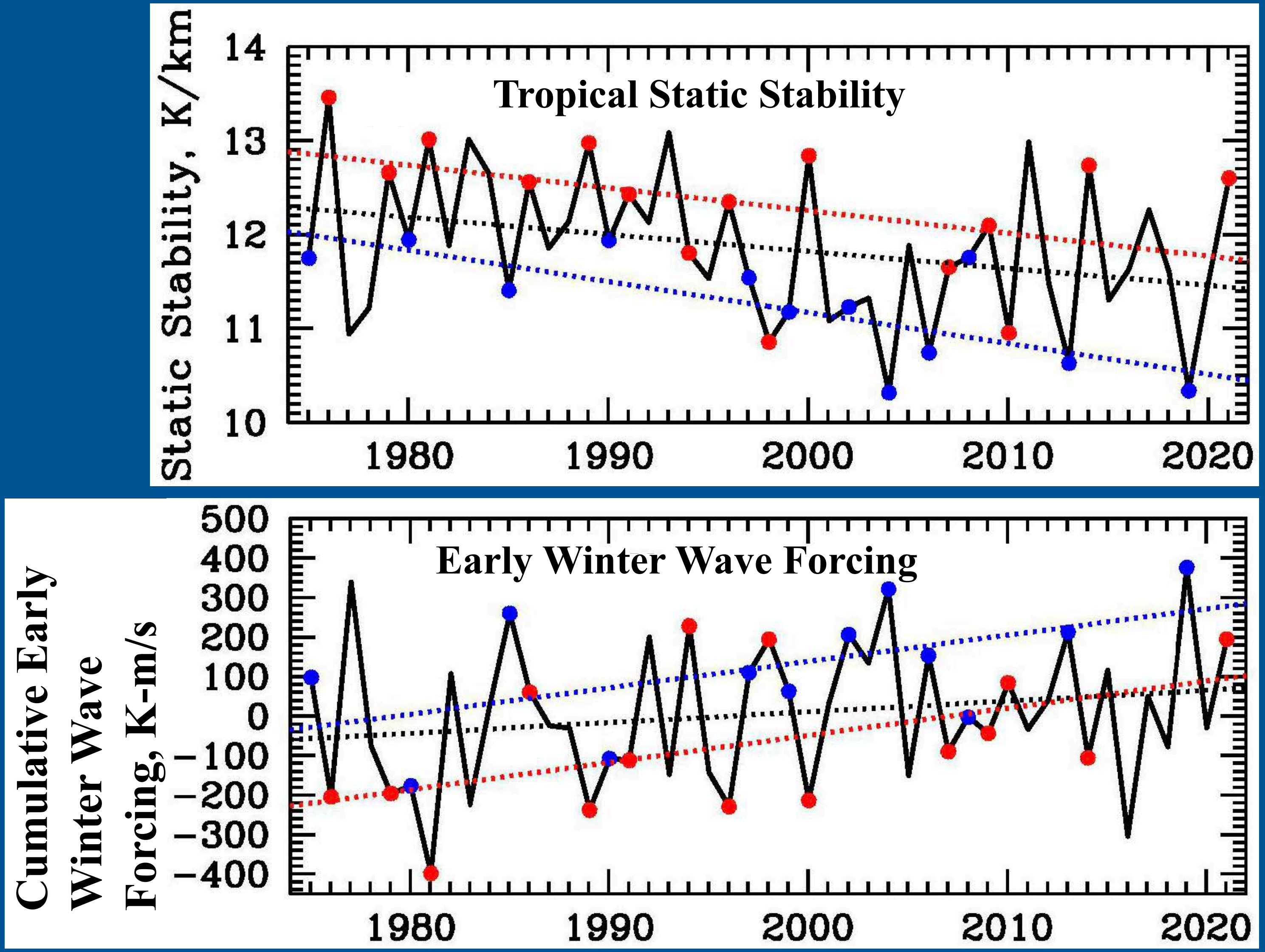
Trends in DJF Mean MJO Amplitude and Tropical Lower Stratospheric Static Stability: 1975-2021

Why is static stability in the tropical lowermost stratosphere decreasing with time since the late 1970s?



Trends in DJF Mean Tropical Lower Stratospheric Static Stability and Early Winter Extratropical Wave Forcing: 1975-2021

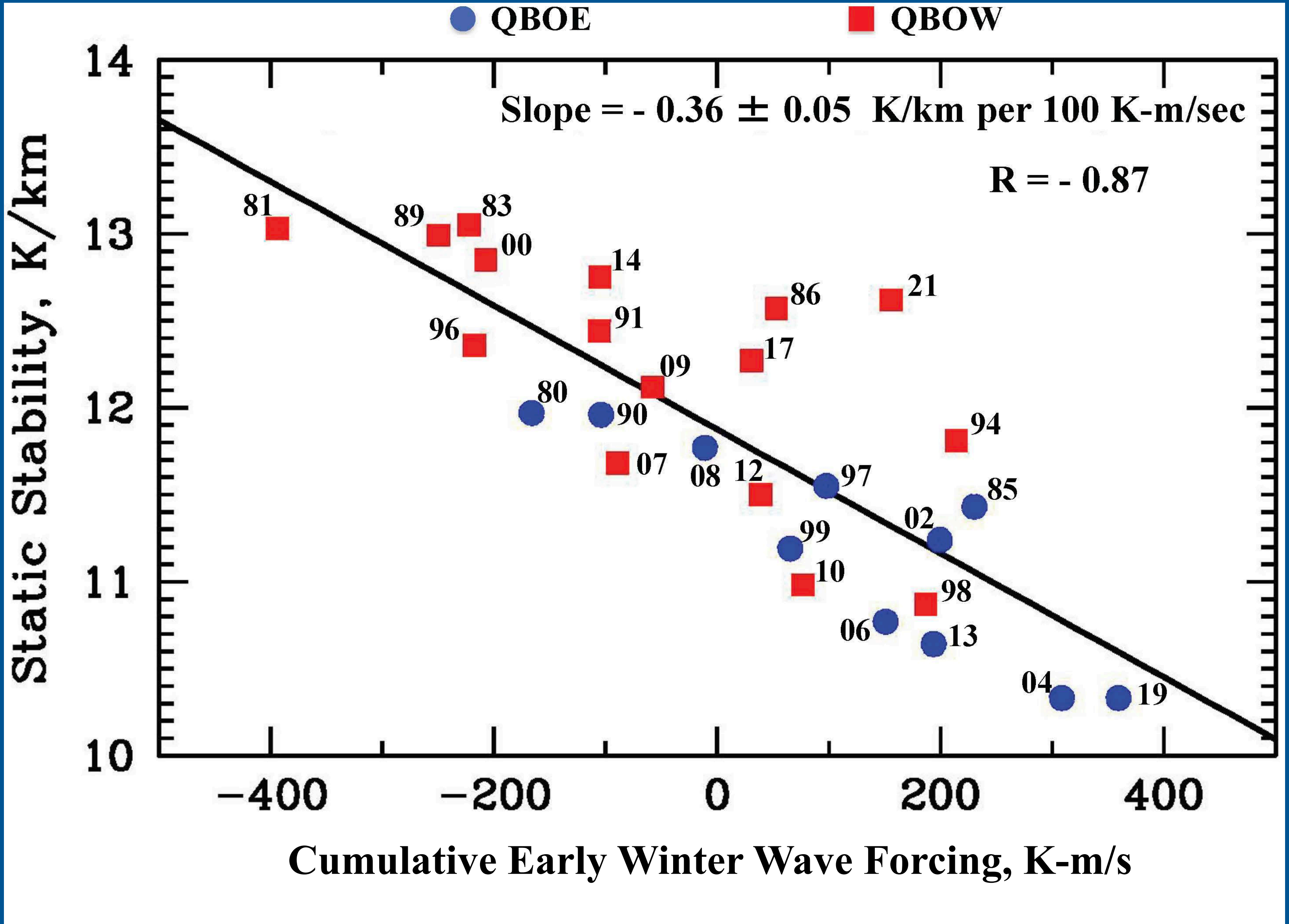
Why is static stability in the tropical lowermost stratosphere decreasing with time since the late 1970s?



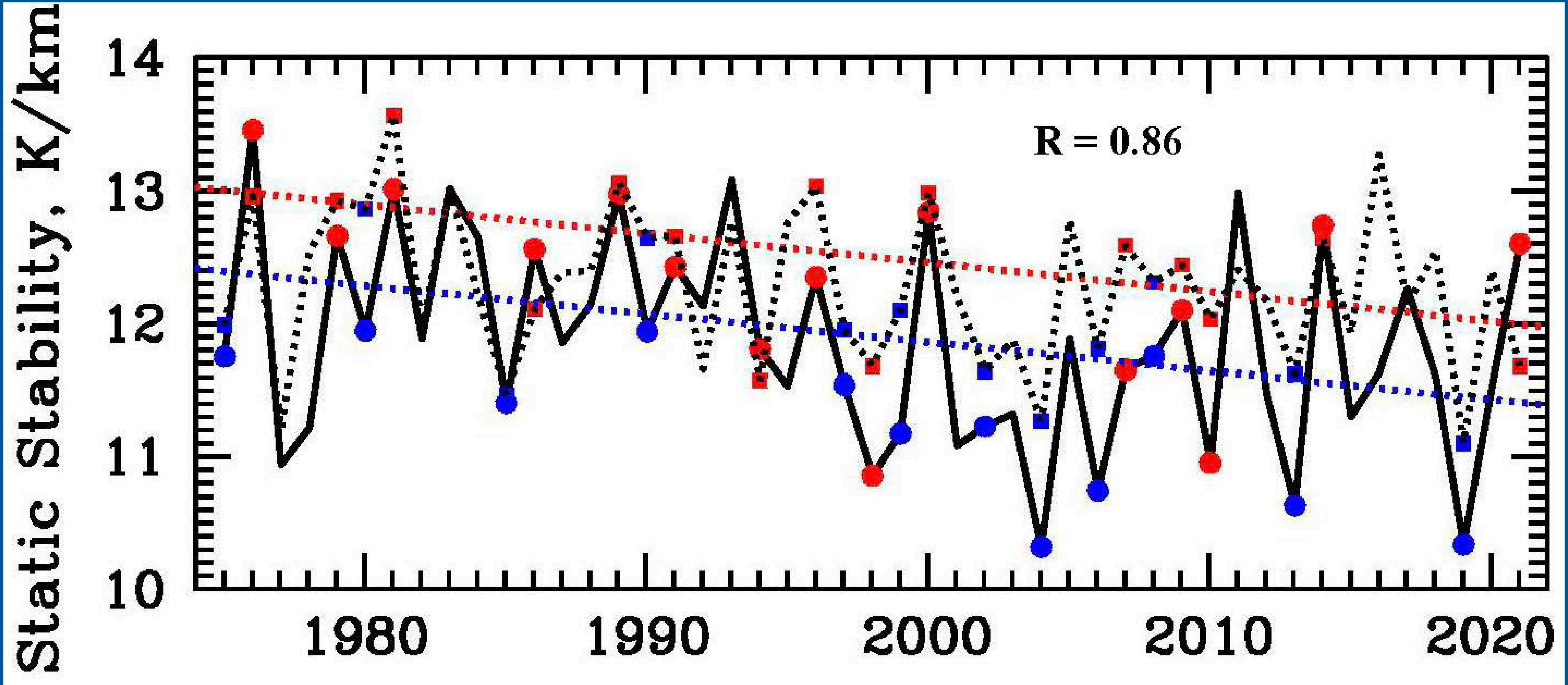
QBOE

QBOW

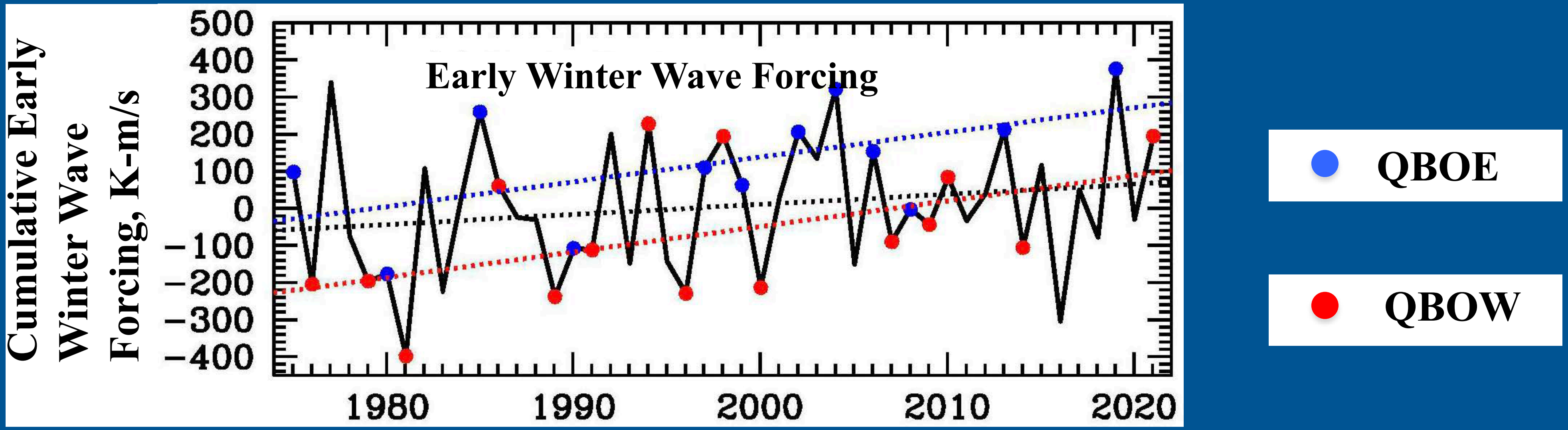
High Inverse Correlation Between Tropical Lower Stratospheric Static Stability in DJF and Early Winter Extratropical Wave Forcing: 1979-2021



Comparison of the static stability time series with an empirical model (dotted line) based on the observed sensitivity of interannual static stability deviations to early winter wave forcing anomalies

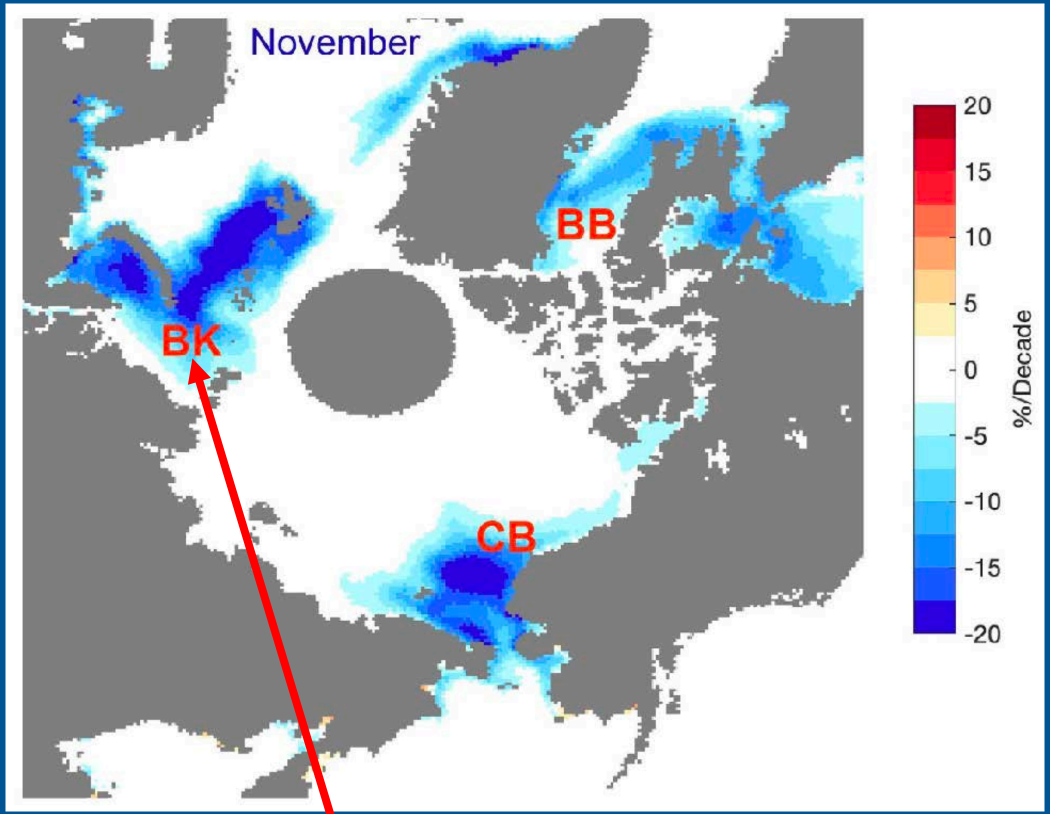


Why has early winter extratropical wave forcing been increasing with time since the late 1970s?



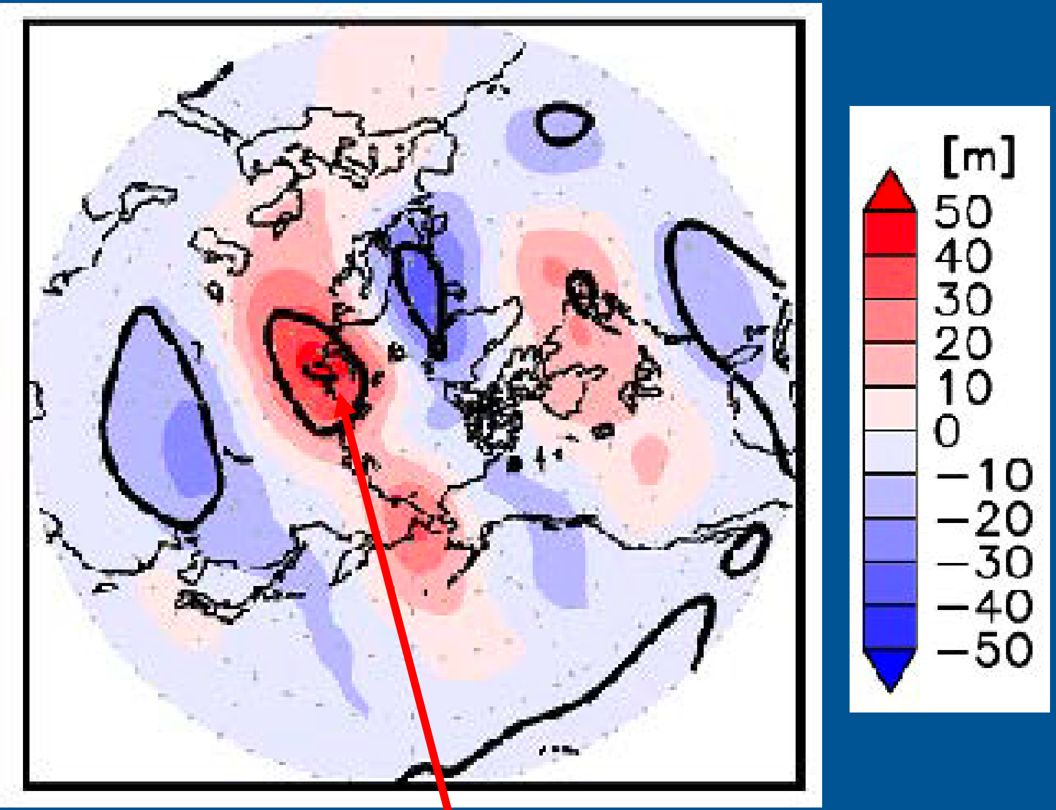
Arctic Sea Ice Loss and Effects on Quasi-Stationary Planetary Waves

Linear Trend in November Sea Ice Concentration, 1979-2019



Largest area of decline is in the Barents-Kara (BK) sea north of Eurasia

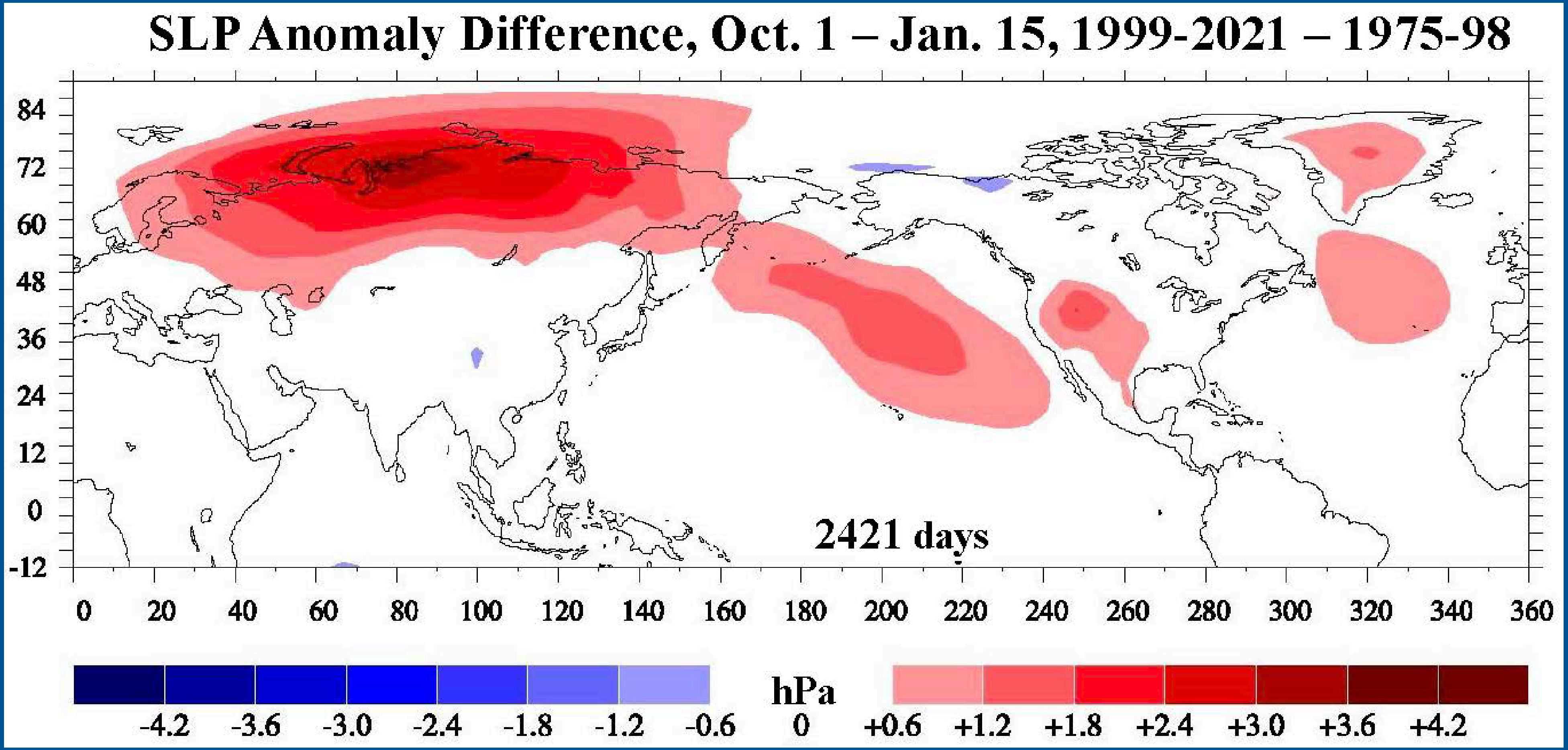
November 300 hPa Geopotential Height Regressed onto BK SIC Index



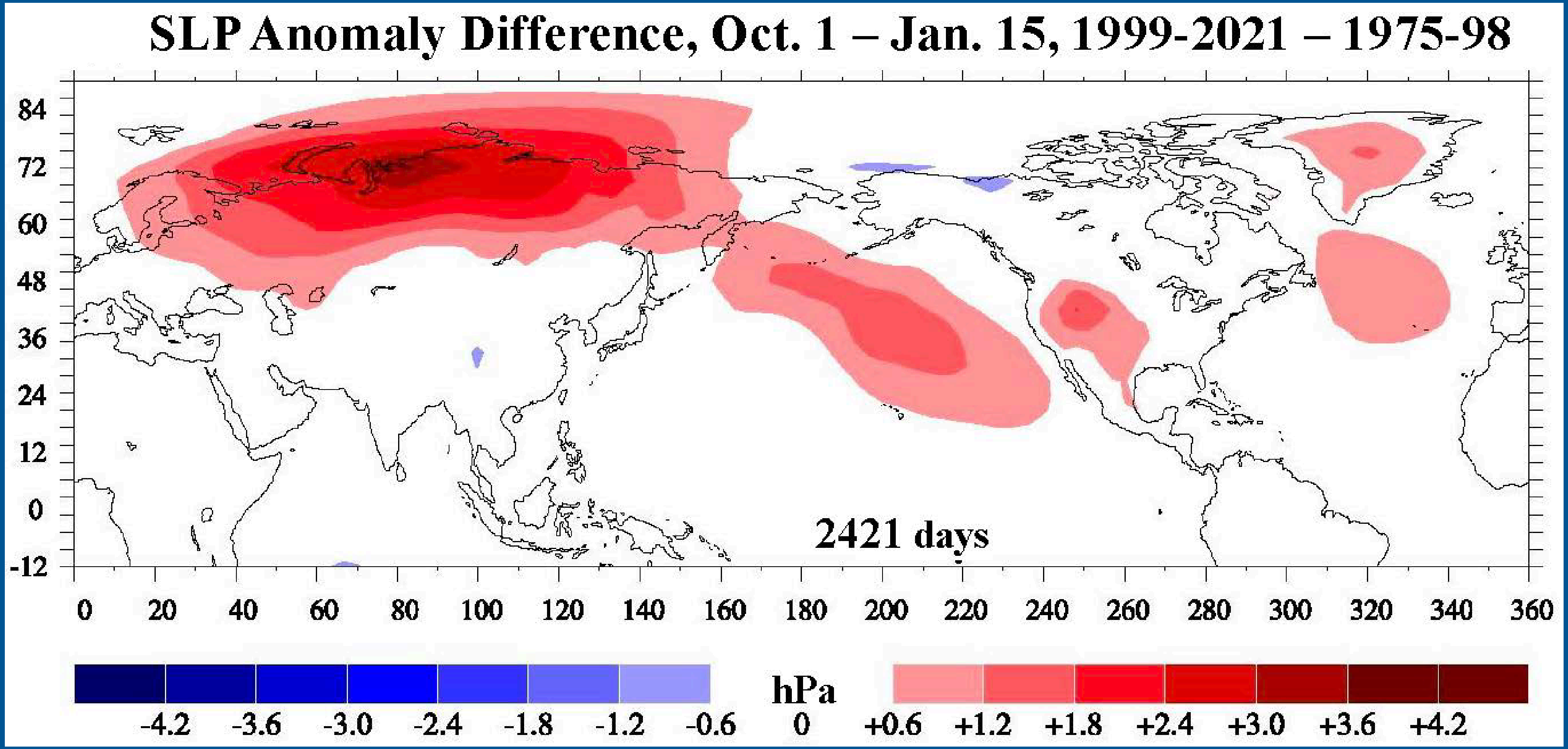
Largest increase in GPH is in the same area on the northern coast of Eurasia

Credit: J. E. Overland et al., ERL, 2021

Sea level pressure (SLP) and tropospheric geopotential heights have increased in late fall and early winter in the area north of Eurasia where Arctic sea ice has been declining most rapidly.



Such an anomalous increase in sea level pressure would constructively interfere with the climatological sea level pattern characterized by the Siberian high and the Aleutian low, thereby increasing tropospheric quasi-stationary wave amplitudes and early winter wave forcing.

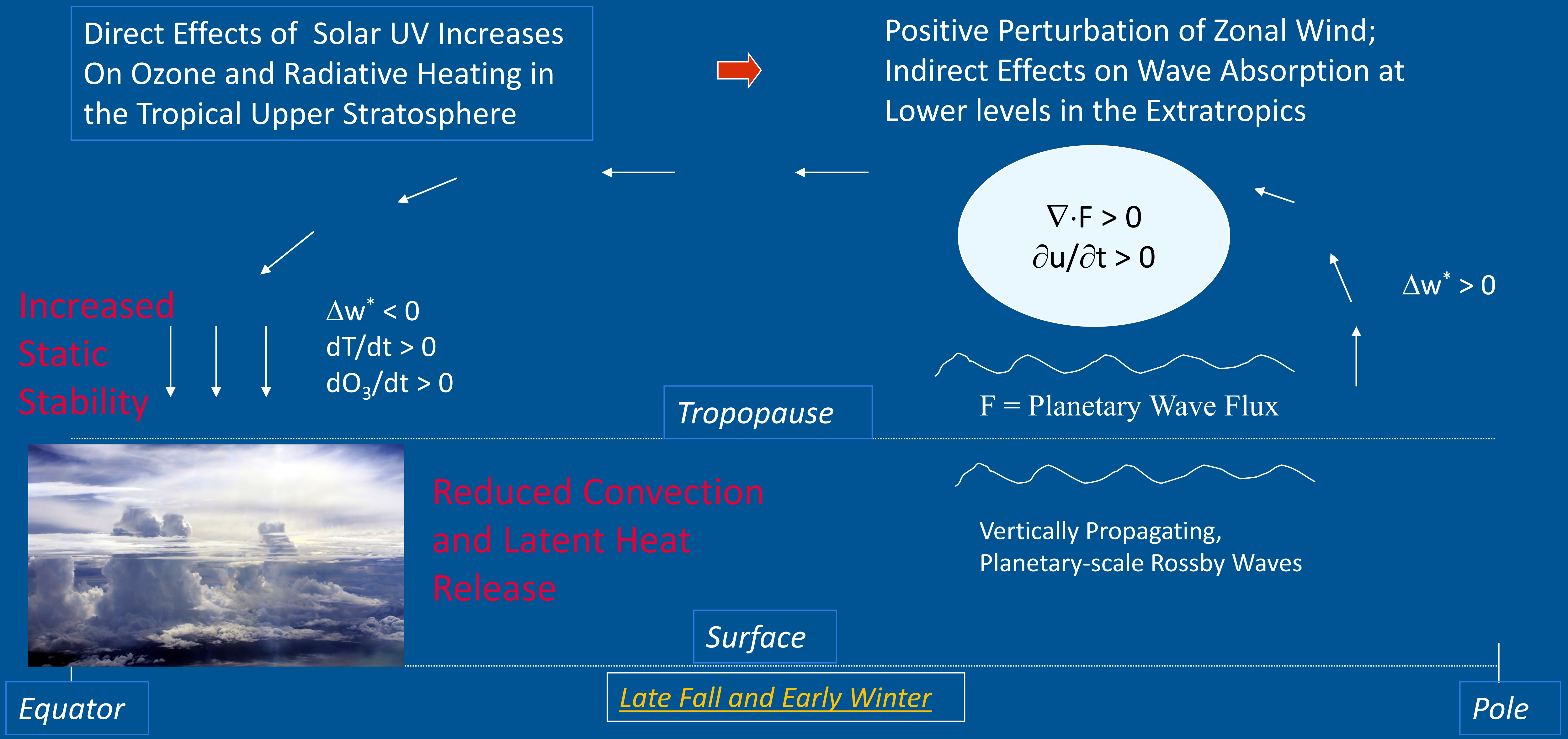


Main Points:

- A modulation of the tropical Madden-Julian oscillation (MJO) by stratospheric forcings (e.g., the QBO) exists and is likely initiated because of effects on static stability in the tropical lowermost stratosphere
- A stronger modulation of the MJO by the QBO has been observed starting in the early 1980s
- Tropical lower stratospheric static stability has declined since the late 1970s due partly to increases in early winter extratropical wave forcing
- The observed trend in wave forcing may be due to larger sea level pressure anomalies over northern Eurasia caused by Arctic sea ice loss

Extra Slides

How Do Stratospheric Effects of Solar Variability Affect the MJO?



How can the Stratospheric Quasi-Biennial Oscillation affect the MJO?

One way is via the QBO induced meridional circulation.

Increased stability in the tropical lowermost stratosphere

Decreased static stability in the tropical lowermost stratosphere

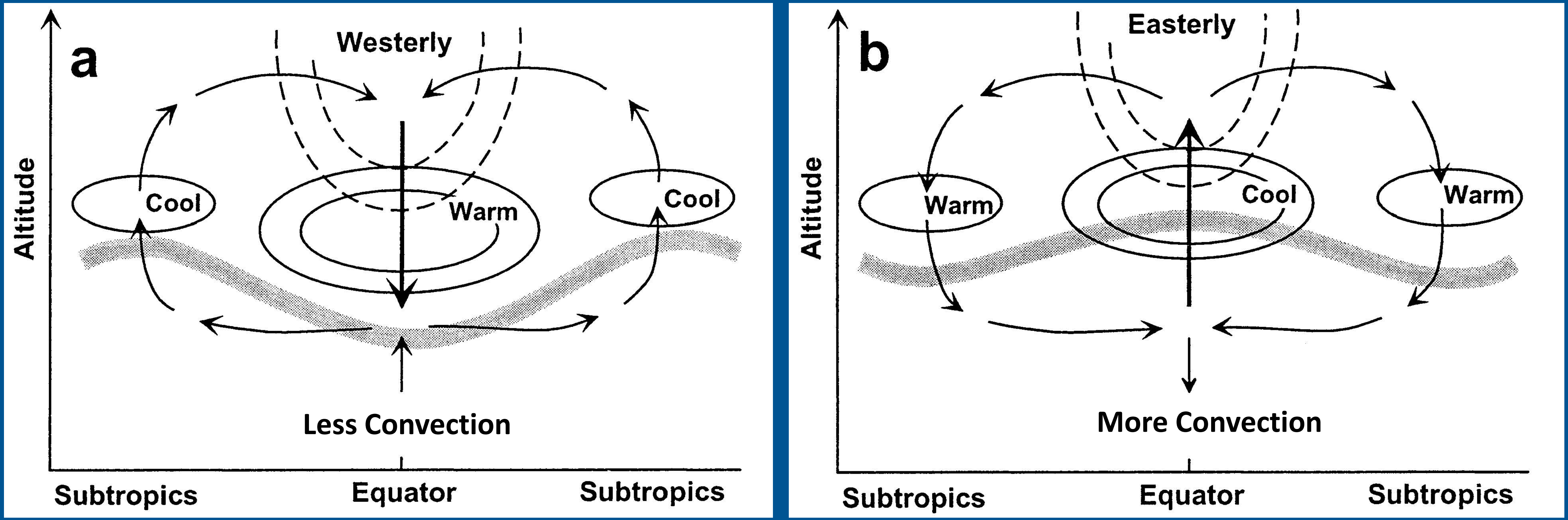
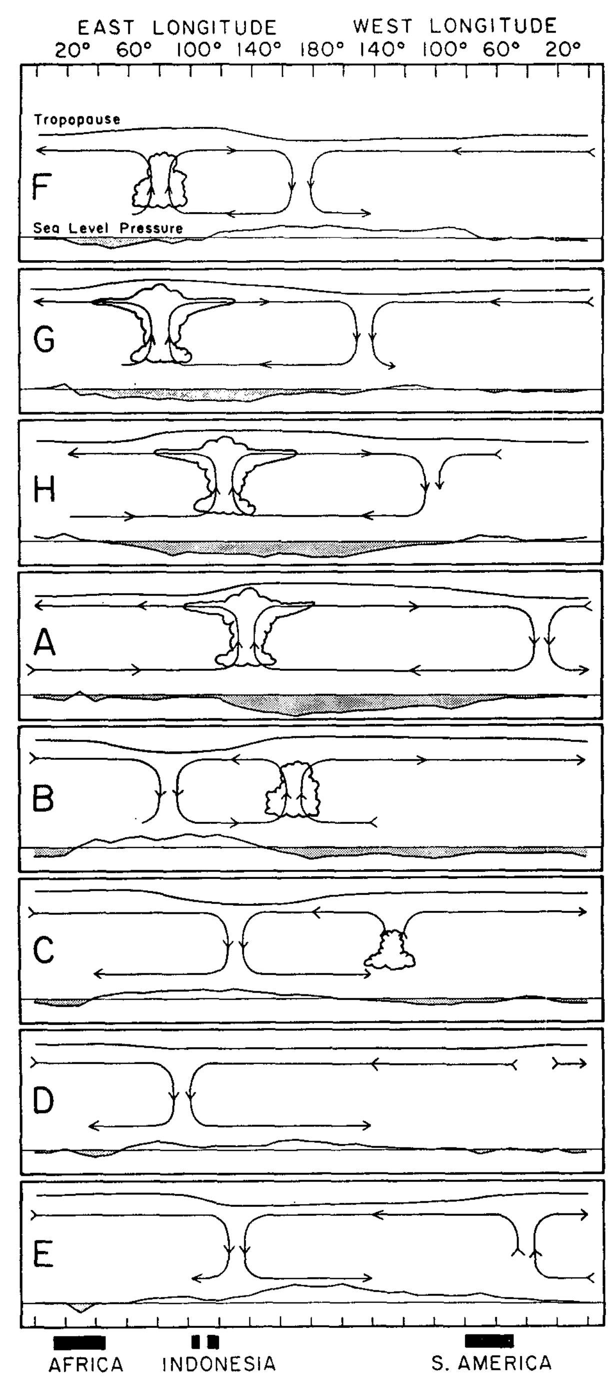


Figure taken from Collimore et al., “On the Relationship Between the QBO and Tropical Deep Convection”, J. of Climate, 2003.

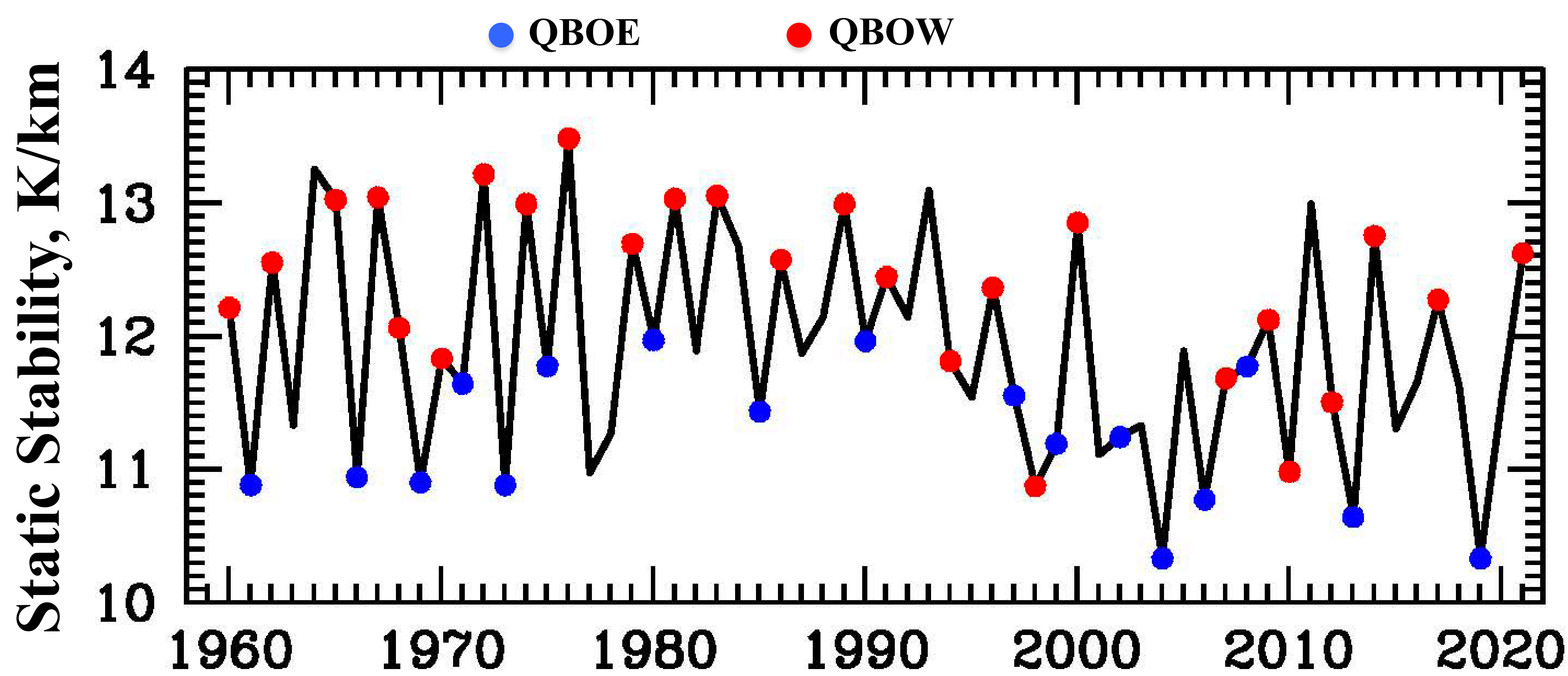
The Tropical Madden-Julian Oscillation Plays an Important Role in Stratosphere-Troposphere Coupling. It is a potentially Important Link in the Sun-Climate Causal Chain.

Unlike normal tropical convection, the MJO extends vertically into the uppermost troposphere so it is possible that conditions at its upper boundary (i.e., static stability) can affect its eastward propagation and intensity.



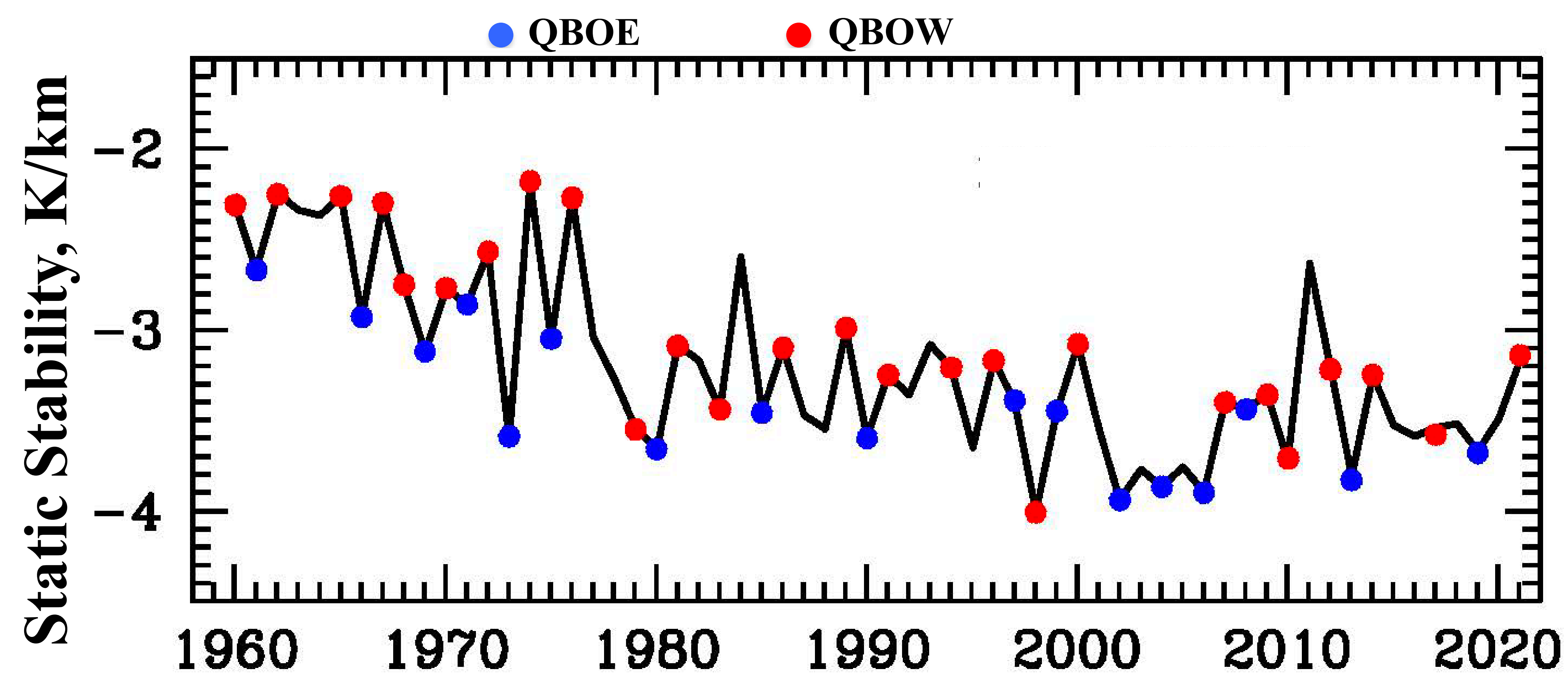
Credit: Madden & Julian, 1972

DJF Mean 70 to 100 hPa Static Stability, 10ºS – 10ºN, 1959-2021



Data Sources: *1979-2021: NOAA; 1959-1978: Calculated from ERA5 reanalysis OLR data*

DJF Mean 100 to 200 hPa Static Stability, 10ºS – 10ºN, 1959-2021

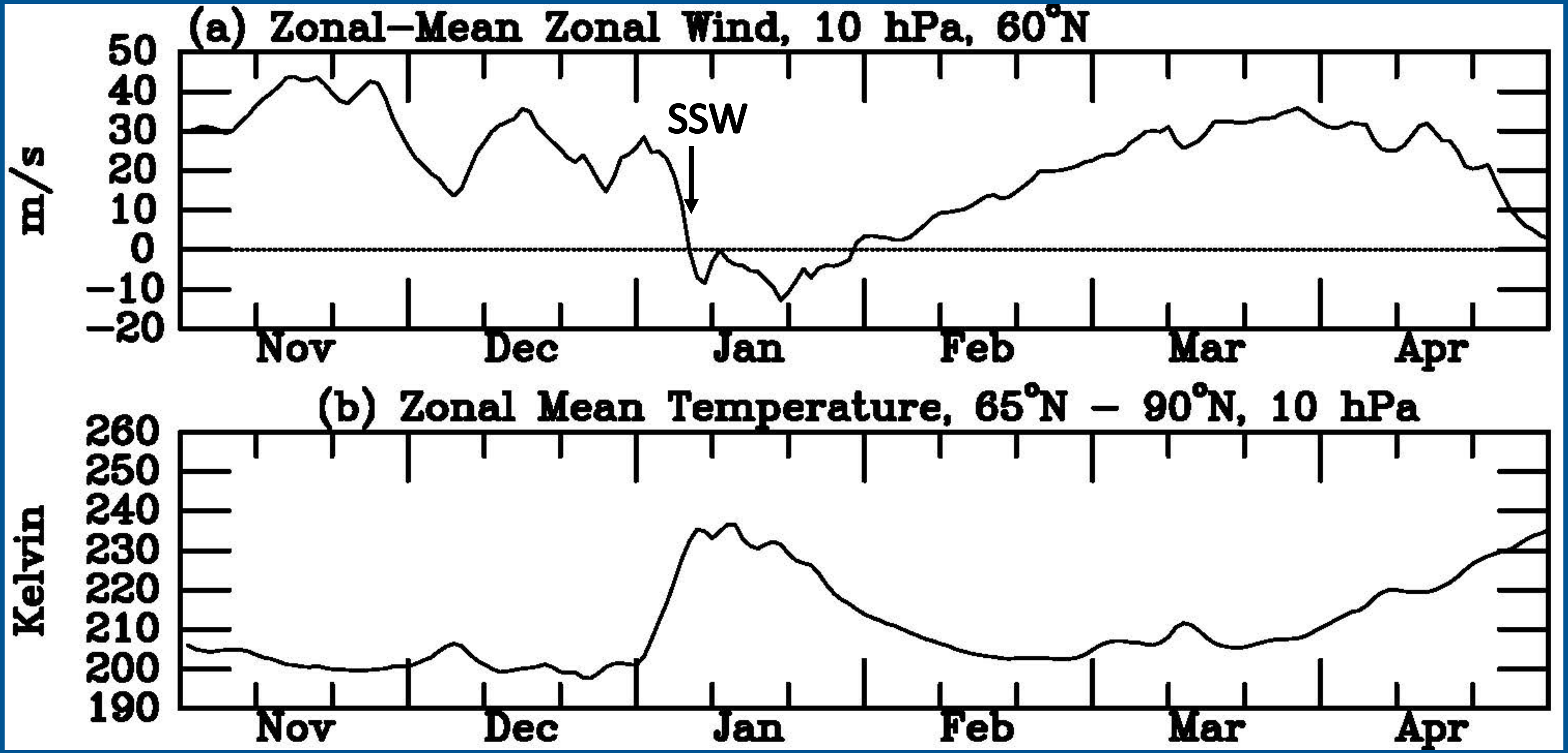


Data Sources: *1979-2021: NOAA; 1959-1978: Calculated from ERA5 reanalysis OLR data*

Introduction

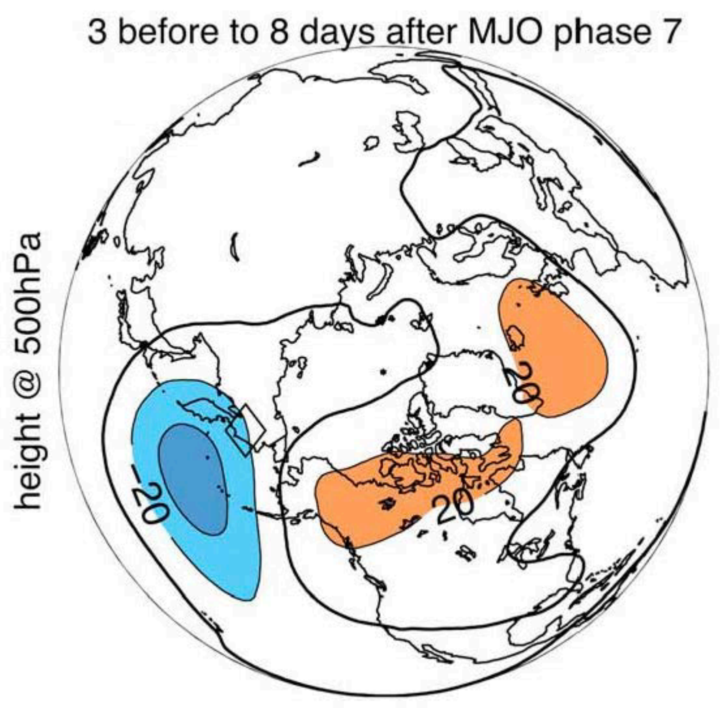
Sudden Stratospheric Warmings (SSWs) are the most dramatic circulation events in the stratosphere, characterized by a complete reversal of the polar vortex in the winter hemisphere (Scherhag, 1952)

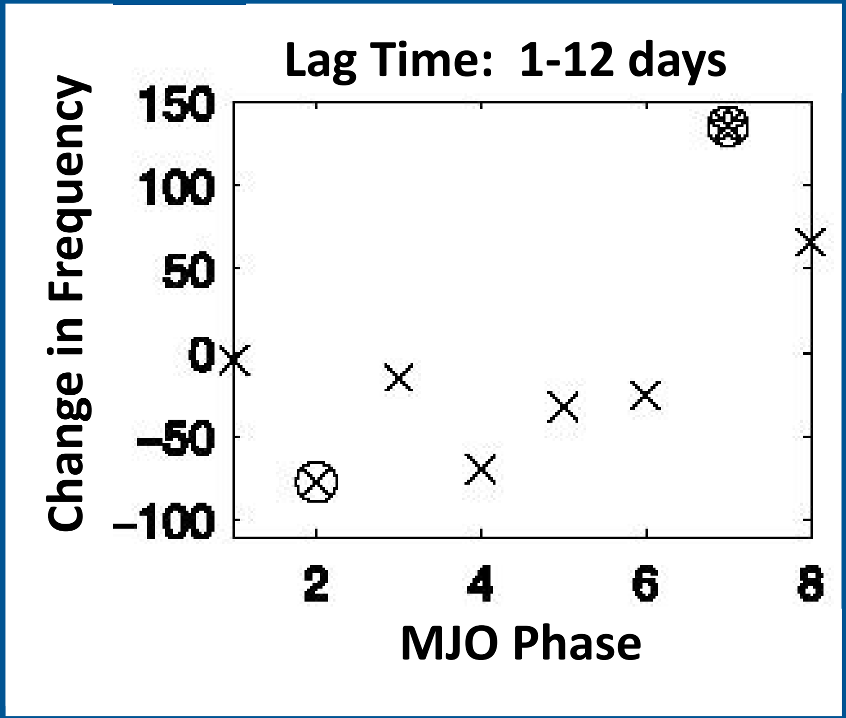
Example of a Sudden Stratospheric Warming on 7 January 2013:



Introduction

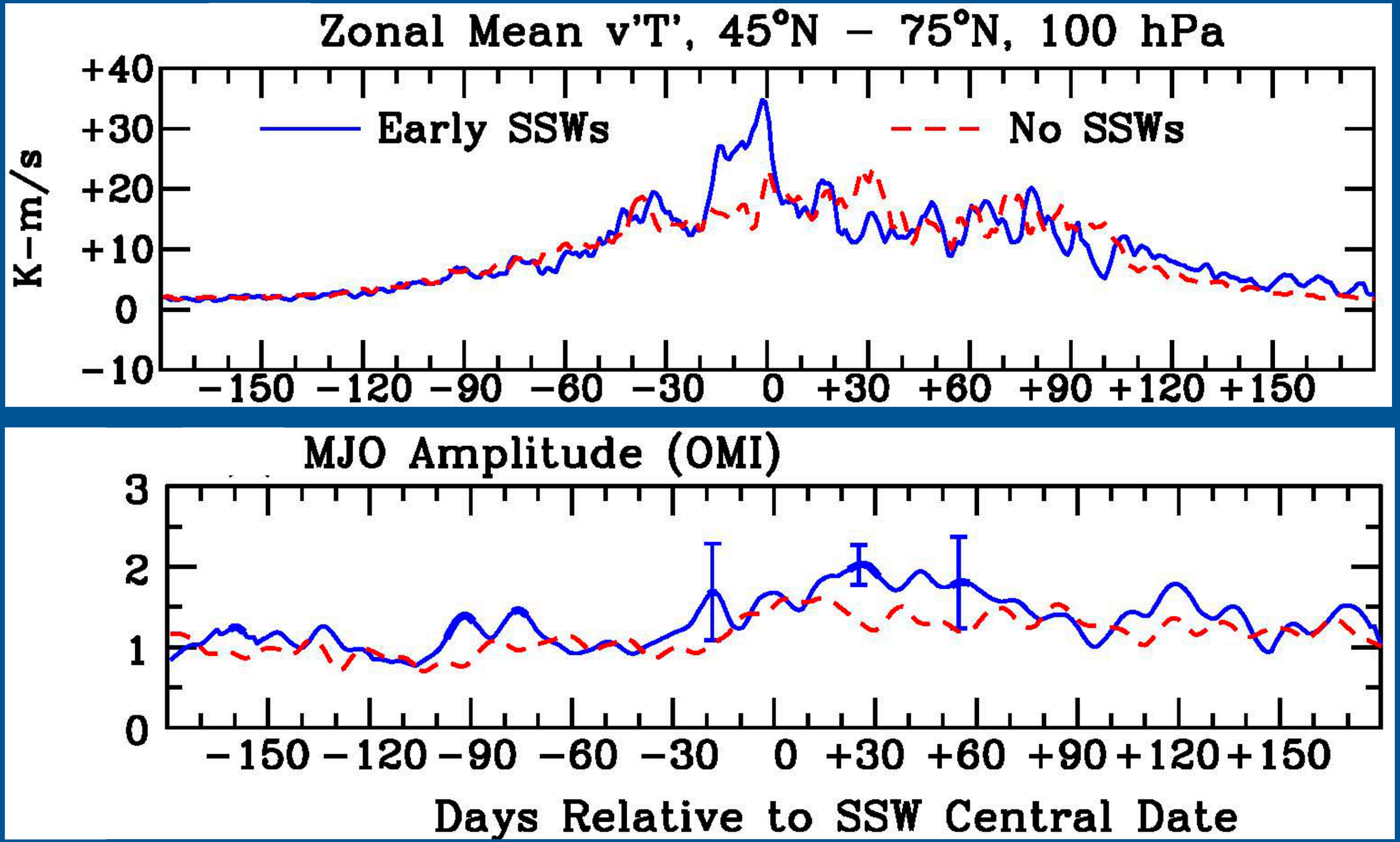
It has previously been found that the MJO can influence the initiation of SSWs in northern winter. Basically, the Aleutian low is deepened following certain MJO phases, which increases the planetary wave one amplitude.





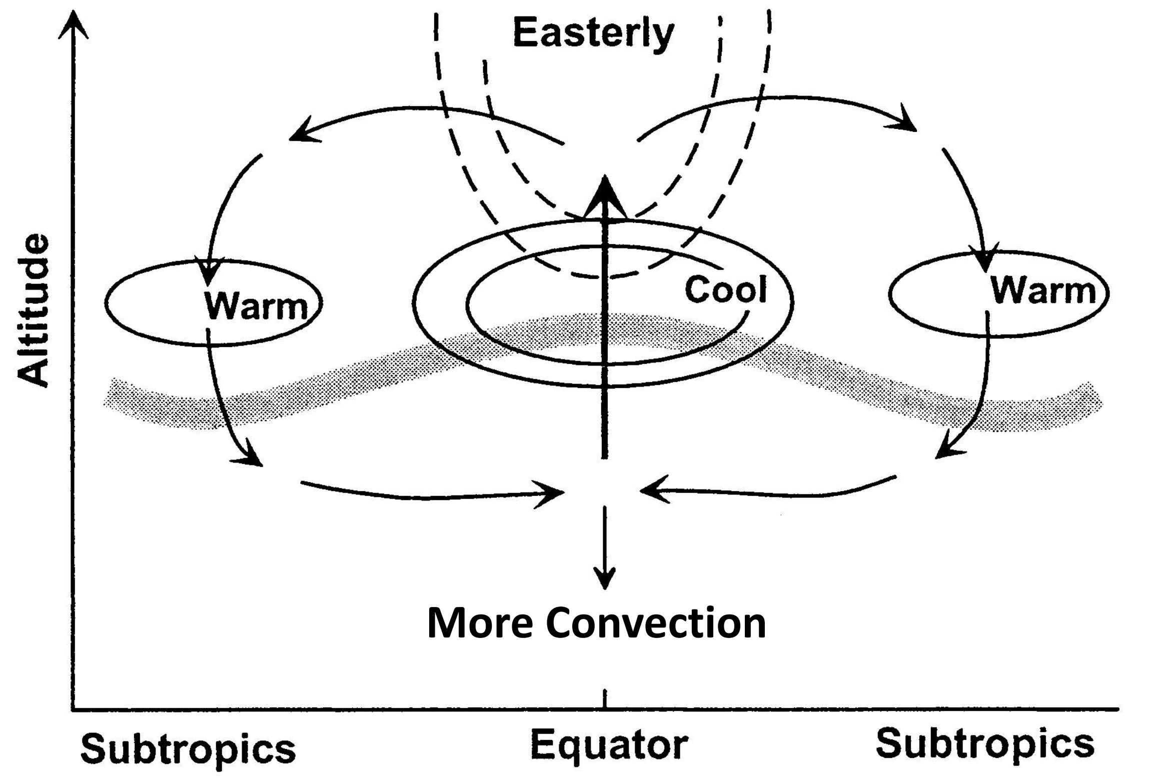
Garfinkel et al., GRL, 2012

Here, we report evidence from both observations and CMIP6 model simulations that the reverse can also happen: SSWs, if they occur in early winter (prior to ~ mid-January), can lead to a strengthening of the MJO.



Hood et al., JGR, 2023

One way in which the QBO can affect static stability in the tropical lower stratosphere is through the QBO induced meridional circulation:



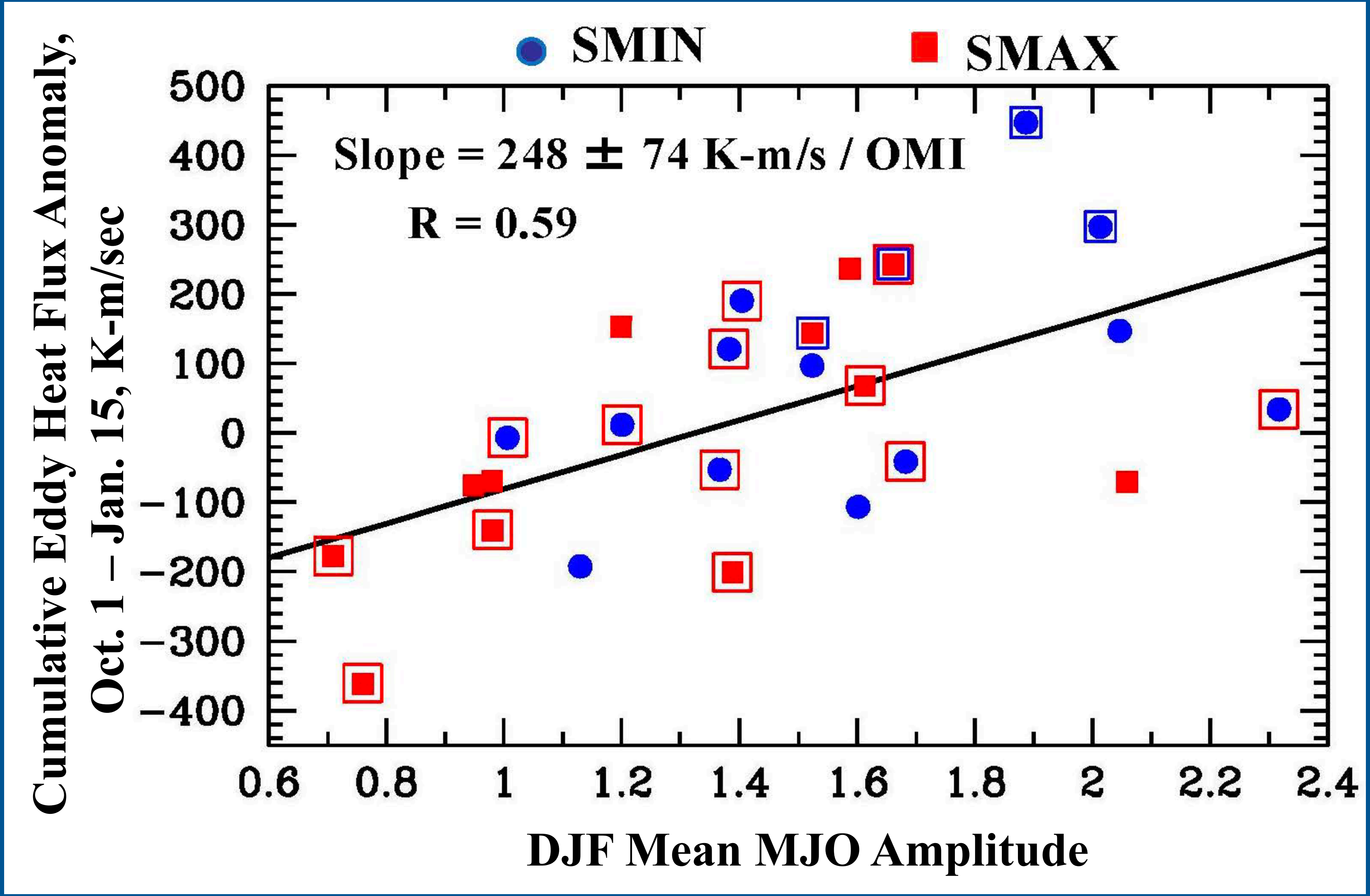
Modified from Collimore et al., J. of Climate, 2003.

<u>Decreased</u> static stability in the tropical lowermost stratosphere

This top-down mechanism would operate in all seasons.

Wave Forcing in Early Winter Plotted vs. MJO Amplitude (DJF):

During SMIN, early winter wave forcing is somewhat stronger and DJF mean MJO amplitudes are larger than during SMAX.

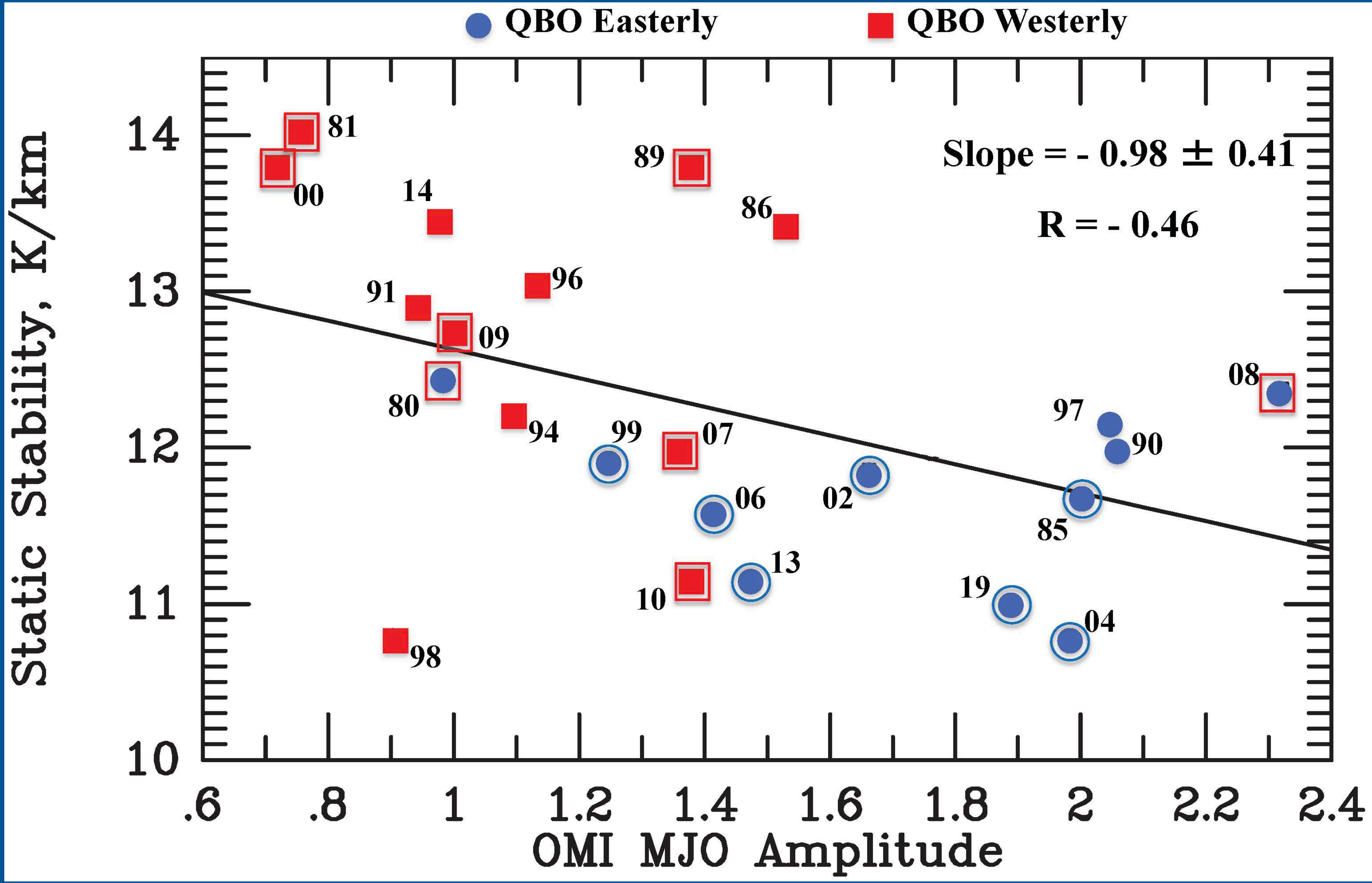


Tropical Lower Stratospheric Static Stability vs. MJO Amplitude (DJF):

QBOE and QBOW Winters

Early Winter SSW

Late Winter SSW



70 to 100 hPa static stability, 10°S – 10°N

Can increased wave forcing in early winter (Holton-Tan effect) be the cause of reduced static stabilities in DJF, which are in turn causing the QBO modulation of the MJO?

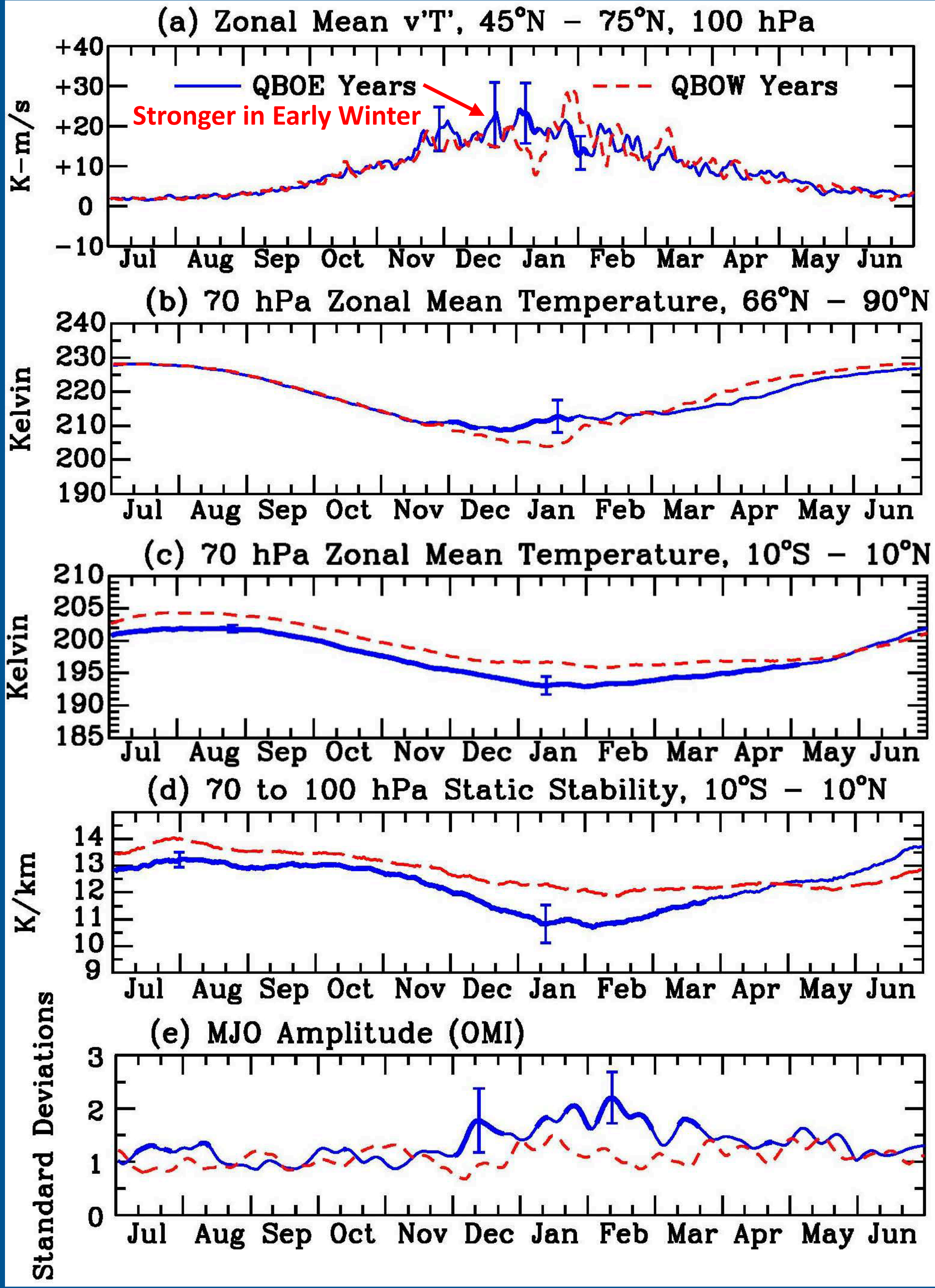
Wave Forcing:

Polar Temperature:

Tropical Temperature:

Tropical Static Stability:

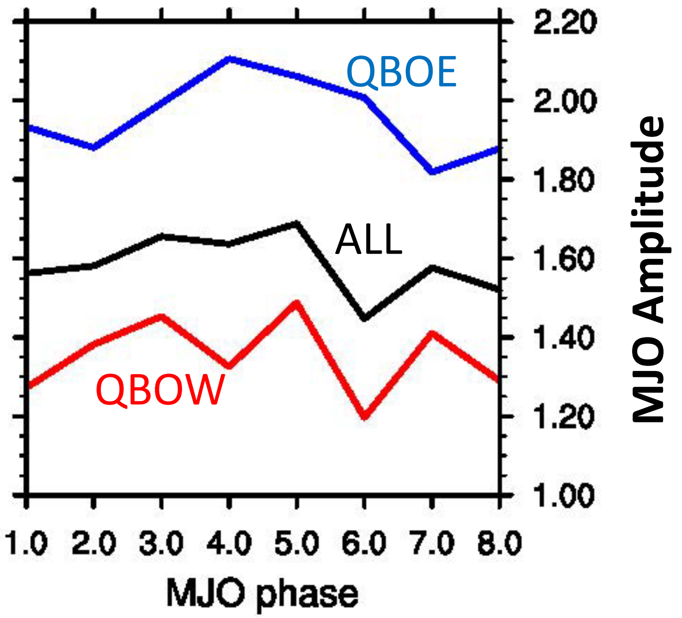
MJO Amplitude:

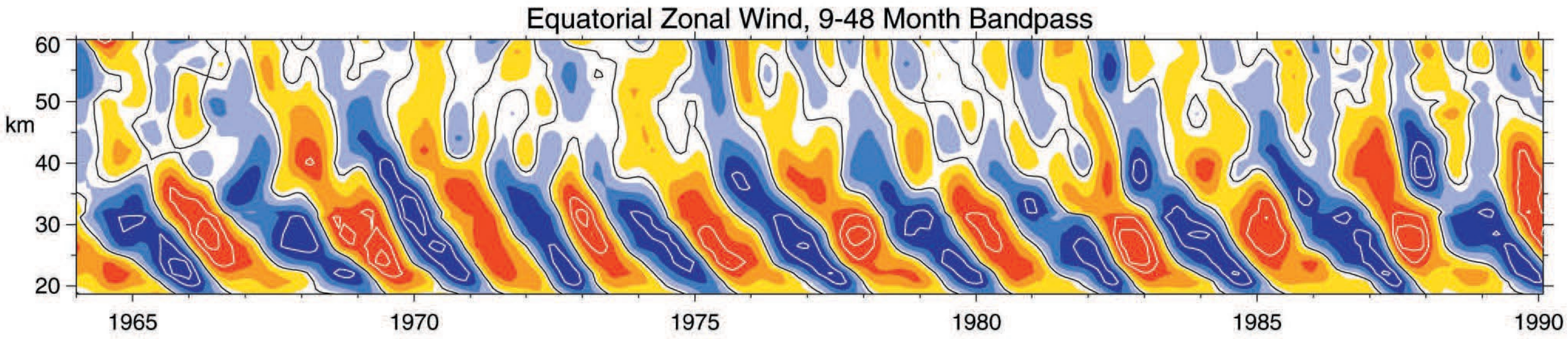


Calculated from ERA5 Reanalysis Data

Beginning about 7 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).

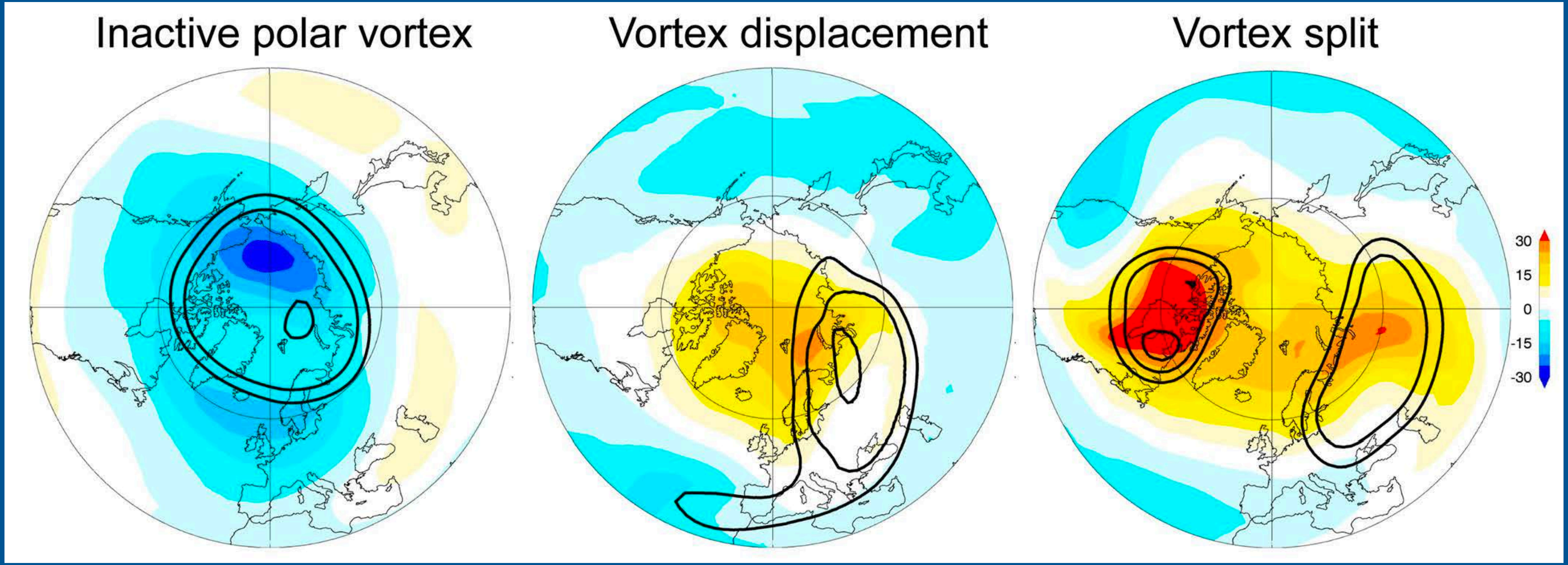
Yoo and Son, GRL, 2016:





Credit: Baldwin et al. 2001

SSWs produce a complete breakdown of the polar vortex, which can have important short-term consequences for tropospheric weather at high latitudes.

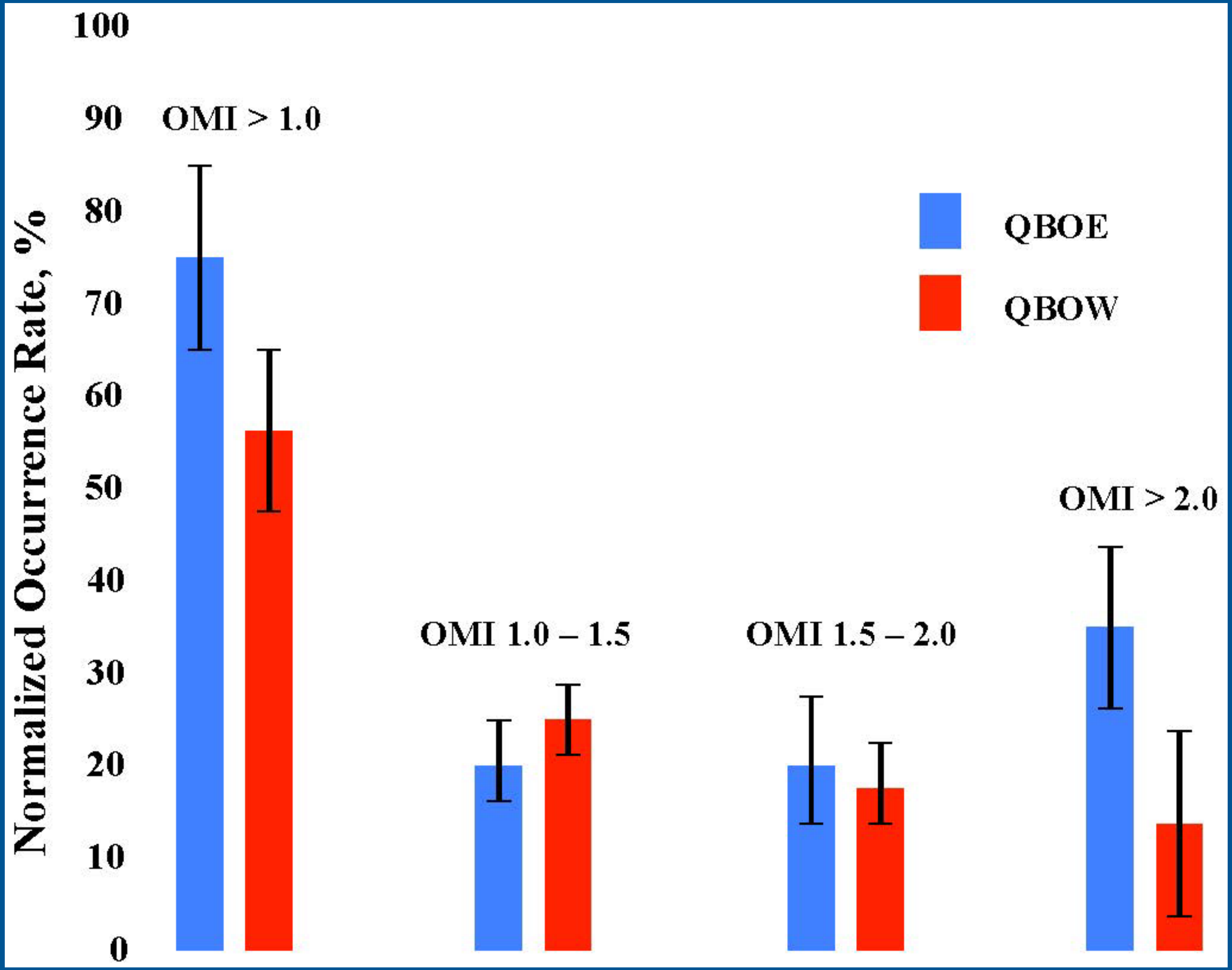


A. H. Butler et al.: A sudden stratospheric warming compendium Earth Syst. Sci. Data, 9, 63–76, 2017

Plotted are temperature anomalies at 10 hPa (shading (K) and potential vorticity at 550 K (contours are for 75, 100, and 125 PV units). MERRA2 reanalysis data are used.

How can a tropospheric convective system like the MJO be influenced by conditions in the lower stratosphere?

<u>Possible Answer:</u>
Only the strongest (OMI > 2) MJO events are significantly affected by the QBO:

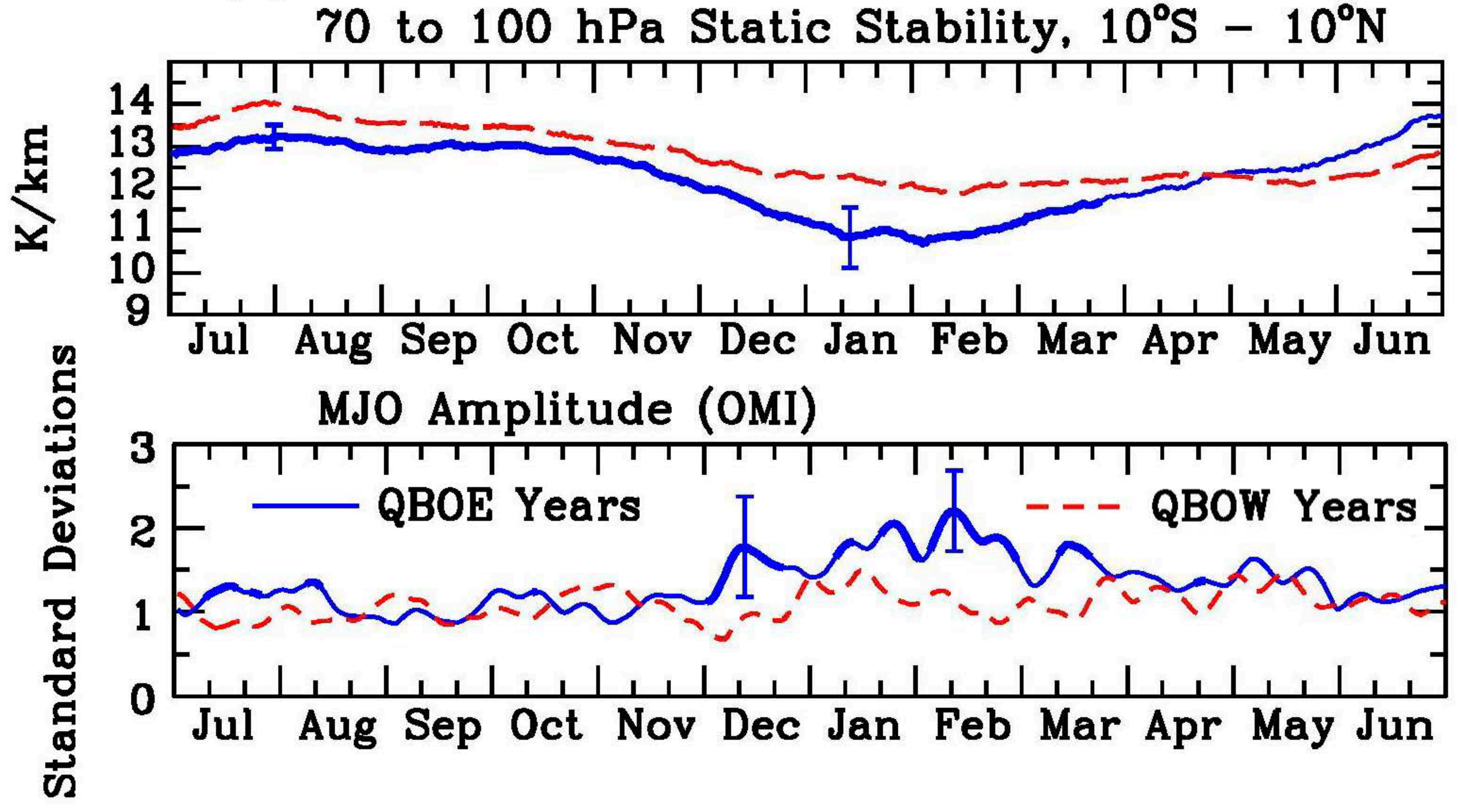


Modified from Hood et al., JAS, 2018.

Composite Analysis of Tropical Lower Stratospheric Static Stability & MJO Amplitude

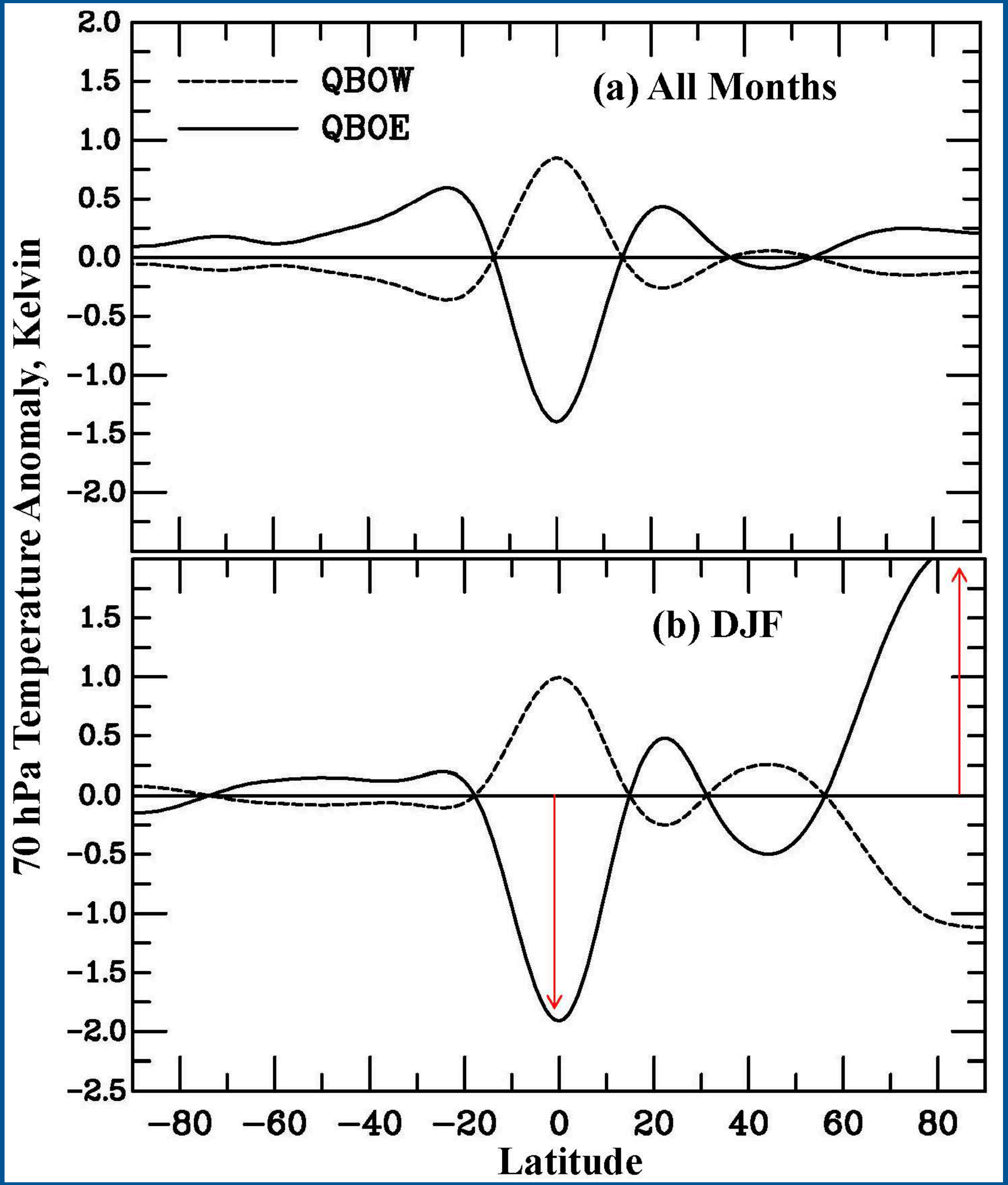
QBOE and QBOW Winters, 1979-2019

Only years that are in a strongly easterly or westerly phase are included.



Heavy blue lines indicate significant differences at 95% confidence

The tropical temperature reduction during QBOE is largest in DJF and is accompanied by a temperature increase at high latitudes.



Calculated from ERA5 Reanalysis Data

What is causing the static stability decrease in QBOE?:

Another possibility is the ”Holton-Tan effect”

2200 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 37

The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb[1]

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(Manuscript received 31 March 1980, in final form 3 July 1980)

ABSTRACT

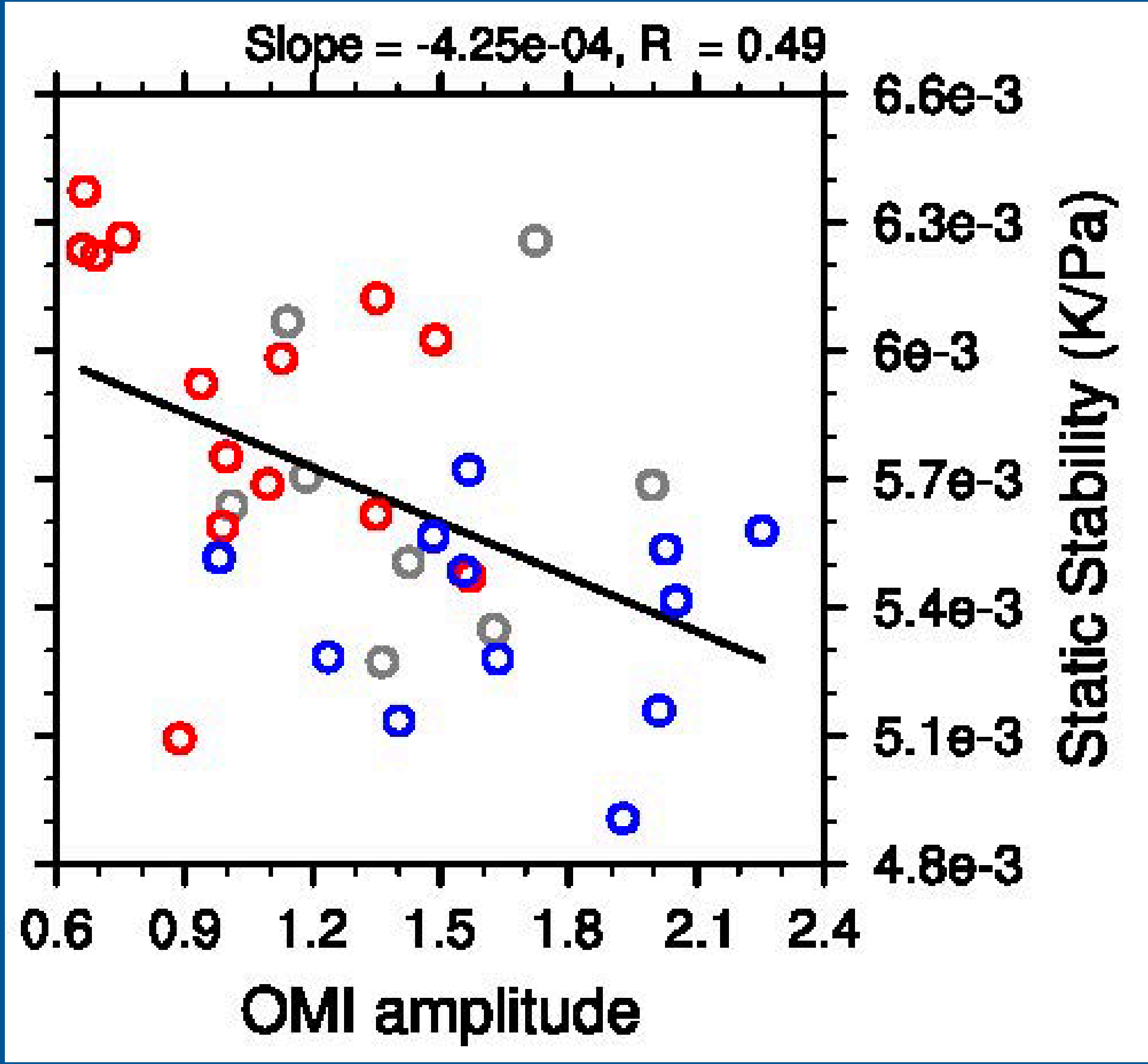
Monthly mean Northern Hemisphere 50 mb geopotential heights for a 16-year period (1962–77) are composited with respect to the phase of the equatorial quasi-biennial oscillation (QBO). The observed zonal mean geopotential height at high latitudes is significantly lower during the westerly phase of the equatorial QBO than during the easterly phase in all months composited.

For this 16-year sample we find that in early winter (November–December) the amplitude of planetary wavenumber 1 is nearly 40% stronger during the easterly phase of the equatorial QBO. In late winter (January–March) the amplitude of planetary wavenumber 2, on the other hand, is nearly 60% stronger during the westerly phase of the equatorial QBO. Data from an additional 6-year sample show a similar

Holton and Tan, JAS, 1980

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

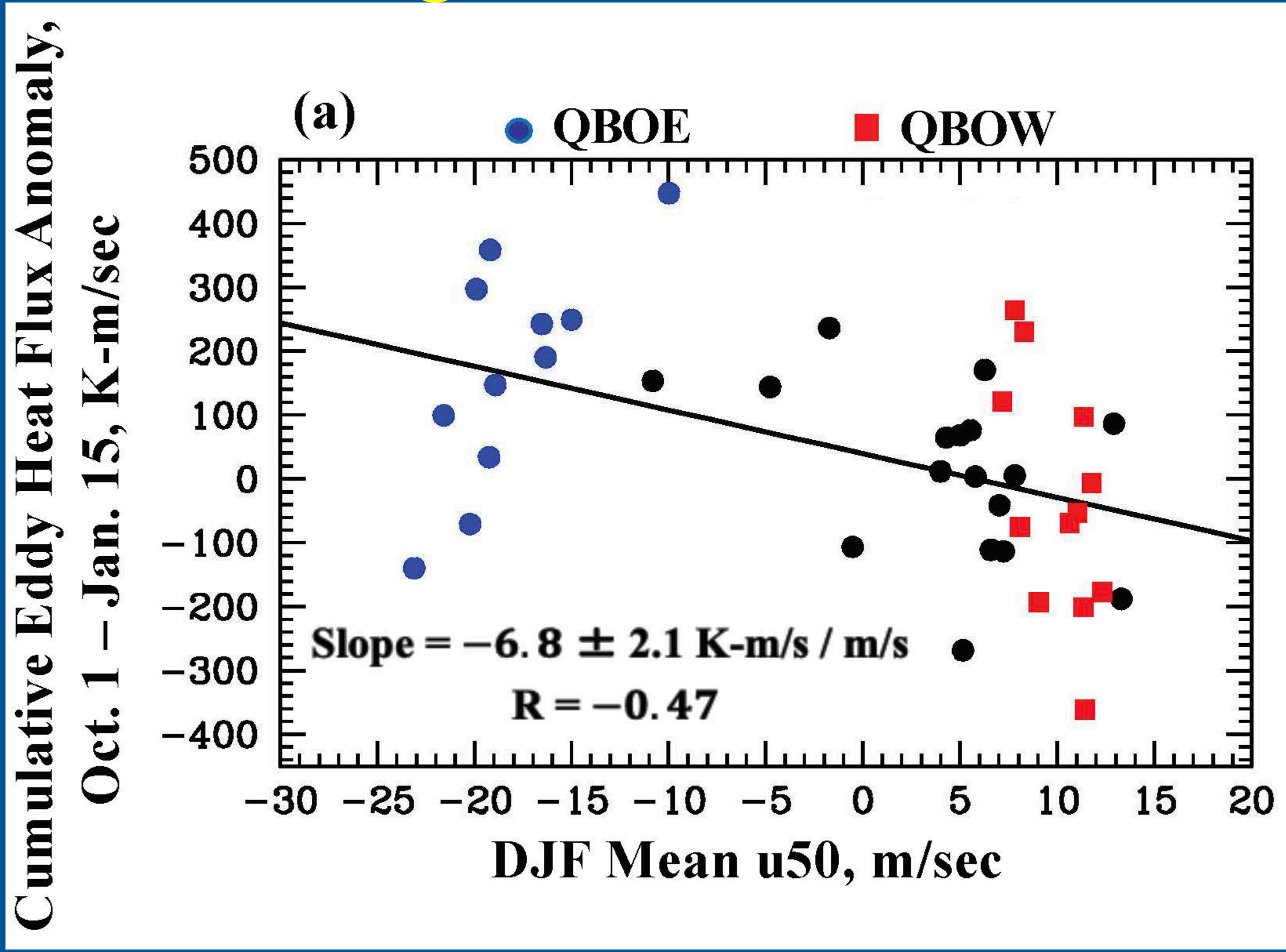
QBOE (blue circles) and QBOW (red circles) Winters



70 to 100 hPa static stability, warm pool region

Yoo and Son, GRL, 2016

Extratropical wave forcing in early winter is larger, on average, in QBOE than in QBOW



Another way to demonstrate the Holton-Tan effect