Seasonal and zonal variations of the MJO impact on upper troposphere/lower stratosphere temperature, circulation, and ozone

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Seasonality of the MJO Impact on Upper Troposphere–Lower Stratosphere Temperature, Circulation, and Composition

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ABSTRACT

Seasonal differences in the impact of the Madden–Julian oscillation (MJO) on tropical and extratropical upper troposphere–lower stratosphere (UTLS) temperature, circulation, and trace gases are examined using trace gases (ozone, carbon monoxide, and water vapor) and temperature from measurements from the Microwave Limb Sounder (MLS) and meteorological fields from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). During boreal winter months (November–February), atmospheric fields

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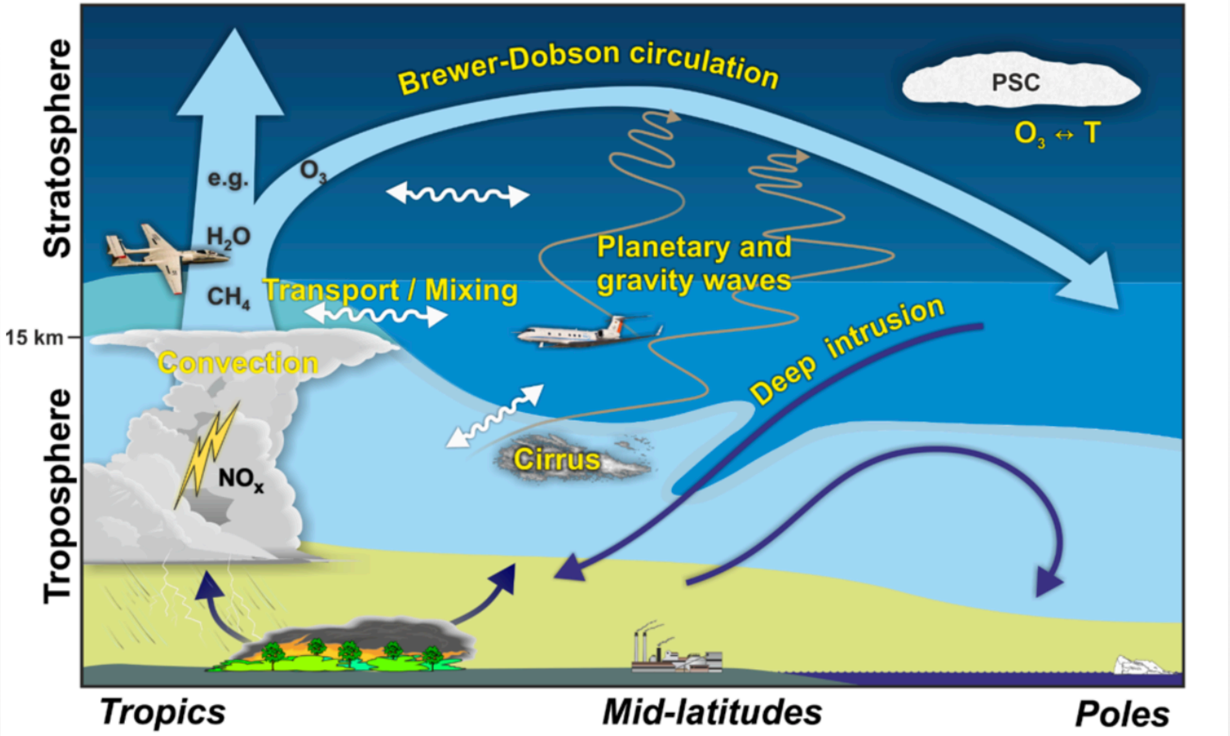
Why do we focus on the UTLS?

- The upper troposphere–lower stratosphere (UTLS) is a unique region of the atmosphere with combined properties of both the troposphere and the stratosphere
- Variations in the radiatively active trace gases (i.e., ozone and water vapor) in the UTLS have a large impact on radiative forcing, influencing surface climate (Lacis et al. 1990; Riese et 2012)
- Atmospheric and oceanic oscillations have a significant impact on the dynamics and composition of the UTLS (Randel and Wu 2015; Fueglistaler et al. 2009a).

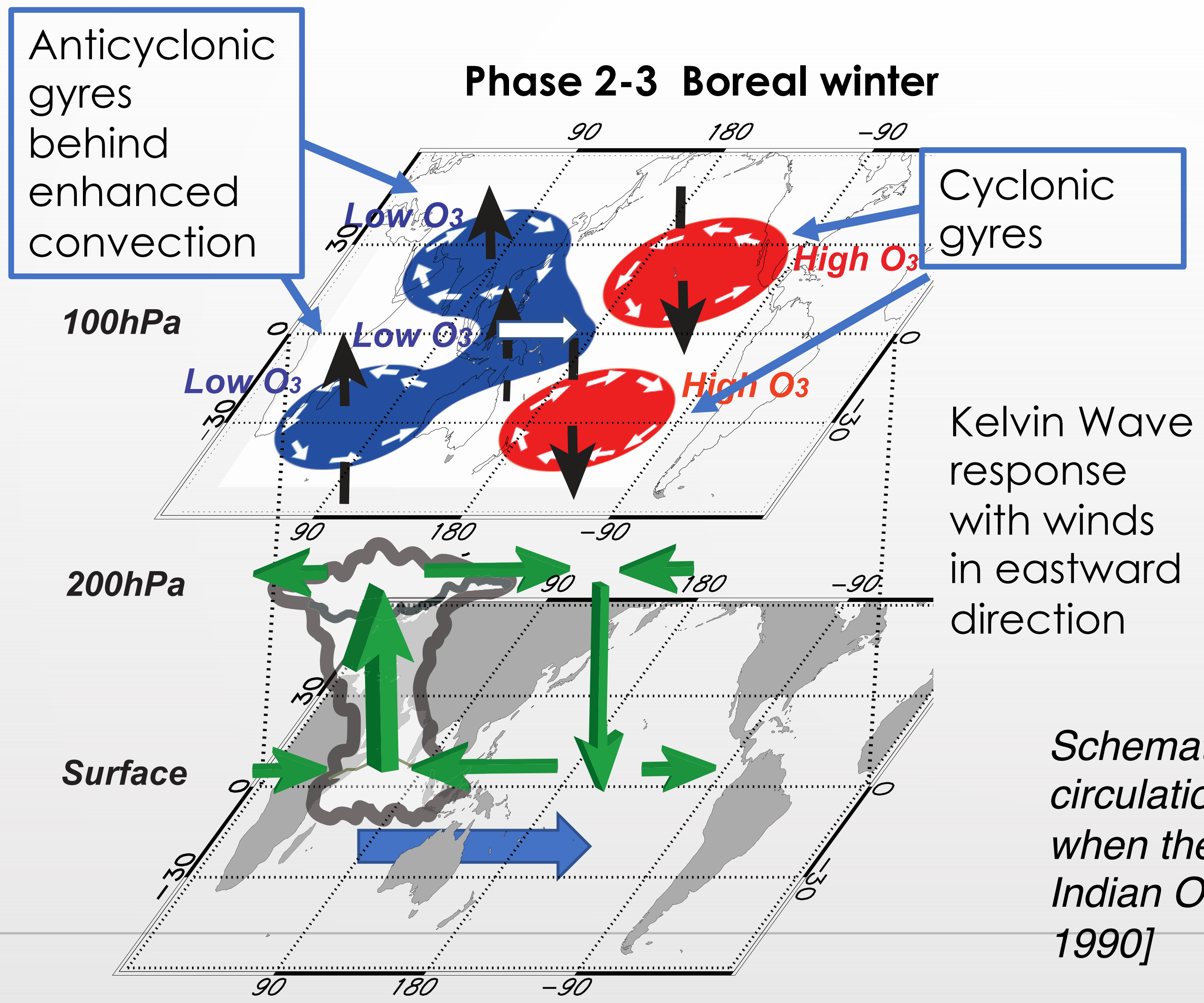


Processes in the upper troposphere and stratosphere

From: https://www.fz-juelich.de/iek/iek-7/EN/Forschung/UTS/uts_node.html

Precise knowledge of variations in T, circulation and composition due to natural processes like the MJO in this key region of the atmosphere is important for model evaluation and in understanding future projections

Vertical structure of the MJO



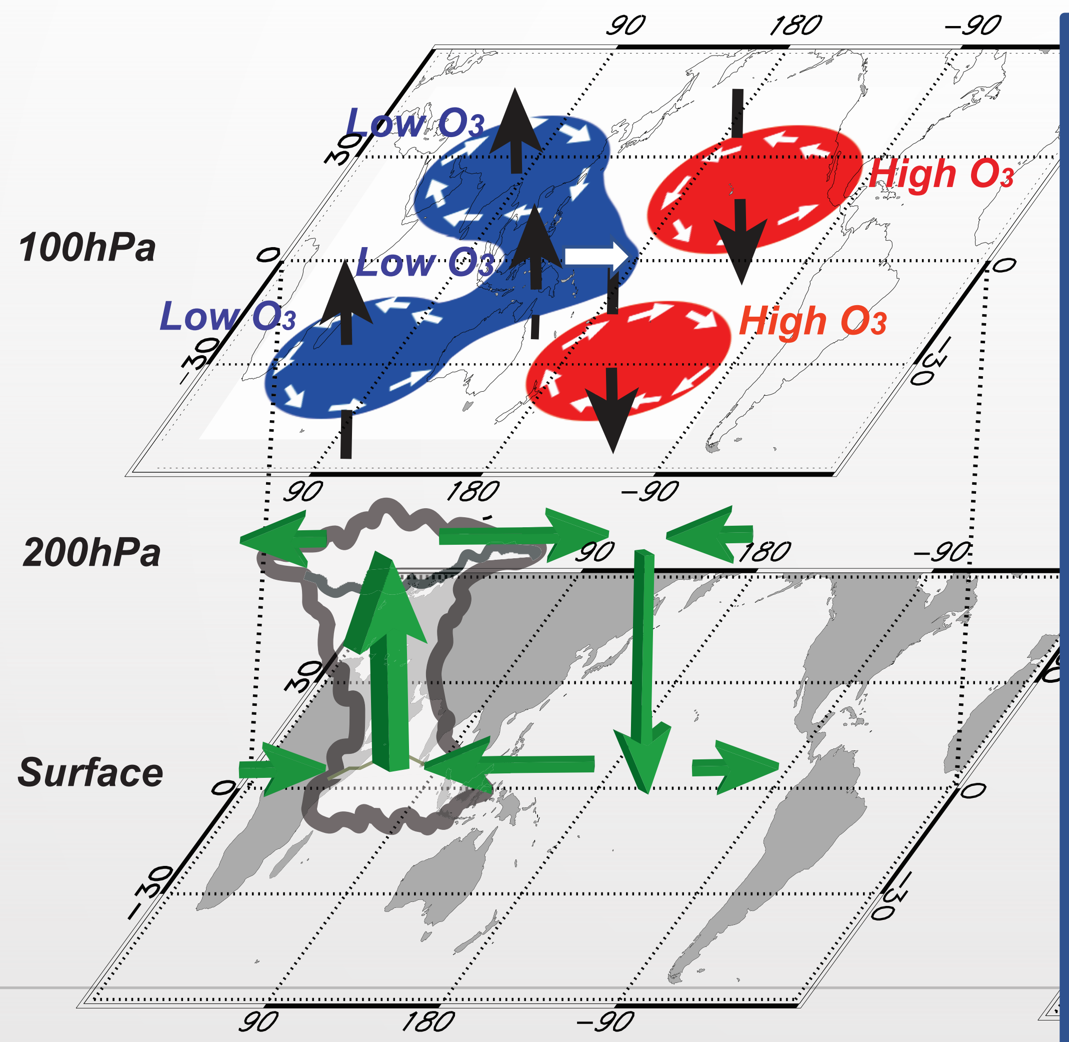
Kelvin Wave response with winds in eastward direction

- Has characteristics of the Rossby wave and Kelvin wave [Gill,1980]
- A major fluctuation in tropical upper troposphere/ lower stratosphere (UTLS) on weekly to monthly timescales.

Schematic depiction of the 100 hPa temperature, circulation and ozone anomalies associated with the MJO when the enhanced convection is centered across the Indian Ocean (RMM1) [adopted from Rui and Wang, 1990]

Vertical structure of the MJO during boreal summer

a) RMM1 boreal winter



b) RMM1 boreal summer ?

Previous studies focused either on:

- **tropospheric circulation** (Knutson et al. 1986; Knutson and Weickmann 1987),
- **boreal winter MJO** (Kiladis et al. 2001; Li et al. 2013; Schwartz et al. 2008; Weickmann et al. 1985),
- **or used full timeseries**(Virts and Wallace 2010, 2014).

Goal of this study: to *emphasize and explain* the differences in the UTLS circulation and trace gas anomalies associated with the MJO during boreal winter (*NDJF*) and summer (*JJAS*) months separately.

DATASETS AND METHODOLOGY

Datasets:

- Observations of ozone and temperature from the Microwave Limb Sounder (MLS, version 4) [Livesey et al., 2015].
- Meteorological fields (U,V, Q) from the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) reanalyses [Gelaro et al., 2017]
- NOAAs daily values of outgoing long-wave radiation (OLR) [Liebmann and Smith, 1996], a proxy for deep convection
- Total diabatic heating rates (Q) is a proxy for upwelling

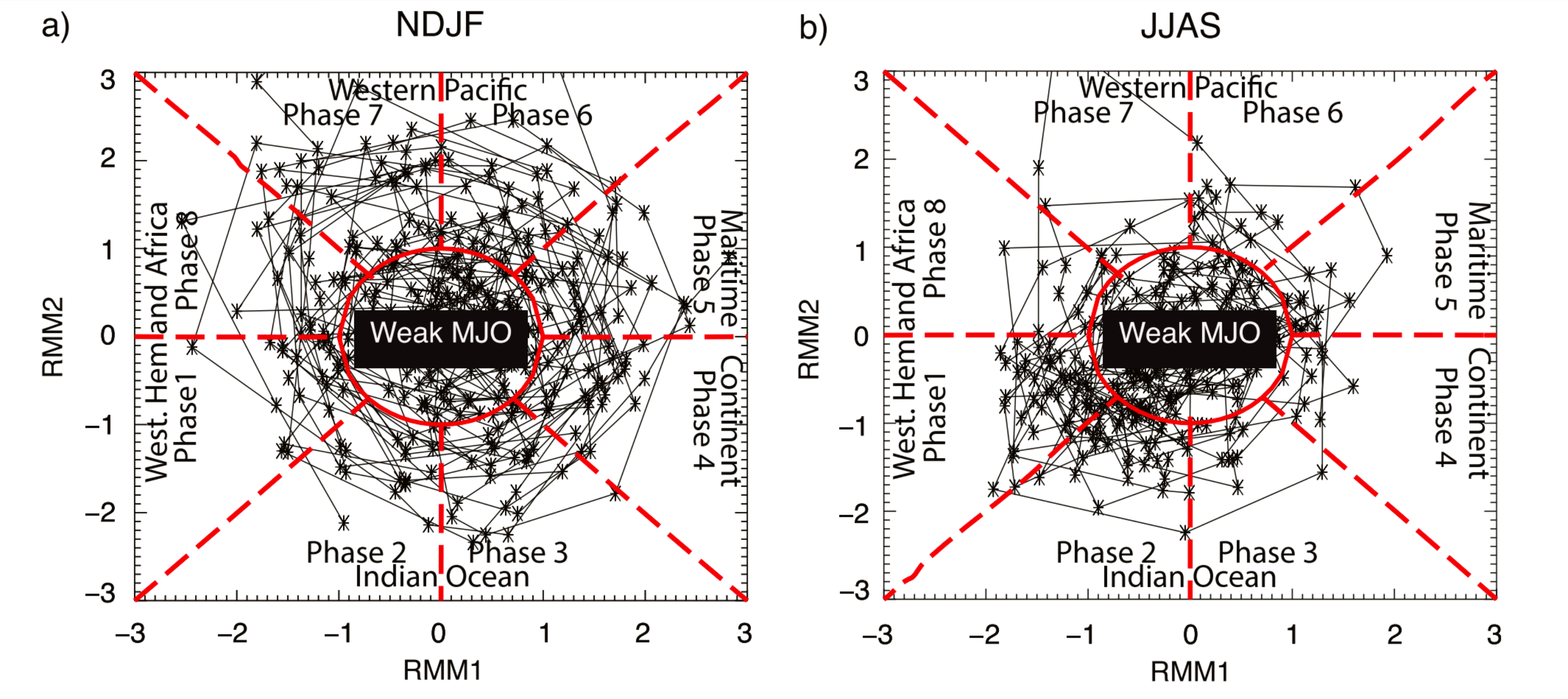
Methodology: all variables are

- *from January 2005 to December 2018 (MLS record)*
- 5-day averaged,
- bandpass-filtered 20-90 days to isolate intraseasonal component,
- linear regressed against MJO index (RMM1 and RMM2)

Seasons: Boreal summer (June – Sept, or **JJAS**) and Boreal winter months (Nov –Feb, or **NDJF**)

Real-time **m**ultivariate **M**JO (**RMM**) index by Wheeler and Hendon [2004]
multivariate EOF analysis of daily 850 hPa zonal winds, 200 hPa zonal winds and OLR (15N -15S)

Phase space defined by two components of RMM

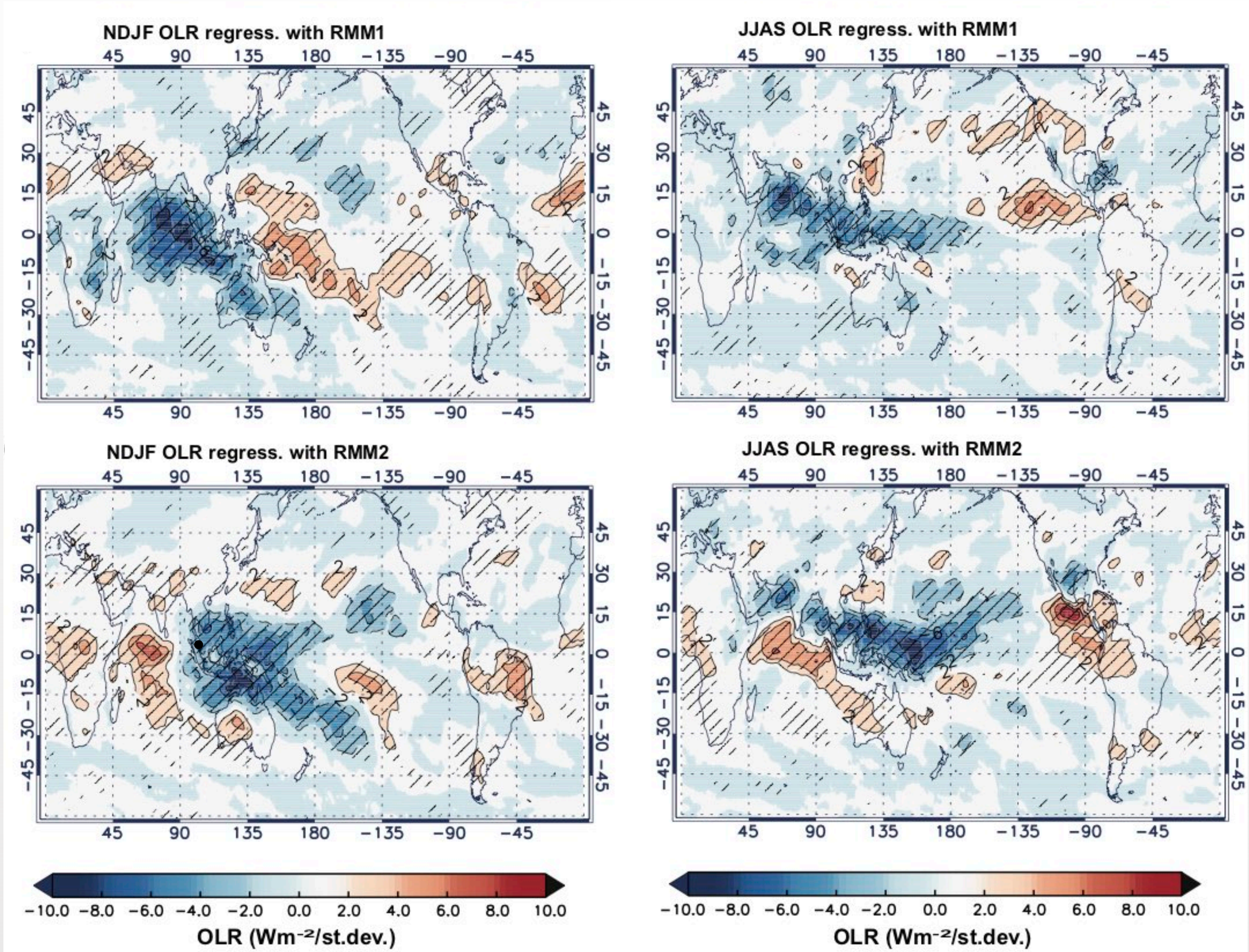


The MJO is stronger and more frequent during boreal winter (NDJF) than summer months (JJAS);

However, there is a good number of moderate to strong events during the summer

Phase space defined by two components of real-time multivariate MJO index (RMM1 and RMM2) for pentads (5-day averages) in (a) Nov- Feb and (b) July -Sept from January 2004 to December 2018. Labeled are the approximate locations of the enhanced convection associated with the MJO (e.g., the Indian Ocean for phases 2 and 3)

SEASONALITY OF THE MJO CONVECTION

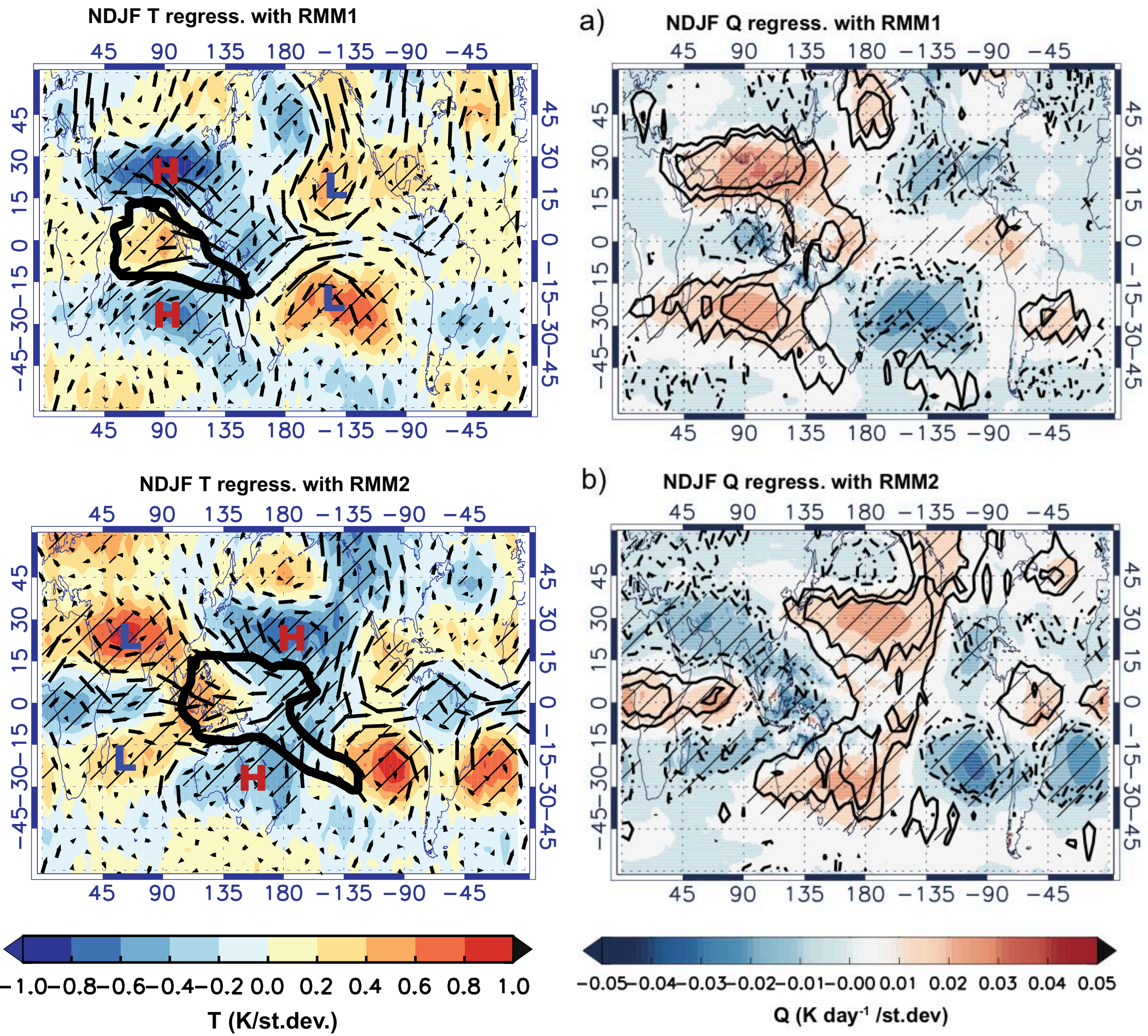


Enhanced convection over Indian Ocean during a peak in RMM1 (top) and over the Maritime Continent and Western Pacific during a peak in RMM2 (bottom)

Well-known northward shift of the OLR during boreal summer months (right)

The MJO propagation during boreal winter (NDJF) and summer (JJAS). Shown are OLR as a proxy for deep convection, regressed into MJO indices (RMM1 and RMM2). Low values of OLR (blue) indicate regions of enhanced convection and vice versa.

Atmospheric temperature and circulation at 100 hPa: boreal winter



- Well-known stationary response of T and circulation over the convective hotspot, resembling a classic "Gill-type" Kelvin-Rossby Wave solution (Gill, 1980)
- Kelvin –Rossby wave response is coupled to the heating source (e.g. convection)

Left: Filtered T (shaded)/horizontal winds (arrows) at 100 hPa,
Right: Diabatic heating rates (Q, positive is for upwelling) with a few T contours, regressed onto (a) RMM1 and (b) RMM2.
Hatching indicates regions that are statistically significant at the 95% confidence level. Centers of high and low pressure systems are indicated by H and L, respectively.

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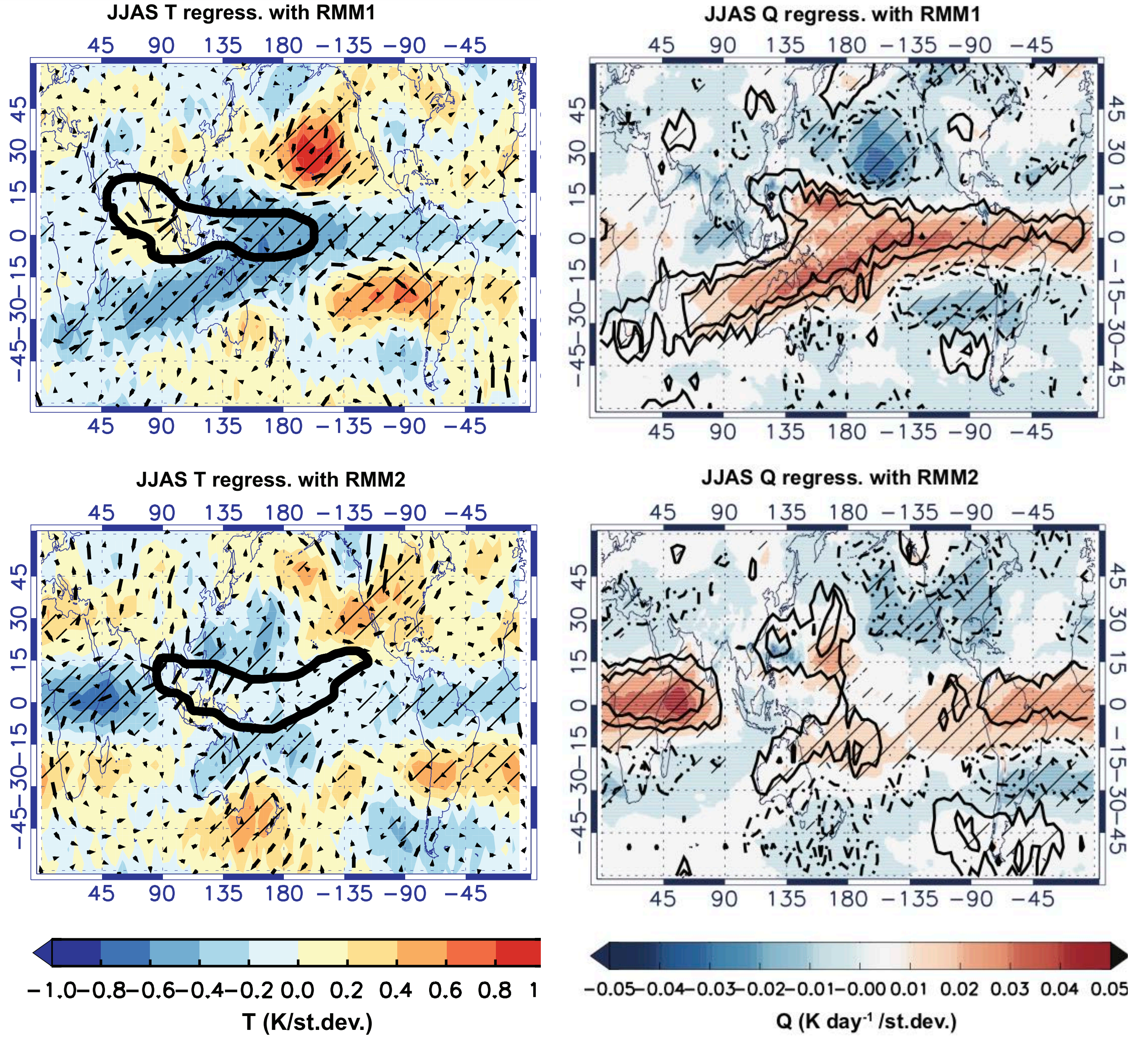
Atmospheric temperature and circulation at 100 hPa: boreal summer



- Uncoupled from the MJO convection free Kelvin wave response with faster moving "Kelvin wave front"
- Zonally uniform tropics-wide cooling (solid thick contours) and upwelling (in red)

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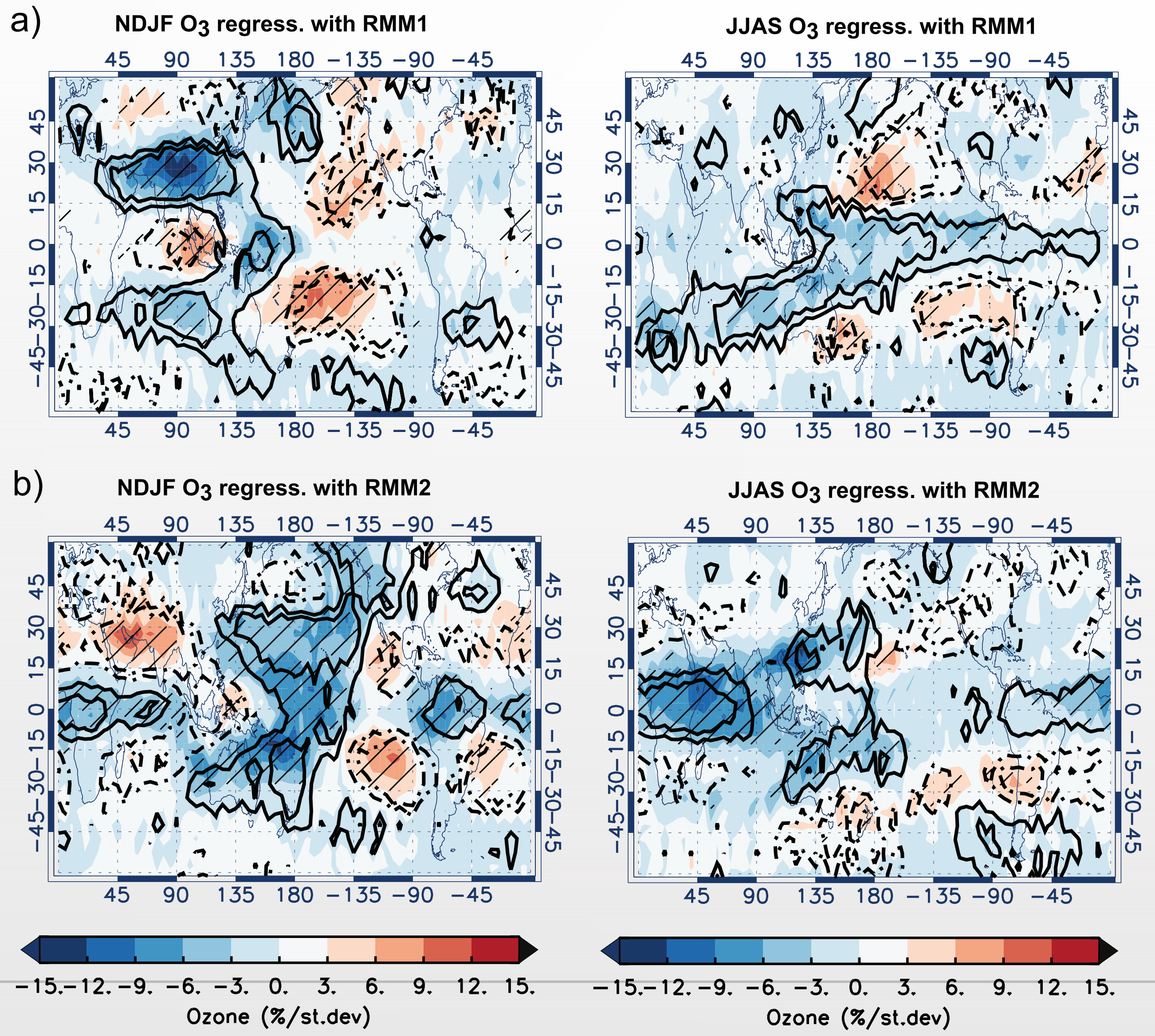
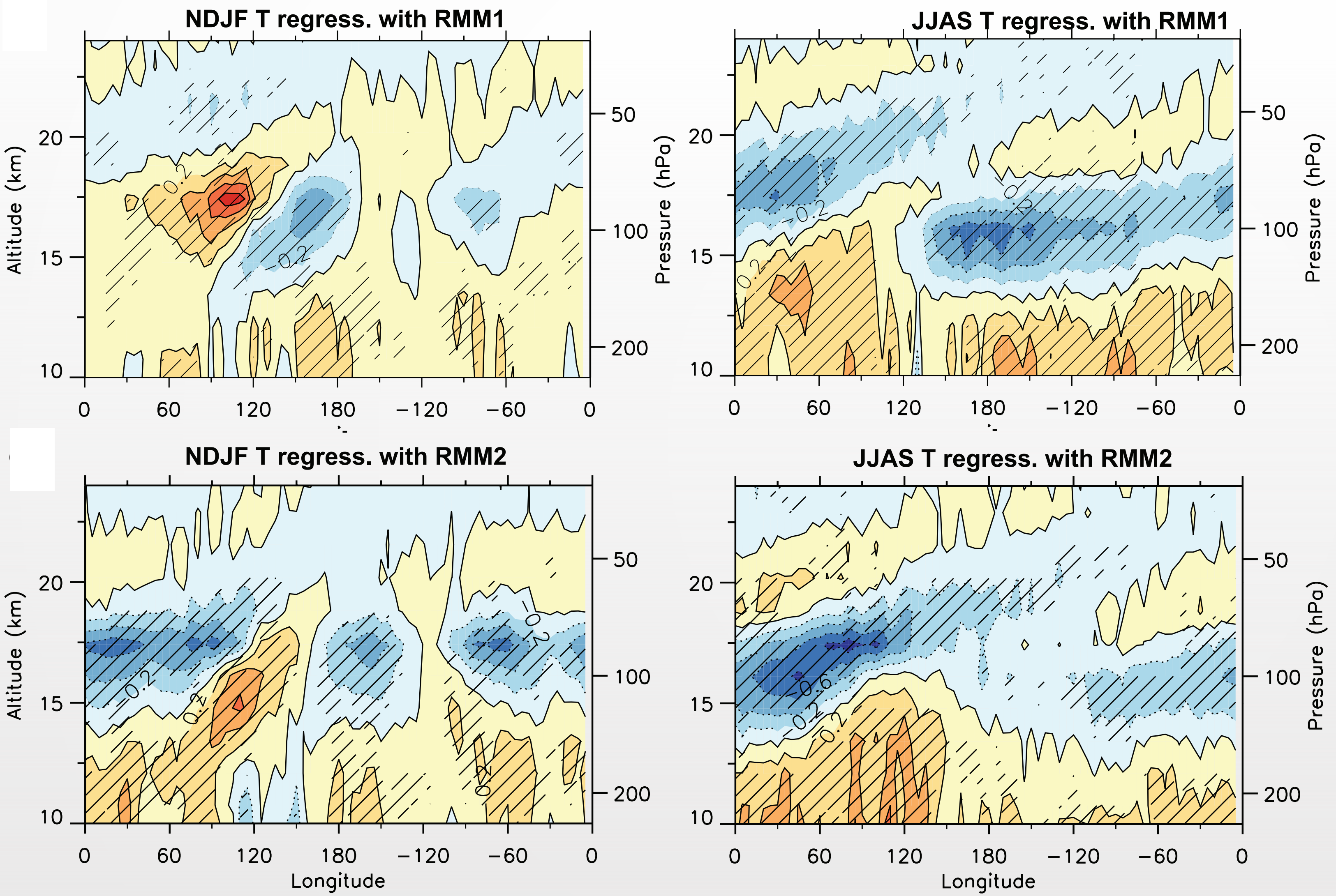
100hPa ozone response to the MJO



- In a good agreement with changes in temperature and vertical motion
- Enhanced upwelling associated with "Kelvin wave front" results in reduction of ozone (e.g., low ozone transport from below)

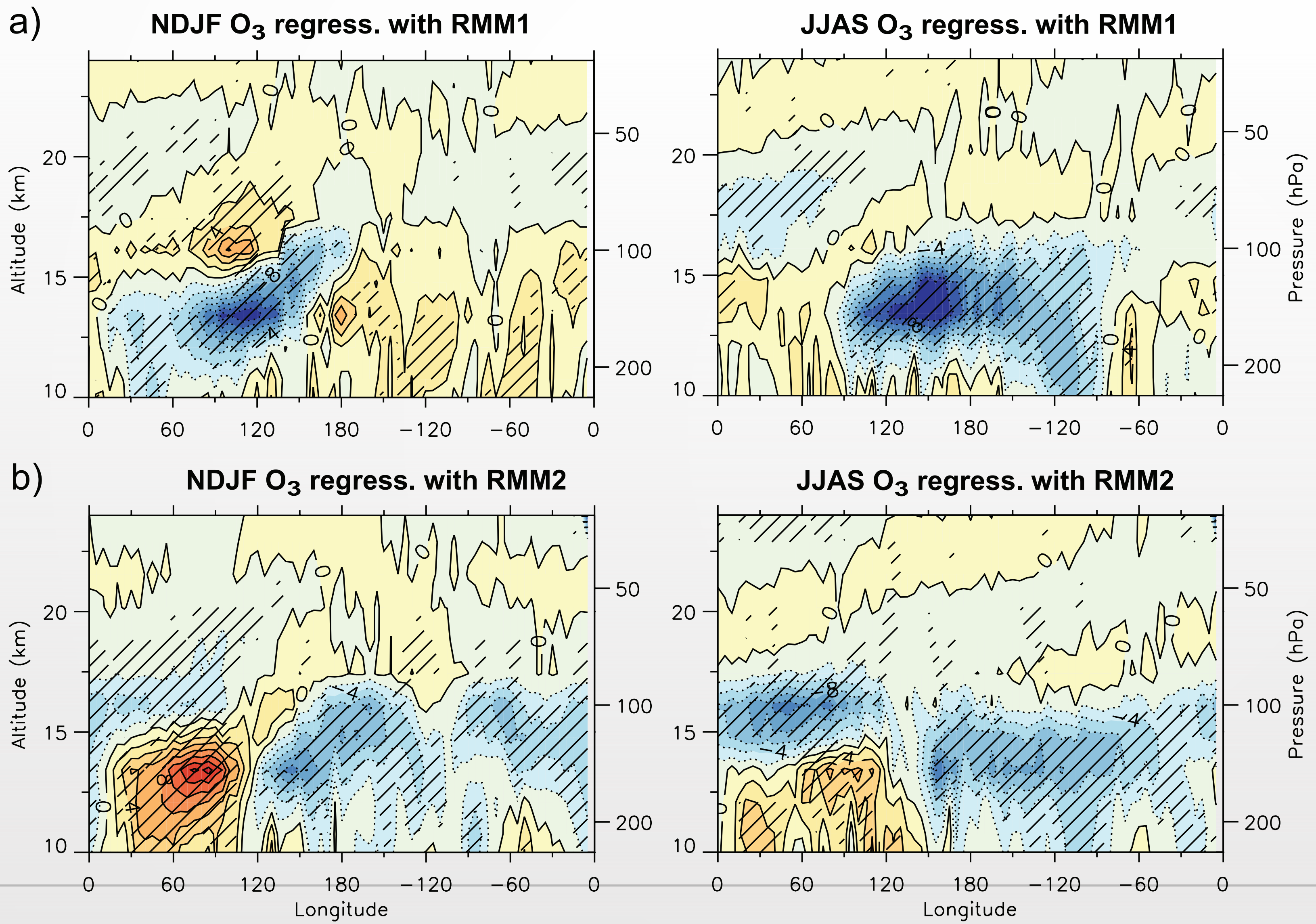
Vertical profiles of temp. sensitivities (5N-5S)



- Kelvin waves can be detected in T perturbations:
  - ❑ Upward and eastward sloping anomalies
  - ❑ Downward phase propagation

Longitudinal - height section along the equator showing filtered T, regressed onto RMM1 and RMM2 during boreal summer and winter months

Vertical profiles of ozone sensitivities (5N-5S)



Longitude-height profiles of the 20-90 day bandpass-filtered ozone, averaged over 5N - 5S and regressed with a) RMM1 and b) RMM2 during boreal winter (NDJF, left) and summer (JJAS, right).

DYNAMICAL CONTROLS

- We apply the analysis of Kelvin wave amplitude by Ryu et al. (2008) for boreal winter (NDJF) and summer (JJAS) separately:

(1)
$$\frac{\partial A}{\partial T} + \frac{\partial AC_{gx}}{\partial X} + \frac{\partial AC_{gz}}{\partial Z} = 0$$

the wave action (A) conservation law for equatorially trapped waves (we follow the rays that are parallel to the local group velocities)

(2)
$$C_{gx}(X,Z,T) = U(X,Z) - N(X,Z)/m(X,Z,T)$$
$$C_{gz}(X,Z,T) = N(X,Z)k(X,Z,T)/m^2(X,Z,T)$$

Group velocity in X and Z direction

After some assumptions (k, m are constants; etc.)

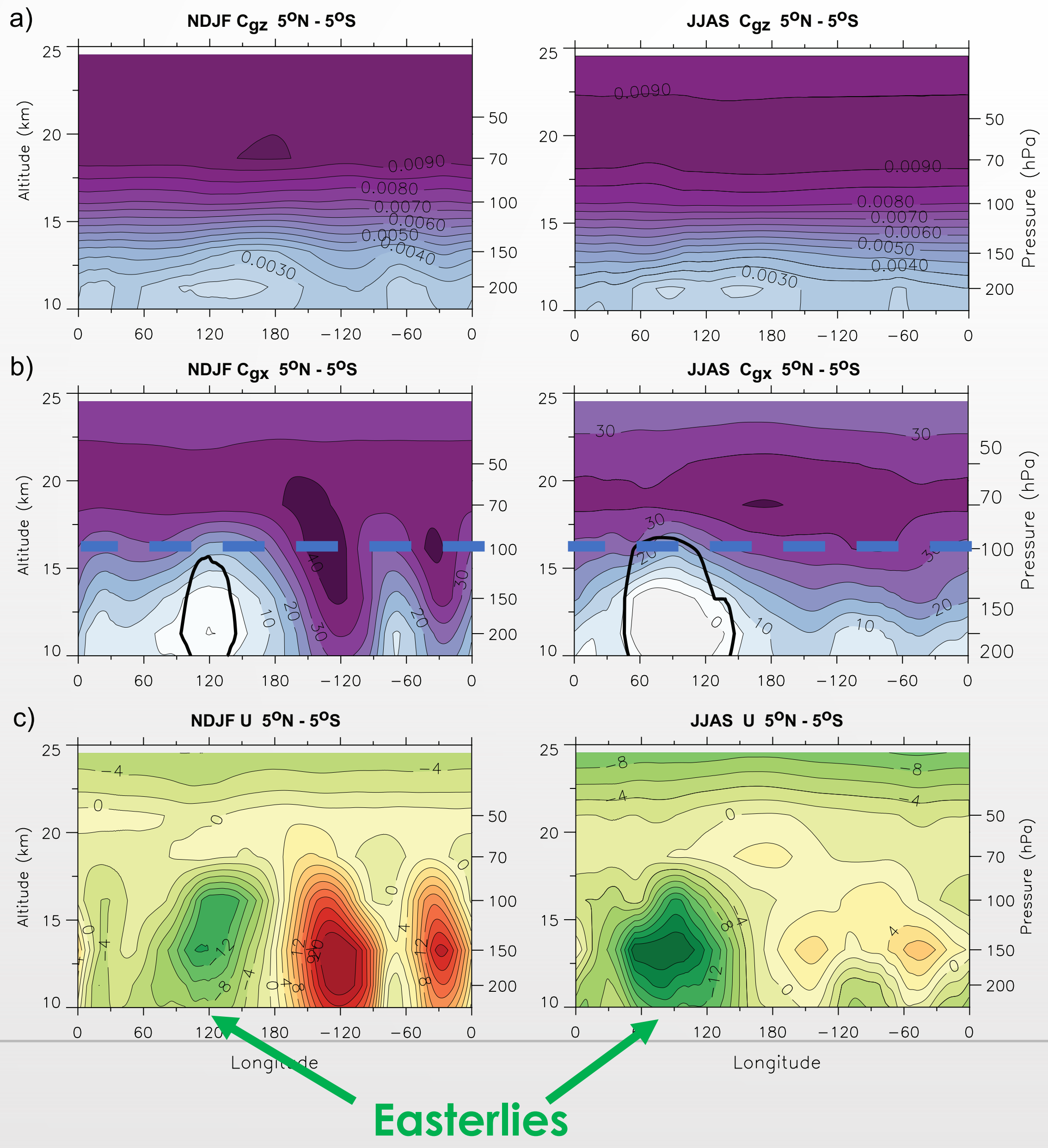
(3-4)
$$AC_{gz} \approx \text{constant along } z.$$

In regions where the rays are sufficiently steep (i.e., almost vertical)

$$AC_{gx} \approx \text{constant along } x.$$

In the regions where rays are nearly horizontal

DYNAMICAL CONTROLS (cont.)



$$C_{gx}(X,Z,T) = U(X,Z) - N(X,Z)/m(X,Z,T)$$

$$C_{gz}(X,Z,T) = N(X,Z)k(X,Z,T)/m^2(X,Z,T)$$ = N(X,Z)x Constant

$AC_{gz} \approx$ constant along z

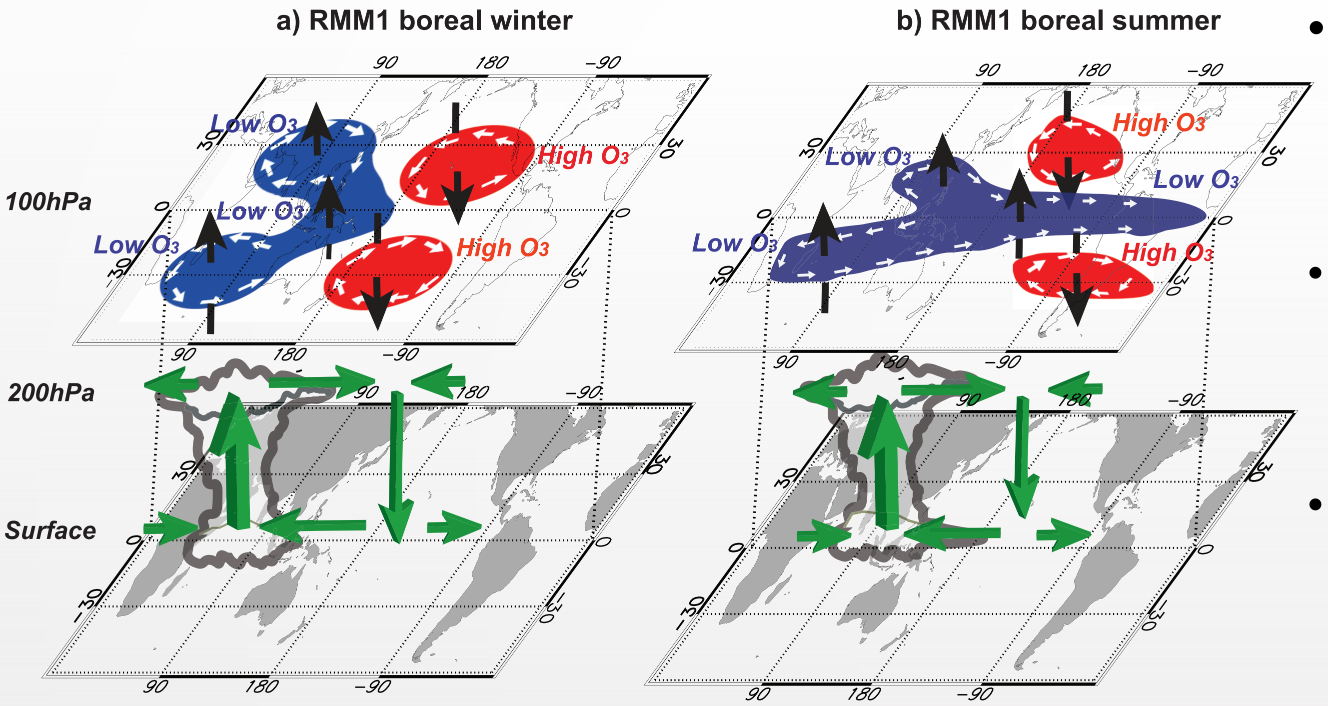
$AC_{gx} \approx$ constant along x.

Seasonal variations in horizontal group velocity (**C_{gx}**, in b) are mainly due to zonal differences in the climatological zonal winds (**U**, in c)

- JJAS Kelvin waves amplify more westward and propagate further east due to:

1) **stronger equatorial easterlies** that are also located more westward, and
2) **weaker westerlies** in the western hemisphere

Conclusions



- **The response of T, circulation, and O_3 during boreal summer is different from the response during boreal winter.**

- NDJF: planetary-scale perturbations consistent with the upper level flow of the model by Gill (1980) and is a combination of Rossby and Kelvin flows patterns.
- JJAS: twin high- and low-pressure extratropical systems are weaker during JJAS with a much stronger equatorial Kelvin wave front.

- The Kelvin wave front produces enhanced upwelling leading to a strong cooling and reduction of ozone.
- Seasonal differences are mainly due to differences in the zonal structure of Kelvin wave horizontal group velocity at the equator, which strongly depends on the background zonal winds (more details are in *Tweedy et al., 2020, JAS*)
- The analysis of MLS observations presented here may be useful for evaluation and validation of the MJO-related physical and dynamical processes

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