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Long-term variability of Rossby wave breaking events over the Indian subcontinent

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1. Introduction

The synoptic scale upper level Rossby wave breaking (RWB) has a great influence on the weather pattern on the underlying regions. The RWB events have been studied extensively in the mid-latitude regions as it is prone to such events which often lead to extreme weather conditions. However, not much studies are available exclusively over the Indian sub-continent except a few cases. In this study, we use reanalysis data and implement a contour searching algorithm to identify the climatology of RWB events over the period 1979-2021. Our algorithm detects 513 RWB events during the analysis period. Our results suggest a increase in the number of RWB events per year during the last two decades. Further, our analysis shows that RWB promotes extreme rainfall events (ERE) by generating instability in the atmosphere allowing enhanced moisture influx over the region. It is also noted that interannual-to-decadal variations in the number of RWB events are linked to global Sea Surface Temperature (SST) conditions in the, particularly in the Pacific ocean.

2. Data and Methodology

The algorithm is based on Moore et al. (2019), Strong and Magnusdottir (2008), and Barnes et al. (2012) and modified for the Indian region

PV thresholds: 1, 1.5, 2 PVU

Pressure levels: 150, 200, 225, 250, 300 hPa

Temporal criteria: Event should exist more than 18 hours

Data used: ERA-5 reanalysis data

Spatial resolution: 1° × 1°

Temporal resolution: 6 hours

NCEP Reanalysis data

$$PV = -g(\zeta_\theta + f)\,\partial\theta/\partial p$$

$$PVU = 1\times10^{-6}\ K\ kg^{-1}\ m^2\ s^{-1}$$

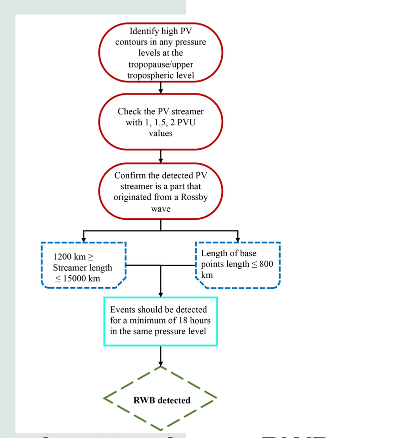

Figure 2: Flowchart to detect RWB event adopted in this study

To examine the physical mechanism associated with RWB both in the upper and the lower levels, an anomaly composite analysis of 127 strong vertically intruded cases (penetration greater than or equal to 450 hPa) has been performed. The anomalies are calculated by subtracting the breaking day features with daily climatologies for the period 1979-202.

Since all the RWB events occur in different regions of the Indian region, the centroid and the relative domain selection captures the properties of the atmosphere in a domain at the time of RWB in a climatological aspect without reducing its signal strength.

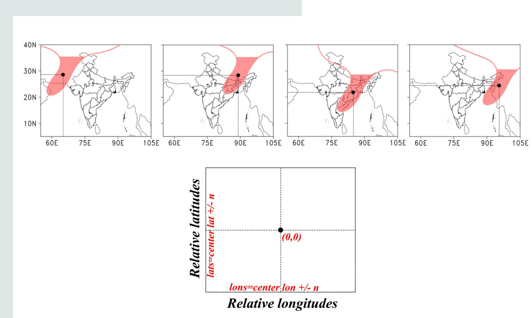

Figure 3: Schematic diagram of the centroid selection

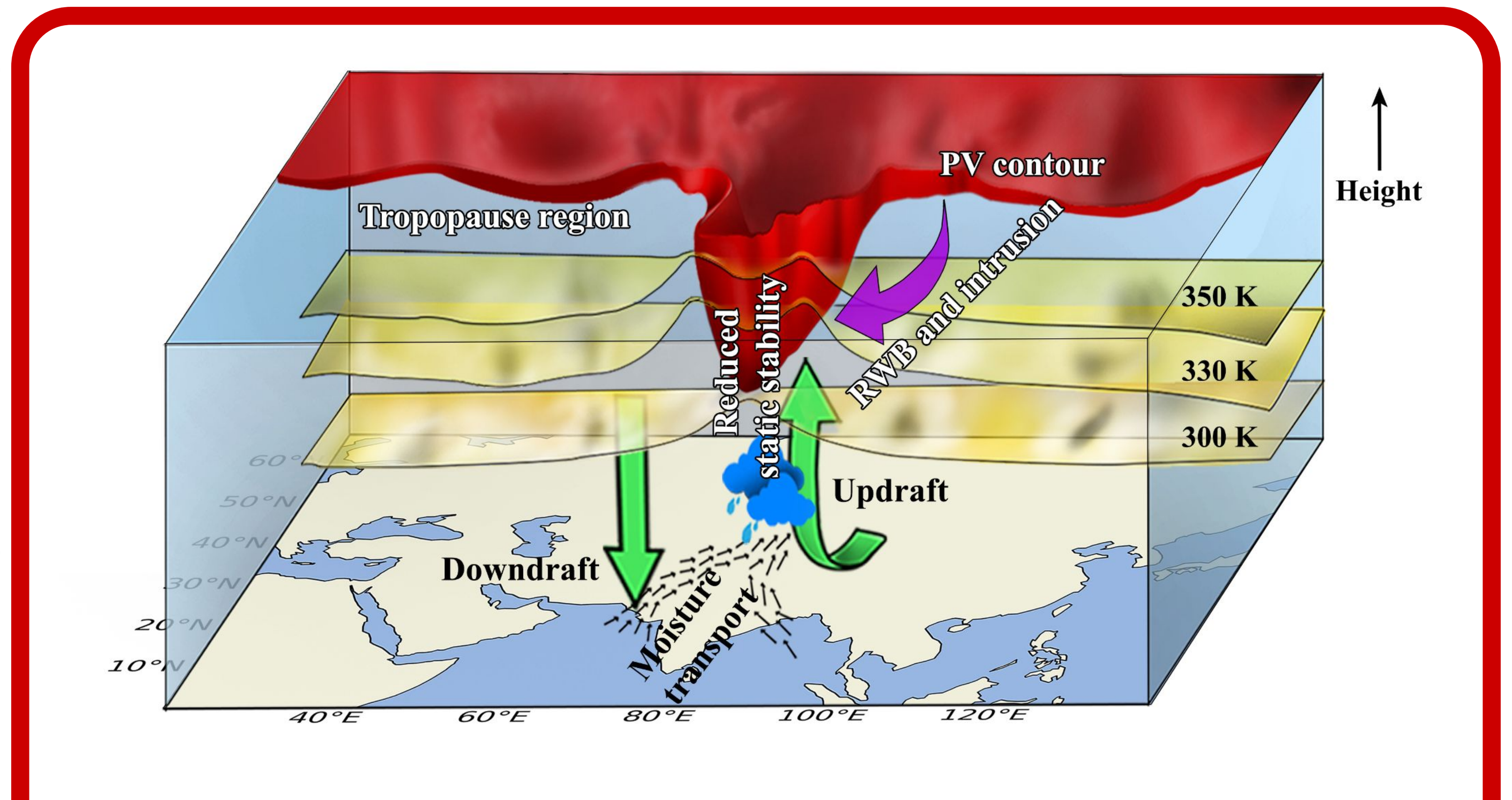

Figure 1: 3D schematic representation of a RWB event and associated changes in the atmosphere.

3. Results and Discussions

3.1 Climatology and variability

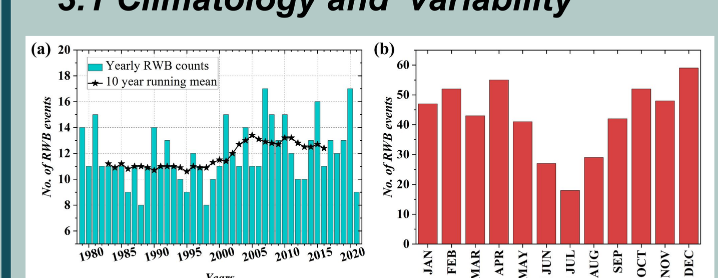

Figure 4:Climatology of RWB occurrence (a) annual variation of the RWB events overlay with the 10-year running mean and (b) monthly climatology for the period 1979-2021.

- ★ A decadal variability in RWB frequency is noticed compared to the compared to the initial decades.
- ★ The monthly variation of the RWB events suggest that number of events are very less (higher) in the summer (winter) months

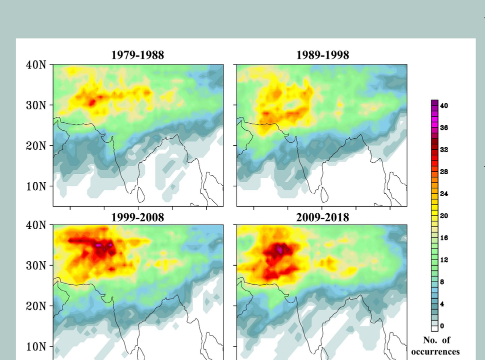

Figure 6: Spatial decadal variability of the number of occurrences of RWB events

- ★ RWB events occur mostly over the northern Indian subcontinent. The peak is located over the northwest during the winter.
- ★ The peak shifts to the central Indian region at the end of winter (February) month and persists until May
- ★ we note that the density of events increased significantly, progressing into the 21st century. Between 1979-1988, total occurrences over the broader region were close to 20-24 events, which increased to 22-26 events during the 1989-1998 period.

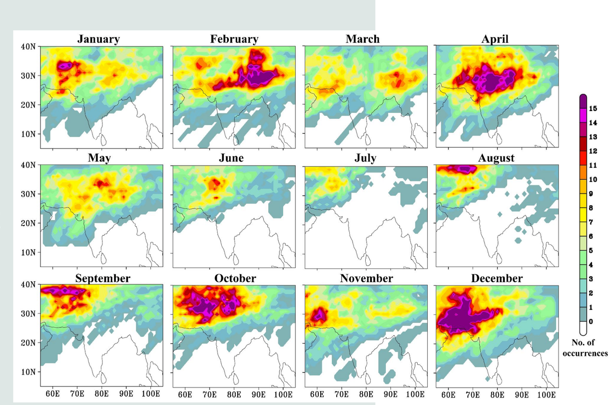

Figure 5:The spatial distribution of monthly climatology of the number of occurrences of RWB events over the Indian subcontinent.

3.2 Vertical and latitudinal occurrence of PV intrusions

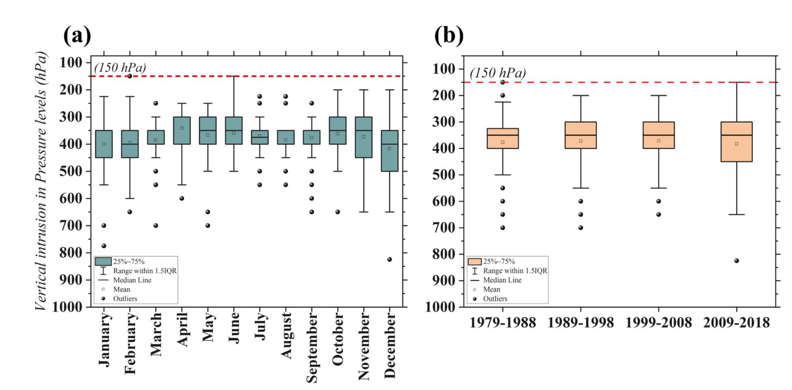

Figure 7:The (a) monthly and (b) decadal variation of the vertical intrusions of RWB events

- ★ Strong intrusions occur during the winter, especially in December. 75% of the values lie close to 500 hPa level with a mean intrusion of 450 hPa level
- ★ Among the intrusions in the last decade, 75% of the intrusions occur at 450 hPa level whereas 75% of intrusions are up to 400 hPa in other windows.
- ★ The latitudinal intrusions are strong in winter and weak in summer months, which highlights the seasonal change of position of the jet stream.
- ★ The strongest latitudinal intrusions are observed in April and November with 75% of the intrusions up to 17° N, on the other hand, the weak intrusions occur in July with 75% of the intrusions up to 27° N

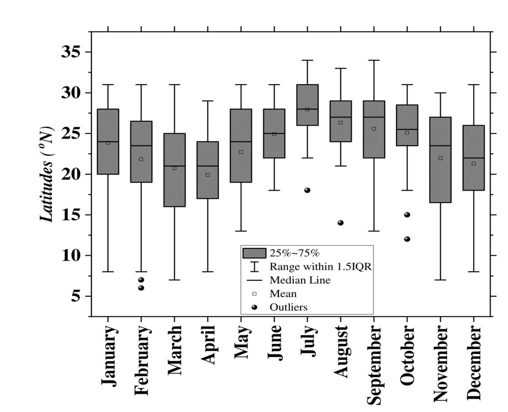

Figure8: The latitudinal intrusions of RWB events

3.3 Wave properties of RWB events

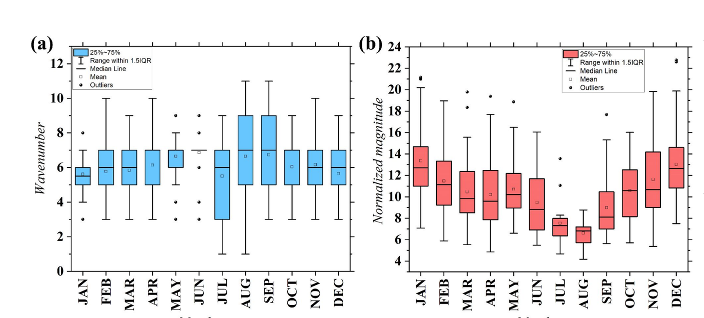

Figure 9: Monthly climatology of (a) wave number and the (b) normalized power in amplitude associated with each breaking events obtained from the FFT analysis during 1979 to 2021

- ★ Most of the breaking events occur with a wavenumber of 5-7.
- ★ Note that in July, 25% of the wave number is 3 whereas 75% of the wavenumbers is 9 during the August and September months. However, the wave number is almost 7 in June.
- ★ The maximum mean amplitude appears during the months of December-January. This indicates that the stronger vertical intrusions co-occur when the amplitude of corresponding waves is higher

3.4 Physical mechanism of RWB and associated extreme rainfall events

- ★ The wind circulation starts developing before 4 days of the RWB and strengthens its amplitude during the breaking day. The strong cyclonic circulation around the centroid indicates the positive upper level PV anomalies.
- ★ The circulation reduces its strength and starts its propagation after breaking events which is clearly visible in the circulation pattern after four days of the breaking. Due to the upper level PV anomalies, the induced wind field penetrates into the troposphere and creates a cyclonic circulation at the lower levels (850 hPa).
- ★ A noticeable positive anomaly in the precipitable water content is present where the induced cyclonic circulation is noticed at the lower levels.

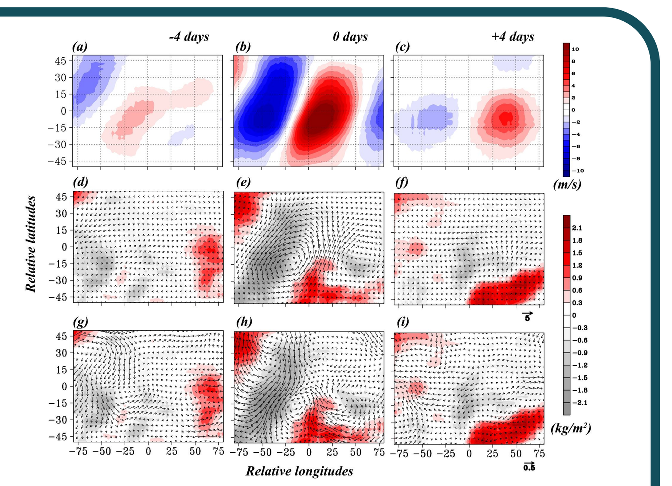

Figure 10: Composite analysis of: (a-c) anomalous meridional winds at 200 hPa, (d-f) anomalous wind circulations at 200 hPa, and (g-i) anomalous wind circulations at 850 hPa for the selected RWB events with a lead and lag of -/+ 4 days, -4 days (a,d,g), zeroth day (b,e,h), and +4 days (c,f,i). Note that the shaded portion represents the Precipitable water anomaly (d-i)

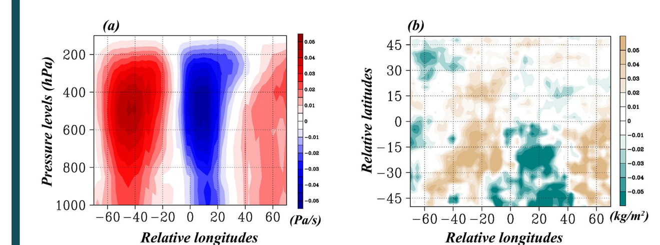

Figure 11: The composites of (a) longitude height section of vertical velocity and (b) moisture convergence on the breaking day.

- ★ A strong subsidence and updraft before and ahead of the breaking streamer are noted. The updraft results in strong convection results in extreme rainfall events.
- ★ The synoptic scale upper-level disturbances affect the surface weather conditions.
- ★ The variation in vertical wind and moisture content leads to changes in the thermodynamic characteristics of the atmosphere.

3.5 Plausible reasons for interannual and inter-decadal variability of RWB

- ★ The correlation seen over the Pacific ocean emphasizes the possible ENSO modulation on the RWB events. It is evident that the Rossby wave train that starts from the central Pacific possesses a significant correlation with RWB events over India.
- ★ The warm SST anomalies over the central Pacific can trigger the convection which in turn initiates the wave propagation in the upper atmosphere. So, it is clear that variations in the SSTs over the Pacific and associated changes in the wave dynamics modulates the RWB events over the study region

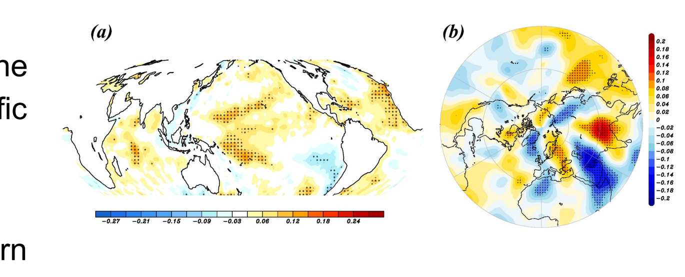

Figure 12: The monthly spatial correlation of RWB events with (a) SST anomalies and (b) meridional wind anomalies at 200 hPa.

4. Conclusions

- ★ **Using the implemented contour searching algorithm applied over the Indian subcontinent, we have detected 513 RWB events analysed for a period of 43 years from 1979 to 2021.**
- ★ **Monthly variations in the number of RWB events show that the maximum events are detected in December month while a minimum in July. The events are reduced in the summer months. We also find a decadal variability in RWB frequency, which suggests that in the recent epoch (after 2000).**
- ★ **The spatial monthly climatology suggests that more events are detected in northern India. Particularly, the events are higher over northwest India from September to January. The vertical intrusions of RWB events are also stronger in the winter months (strongest in December, 75% of intrusions up to 500 hPa).**
- ★ **The composite anomalies of the strong RWB events suggest that meridional wind propagation strengthens on the breaking day. Also, the wind circulation pattern following the RWB promotes moisture convergence over the region resulting in EREs.**
- ★ **The spatial correlation of the RWB events with SST anomalies and meridional wind anomalies at 200 hPa highlights the role of Pacific SSTs on the RWB events and the associated correlation with the upper air meridional winds**

Acknowledgement

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