

UNDERSTANDING THE RESPONSE OF ROSSBY WAVE BREAKING OVER THE INDIAN SUBCONTINENT AND ITS LINKAGE TO EXTREME WEATHER EVENTS

BIYO THOMAS



**CENTRE FOR ATMOSPHERIC SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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Understanding the response of Rossby Wave Breaking
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Biyo Thomas

Centre for Atmospheric Sciences

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CERTIFICATE

This is to certify that the thesis titled **Understanding the response of Rossby Wave Breaking over the Indian subcontinent and its linkage to extreme weather events**, submitted by **Mr. Biyo Thomas**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work carried out by him under the supervision and guidance. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Ravi Kumar Kunchala

Associate Professor

Centre for Atmospheric Sciences (CAS)

Indian Institute of Technology Delhi,

Hauz Khas, New Delhi-110016, India

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The present thesis utilizes several datasets, including reanalysis products (ERA5, CAMS–EAC4, NCEP–DOE II, and IMDAA), in situ observations (CPCB station data and IMD gridded temperature datasets), satellite products (AIRS), and outputs from the mesoscale numerical weather prediction model (WRF). I sincerely thank the respective agencies and organizations for providing open access to these valuable datasets and the model. I also acknowledge the High Performance Computing (HPC) facility at IIT Delhi for the computational support provided during this research, particularly for the modelling work.

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ABSTRACT

The weather of the subtropical Indian region is strongly influenced by dynamical changes in the upper troposphere and lower stratosphere triggered by Rossby Wave Breaking (RWB). These breaking events can substantially modulate regional weather and climate, often leading to sudden and severe extremes. Despite their significance, a comprehensive understanding of RWB characteristics and impacts over the Indian subcontinent remains limited. This thesis presents an in-depth investigation into the climatology, variability, and associated influences of RWB over the Indian region, utilizing the long-term reanalysis and satellite datasets complemented by numerical model simulations.

To address the RWB associated changes over India, we implemented a Potential Vorticity (PV) contour based detection algorithm with region specific constraints to objectively identify RWB events over the Indian subcontinent. A total of 513 RWB events were detected during the period from 1979 to 2021 to investigate the climatological behaviour of RWB. Furthermore, this thesis addressed the influence of RWB on changes in both surface and tropospheric composition. Results reveal a prominent increase ($\sim 20\%$) in the frequency and intensity of RWB events during the last two decades (1999–2018). The events occur most frequently over the northwestern Indian subcontinent during winter, with dominant zonal wavenumbers between 5 and 7 and deep tropospheric intrusions extending to ~ 650 hPa and as low as 7.5°N . RWB events were also found to promote extreme rainfall by generating atmospheric instability and enhancing moisture influx towards the downstream side

of the upper-level PV anomalies at the surface. Further, the results suggest that the large-scale oceanic forcing, particularly Pacific sea surface temperature anomalies, modulates the interannual to decadal variability in RWB activity. This modulation occurs through the influence of these anomalies on the upper-level wave pattern.

Since these breaking events can induce tropopause folding, allowing the mixing of stratospheric ozone into the troposphere, it is essential to understand their role in enhancing tropospheric ozone, particularly at lower atmospheric levels. Accordingly, this thesis investigates the influence of RWB on tropospheric ozone (O_3) variability using satellite observations from the Atmospheric Infrared Sounder (AIRS), together with the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis, for 232 RWB events for the period 2004–2021. The analysis reveals enhanced ozone concentrations during RWB days, with 46% of events facilitating stratosphere-to-troposphere ozone transport. Stronger intrusions are characterized by ozone enhancements of 150–250 ppbv at 100–250 hPa and 10–20 ppbv near 850 hPa. The results highlight that upper-level positive PV anomalies catalyze downward ozone transport during intense RWB, demonstrating the importance of dynamical processes in shaping tropospheric ozone variability and chemistry over India.

In addition, this thesis investigates the influence of RWB on surface temperature and the associated extreme events during the pre-monsoon season (March–May) over the Indian region. Although the impact of RWB on sudden extreme rainfall events has been extensively studied, its role in modulating surface temperature and associated heatwaves remains relatively unexplored. A total of 139 pre-monsoon RWB events were identified during 1979–2021, revealing significant surface temperature amplification on both the western and eastern flanks of the breaking potential vorticity (PV) streamers. These anomalies persist for 3–4 days around the peak breaking day and are linked to upper-level PV anomalies, anti-

cyclonic circulations at 250 hPa, and subsidence at 500 hPa. Decomposition of temperature anomalies shows that surface warming during RWB is primarily driven by diabatic heating on both flanks of the centroid, with stronger adiabatic heating and temperature advection on the western side, resulting in dry, hot conditions and poleward transport of warm air.

Further, the coupling between RWB and heatwaves (HWs) is examined using both observational datasets and reanalysis products over the northwestern Indian region, which has been previously identified as a hotspot for upper-level dynamical influences, particularly blocking patterns. A heatwave identification criterion was applied, and the identified heatwave days were compared with the detected RWB days. The analysis reveals that approximately 33% of pre-monsoon heatwaves are associated with RWB (hereafter RWB-HWs). These RWB-HWs exhibit about 14% stronger maximum temperature anomalies, longer durations, and larger spatial extents compared to heatwaves that occur without RWB influence (nor:HWs). It is found that anomalously persistent mid-tropospheric anticyclonic circulations, along with deep tropospheric ridges and strong subsidence near the breaking troughs, create favourable conditions for the amplification of heatwaves. This atmospheric configuration enhances both diabatic and adiabatic heating, thereby fostering hot and dry surface conditions and intensifying horizontal temperature advection.

To further isolate the upper-level dynamical contribution during an RWB-associated heatwave, a recent RWB-HW event (12–22 March 2022) was simulated using the Weather Research and Forecasting (WRF) model through two experiments: a control run (CNTRL) and a perturbed run (EXPT), in which the upper-level winds and geopotential heights (100–500 hPa) were replaced with their mean climatological conditions. The EXPT simulation showed suppressed RWB features, weakened anticyclonic circulations, altered subsidence, and a reduction of ~ 1 K in surface temperature compared to CNTRL, confirming

the vital role of upper-level breaking dynamics in amplifying surface heat extremes.

Overall, this thesis advances the scientific understanding of RWB events and its multifaceted influence on regional weather extremes and tropospheric composition over the Indian subcontinent. The findings emphasize the importance of upper-level dynamical processes in modulating rainfall, ozone, and heatwaves, offering critical insights to improve the representation of large-scale wave flow interactions and extreme event prediction in a warming climate.

सारांश

सबट्रॉपिकल भारतीय इलाके का मौसम रॉस्बी वेव ब्रेकिंग (RWB) से होने वाले ऊपरी ट्रोपोस्फीयर और निचले स्ट्रेटोस्फीयर में होने वाले डायनामिकल बदलावों से बहुत ज़्यादा प्रभावित होता है। ये ब्रेकिंग इवेंट्स इलाके के मौसम और क्लाइमेट को काफी हद तक बदल सकते हैं, जिससे अक्सर अचानक और गंभीर एक्सट्रीम हालात बन जाते हैं। इनके महत्व के बावजूद, भारतीय उपमहाद्वीप पर RWB की खासियतों और असर की पूरी समझ अभी भी सीमित है। यह थीसिस भारतीय इलाके में RWB के क्लाइमेटोलॉजी, बदलाव और उससे जुड़े असर की गहराई से जांच करती है, जिसमें लंबे समय के रीएनालिसिस और सैटेलाइट डेटासेट के साथ न्यूमेरिकल मॉडल सिमुलेशन का इस्तेमाल किया गया है।

भारत में RWB से जुड़े बदलावों को समझने के लिए, हमने भारतीय उपमहाद्वीप में RWB घटनाओं की सही पहचान करने के लिए क्षेत्र के हिसाब से सीमाओं के साथ एक पोटेंशियल वॉर्टिसिटी (PV) कंटूर आधारित डिटेक्शन एल्गोरिदम लागू किया। RWB के क्लाइमेट बिहेवियर की जांच करने के लिए 1979 से 2021 के समय में कुल 513 RWB घटनाओं का पता चला। इसके अलावा, इस थीसिस में सतह और ट्रोपोस्फेरिक बनावट दोनों में बदलावों पर RWB के असर के बारे में बताया गया है। नतीजों से पता चलता है कि पिछले दो दशकों (1999–2018) के दौरान RWB घटनाओं की फ्रीक्वेंसी और इंटेन्सिटी में काफी बढ़ोतरी ($\sim 20\%$) हुई है। ये घटनाएं सबसे ज़्यादा उत्तर-पश्चिमी भारतीय उपमहाद्वीप में सर्दियों के दौरान होती हैं, जिसमें प्रमुख ज़ोनल वेवनंबर 5 और 7 के बीच होते हैं और गहरे ट्रोपोस्फेरिक इंटूज़न ~ 650 hPa तक और 7.5°N तक कम होते हैं। यह भी पाया गया कि RWB इवेंट्स एटमोस्फेरिक अस्थिरता पैदा करके और सतह पर ऊपरी लेवल की PV गड़बड़ियों के नीचे की तरफ नमी के बहाव को बढ़ाकर बहुत ज़्यादा बारिश को बढ़ावा देते हैं। इसके अलावा, नतीजों से पता चलता है कि बड़े पैमाने पर समुद्री दबाव, खासकर प्रशांत समुद्र की सतह के तापमान की गड़बड़ियां, RWB एक्टिविटी में साल-दर-साल से लेकर दशक भर में होने वाले बदलाव को कंट्रोल करती हैं। यह बदलाव ऊपरी लेवल के वेव पैटर्न पर इन गड़बड़ियों के असर से होता है।

क्योंकि ये ब्रेकिंग इवेंट्स ट्रोपोपॉज फोल्डिंग को बढ़ावा दे सकते हैं, जिससे स्ट्रेटोस्फेरिक ओज़ोन ट्रोपोस्फीयर में मिल सकता है, इसलिए ट्रोपोस्फीयर ओज़ोन को बढ़ाने में उनकी भूमिका को समझना ज़रूरी है, खासकर निचले एटमोस्फेरिक लेवल पर। इसलिए, यह थीसिस 2004–2021 के समय के लिए 232 RWB इवेंट्स के लिए, कोपरनिकस एटमोस्फियर मॉनिटरिंग सर्विस (CAMS) रीएनालिसिस के साथ एटमोस्फेरिक इंफ्रारेड साउंडर (AIRS) से सैटेलाइट ऑब्ज़र्वेशन का इस्तेमाल करके ट्रोपोस्फेरिक ओज़ोन (O₃) में बदलाव पर RWB के असर की जांच करती है। एनालिसिस से पता चलता है कि RWB दिनों के दौरान ओज़ोन कंसंट्रेशन बढ़ जाता है, जिसमें 46% इवेंट्स स्ट्रेटोस्फीयर-से-ट्रोपोस्फीयर ओज़ोन ट्रांसपोर्ट को आसान बनाते हैं। ज़्यादा मज़बूत घुसपैठ की पहचान 100–250 hPa पर 150–250 ppbv और 850 hPa के पास 10–20 ppbv के ओज़ोन बढ़ने से होती है। नतीजों से पता चलता है कि ऊपरी लेवल की पॉजिटिव PV गड़बड़ियां, तेज़ RWB के दौरान नीचे की ओर ओज़ोन ट्रांसपोर्ट को बढ़ावा देती हैं, जो भारत में ट्रोपोस्फेरिक ओज़ोन में बदलाव और केमिस्ट्री को बनाने में डायनामिक प्रोसेस के महत्व को दिखाता है।

इसके अलावा, यह थीसिस भारतीय क्षेत्र में प्री-मॉनसून सीज़न (मार्च-मई) के दौरान सतह के तापमान और उससे जुड़ी बहुत ज़्यादा घटनाओं पर RWB के असर की जांच करती है। हालांकि अचानक बहुत ज़्यादा बारिश की घटनाओं पर RWB के असर की बहुत ज़्यादा स्टडी की गई है, लेकिन सतह के तापमान और उससे जुड़ी हीटवेव को कंट्रोल करने में इसकी भूमिका काफ़ी हद तक पता नहीं चली है। 1979-2021 के दौरान कुल 139 प्री-मॉनसून RWB घटनाओं की पहचान की गई, जिससे ब्रेकिंग पोटेंशियल वॉर्टिसिटी (PV) स्ट्रीमर्स के पश्चिमी और पूर्वी दोनों किनारों पर सतह के तापमान में काफ़ी बढ़ोतरी का पता चला। ये गड़बड़ियां पीक ब्रेकिंग डे के आसपास 3-4 दिनों तक बनी रहती हैं और ऊपरी लेवल की PV गड़बड़ियों, 250 hPa पर एंटीसाइक्लोनिक सर्कुलेशन और 500 hPa पर धंसने से जुड़ी होती हैं। टेम्परेचर की गड़बड़ियों का डीकंपोज़िशन दिखाता है कि RWB के दौरान सरफेस वार्मिंग मुख्य रूप से सेंट्रॉइड के दोनों किनारों पर डायबेटिक हीटिंग की वजह से होती है, जबकि पश्चिमी तरफ ज़्यादा मज़बूत एडियाबेटिक हीटिंग और टेम्परेचर एडवेक्शन होता है, जिससे सूखे, गर्म हालात बनते हैं और गर्म हवा ध्रुव की ओर जाती है।

इसके अलावा, RWB और हीटवेव (HWS) के बीच कपलिंग की जांच उत्तर-पश्चिमी भारतीय क्षेत्र में ऑब्ज़र्वेशनल डेटासेट और रीएनालिसिस प्रोडक्ट्स दोनों का इस्तेमाल करके की जाती है, जिसे पहले ऊपरी लेवल के डायनामिकल असर, खासकर ब्लॉकिंग पैटर्न के लिए एक हॉटस्पॉट के तौर पर पहचाना गया है। एक हीटवेव आइडेंटिफिकेशन क्राइटेरिया लागू किया गया, और पहचाने गए हीटवेव दिनों की तुलना पता चले RWB

दिनों से की गई। एनालिसिस से पता चलता है कि लगभग 33% प्री-मॉनसून हीटवेव RWB (इसके बाद RWB:HWs) से जुड़ी होती हैं। ये RWB-HWs, RWB असर (nor:HWs) के बिना होने वाली हीटवेव की तुलना में लगभग 14% ज्यादा ज्यादा तापमान की गड़बड़ियां, ज्यादा समय और ज्यादा जगह का फैलाव दिखाते हैं। यह पाया गया है कि असामान्य रूप से लगातार मिड-ट्रोपोस्फेरिक एंटीसाइक्लोनिक सर्कुलेशन, गहरी ट्रोपोस्फेरिक रिज और ब्रेकिंग ट्रफ के पास मजबूत धंसाव के साथ, हीटवेव के बढ़ने के लिए अच्छी स्थितियां बनाते हैं। यह एटमोस्फेरिक बनावट डायबेटिक और एडियाबेटिक हीटिंग दोनों को बढ़ाती है, जिससे गर्म और सूखी सतह की स्थिति बनती है और हॉरिजॉन्टल टेम्परेचर एडवेक्शन तेज होता है।

RWB से जुड़ी हीटवेव के दौरान ऊपरी लेवल के डायनामिकल योगदान को और अलग करने के लिए, हाल ही में हुए RWB-HW इवेंट (12-22 मार्च 2022) को वेदर रिसर्च एंड फोरकास्टिंग (WRF) मॉडल का इस्तेमाल करके दो एक्सपेरिमेंट के ज़रिए सिमुलेट किया गया: एक कंट्रोल रन (CNTRL) और एक पर्टर्ब्ड रन (EXPT), जिसमें ऊपरी लेवल की हवाओं और जियोपोटेंशियल हाइट (100-500 hPa) को उनके औसत क्लाइमेटोलॉजिकल कंडीशन से बदल दिया गया। EXPT सिमुलेशन ने CNTRL की तुलना में दबे हुए RWB फीचर्स, कमजोर एंटीसाइक्लोनिक सर्कुलेशन, बदला हुआ सबसिडेंस और सतह के तापमान में ~ 1 K की कमी दिखाई, जिससे सतह की गर्मी को बढ़ाने में ऊपरी लेवल के ब्रेकिंग डायनामिक्स की अहम भूमिका की पुष्टि हुई।

कुल मिलाकर, यह थीसिस RWB इवेंट्स की साइंटिफिक समझ और भारतीय उपमहाद्वीप में क्षेत्रीय मौसम की चरम स्थितियों और ट्रोपोस्फेरिक बनावट पर इसके कई तरह के असर को आगे बढ़ाती है। नतीजे बारिश, ओज़ोन और हीटवेव को कंट्रोल करने में ऊपरी लेवल की डायनामिक प्रोसेस के महत्व पर ज़ोर देते हैं, और गर्म होते मौसम में बड़े पैमाने पर वेव फ्लो इंटरैक्शन और चरम घटनाओं की भविष्यवाणी को बेहतर बनाने के लिए ज़रूरी जानकारी देते हैं।

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