INVESTIGATION OF DRY AIR INTRUSION OVER THE ARABIAN SEA AND ITS IMPLICATIONS FOR INDIAN SUMMER MONSOON

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by

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Dedicated to ...

My beloved Parents

Mrs. Beena Singh &
Mr. Sanjay Singh

Certificate

This is to certify that the thesis entitled **"INVESTIGATION OF DRY AIR INTRUSION OVER THE ARABIAN SEA AND ITS IMPLICATIONS FOR INDIAN SUMMER MONSOON"**, submitted by **Mr. Rahul Singh** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bonafide research work carried out by him under my guidance and supervision. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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Abstract

The dry air intrusion over India during summer monsoon break phases is well known. It has been argued that this dry air originates over the desert regions of West Asia. During the summer monsoon season, a reservoir of saturation deficit air is identified over the western and northern Arabian Sea in the present study. The monsoon low-level jet (LLJ) which transports the moisture to continental India in the active phase of monsoon, transports the dry air to northern and central India during the break phase. The LLJ undergoes a weakening and broadening before the monsoon break phase in response to increased barotropic instability. The broadening of the LLJ leads to an intensification of zonal flow in the poleward flanks and a weakening at the core. The development of a positive meridional gradient in sea surface temperature over the northern Arabian Sea favors an increase in the low-level zonal flow in the north, which advects the moist deficit air across northwest India. The dry air intrusion results in enhanced static stability over northern and central India and a strong suppression of convection. Further, the enhanced static stability weakens zonal flow from the northern Arabian Sea region and leads to the demise of the dry air intrusion. Thus, internal mechanisms are responsible for the dry air intrusion over India and its termination during the break phase of the summer monsoon. An index for the dry air intrusion is constructed based on the saturation deficit transport. This dry air intrusion index is used to identify the dry air intrusion events during monsoon breaks. The statistics show that most of the break events are found to be in close coincidence with dry air intrusion activity. It is also observed that the dry air intrusion and the monsoon breaks are happening simultaneously, suggesting that it is difficult to establish a cause-effect relationship.

It is now evident that the strengthening of monsoon LLJ in the northern parts of the Arabian Sea during the break phase of Indian summer monsoon (ISM) helps in transporting this dry air towards northwestern India. Hence, over northwestern India (NWI), a weakening (strengthening) of the zonal flow over the northern Arabian Sea can reduce (enhance) the influx of unsaturated air to the NWI and thereby enhance (reduce) precipitation there. The variability in the zonal flow over the northern Arabian Sea is a direct geostrophic response to the variability in the meridional pressure gradient over NWI. The inter-annual variability in the mean sea

level pressure over the region explains the inter-annual variability of ISM precipitation during July-August over northwestern India. The contribution of El Niño Southern Oscillation in the inter-annual variability of precipitation over this region is not significant.

Although the existence of dry air intrusion is well-documented through observations, its representation in climate models remains uncertain. It is important to enhance our understanding of the process of dry air advection in climate models to assess their fidelity in simulating the climate over the region. Most climate models participated in the sixth phase of Coupled Model Intercomparison Project (CMIP6) models analyzed in this study realistically simulate the observed pattern of dry air advection over continental India during the summer monsoon break phase. Some models also simulate dry air transport from West Asia, possibly due to an overly smoothed representation of orography. Furthermore, the majority of CMIP6 models successfully capture the intrinsic modes associated with the dry monsoon phase, as demonstrated by empirical orthogonal function analysis on low-level zonal winds. It suggests that the global climate models exhibit better skill in simulating the dry processes of the monsoon compared to moist processes. These findings uncover previously under-explored aspects of the monsoon, which are essential for accurately assessing future regional climate changes. Further, the orography of the Hindu Kush region significantly influences precipitation variability in continental India by controlling the dynamics of dry air advection. Therefore, accurate representation of orography in climate models is essential to reduce precipitation bias. Many studies have reported a poleward shift of the monsoon LLJ in recent decades, which is projected to continue in a warming climate. The role of the LLJ in a warming climate is crucial, as it is the primary carrier of dry air to continental India. In a warming climate, the LLJ becomes more zonal in some models, leading to an increase in break days in the SSP 585 scenario, and becomes inclined, parallel to the Arabian Peninsula coastline, when break days decrease. This change may be due to the strengthening or weakening of the meridional component of horizontal wind, which affects moisture transport from the Arabian Peninsula and the northern Arabian Sea.

सार

ग्रीष्म मानसून विराम के चरणों के दौरान भारत में शुष्क हवा का आक्रमण सर्वविदित है। यह तर्क दिया गया है कि यह शुष्क हवा पश्चिम एशिया के रेगिस्तानी क्षेत्रों से उत्पन्न होती है। ग्रीष्मकालीन मानसून के मौसम के दौरान, वर्तमान अध्ययन में पश्चिमी और उत्तरी अरब सागर के ऊपर संतृप्ति की कमी वाली हवा के भंडार की पहचान की गई है। मानसून निम्न–स्तरीय जेट (एलएलजे) जो मानसून के सक्रिय चरण में नमी को महाद्वीपीय भारत तक पहुंचाता है, ब्रेक चरण के दौरान शुष्क हवा को उत्तरी और मध्य भारत में पहुंचाता है। बढ़ी हुई बारोट्रोपिक अस्थिरता के जवाब में मानसून ब्रेक चरण से पहले एलएलजे कमजोर और चौड़ा हो जाता है। एलएलजे के चौड़ीकरण से ध्रुवीय किनारों में आंचलिक प्रवाह तेज हो जाता है और कोर कमजोर हो जाता है। उत्तरी अरब सागर के ऊपर समुद्र की सतह के तापमान में एक सकारात्मक मेरिडियनल ग्रेडिएंट का विकास उत्तर में निम्न–स्तरीय आंचलिक प्रवाह में वृद्धि का पक्ष लेता है, जो पूरे उत्तर पश्चिम भारत में नम हवा की कमी को दर्शाता है। शुष्क वायु घुसपैठ के परिणामस्वरूप उत्तरी और मध्य भारत में स्थैतिक स्थिरता बढ़ जाती है और संवहन का एक मजबूत दमन होता है। इसके अलावा, बढ़ी हुई स्थैतिक स्थिरता उत्तरी अरब सागर क्षेत्र से क्षेत्रीय प्रवाह को कमजोर कर देती है और शुष्क हवा की घुसपैठ को समाप्त कर देती है। इस प्रकार, आंतरिक तंत्र भारत में शुष्क हवा की घुसपैठ और ग्रीष्मकालीन मानसून के ब्रेक चरण के दौरान इसकी समाप्ति के लिए जिम्मेदार हैं। संतृप्ति घाटे के परिवहन के आधार पर शुष्क वायु घुसपैठ के लिए एक सूचकांक का निर्माण किया जाता है। इस शुष्क वायु घुसपैठ सूचकांक का उपयोग मानसून अवकाश के दौरान शुष्क वायु घुसपैठ की घटनाओं की पहचान करने के लिए किया जाता है। आँकड़े बताते हैं कि ब्रेक की अधिकांश घटनाएँ शुष्क वायु घुसपैठ गतिविधि के साथ घनिष्ठ संयोग में पाई जाती हैं। यह भी देखा गया है कि शुष्क हवा का प्रवेश और मानसून का टूटना एक साथ हो रहा है, जिससे पता चलता है कि कारण–प्रभाव संबंध स्थापित करना मुश्किल है।

अब यह स्पष्ट है कि भारतीय ग्रीष्मकालीन मानसून (आईएसएम) के ब्रेक चरण के दौरान अरब सागर के उत्तरी हिस्सों में मानसून एलएलजे की मजबूती इस शुष्क हवा को उत्तर–पश्चिमी भारत की ओर ले जाने में मदद करती है। इसलिए, उत्तर–पश्चिमी भारत (एनडब्ल्यूआई) में, उत्तरी अरब सागर के ऊपर आंचलिक प्रवाह के कमजोर (मजबूत होने) से एनडब्ल्यूआई में असंतृप्त हवा का प्रवाह कम (बढ़) सकता है और इस तरह वहां वर्षा में वृद्धि (कम) हो सकती है। उत्तरी अरब सागर के ऊपर आंचलिक प्रवाह में परिवर्तनशीलता एनडब्ल्यूआई पर मध्याह्नीय दबाव प्रवणता में परिवर्तनशीलता के लिए एक सीधी भूगर्भीय प्रतिक्रिया है। क्षेत्र पर औसत समुद्री स्तर के दबाव में अंतर–वार्षिक परिवर्तनशीलता उत्तर–पश्चिमी भारत में जुलाई–अगस्त के दौरान आईएसएम वर्षा की अंतर–वार्षिक परिवर्तनशीलता को बताती है। इस क्षेत्र में वर्षा की अंतर–वार्षिक परिवर्तनशीलता में अल नीनो दक्षिणी दोलन का योगदान महत्वपूर्ण नहीं है।

यद्यपि शुष्क वायु घुसपैठ का अस्तित्व अवलोकनों के माध्यम से अच्छी तरह से प्रलेखित है, जलवायु मॉडल में इसका प्रतिनिधित्व अनिश्चित बना हुआ है। क्षेत्र में जलवायु का अनुकरण करने में उनकी निष्ठा का आकलन करने के लिए जलवायु मॉडल में शुष्क वायु संवहन की प्रक्रिया के बारे में हमारी समझ को बढ़ाना महत्वपूर्ण है। अधिकांश जलवायु मॉडलों ने युग्मित मॉडल इंटरकंपेरिसन प्रोजेक्ट (सीएमआईपी6) के छठे चरण में भाग लिया, इस अध्ययन में विश्लेषण

किए गए मॉडल ग्रीष्मकालीन मानसून ब्रेक चरण के दौरान महाद्वीपीय भारत पर शुष्क वायु संवहन के देखे गए पैटर्न का वास्तविक रूप से अनुकरण करते हैं। कुछ मॉडल पश्चिम एशिया से शुष्क वायु परिवहन का भी अनुकरण करते हैं, संभवतः ऑरोग्राफी के अत्यधिक सुचारू प्रतिनिधित्व के कारण। इसके अलावा, अधिकांश सीएमआईपी6 मॉडल शुष्क मानसून चरण से जुड़े आंतरिक तरीकों को सफलतापूर्वक पकड़ लेते हैं, जैसा कि निम्न–स्तरीय क्षेत्रीय हवाओं पर अनुभवजन्य ऑर्थोगोनल फ़ंक्शन विश्लेषण द्वारा प्रदर्शित किया गया है। यह सुझाव देता है कि वैश्विक जलवायु मॉडल नम प्रक्रियाओं की तुलना में मानसून की शुष्क प्रक्रियाओं का अनुकरण करने में बेहतर कौशल प्रदर्शित करते हैं। ये निष्कर्ष मानसून के पहले से कम खोजे गए पहलुओं को उजागर करते हैं, जो भविष्य के क्षेत्रीय जलवायु परिवर्तनों का सटीक आकलन करने के लिए आवश्यक हैं। इसके अलावा, हिंदू कुश क्षेत्र की भौगोलिक स्थिति शुष्क वायु संवहन की गतिशीलता को नियंत्रित करके महाद्वीपीय भारत में वर्षा परिवर्तनशीलता को महत्वपूर्ण रूप से प्रभावित करती है। इसलिए, वर्षा पूर्वाग्रह को कम करने के लिए जलवायु मॉडल में भौगोलिक स्थिति का सटीक प्रतिनिधित्व आवश्यक है। कई अध्ययनों ने हाल के दशकों में मानसून एलएलजे में ध्रुवीय बदलाव की सूचना दी है, जिसके गर्म जलवायु में जारी रहने का अनुमान है। गर्म होती जलवायु में एलएलजे की भूमिका महत्वपूर्ण है, क्योंकि यह महाद्वीपीय भारत के लिए शुष्क हवा का प्राथमिक वाहक है। गर्म जलवायु में, एलएलजे कुछ मॉडलों में अधिक क्षेत्रीय हो जाता है, जिससे एसएसपी 585 परिदृश्य में ब्रेक के दिनों में वृद्धि होती है, और जब ब्रेक के दिन कम हो जाते हैं, तो यह अरब प्रायद्वीप समुद्र तट के समानांतर झुका हुआ हो जाता है। यह परिवर्तन क्षैतिज हवा के मध्याह्न घटक के मजबूत होने या कमजोर होने के कारण हो सकता है, जो अरब प्रायद्वीप और उत्तरी अरब सागर से नमी परिवहन को प्रभावित करता है।

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Abbreviations

AGCM	Atmospheric General Circulation Model
BoB	Bay of Bengal
CAM	Community Atmosphere Model
CESM	Community Earth System Model
CMIP6	Coupled Model Intercomparison Project Phase Sixth
DAI	Dry Air Intrusion Index
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
IOD	Indian Ocean Dipole
IMD	India Meterological Department
ISM	Indian Summer Monsoon
ISMR	Indian Summer Monsoon Rainfall
LLJ	Low Level Jet
NOAA	National Oceanographic and Atmospheric Administration
NWI	Northwestern (or Northwest) India
OLR	Outgoing Longwave Radiation
SENS	Sensitivity
SRP	Silk Road Pattern
SST	Sea Surface Temperature
TRMM	Tropical Rainfall Measuring Mission