Investigation of Dry Air Intrusion over the Arabian Sea and Its Implications for Indian Summer Monsoon

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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.