論文の内容の要旨

A comprehensive study on seasonal variations of low-level clouds and associated air-sea interactions in the South Indian Ocean

（南インド洋上の下層雲の季節変動と

それに関わる大気海洋相互作用の包括的研究）

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Low-level clouds strongly cool the earth as they reflect a large fraction of insolation while emitting longwave radiation nearly as much as the earth's surface. Since their formation is governed by small-scale turbulent processes and microphysics, however, low-level clouds are not well represented in global climate models, introducing uncertainties into future climate projections. Climatologically, low-level clouds prevail over the eastern portion of the basins, and several studies suggested the active roles of such low-level clouds on the maintenance of subtropical highs through their albedo effect and/or longwave radiative cooling from their cloud-top.

The present study focuses on the South Indian Ocean. The subtropical high resides over the eastern portion of the basin in summer, while it strengthens and shifts westward in winter. Correspondingly, the area of large low-cloud fraction (LCF) over the South Indian Ocean also shows westward extension from summer. Such distinct seasonality of the subtropical high and low-level clouds cannot be seen in the other subtropical ocean basins. In addition, there is a prominent sea surface temperature (SST) front along the Agulhas Return Current in the South Indian Ocean (thus referred to as the Agulhas SST front). The associated cross-frontal gradient of surface sensible heat flux (SHF) maintains a surface baroclinic zone, forming a storm track. Thus the storm-track activity in the South Indian Ocean is active throughout the year, and maximized in winter. Furthermore, the Asian summer monsoon located to the north, which is one of the strongest seasonal variations in the Earth, may affect the subtropical high in the South Indian Ocean remotely in austral winter. Considering those intriguing points, however, the coupling between the subtropical high and low-level clouds via SST as well as its modulation by the storm-track activity maintained by the Agulhas SST front and the Asian summer monsoon in austral summer have not been assessed yet. This study elucidate those using satellite observations and a series of dynamical and general circulation model experiments.

In summer, we have found that low-level clouds are essential for the maintenance of the subtropical high. Our sensitivity experiments with a coupled general circulation model (CM2.1) confirmed that low-level clouds reinforce the summertime subtropical high (~+5 hPa) so that the high as the planetary wave component would almost vanish without the radiative effects of the subtropical low-level clouds. During the warm season, the albedo effect of low-level clouds strongly lowers SST under the strong summertime insolation, especially in the eastern portion of the basin (~−4 °C in the CM2.1 experiments). The lowered SST hinders the southward displacement (or expansion) of the ITCZ, reducing precipitation from deep clouds in the equatorward portion of the subtropical South Indian Ocean. The anomalous diabatic cooling associated with the reduced precipitation induces an anticyclonic response to its southwest, reinforcing the surface subtropical high. Our dynamical model experiments have elucidated that the reinforcement through the anomalous condensation heating is predominant in the feedback from low-level clouds. The high is also modestly reinforced by the augmented in-atmosphere radiative cooling, which is attributable to the reduced longwave radiative heating by high-level clouds associated with the reduced deep convection as well as the cloud-top longwave cooling from low-level clouds. The dynamical model experiments with individual diabatic heating component taken from an atmospheric reanalysis data (JRA-55) have also confirmed the predominance of the reduced precipitation for the maintenance of the high as the planetary wave component. Still, the shallow cooling-heating couplet between the cool South Indian Ocean and the heated Australian continent acts to suppress deep convection by invoking surface divergence and alongshore winds, which act to lower SST by enhanced evaporation, upper-ocean mixing, coastal upwelling and weakening of the Leeuwin Current, off the west coast of Australia. The analysis has also revealed that forcing from sub-monthly eddies as well as remote influences from the tropics is negligible for the maintenance of the summertime subtropical high over the South Indian Ocean.

In winter, the westward-shifted subtropical high contributes to the wintertime enhancement and westward expansion of low-cloud cover by invoking the mid-tropospheric subsidence, which enhances lower-tropospheric stability, and the southeasterly Trades that enhance upward SHF, both across the entire subtropical basin. Our sensitivity experiments with CM2.1 have elucidated that those low-level clouds feed back onto the equatorward portion of the subtropical high (∼+1.5 hPa) through augmenting cloud-top longwave cooling. They also reinforce the high modestly through the reduced turbulent heating associated with the lowered SST. In contrast to the summertime case, suppression of deep convection by low-level clouds is weak, leading to a smaller contribution to the maintenance of the high. This is probably because the reduced lowering of SST due to the weaker cloud radiative forcing under reduced wintertime insolation along with climatologically low SST and the enhanced winter-hemisphere Hadley cell, suppressing precipitation even in the absence of low-level clouds. Nevertheless, it has been demonstrated that there exists a coupling between the subtropical high and low-level clouds also in winter.

This study has also revealed the modulations of the aforementioned coupling by the seasonally enhanced storm-track activity maintained by the Agulhas SST front. We have shown that the enhanced storm-track activity maintained by the Agulhas SST front is also important for the enhanced LCF, because migratory synoptic-scale eddies along the storm track augment upward SHF by enhancing cold advection over the warmer side of the wintertime subtropical SST front located at ∼30°S and increasing the climatological-mean scalar wind speed where climatological-mean southerlies are weak (25°S-30°S). This is presumably one of the reasons why SHF emerges as an important cloud-controlling factor for the seasonal cycle of LCF in the subtropical South Indian Ocean. The storm-track activity is even more important for the maintenance of the poleward portion of the subtropical high through the convergences of eddy heat and vorticity fluxes and the resultant acceleration of the climatological-mean westerlies on the poleward side of the high, as shown by the dynamical model experiments. The atmospheric general circulation model experiments further indicate that the Agulhas SST front acts to reinforce the high by energizing the storm-track activity.

The dynamical model experiments have also revealed that unlike in austral summer, the coupled system can be modulated by the remote influence from the tropics, especially the Asian summer monsoon region. The enhanced deep convection over the Asian summer monsoon regions as well as the equatorial eastern Indian Ocean and western Pacific acts not only to shift the subtropical high westward but also to enhance mid-tropospheric subsidence and equatorward surface winds over the central and western portions of the subtropical South Indian Ocean. The induced subsidence acts to stabilize and dry the free troposphere and the equatorward surface winds yield near-surface cold advection, both of which are favorable for the low-level cloud formation but unfavorable for the development of deep precipitating clouds. The resultant enhanced radiative cooling and reduced deep condensation heating can further reinforce the surface subtropical high.

Thus the present study has assessed the impacts of low-level clouds on the subtropical high and their seasonality in the South Indian Ocean quantitatively, deepening the understanding of the coupling between the subtropical high and low-level clouds. The present study has also indicated that the storm-track activity energized by the Agulhas SST front contributes to the maintenance of the wintertime subtropical high and low-level clouds, and that the deep convection around the Asian summer monsoon region as well as the equatorial Indian Ocean and western Pacific facilitates the westward shift and strengthening of the wintertime subtropical high in the South Indian Ocean, elucidating the mechanisms for the distinct seasonality of the subtropical high and low-level clouds in the South Indian Ocean.