Solar cycle modulation of the North Atlantic Oscillation: The role of Rossby wave breaking, internal wave reflection and critical layer instability

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Abstract: Rossby wave breaking (RWB), a process that is known to be very sensitive to the meridional gradient of potential vorticity (PV), plays an important role in the dynamics and meridional transfer of the Earth's atmosphere. In the winter stratosphere, the meridional PV gradient is largely defined by the vertical structure and meridional extent of the polar vortex. Solar ultra-violet (UV) radiation that varies a few percent over an 11-year is readily absorbed by stratospheric ozone, gives rise to a decadal variation of stratospheric temperature. Studies have suggested that the solar forcing may affect the planetary-scale Rossby wave propagation and breaking, as well as wave mean-flow interaction. Further feedbacks in the lower atmosphere are expected via the stratosphere-troposphere coupling, whereby the solar cycle may in turn lead to a preferred phase of large-scale atmospheric mode such as the North Atlantic Oscillation (NAO).

This study investigates these feedback processes using the reanalysis data set in both pressure and isentropic coordinates from the National Centers for Environmental Prediction Climate Forecast System (NCEP/CFSR). Our focus is on the seasonal development and a downward transfer of the upper stratospheric solar UV signals. We demonstrate that the feedback processes involved a sharpening of the PV gradient in the subtropical upper stratosphere in association with enhanced breaking of quasi-stationary waves in early winter. Eastward propagating transient waves with zonal wavenumber one and 5-7 day periodicity were generated in the upper stratospheric surf zone as the part of absorption, reflection and overreflection cycle of nonlinear critical layers. These internally generated waves then propagated polewards with filaments of low PV air extruding from the subtropics and stirring into the polar latitudes. As these waves meet their critical layers, their subsequent growth of breaking lead to the formation of turning surfaces in the high-latitude upper stratosphere. In middle winter, a feedback process between the eddy momentum fluxes of the reflected waves from the polar upper stratosphere and the polar vortex in the middle stratosphere gave rise to enhanced downward wave propagation along the polar vortex edge. As high PV air being continuously transferred into the extratropical lower stratosphere via enhanced downward wave propgation, the westerlies in the polar lower stratosphere were strengthened via critical layer instability. Such changes in background meanflow then lead to a latitudinal shift of synoptic wave breaking in the troposphere that was manifested by significantly reduced anti-cyclonic and moderate increased cyclonic RWB events. These effects are dynamically consistent with a positive NAO at solar maximum. Nevertheless, the observed correlations among the 11-year solar cycle, the RWBs and the NAO may be specific to the recent period owing to the relatively small amplitudes of transient planetary-scale Rossby waves.

Key words: Rossby wave breaking, solar ultraviolet radiation, critical layer wave reflection and instability.