Meridional shifts of the Gulf Stream (GS) jet on interannual to decadal timescales and the corresponding oceanic changes around the GS are investigated using a near global eddy-resolving ocean model (OFES) hindcast from 1960 to 2003. Simulated variability in the shifts of the GS jet axis shows good agreement with available observations, and lags atmospheric fluctuations characterized by the North Atlantic Oscillation by about 2 years. We revealed that this lagged response of the GS jet to the atmospheric variations is attributed to the westward propagation of the undulation of the jet axis, which has a wavelength of about 4,000 km and a displacement of 50 km with a phase speed of about 2.8 cm s$^{-1}$. The direction and phase speed of the propagation of the undulation can be explained by a thin-jet theory. The shifts of the jet axis in the downstream region are likely induced by wind fluctuations through Ekman convergence over the central North Atlantic. Associated with the northward (southward) shift of the jet axis is sea surface temperature warming (cooling) around and north of the jet. Our numerical results suggest that the GS jet brings the atmospheric signals from the central to the western North Atlantic, and the resultant meridional shift of the jet induces the notable oceanic changes around the GS.