Progress in Oceanography 154 (2017) 38–48

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Variability of the climatic oceanic frontal zones and its connection with the large-scale atmospheric forcing

Alexander S. Kazmin

P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Prosp., Moscow 117997, Russia

ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form 26 December 2016
Accepted 4 April 2017
Available online 3 May 2017

Keywords:
Oceanic fronts
Seasonal variations
Long-term changes
Atmospheric forcing
World Ocean

ABSTRACT

Global satellite sea surface temperature (SST) measurements and NCEP/NCAR reanalysis wind data for the period of 1982–2009 have been used to study the seasonal and interannual variability of the main climatic oceanic frontal zones (OFZ; subpolar, subtropical and equatorial) associated with the large-scale atmospheric forcing. The seasonal variability of the OFZ is manifested in variations of their intensity (magnitude of the meridional gradient of SST) and latitudinal position of the cores (defined as areas of maximum SST gradient). The maximum intensity of the subpolar OFZ is observed in summer of the corresponding hemisphere, while subtropical OFZ are intensified synchronously in both hemispheres during boreal winter. Subtropical OFZ cores in both hemispheres shift synchronously to the south/north during the winter/summer of the Northern hemisphere, which is caused by the seasonal meridional migration of the areas of the maximum convergence of Ekman transport. All subpolar and subtropical OFZ reveal a pronounced quasi-decadal (7–10 years) variability, manifested in the variations of their intensity and latitudinal position of the zones' cores. Strengthening of the SST gradient is accompanied by a displacement of the zones' cores to the north in both hemispheres for subpolar OFZ, while subtropical OFZ cores migrate to the poles in this situation. Positive correlations between the maximum magnitude of the meridional gradient of zonally averaged SST and meridional shear of zonal wind (which is an estimate of the Ekman convergence intensity) were found for all subpolar and subtropical OFZ. Variability of the latitudinal position of subpolar OFZ cores is associated with the Ekman advection variability due to zonal wind variations (strengthening of zonal wind results in a shift of subpolar OFZ cores to the south/north in the Northern/Southern hemispheres). A period of the variability of the North Pacific equatorial OFZ is 4–5 years and is determined by the variability of the ENSO system. During the El Niño events, the sharp decrease of the intensity of the equatorial OFZ take place.

1. Introduction

Fronts and frontal zones are integral structural elements of the World Ocean, occur over the entire range of spatial scales from a few tens of meters to oceanic basins size, are formed by diverse frontogenetic mechanisms and play an important role in hydrophysical and biological processes. Of the most interest is the large-scale climatic oceanic frontal zones (OFZ) maintained by the global redistribution of momentum and heat fluxes. These OFZ have zonal extension of the oceanic basins scale and meridional width of a few (up to 10) degrees of latitude (theirs cores, or areas of maximum SST gradient are up to 2–3 degrees of latitude). Variability and frontogenesis in the OFZ serve as an integral indicator of the ocean–atmosphere interaction. Since the climatic OFZ are components of a global circulation system, it is reasonable to study their variability over the entire area of the World Ocean (global approach). This analysis is possible only with the use of the global satellite sea surface temperature (SST) measurements. In one of the first studies of this kind (Kazmin and Rienecker, 1996), a 12-year time series of SST measurements was successfully used to investigate the climatology and seasonal (and, in part, interannual) variability of OFZ over the World Ocean. In the next two decades, due to the progress in computing capabilities, the studies were concentrated predominantly on the model simulations, and a significant progress was achieved in this field. E.g., Dinniman and Rienecker (1999) used a primitive equation model (Geophysical Fluid Dynamics Laboratory's MOM 2) with one degree of spatial resolution to simulate the seasonal cycle of frontogenesis in subpolar and subtropical frontal zones of the North Pacific and confirmed the observational results presented earlier by Kazmin and Rienecker (1996). Nonaka et al. (2006) and Nonaka et al. (2008) used an eddy-resolving OGCM simulations

---

E-mail address: akazmin@ocean.ru

http://dx.doi.org/10.1016/j.pocean.2017.04.012
0079-6611/© 2017 Elsevier Ltd. All rights reserved.

to investigate the mechanisms of interannual-to-decadal variability in the Kuroshio-Oyashio Extention region with particular emphasis on that of Oyashio and Kuroshio Extention (subpolar) fronts. They found that as a decadal-scale pattern change from a warm period around 1970s to a cool period in the mid-1980s, those fronts in the model simulation migrate southward as observed, and the associated pronounced cooling is confined mainly to those frontal zones (Nonaka et al., 2006). Thomas and Lee (2005) used an analytic theory and non-hydrostatic numerical simulations to demonstrate the mechanism by which the down-front winds lead to frontogenisis in the mid-latitude OFZ. Ogava et al. (2016) explores the possible impact of midlatitude oceanic frontal zones on annular mode signatures in the wintertime of the Southern Hemisphere using atmospheric GCM. By systematically changing the latitude of frontal gradient in the SST profile, theirs experiments reveal that the characteristics of the wintertime annular mode exhibit strong sensitivity to the position of the SST front situated at midlatitude or subpolar latitude. The annular mode was interpreted as a manifestation of wobble of the extratropical tropospheric circulation between two dynamical regimes – one under the strong influence of SST gradient and the other under the strong control of atmospheric internal dynamics unrelated to the lower-boundary condition. In fact, this interpretation offers insight into the observed interbasin differences in the wintertime signature of the southern annular mode that are embedded in the zonally symmetric anomalies. Those findings suggest a possible reinterpretation of the climatological-mean state observed in the wintertime Southern Hemisphere as the superposition of those two dynamical regimes.

In addition, a number of studies based on both observational and modelling approach were dedicated to role of the OFZ in ocean-atmosphere interaction and possible impact of frontal variability on the large-scale atmospheric circulation. E.g., Qiu (2002) described in detail the large-scale structural change (an oscillation between an elongated and a contracted state) observed in the Kuroshio Extension system. He mentioned that the causes for this structural change are the basin-wide external wind forcing and nonlinear dynamics associated with the internal recirculation gyre. Nakamura et al. (2008) showed that observations indicate that midlatitude weather systems are organized into "storm tracks" near oceanic frontal zones with pronounced SST gradients. A pair of atmospheric general circulation model (GCM) experiments with zonally uniform SST profiles prescribed showed that their observed collocation is not fortuitous. In one experiment, a storm track was anchored around a midlatitude SST front that maintains near-surface thermal gradients and energizes eddies. Westerly momentum transport by eddies produces a well-defined polar-front jet along the front, even in winter when a subtropical jet stream intensifies. In the other GCM experiment, removal of the SST front leads to a substantial weakening in eddy activity, especially in winter. It also leads to a weakening of the annular mode – the dominant mode of westerly-jet variability – and its notable structural distortion in winter. Though idealized, the experiments suggested the importance of midlatitude oceanic fronts for the tropospheric circulation and its variability. Sallee et al. (2008) used historical hydrographic profiles, combined with recent Argo floats profiles, to obtain an estimate of the mean geostrophic circulation in the Southern Ocean. Thirteen years of altimetric sea level anomaly data were added to reconstruct the time variability of sea level, and this dataset was analyzed to identify and monitor the position of the two main fronts of the Antarctic Circumpolar Current during the period 1993–2005. The authors relate their movements to the two main atmospheric climate modes of the Southern Hemisphere: the Southern Annular Mode (SAM) and the El Niño–Southern Oscillation (ENSO). The study finds that although the fronts are steered by the bathymetry, which sets their mean pathway on first order, in flat-bottom areas the fronts are subject to large meandering because of mesoscale activity and atmospheric forcing. While the dominant mode of atmospheric variability in the Southern Hemisphere, SAM, is relatively symmetric, the oceanic response of the fronts is not, showing substantial regional differences. Around the circumpolar belt the fronts vary in latitude, exposing them to different Ekman transport anomalies induced by the SAM. Three typical scenarios occur in response to atmospheric forcing: poleward movement of the frontal structure in the Indian Basin during positive SAM events, an equatorward movement in the central Pacific, and an intensification without substantial meridional movement in the Indo-Pacific basin. This study also showed the geographical regions that are dominated by a SAM or ENSO response at low and high frequencies. Ocean-atmosphere interaction over the Northern Hemisphere western boundary current (WBC) regions (i.e., the Gulf Stream, Kuroshio, Oyashio, and their extensions) was reviewed by Kwon et al. (2010) with an emphasis on their role in basin-scale climate variability. They showed that SST anomalies exhibit considerable variance on interannual to decadal time scales in these regions. Low-frequency SST variability is primarily driven by basin-scale wind stress curl variability via the oceanic Rossby wave adjustment of the gyre-scale circulation that modulates the latitude and strength of the WBC-related oceanic fronts. Rectification of the variability by mesoscale eddies, reemergence of the anomalies from the preceding winter, and tropical remote forcing also play important roles in driving and maintaining the low-frequency variability in these regions. In the Gulf Stream region, interaction with the deep western boundary current also likely influences the low-frequency variability. Surface heat fluxes damp the low-frequency SST anomalies over the WBC regions; thus, heat fluxes originate with heat anomalies in the ocean and have the potential to drive the overlying atmospheric circulation. While recent observational studies demonstrate a local atmospheric boundary layer response to WBC changes, the latter's influence on the large-scale atmospheric circulation is still unclear. Nevertheless, heat and moisture fluxes from the WBC into the atmosphere influence the mean state of the atmospheric circulation, including anchoring the latitude of the storm tracks to the WBCs. Furthermore, many climate models suggest that the large-scale atmospheric response to SST anomalies driven by ocean dynamics in WBC regions can be important in generating decadal climate variability. As a step toward bridging climate model results and observations, the degree of realism of the WBC in current climate model simulations was assessed (Kwon et al., 2010). The Kuroshio Extension (KE) fluctuates between its different dynamic regimes on (quasi) decadal time scales. In its stable (unstable) regime, the KE jet is strengthened (weakened) and less (more) meandering. Masunaga et al. (2016) investigated wintertime mesoscale atmospheric structures modulated under the changing KE regimes, as revealed in high-resolution satellite data and data from a particular atmospheric reanalysis (ERA-Interim). In the unstable KE regime, a positive anomaly in sea surface temperature (SST) to the north of the climatological KE jet accompanies positive anomalies in upward heat fluxes from the ocean, surface wind convergence, and cloudiness. As revealed in the atmospheric reanalysis, these positive anomalies coincide with local lowering of sea level pressure, weaker vertical wind shear, warming and thickening of the marine atmospheric boundary layer (MABL), anomalous ascent, and convective precipitation. In the stable KE regime, by contrast, the corresponding imprints of sharp SST gradients across the KE and Oyashio fronts on the wintertime MABL are separated more distinctly, and so are the surface baroclinic zones along those two SST fronts. In the ERA-Interim data, such mesoscale imprints of the KE variability as above are not well represented in a period during which the resolution of SST data prescribed is relatively low. This study elucidates the importance of high-resolution SST