Preface

It has been widely accepted that extratropical oceans vary in their passive response to mechanical and thermal forcing exerted by variability in the overlying atmosphere that is generated locally by internal dynamics or remotely through teleconnection from the coupled ocean–atmosphere variability in the tropics, including the El Niño/Southern Oscillation (ENSO). In the tropics, sea-surface temperature (SST) is generally so high that its small changes can modulate activity of cumulus convection to allow effective coupling of ocean/atmosphere variability. The anomalous latent heat release in the troposphere can change vertical motion in the tropics, the influence of which can reach into the extratropics via atmospheric teleconnection. In the extratropics, where SST is generally lower, its variability has been believed to exert no significant influence on the overlying atmosphere. Rather, over each of the midlatitude ocean basins, especially in winter, synoptic-scale cyclone and anti-cyclones that recurrently develop and migrate along a stormtrack act to maintain persistent, basin-scale atmospheric anomalies, regardless of whether they are generated under the remote influence of tropical variability or through internal atmospheric dynamics. The involvement of those migratory eddies renders the extratropical atmospheric anomalies more barotropic with enhanced surface wind anomalies, consequently forcing basin-scale SST anomalies by modifying latent and sensible heat fluxes (hereafter LHF and SHF, respectively) from the sea surface and/or modulating sub-surface mixing and associated entrainment at the mixed-layer bottom. In fact, statistical analysis based on in situ SST observations in a rather coarse spatial resolution, as often in practice until recently, tends to extract such basin-scale SST anomalies as a consequence of atmospheric variability, whose polarities are such that negative SST anomalies are associated with enhanced heat release into the atmosphere and vice versa (Kushnir et al. 2002).

The passive response of the extratropical ocean to atmospheric variability is consistent with the established notion that the potential predictability of the extratropical atmospheric circulation is found basically in the teleconnection from coupled ocean/atmosphere variability in the tropics. Nevertheless, the passiveness of the extratropical ocean may sound rather counterintuitive if a climatic role of the subtropical gyres in poleward heat transport is considered. In each of the basins, a huge amount of heat transferred by a gyre from the tropics is intensively released into the atmosphere through LHF and SHF from a narrow western boundary current (WBC) in the subtropics and midlatitudes, including the Kuroshio current and the Gulf Stream in the Northern Hemisphere and the Brazil, East Australian and Agulhas currents in the Southern Hemisphere. Each of the warm WBCs, especially its eastward extension, tends to be confluent with a cold current, forming an oceanic frontal zone with a sharp SST gradient and active meso-scale eddies. The variability of the frontal zone as a response of the ocean gyre to wind stress anomalies can yield strong SST anomalies and act to exert thermodynamic forcing on the atmosphere by modifying heat and moisture release

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(Kelly et al. 2010; Kwon et al. 2010). These WBCs and associated frontal zones, which the authors call “hot spots”, can, therefore, be significant in shaping the tropospheric circulation and forcing its variability. Owing to their narrowness, however, the variability of the “hot spots” is difficult to identify with in situ SST data. The climatic significance of the “hot spots” had not been highlighted until both high-resolution satellite measurement of SST, sea-surface height, surface winds and precipitation and high-resolution modeling of the ocean and atmosphere became available in recent years (Nonaka and Xie 2003; Xie 2004; Small et al. 2008; Chelton and Xie 2010).

Recent satellite data and high-resolution numerical modeling have revealed the complex nature of multi-scale air-sea interaction within the “hot spots”. For example, satellite scatterometer measurements have revealed meso-scale patterns of surface wind convergence/divergence generated under the background winds blowing across a frontal SST gradient (Chelton et al. 2004; O’Neill et al. 2010), as the vertical mixing by wind momentum is enhanced on the warner side of an SST front. Through this vertical mixing mechanism, surface winds blowing along the SST front act to generate shear vorticity, while cross-frontal winds act to generate surface convergence or divergence. A frontal SST gradient also yields surface convergence/divergence through enhanced (suppressed) heat release from the ocean on the warmer (cooler) side of the front that hydrostatically acts to lower (raise) surface pressure and resultant frictional convergence (divergence) (Shimada and Minobe 2011; Tanimoto et al. 2011). Generated through this pressure adjustment mechanism or the vertical momentum mixing mechanism (Schneider and Qiu 2015), the surface convergence yields ascending motion at the top of the boundary layer, acting to enhance cloudiness and precipitation locally (Tokinaga et al. 2009; Tanimoto et al. 2011; Masunaga et al. 2015). Through essentially the same mechanisms, meso-scale oceanic eddies can also leave meso-scale imprints on surface wind, cloudiness and precipitation patterns. The meso-scale imprints are generally confined into the planetary boundary layer. Particularly high SST along the Gulf Stream or Kuroshio current, however, can organize deep convective clouds, especially under the warm, moist airflow from the tropics, accompanying organized free-tropospheric ascent and latent heat release (Minobe et al. 2008; Sasaki et al. 2012; Miyama et al. 2012).

The WBCs and associated oceanic frontal zones alsoinfluence recurrent development of extratropical cyclones and anticyclones and, thereby, formation of a stormtrack (Nakamura et al. 2004). Those atmospheric eddies under development act to relax the surface air temperature (SAT) gradient, which is essential for their baroclinic development. Eddy-associated cross-frontal surface winds enhance cross-frontal SHF contrasts, which can effectively restore the SAT gradient to maintain a surface baroclinic zone and, thereby, allowing recurrent development of baroclinic eddies for the formation of a stormtrack and an associated eddy-driven westerly jet (Hotta and Nakamura 2011). The frontal SST gradient is, nevertheless, maintained despite the differential heat release into the atmosphere, owing to the deep-ocean mixed layer under the strong surface westerlies with storminess and the differential thermal advection by the confluent warm and cool currents. It has been pointed out that variability of the subarctic frontal zone in the Kuroshio-Oyashio Extension (KOE), a prominent oceanic frontal zone in the North Pacific, generates pronounced decadal SST variability that can force basin-scale atmospheric anomalies, manifested as the anomalous surface Aleutian Low, by modulating stormtrack activity (Frankignoul et al. 2011; Taguchi et al. 2012). It has been also pointed out that an oceanic frontal zone is important for maintaining the annular-mode variability, which is manifested as variability of the eddy-driven jet (Nakamura et al. 2008). Through these processes, the WBCs and associated oceanic frontal zones can influence basin-scale or even hemispheric-scale atmospheric circulation and climate.

Thus far, multi-scale oceanic impacts on the atmosphere have been emphasized to highlight the climatic significance of the WBCs and associated fronts as climatic “hot spots”. Their significance, of course, also lies in the oceanic aspects themselves, including jets, fronts, eddies and streamers, which are involved in the intense heat and moisture release to the atmosphere. The locally enhanced heat release from the warm sea surface in winter enhances subsurface mixing and, thereby, contributes to the mixed-layer deepening and the mode of water generation and, thereby, influencing the density distribution in the ocean interior (Oka and Qiu 2012). Such a "hot spot" as the KOE region thus acts as a communicator between the interior ocean and the surface layer, and the Kuroshio Extension (KE) variability as discussed below can be translated into the interior by modulating the mode water formation (Oka et al. 2012).

An ocean jet associated with a WBC, if dynamically unstable, can generate meso-scale eddies, and the degree of its instability varies in time. The KE jet, for example, fluctuates between stable and unstable regimes on quasi-decadal scales (Qiu and Chen 2005). In its unstable regime, the KE is weaker, meandering and generating meso-scale eddies vigorously. Warm-core eddies thus pinched off the KE give rise to positive SST anomalies to its north (Sugimoto and Hanawa 2011). In the stable regime, by contrast, the SST is lower, as the eddy generation is suppressed from the intensified KE that flows more zonally. The eddy generation itself is through internal dynamics of the KE jet and can be modulated without wind forcing. In reality, however, oceanic Rossby waves forced by wind stress variations in the central Pacific propagate westward, while associated sea surface height anomalies become concentrated into the jet to effectively modify it (Sasaki and Schneider 2011). The wind variations thus act as a "pace maker" for the quasi-decadal KE variability by triggering its regime transition (Taguchi et al. 2007). Meanwhile, modulated meso-scale eddy activity can lead to modulations in sub-meso-scale streamers and associated vertical motion (Sasaki et al. 2014).

As discussed above, the climatic significance of "hot spots" has recently been revealed through substantiation of an active role of the WBCs and associated frontal zones in the climate system. This recent progress is the outcome of rapidly growing attention to this subject by the international community. Toward this progress, contributions from Japanese scientists are substantial, including those from the project "Multi-Scale Air-Sea Interaction under the East-Asian Monsoon: A 'Hot Spot' in the Climate System". This so-called "Hot Spot" project is funded from summer 2010 to spring 2015 by the Ministry of Education, Culture, Sports, Science and Technology, in which a hundred scientists and graduate students from both the oceanography and meteorological societies participated. The primary target of the project is the KOE region and the East Asian marginal seas, namely the Yellow and East China Seas and the Seas of Japan and Okhotsk, as the most profound "hot spot" in the climate system. Specifically, the climatological-mean sensible and latent heat release from the ocean based on the "Japanese Ocean Flux Data sets with Use of Remote Sensing Observations" (J-OFURO2) data (Kubota and Tomita 2007) in January is about 2 PW over the western North Pacific, which is much greater than around the Gulf Stream (0.9 PW). This region is characterized by sharp thermal contrasts in both meridional and zonal directions under the influence of the East-Asian monsoon and the confluence of the Kuroshio and Oyashio currents. By unifying advanced high-resolution numerical modeling on the Earth Simulator and new-generation satellite data, and by conducting in situ observation campaigns, we aim to deepen our understanding of multi-scale interactive processes actively involved in the air-sea heat and freshwater exchanges and their influence on the climate variability. The main topics of the project include multi-scale air-sea interactions over the marginal seas and KOE region under strong influence of the East Asian monsoon, in addition to a comparison with those in other "hot spots" over the globe. The project mainly investigates physical aspects of oceanic and atmospheric processes occurring in the "hot spots", while also studying chemical and biological aspects in the KOE region and East Asian marginal seas.

This special section includes a review paper and eight original papers, all of which are outcomes of the “Hotspot Project”. The section begins with a review paper by Kida et al. (2015), which offers a thorough description of oceanic fronts in the western North Pacific, East Asian marginal seas and coastal seas around Japan. The description is based on common metrics with particular emphasis placed on the structure and variability of the fronts and their roles in air-sea interaction. A metric table will provide a useful benchmark for assessing the reproducibility of those fronts in numerical models.

Sasaki and Minobe (2015) presented climatological statistics of oceanic rings detached from the KE jet, including their time evolution through a new detection method applied to satellite altimeter observations. They also relate the interannual and decadal variability of those rings to the strength of the KE jet and SST variations.

Kawai et al. (2015) presents an overview of an intensive observation campaign carried out by the “Hotspot Project” in early July 2012. The campaign features the first successful in situ observations of the marine atmospheric boundary layer with three research vessels that were aligned together meridionally in going back and forth across the sharp SST front along the KE jet. The paper describes observed cross-frontal changes in cloud base height and downward infrared radiation, which can be regarded as a response to the frontal SST gradient, as confirmed by numerical simulations. The campaign also revealed a rapid northward displacement of the SST front, which was not captured well in any objectively analyzed SST data sets.

An observational study by Faure and Kawai (2015) clarifies the seasonality in the mechanisms through which SST anomalies in the subarctic frontal zone, including the surface heat fluxes, entrainment at the mixed-layer bottom and lateral advection. Hosoda et al. (2015a) show that the summertime heat penetration into the subsurface layer must be incorporated to reproduce the seasonal SST evolution observed in the North Pacific. Unlike what has been believed, a major fraction of the net downward heat flux is found to reach below the shallow seasonal thermocline. They introduce a concept of heat penetration depth for defining the effective upper-ocean heat capacity in the warm season. In a companion paper, Hosoda et al. (2015b) showed that in the western North Pacific, early-summer temperature variability often extends well below the seasonal thermocline in association with variability in the KE jet.

Through observational data analysis and numerical modeling, Nakamura et al. (2015) attribute particular seasonality of a small meander of the Kuroshio off the Kyushu Island of Japan to local wind forcing. They point out that the effects exerted by the northeasterly monsoonal winds on the Kuroshio Current to the north of Okinawa Island in the autumn and early winter are of particular importance for the small meander that tends to occur in winter through early spring.

Wada (2015) focuses on an unusual event of rapid typhoon intensification observed around the Kuroshio front to the south of Japan. Simulations with an atmosphere-wave-ocean model reveal a critical role in the rapid intensification and associated torrential rainfall.

Finally, Aoki et al. (2015) report trends observed in surface and subsurface temperatures around the Antarctic Circumpolar Current and associated frontal zones. Utilizing an eddy-resolving model simulation, they discuss processes that caused different horizontal patterns between the surface and subsurface temperature trends.

Each of the papers included in this special section presents important new ideas and/or findings related to the “Hotspot Project”. These findings, besides those published elsewhere, elucidate various multi-scale processes in the ocean and atmosphere and their interactions that characterize the “hot spots” to substantiate their climatic significance. Although most of the findings are concerning the KOE region and the East Asian marginal seas, they, overall, must be commonly applicable to other climatic “hot spots”. Over the last century, all the five “hot spots” have undergone warming trends much faster than the the global oceanic average (Wu et al. 2012), suggesting increasing climatic significance of the “hot spots”. We hope that this special section, as a highlight of the “Hotspot Project”, makes an important contribution to the advancement of our understanding of climatic “hot spots” and, thereby, the broadening of our knowledge of extratropical air-sea interaction, a rapidly developing area of climate science that has been drawing increased attention of the international community. We also hope that the papers in this special section can interest researchers and students in ocean, atmosphere and climate sciences, and, thereby, more scientists, particularly those of the younger generation, will participate in further advancement of our understanding of extratropical air-sea interaction and its role in the climate system.

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Hisashi Nakamura
Atsuhiko Isobe
Shoshiro Minobe
Humio Mitsudera
Masami Nonaka
Toshio Suga

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