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Authors: Bian, Changwei, Jiang, Wensheng, Pohlmann, Thomas, and Sündermann, Jürgen

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Changwei Bian[†]**, Wensheng Jiang**[‡§*]**, Thomas Pohlmann**[#]**, and Jürgen Sündermann**[#]

[†] Key Laboratory of Physical Oceanography
Ocean University of China
Qingdao, Shandong 266100, P. R. China

[‡] Laboratory of Marine
Environment and Ecology
Ocean University of China
Qingdao, Shandong 266100, P. R. China

[#] Institute of Oceanography
University of Hamburg
Hamburg, Germany

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ABSTRACT

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The Bohai Sea used to be one of the most important fishing grounds in China. Recently, its ecological functions have declined rapidly due to the heavy anthropogenic activities which make ecological environment protection and restoration particularly topical in this region. Understanding the oceanographic conditions of the Bohai Sea is essential to evaluate the living environment (*e. g.* temperature and salinity) of planktons and transport fluxes of nutrients, sediments and contaminations. In this paper, we will analyze the published literature and data sets containing field observations, remote sensing reconstructions and numerical model results, and describe the principle features of the hydrodynamic system in the Bohai Sea, such as external forces, thermohaline patterns, tides, waves, currents and substance transport processes. The objective of this paper is to provide a general picture of the hydrography of the Bohai Sea; by this means the work may be beneficial for studies in other disciplines, too.

ADDITIONAL INDEX WORDS: *Thermohaline, tide, circulation and transport processes.*

INTRODUCTION

In the western Pacific, the marginal Bohai Sea (Figure 1) is a shallow semi-closed sea with a total area of 77,000 km^2 and an
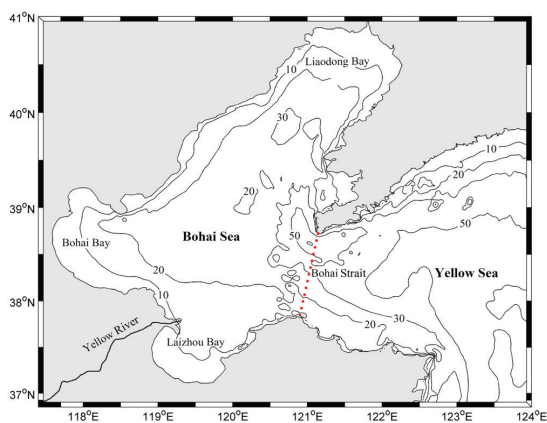

Figure 1. Bathymetry of the Bohai Sea (m). The dashed line indicates the boundary between the Bohai Sea and the Yellow Sea

average water depth of 18 m. The Bohai Sea used to be one of the most important fishing grounds in China and possesses a large amount of oil fields which provide natural resources for the economic development of the coastal regions. In recent decades, the massive human activities such as land reclamation, pollutant discharged from rivers and oil field exploitation caused a sharp deterioration of the marine ecological system in the Bohai Sea (Gao *et al.*, 2015; Pelling *et al.*, 2013; Wang, 2015). Today, as environmental problems attract more and more attention, a lot of research projects have been launched to study the physical, chemical, geological and biological characteristics of the Bohai Sea.

In general, the Bohai Sea is divided into five regions: Liaodong Bay, Bohai Bay, Laizhou Bay, Central Bohai Sea and Bohai Strait. The Bohai Sea is characterized by a basin shape and deepens gradually from a depth of less than 20 m in the three coastal bays to the Central Bohai Sea. The northern Bohai Strait with a maximum water depth of about 70 m plays an important role in steering the water exchange between Yellow Sea and Bohai Sea. As generally in the ocean, the physical system of the Bohai Sea is determined by the space-time distribution of seven macroscopic variables: temperature, salinity, density, pressure and the three components of the velocity vector. These variables help to distinguish one water mass from another, and to study and understand the motions of the sea water in response to the governing forces. Suspended and dissolved substances (*e.g.* suspended particle matter (SPM), contaminants and nutrients) are considered as physical properties as well, which is a reasonable assumption as

long as chemical and biological processes can be neglected. These substances are of particular importance, because their spreading and deposition control the biological and morphological state of the Bohai Sea.
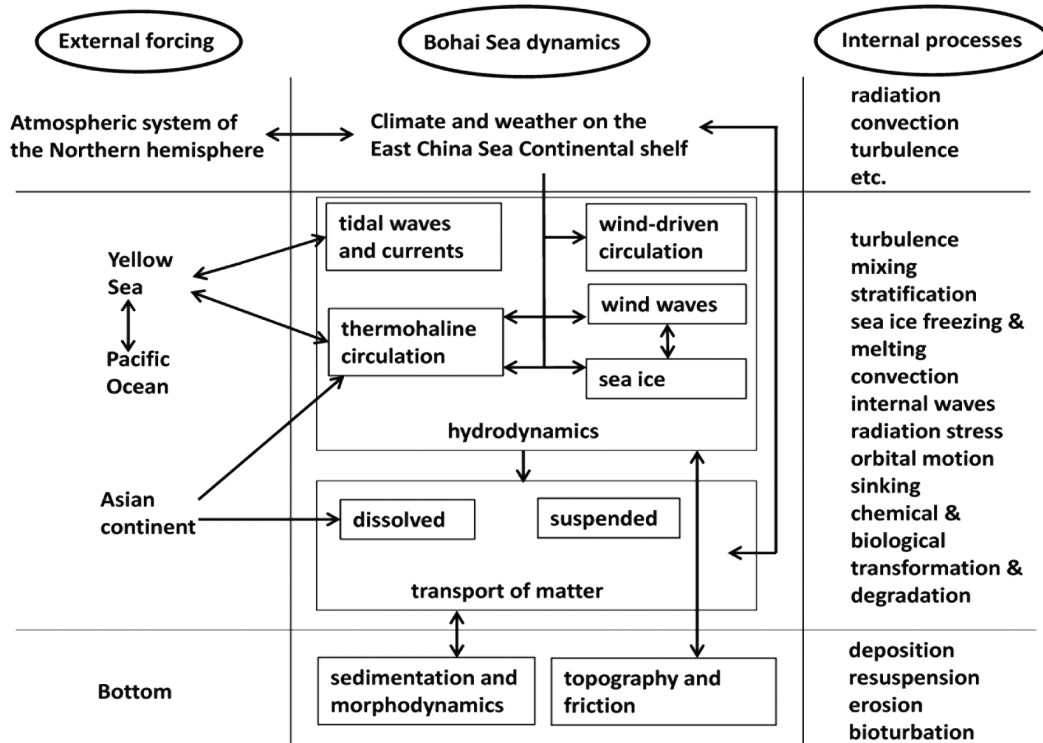

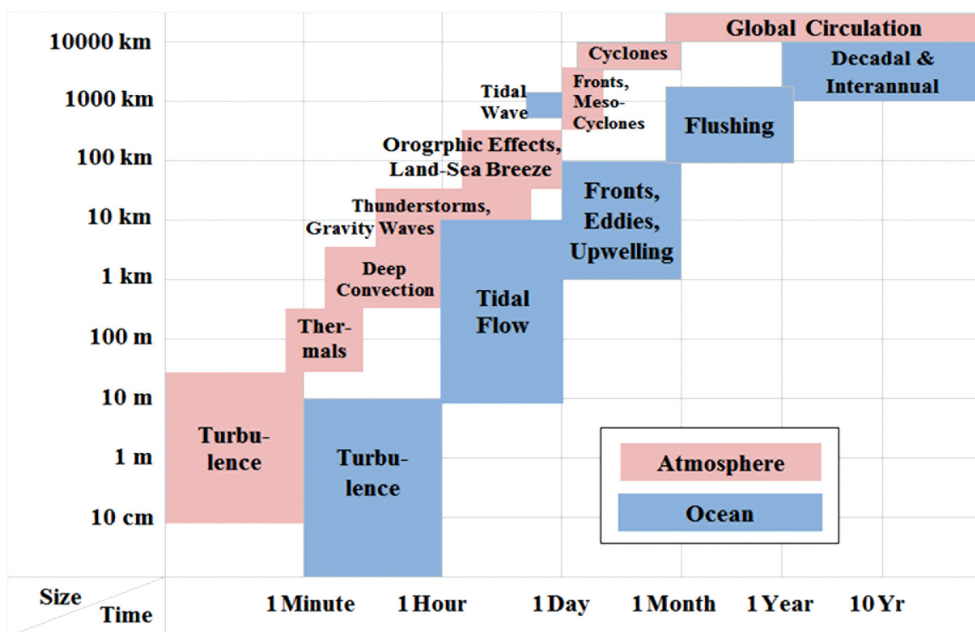Figure 2. Scheme of interactions within the physical system

Figure 3. Scale spectrum of the physical system

Bohai Sea dynamics are characterised by the regional interaction among the atmosphere, the hydrosphere and the lithosphere on the East Asian shelf exhibiting a broad spectrum of spatial and temporal scales (Figure 2 and Figure 3). Specific features of the physical system mainly include tides, surface waves, baroclinic eddies, internal waves, convection, turbulence, *etc*. Principally, the physical, chemical, biological and morphological compartments of the Bohai Sea system cannot be separated due to their strong interactions with each other. Certainly, the physical signal is essential for the transportation of chemical and biological substances within the whole ecosystem. But there is also a feedback depending on the scales considered, *e.g.* radiation flux, albedo, surface films, surface roughness and morphology.

Our knowledge of hydrology in the Bohai Sea is based on field observations, remote sensing reconstructions and model simulations. Since 1950s, comprehensive investigations have been conducted in the Bohai Sea to determine the temporal and spatial variability of physical, chemical and biological components. The State Scientific and Technological Commission of China organized the "Chinese National Comprehensive Oceanographic Survey (1958−1960)" which for the first time systematically expounded hydrographic and biogeochemical features of the Bohai Sea. After that, several comprehensive investigations were carried out, such as "Research on the Prediction of Water Quality and the Physical Self-Purification Capability of the Bohai Sea and the Ten Bays in China (1985 − 1986)", "Study of China Shelf Sea Circulation and Its Dynamics (1992−1995)", and "Analysis and Modelling of the Bohai Sea Ecosystem (1997−2000)" (Sündermann and Feng, 2004). These investigations provided fundamental knowledge of the temporal and spatial variability of the hydrography in the Bohai Sea. Since 1980s, remote sensing images have been used to study features of sea surface temperature (SST) and sea ice in the Bohai Sea (Jiang and Wen, 1987; Peng and Bernstein, 1985). In the recent two decades, remote sensing techniques were widely used to study sea level rise, SPM, wind and salinity distributions, because modern satellites provide continuous and high temporal and spatial resolution of these parameters (Liu *et al.*, 2010; Shi and Wang, 2012; Wang *et al.*, 2014). On the other hand, only the sea surface layer signals can be detected by satellite which limits the effect of remote sensing

on hydrology studies. As a complete all-round tool, numerical modeling has become the main way to study the physical environment of the Bohai Sea since the 1980s. Although a number of previous numerical studies of the Bohai Sea have elaborated the state of one to several of these physical variables only a consensus has been reached concerning the basic characteristics of these variables. On the other hand, there are still unresolved issues regarding smaller scale features due to lack of sufficient field data which could help to verify the numerical results. Nevertheless, the best overall information to date is given by hydrodynamic models of the Bohai Sea, and hence, most physical results used in this paper are based on numerical models.

A lot of literature has been published concerning the hydrographic and hydrodynamic conditions of the Bohai Sea, most of which only focus on one or few variables, and in some cases may even have contradictory findings. Thus, a comprehensive literature synthesis is required to obtain a clear understanding of the physical features of the Bohai Sea and to notice the contradictions and confusions in existing studies. In the following, the external forces of the Bohai Sea are firstly introduced. Then the specific features of the physical system are described, namely thermohaline regime, wind-driven regime, tidal-driven regime and transport processes.

EXTERNAL FORCING

The Bohai Sea is a part of the East China Sea continental shelf, and its physical state is essentially determined by the adjacent Pacific Ocean, the Asian continent and the atmosphere of the northern hemisphere.

Pacific Ocean

The relatively narrow Bohai Strait allows the exchange of matter, heat and momentum between the Bohai Sea and the open ocean. The Yellow Sea forms the transition between the Bohai Sea and the Pacific Ocean. Planetary waves generated by astronomical and atmospheric forces in the ocean propagate over the shelf break through the East China Sea and the Yellow Sea into the Bohai Sea resulting in sea level changes, tides and water mass transports. In contrast, continental fresh water discharges from the Bohai Sea influence the water characteristics of the North Pacific.
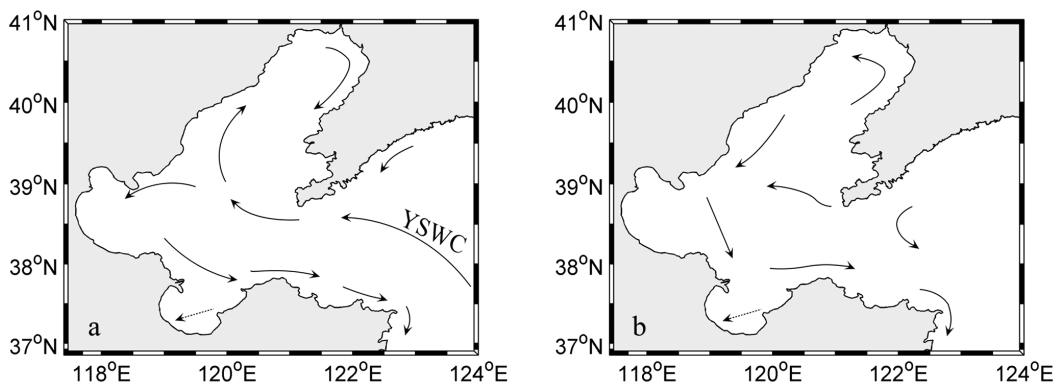

Figure 4. Schematic diagrams of the general circulation system in the Bohai Sea for (a) winter and (b) summer. Source: after Guan (1994)

The circulation system in the Bohai Sea (Figure 4) shows that the main inflow occurs along the northern Bohai Strait by the intrusion of the Yellow Sea Warm Current (YSWC) in winter. In the southern Bohai Strait, the Bohai Sea water flows out all the year (Bian et al., 2013; Guan, 1994). Altogether, the net transport through the Bohai Strait is a superposition of continental outflow and Yellow Sea inflow. It has to be noted that the evaluation of the water exchange between the Bohai Sea and Yellow Sea is important for the import and export of substances. However, water exchange fluxes are rarely estimated by field investigations, and hence, most water exchange rates given for the study areas are based upon model results. Due to different models using different assumptions and forcings, the simulated results of water fluxes into the Bohai Sea differ in the range between 5×10^3 and 8×10^4 m^3/s (Bi et al., 2015; Lin et al., 2002; Wei et al., 2003).

Moreover, the interannual variability of the Pacific, mainly the ENSO (and other fluctuations), has also been observed in the Bohai Sea and affects the physical environment of this area. Studies based on satellite remote sensing data indicate that ENSO events dominate the interannual changes of sea level and are also correlated with the interannual SST anomaly in the Bohai Sea (Liu et al., 2010; Wu et al., 2005).

Terrestrial input

The continent affects the Bohai Sea by river discharged freshwater, dissolved and suspended matters. There are more than 40 rivers around the Bohai Sea, and about 7.2×10^{10} m^3 freshwater, 1.3×10^{10} t sediment, 3×10^{10} t waste water, 2×10^4 t contaminants are directly discharged into the Bohai Sea annually (Zhang et al., 2006). The freshwater input causes vertical and horizontal variations of salinity in estuarine areas, further forming stratification and fronts that act as barriers to water mixing. The Yellow River (also called Huanghe River), as the second largest river in the world in terms of sediment load, discharges 1.1×10^9 t of sediment into the Bohai Sea annually (Milliman and Meade, 1983). Approximately 70 ~ 90% of the sediment transported to the sea is deposited at the mouth of the Yellow River (Bornhold et al., 1986; Martin et al., 1993), finally determining the morphological changes in the Bohai Sea. Sediment discharged from the Yellow River decreased sharply over the past 60 years with a reduction of about 75% due to the influence of human activities and climate changes (Zhang et al., 2012), and the sediment load from the Yellow River will most likely remain small over the next 2 to 3 decades (Ren, 2006).

The Bohai Sea experienced rapid coastline changes due to natural developments of the Yellow River delta and large-scale anthropogenic land reclamation. Satellite remote sensing studies indicated that over the last three decades the newly formed land reclamation area in the Bohai Sea cover 2278 km^2 (Li et al., 2013). These morphological changes induced by the coastal development have significant effects on the tidal regime in the Bohai Sea, leading to a rise of the tidal amplitude and the onshore sediment transport (Pelling et al., 2013; Song et al., 2013). And most importantly, the reclamation seriously damages the marine ecosystem, disturbs or takes away coastal wetland and reduces biodiversity.

Atmosphere

The atmosphere and the ocean form a coupled system, exchanging heat, momentum and water at the air-sea interface. Through the heat and momentum exchange, the atmosphere significantly affects the general circulation of the Bohai Sea as well as the vertical structure of the water column due to turbulence. The distribution of the wind direction and speed determines the major current patterns in the Bohai Sea. The wind further controls the spectrum of surface waves in the Bohai Sea, and cyclones and winter storms can lead to storm surges. Precipitation on the Northwest Pacific shelf influences the salinity of the Bohai Sea and its seasonal variability directly or via continental river discharge.

Table 1. *Crucial factors of the atmosphere-sea interaction in the Bohai Sea (Sun, 2006)*

	Solar radiation (MJ/m^2)	Air temperature (℃)	Wind speed (m/s)	Precipitation (mm/month)
Winter	250 ~ 260	−4 ~ −2	5 ~ 7	2
Summer	600 ~ 650	24 ~ 25	4 ~ 5	140

Bottom sediment

The bottom represents a source or sink for sediment (by erosion, resuspension, deposition) and attached substances. As indicated, the Yellow River discharges large amounts of sediment into the Bohai Sea annually, and sediment transport processes in the Bohai Sea significantly influence the coastline and morphological features and as a consequence currents and sea surface waves. Related biogeochemical processes are important for the bottom sediment movement. For example, bioturbation in seabed sediments resulting from feeding, burrowing and habitat construction of benthic organisms can affect the sediment erosion threshold and transport rates.

THE THERMOHALINE REGIME

The thermodynamic state of the Bohai Sea is characterised by the 4D distributions of temperature, salinity and baroclinic circulation. The salinity and temperature characteristics of different areas are strongly influenced by heat, fresh water and momentum exchange with the atmosphere, and by the local freshwater supply via rivers.

Figure 5 shows the distribution of model simulated climatological SST in the Bohai Sea. In winter, under the control of Siberian high-pressure air masses, the SST of the coastal regions is low (−0.5 ~ 2℃), while the SST in the Central Bohai Sea is relatively high (2 ~ 4℃) (Figure 5a). These results are consistent with field observations and satellite reconstructed SST results (Bao et al., 2002; Shi and Wang, 2012; Xu et al., 2008). Due to the summer monsoon, the SST increases rapidly in summer and varies between 21℃ and 25℃, showing higher SST values in the Central Bohai Sea compared to coastal areas. In contrast, both in-situ measured and satellite reconstructed SST distributions showed higher SST values in the coastal areas compared to the Central Bohai Sea in summer (Bao et al., 2002; Shi and Wang, 2012; Xu et al., 2008). Figure 5c presents the time series of the spatially averaged SST over the entire Bohai Sea, manifesting the strong seasonality. The SST variability ranges from the lowest values of 4℃ to 5℃ in February to the highest of 25℃ in August which consists with results from field investigation (Liu et al., 2003).
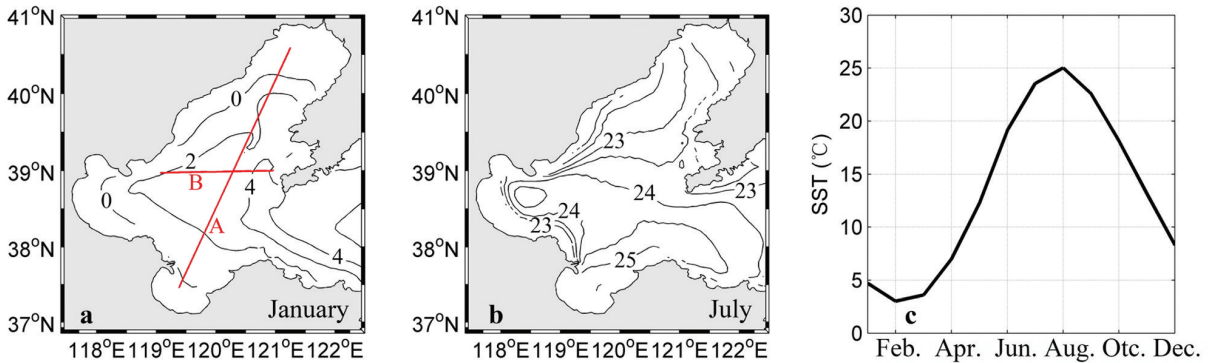
Figure 5. Climatological SST distribution (°C) in the Bohai Sea for (a) January (b) July and (c) time series of spatial mean. Source of data: HYbrid Coordinate Ocean Model (HYCOM dataset). The straight lines show the locations of SST vertical profiles in Figure 7
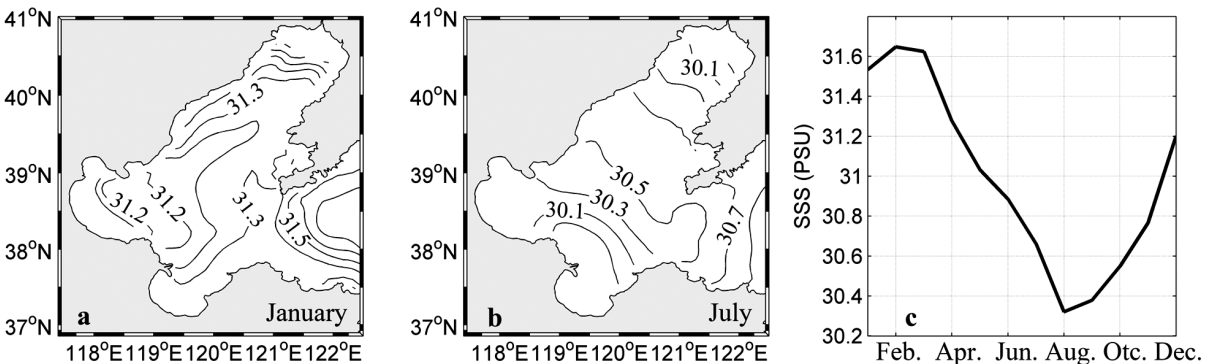

Figure 6. Climatological SSS distribution (without units) in the Bohai Sea for (a) January (b) July and (c) time series of spatial mean. Source of data: HYbrid Coordinate Ocean Model (HYCOM dataset)

The sea surface salinity (SSS) in the Bohai Sea is subject to salt water intrusion from the YSWC, fresh water discharged by rivers, precipitation and evaporation. The spatial SSS distribution patterns are similar in winter and summer, showing high salinity in the Central Bohai Sea and Bohai Strait and low salinity in the coastal regions (Figure 6a, b). The tongue shape isohaline in the Bohai Strait indicates inflow of high salinity YSWC water while the salinity in the Yellow River estuary decreases dramatically in summer due to the river runoff. The time series of the spatial mean SSS over the entire region indicates that the salinity in the Bohai Sea is highest in February with a mean value of about 31.6 and decreases to 30.3 in August due to the strong precipitation and increased river runoff in summer (Figure 6c). The model results are able to reproduce the principle characteristics of salinity distribution in the Bohai Sea when compared with field observations (Bi et al., 2015; Liu et al., 2003; Lv et al., 2009). The field investigation studies also show that the salinity of the Bohai Sea increased at a range of 1 to 5 in the recent decades (Bi et al., 2015), and the salinity increased to around 10 from 1960s to 1990s in the Yellow River estuary due to the runoff reduction of the Yellow River (Wu et al., 2004).

The vertical temperature profiles at Transect A and B (Figure 5a) are shown in Figure 7. In January, the whole Bohai Sea is well mixed with vertically uniform temperatures. In April, as solar heat input increases, a thermocline emerges in the southern Bohai Sea (Figure 7a), and subsequently establishes over large areas of the western Bohai Sea (Figure 7b). The strength of thermocline reaches its maximum in July. After that, enhanced storm activity and seasonal cooling destroy the surface layer thermocline in October. The seasonal variation is mainly related to the heat flux input and wind intensity. In winter, heat is transported from the warm sea surface water to the colder atmosphere, leading to a higher surface water density and a resulting instability of water stratification, which in combination with strong winds entirely mixes the water column. In summer, warm surface water is lighter than the cold bottom water and the weaker winds are not strong enough to break-up the stable stratification, and thus the strength of thermocline reaches its maximum at the end of the summer. Compared to field observations in summer, the thermocline simulated by the models is weak especially in the upper layer (Ju et al., 2013; Lin et al., 2006), which could be attributed to insufficient surface mixing – a common problem of ocean models (Ezer, 2000).

The temperature and salinity distribution also influences the velocity fields by producing density gradients, which in turn cause baroclinic currents, representing the thermohaline-driven part of the total flow in the Bohai Sea. The latter is superimposed by the barotropic currents which are driven by wind and tides. Results of numerical circulation models show that the thermohaline-driven

circulation in the Bohai Sea plays a more important role in the summer circulation system than the wind-driven circulation (Wan et al., 2004; Wei et al., 2003).

Seasonal sea ice is another feature that affects the SST, wave characteristics, ocean circulation, and stratification. The Bohai Sea coastal regions are continuously covered by sea ice during the winter season (Figure 8). In Liaodong Bay, the ice persists over 3 months with a coverage extending offshore over ~70 km. In contrast, sea ice occurs for about two months with a ~20 km offshore distance in Bohai Bay and Laizhou Bay. It has to be noted that the existence of sea ice in winter blocks the heat and momentum exchange between atmosphere and ocean and by this means affects all the above mentioned parameters.

THE WIND-DRIVEN REGIME

The wind field in the Bohai Sea is dominated by the Asian monsoon. Strong northerly monsoon winds and relatively stormy conditions dominate the winter time with an average wind speed of 2.5 ~4 m/s, while weaker southerly monsoon winds generally prevail in summer with an average wind speed of 2 ~2.7 m/s (Figure 9a, b). It should be noted that the climatological winds may underestimate the actual wind speeds. The satellite wind data (QuikSCAT) show that the directly observed wind speeds in the Bohai Sea are ranging from 5.5 to 7 m/s and 5 to 5.5 m/s in winter and summer, respectively (Xu et al., 2013).
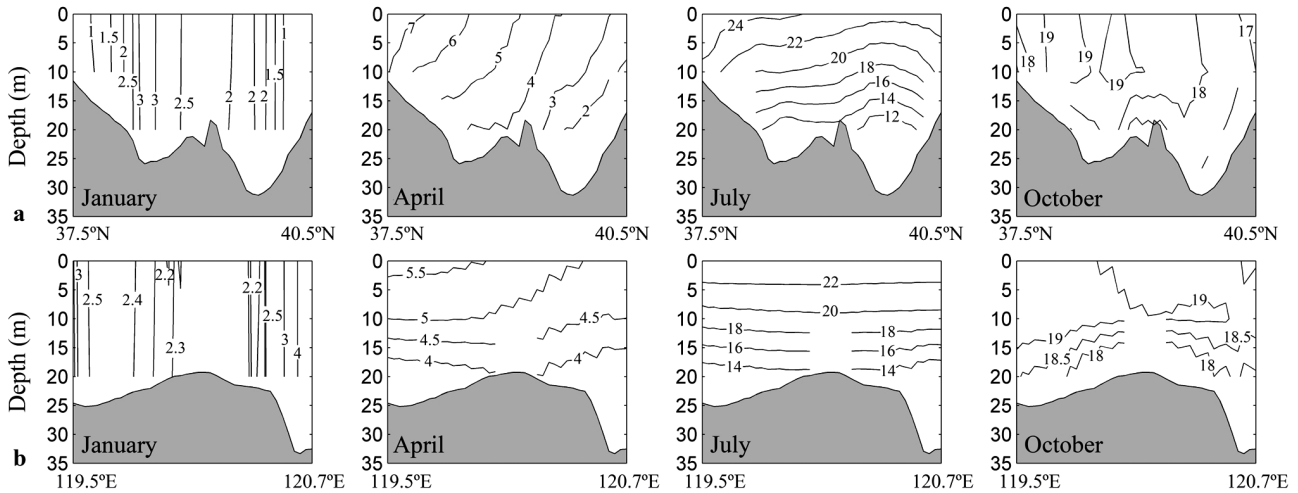

Figure 7. Seasonal variability of vertical temperature profiles (°C) for (a) Transect A and (b) Transect B. The locations of Transect A and B are shown in Figure 5a. Source of data: HYbrid Coordinate Ocean Model (HYCOM dataset)
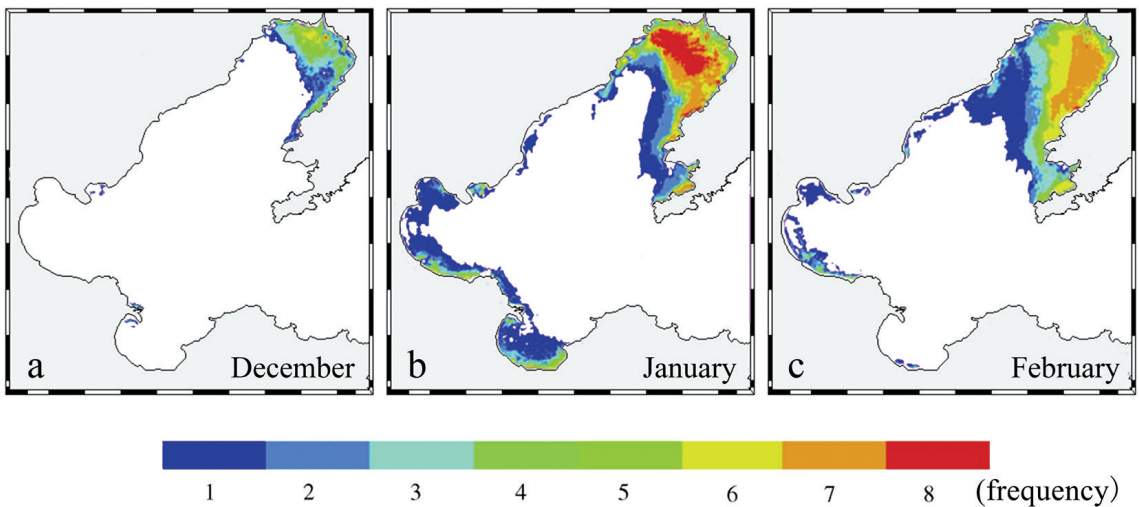

Figure 8. Sea ice occurrence (frequency) in the Bohai Sea from MODIS-Aqua observations between 2002 and 2010 for (a) December, (b) January, and (c) February. Blank areas mean no sea ice occurs during the month. Source: redrawn based on Shi and Wang (2012)
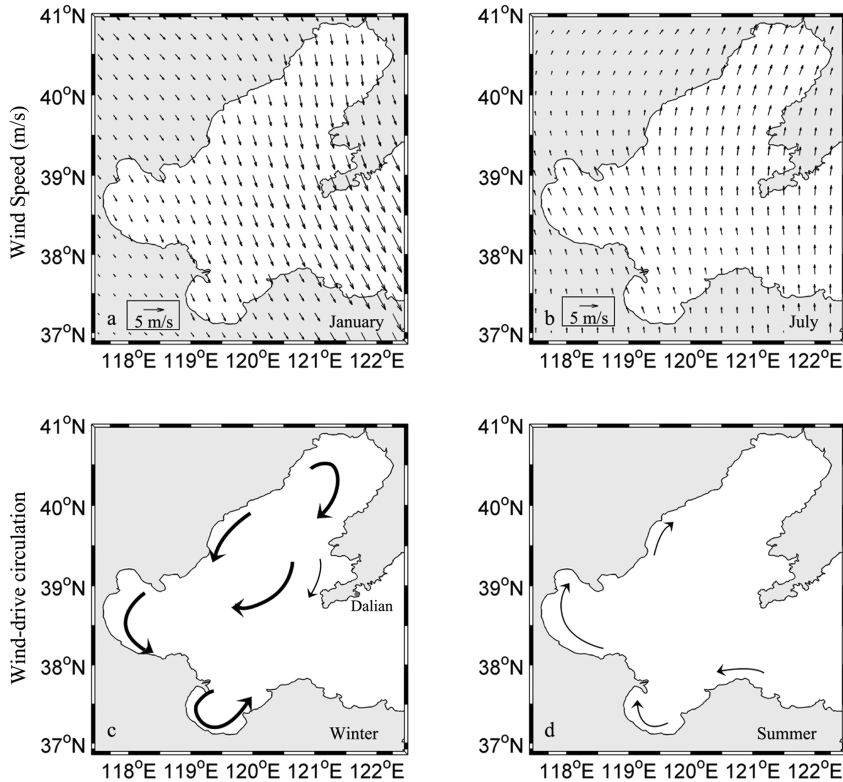
Figure 9. Climatological wind patterns in the Bohai Sea for (a) January and (b) July, and schematic wind-driven circulation for (c) Winter and (d) Summer. Source of data: climatological wind data are from European Centre for Medium-Range Weather Forecasts (ECMWF). Wind-driven circulation results are from Huang *et al.* (1996)

Numerical studies have shown that the wind-driven circulation dominates the Bohai Sea circulation system in winter exhibiting a strong southward current along the western shore with current speeds of 8 ~ 20 cm/s and a south-westward anticyclonic flow in the Liaodong Bay with current speed of 4 ~ 10 cm/s (Figure 9c). Overall, these model results show a similar pattern that the observed circulation given in Figure 4a. In summer, in the Bohai Sea the wind-driven circulation is weaker, flowing westward along the southern shore and northward along the western shore with current speed of 4 ~ 10 cm/s (Figure 9d).

Storm surges resulting from wind and atmospheric pressure extremes constitute a serious hazard to the Bohai Sea by dramatically rising sea level within a short period of time. Storm surges in Chinese seas can be classified into two types: tropical storm surges and extratropical storm surges. Unlike other marginal seas of China, the Bohai Sea is less susceptible to tropical cyclones. But cold air out-breaks and extratropical cyclones in winter cause severe storm surges mainly affecting the southwestern part of the Bohai Sea (Zhao and Jiang, 2011). Tidal gauge data indicate that storm surges cause a sea level rise in the range of 0.7 ~ 0.8 m (1979 ~ 1995) at Dalian station (location in Figure 9c).

Surface waves are generated by the wind. Although their influence on the large-scale circulation and transport is relatively small, they are of significance for dynamical processes as they generate turbulence, shear stress by orbital motion and radiation stress. In turn these processes are important for the resuspension and vertical dispersion of bottom sediment, especially in the shallow Bohai Sea. The seasonal variation of the significant wave height in the Bohai Sea is dominated by the wind stress, with amplitudes ranging from 0.5 ~ 1.2 m in winter to 0.05 ~ 0.65 m in summer (Figure 10). Due to the bathymetry, both in winter and summer the largest wave heights are found in the Central Bohai Sea and the wave heights decrease towards the coast. These model simulated wave height patterns are consistent with observations, however, the latter show higher values, with observed maximum averaged wave height of 1.5 and 1.0 m in winter and summer, respectively (Chen, 1992). The dominant wave direction in the Bohai Sea is north and northwest in winter and south in summer, and the wave period is 2.6 ~ 3.5 s in winter and 2.5 ~ 2.7 s in summer (Chen, 1992).

THE TIDAL-DRIVEN REGIME

The dynamics of the Bohai Sea is significantly influenced by astronomical tides. These are co-oscillations with the autonomous tidal waves of the Pacific Ocean. The specific geometry of the Bohai Sea basin implies eigen-periods and hence resonance in the semi-diurnal spectral range. The superposition of the semidiurnal principal lunar and solar tides M_2 and S_2 causes a significant spring-neap rhythm. Tides superimpose any other motion in the Bohai Sea and dissipate energy, mix water masses, prevent ther-

mohaline stratification and strongly influence the sediment dynamics.

Tidal elevations are penetrating from the Pacific into the Bohai Sea moving anti-clockwise as a Kelvin wave through the entire basin. There are two amphidromic points of M_2 (Figure 11a): one is near the mouth of the Yellow River at the south-western coast, and the other one is located offshore of Qinhuangdao at the north-western coast. The model simulated maximum amplitude of the M_2 tide is about 110 cm in Liaodong Bay and 70 cm in Bohai Bay (Hainbucher et al., 2004) which are about 10% smaller than the M_2 amplitude calculated from TOPEX/Poseidon altimetry data and other model studies (Bian et al., 2013; Huang et al., 1996; Pelling et al., 2013).

The tidal currents are the most energetic feature and dominate any other flow in the Bohai Sea with current speed of 20 ~ 80 cm/s (Figure 11b). In the Central Bohai Sea and the Bohai Strait, the tidal current exhibits stretched ellipses of a counter-clockwise rotating flow, while tidal ellipses are distorted to a rectified flow in the three bays. There are three regions of strong tidal current in the Bohai Sea: the Bohai Bay, the Liaodong Bay and the northern Bohai Strait.

Nonlinear processes generate non-harmonic tidal motions and, as a consequence, non-vanishing residual currents and transports. The tide-induced residual circulation is an important component of the circulation in the Bohai Sea. Wei et al. (2004) calculated the tidal residual currents using the five major tidal constituents (M_2, S_2, N_2, K_1 and O_1) (Figure 12). Generally, the tidal residual current field is weaker than the wind-driven circulation. In the surface layer, the Lagrangian residual currents form a clockwise flow in the Bohai Bay and the Liaodong Bay. In contrast, it flows north-eastwards into the Laizhou Bay and the central Bohai Sea with current speeds of 1 ~ 5 cm/s. In the bottom layer strong residual currents flow north-eastwards into the Liaodong Bay showing current speeds between 1 ~ 5 cm/s.
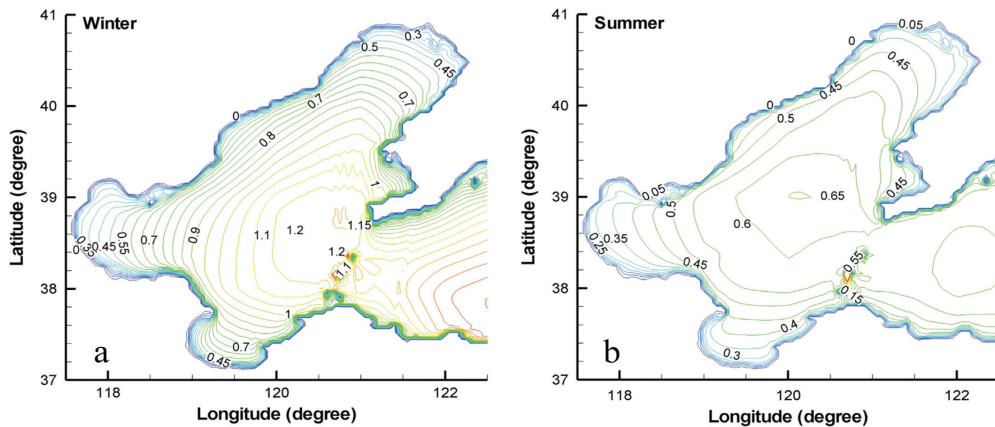

Figure 10. Characteristics of seasonally averaged significant wave height (m) for (a) winter and (b) summer. Source: Lv et al. (2014)
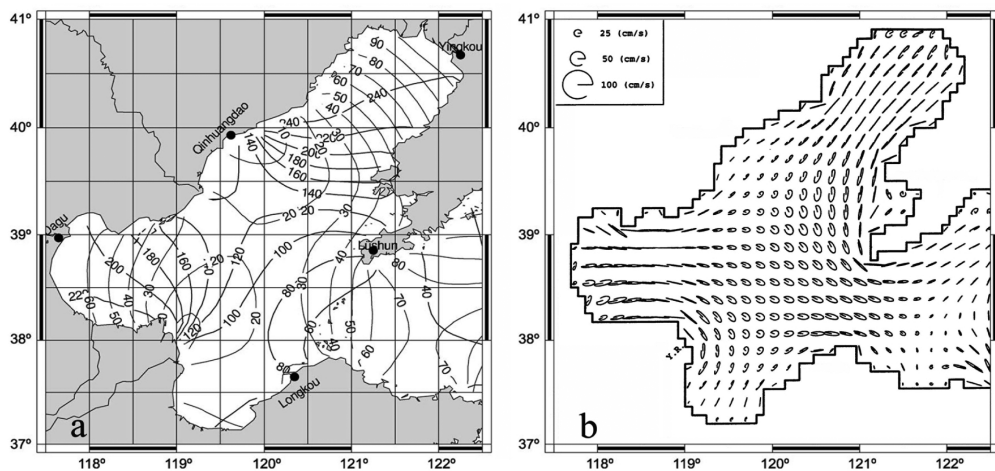

Figure 11. (a) Co-tidal lines (degrees) and co-range lines (cm), (b) tidal ellipses of M_2 constituent in the Bohai Sea. Source: Co-tidal lines and co-range lines from Hainbucher et al. (2004), tidal ellipses adapted from Huang (1995)
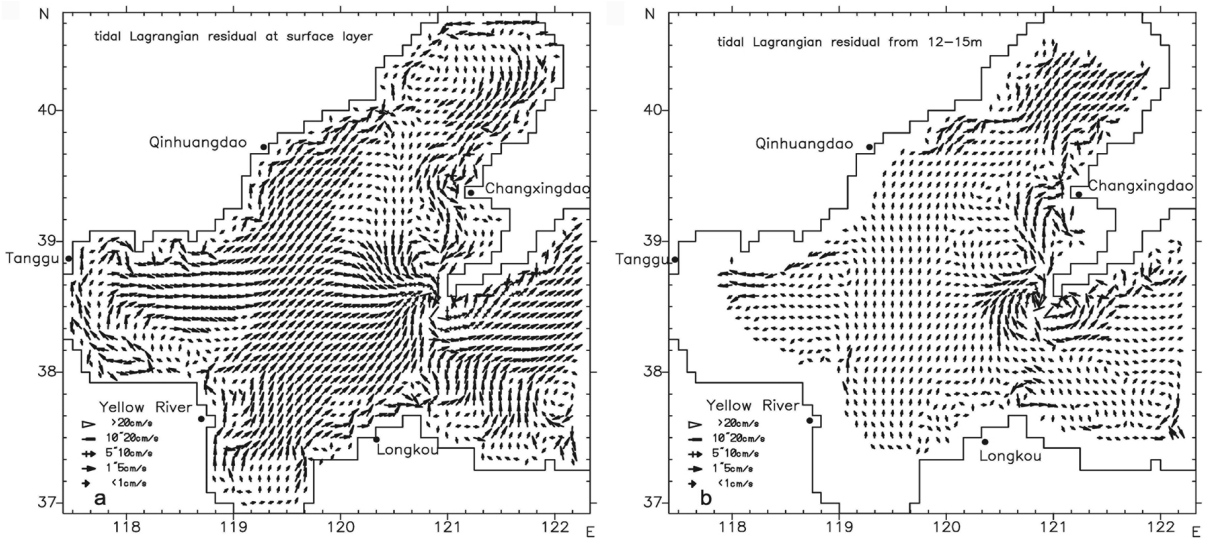
Figure 12. Lagrangian tidal residual current at (a) the surface layer and (b) between 12 and 15 m of the Bohai Sea. Source: from Wei *et al.* (2004)
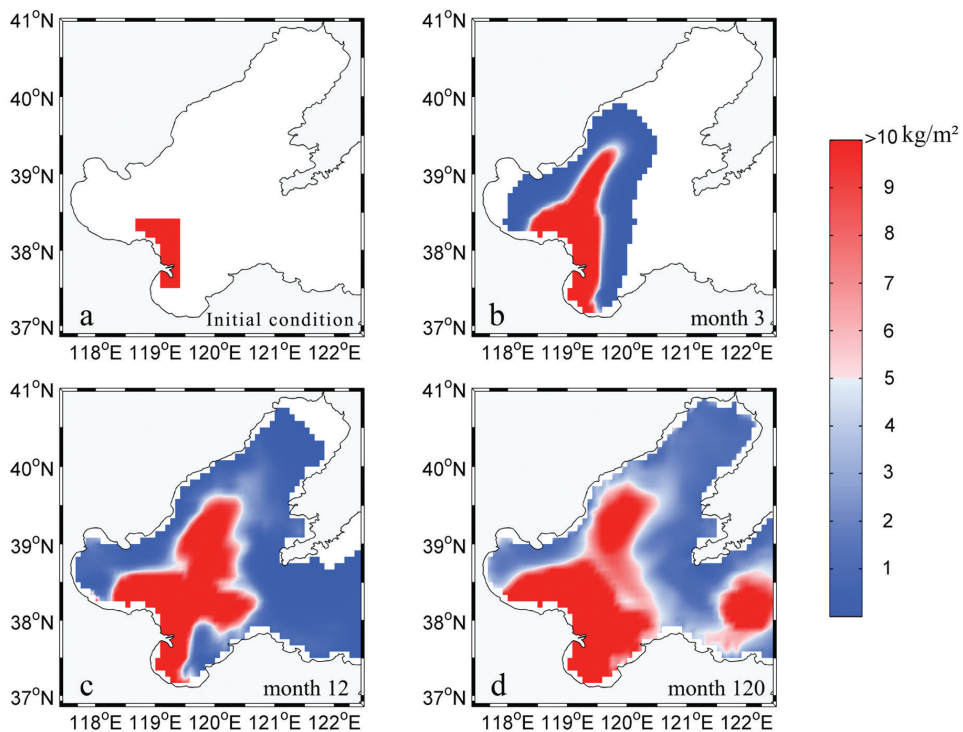

Figure 13. Simulated deposited sediment mass (kg/m²) in the Bohai Sea for (a) Initial condition (b) after 3 months (c) after 12 months and (d) after 120 months. Source of data: model results after Bian *et al.* (2013)

It should be noticed that the Bohai Sea has experienced rapid coastline changes recently due to natural developments of the Yellow River delta and large-scale anthropogenic land reclamation which substantially alters the tidal dynamics of this area. A numerical tidal model showed that the M_2 tidal amplitudes have changed by up to 0.2 m over the last three decades due to the rapid coastal development (Pelling *et al.*, 2013), and another numerical model showed that besides tidal amplitudes, the tidal energy flux is also affected by the land reclamation in the Bohai Sea (Song *et al.*, 2013).

TRANSPORT PROCESSES

Dissolved and particulate, organic and inorganic substances in the Bohai Sea waters are transported within the current regimes described above. Their spreading and deposition control the biological and sedimentological dynamics, and hence, the ecological and morphological state of the Bohai Sea. To quantitatively understand the transport timescales of dissolved material discharged from large rivers into a semi-enclosed sea, the age of Yellow River water in the Bohai Sea was calculated using numerical models (Liu et al., 2012). The results showed that the Yellow River water has a mean age of 3.0 years for the entire Bohai Sea, with a range of 1.2 ~ 3.9 years increasing from the Yellow River estuary towards the Liaodong Bay. Other model studies used different methods to evaluate the water exchange ability of the Bohai Sea, i.e. Wei et al. (2002) used a dispersion model to estimate the half-life time of the Bohai Sea (the time which is needed to reduce the initial concentration within the study area by 50%). The model results showed that Laizhou Bay has the highest exchange ability and the Liaodong Bay has the lowest one with half-life times varying from 0.5 to 3.5 years. Turnover times are also a good measure to evaluate the water exchange ability of a marine system. They refer to the amount of time required to replace the entire water body of this system by inflowing water. Hainbucher et al. (2004) calculated turnover times of the Bohai Sea and found that the whole Bohai Sea needs almost half a year for a total renewal of water masses.

Besides advection by the flow field, the concentrations of substances are also determined by some other processes such as mixing, biogeochemical decay, deposition, resuspension, etc. Sinking, flocculation and bottom processes (e.g. bioturbation) are also important for the sediment dynamics. It is important to note, that the sediment transport budget finally determines the morphological changes in the Bohai Sea. Numerical studies of the sediment transport in the Bohai Sea (Figure 13) showed that the sediments discharged by the Yellow River are transported to the north-western Bohai Sea due to the residual currents (Bian et al., 2013; Jiang et al., 2004). After 12 months, the Yellow River discharged sediments almost cover the whole Bohai Sea. After 120 months, a large amount of sediment is deposited in the Yellow River estuary and the Central Bohai Sea area with a deposited sediment mass of more than 10 kg/m^2 (equal to a sediment accumulation rate of 0.4 cm/yr).

CONCLUSIONS

Based on literature, remote sensing reconstructions and model data sets, this paper briefly describes the geographical features, external forces and principal dynamics of the Bohai Sea. To sum up, the astronomical tides are the dominant force in the Bohai Sea, they enhance all mixing processes and transport dissolved and suspended material through the residual currents. Beyond the tides, the main external force is the atmospheric flux of momentum resulting in a wind-driven circulation which on longer time scales plays a more important role in the substance transport than the tidal residual currents, and moreover, enhances mixing processes mainly in the upper ocean layer. The atmospheric heat fluxes dominate the seasonal variations of SST and in turn affect the mixing processes and the circulation system to a certain

extent. The atmospheric fresh water flux and the Yellow River runoff determine the SSS pattern in the Bohai Sea. The intrusion water from the Yellow Sea also influences the thermohaline regime. Although there is general agreement on the basic dynamics of the Bohai Sea, uncertainties still exist regarding the water exchange at the Bohai Strait and the detailed circulation patterns in some specific regions.

It must be restated that due to the lack of high time-space resolution field data in the Bohai Sea, numerical results are used here to provide a qualitative understanding of the physical environment of the Bohai Sea. As indicated in the text, the model results show certain differences compared to observations probably due to underlying assumptions and simplifications in the model, especially with regard to the thermohaline regime. Recently, more and more projects have been launched to investigate the physical and biogeochemical characteristics of the Bohai Sea, and remote sensing is also widely used nowadays to support the reconstruction of these variables. These newly available data sets could be used to verify and improve existing oceanographic models, but furthermore, they could be employed for data assimilation which will be an additional method to provide a more accurate physical state of the Bohai Sea system.

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