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An overview on water masses in the China seas

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This paper overviews progress in the research of water mass classification in the China seas, consisting of the Bohai Sea, the Yellow Sea, the East China Sea, the Taiwan Strait and the South China Sea. So far, oceanographers have achieved systematic research results in terms of the concept and definition, theory and method, characteristics and variation of water masses in the China seas. Here 3-D visualized diagrams are developed to illustrate spatial distributions of classified water masses in the China seas. Meanwhile, core values or ranges of temperature and salinity for individual water mass are integrated. Seasonal variations and formation mechanisms of water masses are briefly analyzed.

KEYWORDS

water mass, China seas, overview, clustering analysis method, 3-D visualized diagram

Introduction

A water mass is a finite or infinite body of water with definite and conservative physicochemical characteristics (Defant, 1929). Being regarded as a basic property, the water mass is one of the earliest research topics of regional oceanography. Compared with water masses in the deep basin, the water masses in the coastal oceans and the marginal seas generally have more complex structure, smaller size, and stronger seasonal variation. Studies of water masses mainly focus on the division of water mass boundaries, especially the mixing zones between water masses, and the determination of their variations (Yu, 1989).

The China seas (Figure 1) consist of the Bohai Sea (BS), the Yellow Sea (YS), the East China Sea (ECS), the Taiwan Strait (TS) and the South China Sea (SCS). Due to different geographical environment and hydrologic characteristics, method for the water mass analysis varies in the case of individual sea. Since 1950s, many oceanographers, especially the Chinese investigators, have done a lot of research on water masses in the China seas and obtained abundant results (Wei et al., 2019). However, except for the overview (Yu, 1989) on the analysis methods of water mass, there is hardly a comprehensive review on the research progress of water mass analysis in the China seas.

From 2005 to 2011, the State Oceanic Administration of China supervised the project “Comprehensive Investigation and Evaluation of the China Seas”. Abundant and high precision cruise survey data were obtained by using advanced technology. In addition, a large number of cruise-measured data were obtained from major and key research projects during the past 20 years. These data provide an important baseline for the water mass analysis, and enhance the new understanding of the distribution and seasonal variation of water mass in the China seas (e.g., Qiao et al., 2012; Xiong et al., 2012; Hu et al., 2020). During this period, the water mass research obtained new insights on the seasonal variation of water masses in the eastern Beibu Gulf (Chen et al., 2011), interannual variation of summertime water masses in the southern TS (Hu et al., 2011), and the formation and evolution of the cold water mass in the YS (Bao et al., 2010; Yuan et al., 2013; Zhu et al., 2017). In addition, some progresses have been made on the water mass classification in the northern SCS (Cheng et al., 2014; Gao et al., 2020), the eddy structure and flow patterns of the intermediate layer in the Luzon Strait (Xie et al., 2011), and the influence and role of Pacific subsurface water on the water mass in the northern SCS (Zhu et al., 2019).

Table 1 lists a collection of papers on water mass analysis in the China seas from 1980 to 2020 according to the analysis methods and study areas.

Water masses in the Bohai Sea, the Yellow Sea, and the East China Sea

The BS, the YS and the ECS are geographically adjacent to each other, thus, they are often treated as a whole in the water mass analysis. Based on the previous results, we illustrate 3-D schematic diagrams of water masses in the surface and near-bottom layers of the BS, the YS and the ECS in winter (December to February of the following year) and summer (June to August) (Figure 2), and then list the temperature and salinity ranges of individual water mass in Table 2.

From Figure 2A, one can see that in winter, the surface layer of the BS, YS and ECS is classified into 9 water masses: ① Mixed Water of the BS and YS (BY), ② Coastal Water of the BS (BS), ③ Coastal Water of the YS (YS), ④ YS Water (Y), ⑤ Mixed Water of the YS and the ECS (YE), also known as the YS Warm Current Water, ⑥ Coastal Diluted Water of the ECS (EF), ⑦ Surface Water of the ECS (ES), ⑧ Modified Surface Water of Kuroshio in the ECS (EK), and ⑨ Surface Water of Kuroshio (KS). There are 11 water masses in the bottom layer (or near-bottom layer): ① BY, ② BS, ③ YS, ④ Y, ⑤ YE, ⑥ EF, ⑦ Mixed Water of the ECS (E), which is included in the mixed water system (Li et al., 1989b) due to strong mixing in winter although its temperature and salinity characteristics are basically consistent with those of ES (Li and Su, 2000),

TABLE 1 A collection of papers on water mass analysis by classification method and sea areas in the China seas from 1980 to 2020.

Classification method	Sea area	Contributions
Clustering Analysis	BS, YS and ECS	Su et al., 1983; Li et al., 1983; Qiu et al., 1984; Xu, 1984; Wang et al., 1986; Miao et al., 1987; Li et al., 1989b; Lu, 1989; Wang et al., 1989; Zhang et al., 1989; Yang et al., 1992; Zhang and Wang, 2004
	SCS	Huang and Huang, 1983; Li et al., 1987; Li and Zhan, 1988; Fan et al., 1988; Li et al., 1989a; Liu et al., 2001; Zhu and Ji, 2002; Li et al., 2002a; Li et al., 2002b; Cheng et al., 2014; Zhu et al., 2019
	TS	Li et al., 1990; Liang and Li, 1991; He, 1994; Huang and Ji, 1995; Xiao et al., 2002; Jan et al., 2006; Hu et al., 2011
	Beibu Gulf	Chen et al., 2008; Chen et al., 2009; Chen et al., 2011
Discriminant Analysis Method	ECS	Hong and Yang, 2005
	SCS	Li et al., 1989a; Li et al., 1998; Liu et al., 2001; Li et al., 2002a; Li et al., 2002b
Corresponding Analysis Method (including T-S diagram)	YS and ECS	Su, 1980; Xu, 1984; Chen et al., 1995; Su et al., 1996; Zhang et al., 1996; Pan and Huang, 1997; Zou et al., 2000; Yu et al., 2006; Wu et al., 2014
	SCS	Li, 1987; Tian and Wei, 2005; Xie et al., 2011
	TS	Fan, 1982; Shaw, 1989; Weng et al., 1992; Xiao et al., 2002; Jan et al., 2006; Liu et al., 2008
	Beibu Gulf	Chen, 1986
Envelope Curve Method	ECS	Zhang et al., 2009
	SCS	Li et al., 2004
Quadrangle Method	ECS	Chen et al., 1995
	SCS	Tian and Wei, 2005
Similar coefficient	YS	Weng et al., 1988
T-S Similarity Number Method	SCS	Zhu et al., 2019
sigma-pi diagram	SCS	Gao et al., 2020

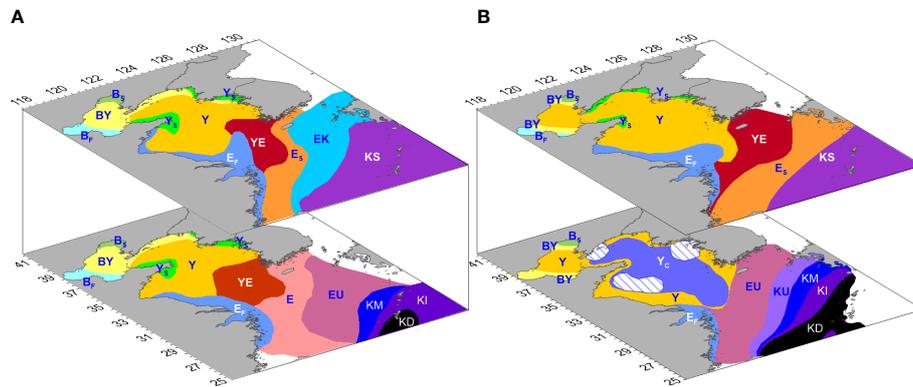


FIGURE 2 Water mass distribution in surface and bottom layers of the Bohai Sea, the Yellow Sea and the East China Sea in (A) winter and (B) summer. Yellow-BY, Dull green-BS, Ice blue-BF, Deep yellow-Y, Green-YS, Electric blue-YC, Baby blue-EF, Red-YE, Orange-ES, Bright blue-EK, Violet-KS, Pink-E, Dusty rose-EU, Light violet-KU, Blue-KM, Dark violet-KI, Black-KD. Shadow areas-YC cold centers. (Redrawn and integrated from: Su et al., 1983; Qiu et al., 1984; Miao et al., 1987; Li et al., 1989a; Lu, 1989; Zhang et al., 1996; Pan and Huang, 1997; Li and Su, 2000).

TABLE 2 Temperature and salinity ranges of water masses in the Bohai Sea, the Yellow Sea and the East China Sea.

Water mass	Temperature (°C)		Salinity	
	Winter	Summer	Winter	Summer
BY (Mixed Water of the BS and YS)	-1.0~2.0	25.0~27.0	31.0~31.9	30.0~31.0
BS (Coastal Water of the BS)	-1.0~2.0	23.0~27.0	<30.0	<30.0
YS (Coastal Water of the YS)	2.0~4.0	24.0~25.0	<31.0	<30.0
YC (YS Cold Water Mass)	—	6.0~15.0	—	31.5~32.8
Y (YS Water)	2.0~9.0	22.0~27.0	31.5~33.0	30.0~32.8
YE (Mixed Water of the YS and the ECS)	9.0~19.0	27.0~28.0	32.3~34.5	32.0~33.0
EF (Coastal Diluted Water of the ECS)	4.0~14.0	24.0~28.0	15.8~18.9	24.2~30.5
ES (Surface Water of the ECS)	13.0~17.0	27.0~29.0	33.8~34.4	33.5~34.2
E (Mixed Water of the ECS)	13.0~17.0	—	33.8~34.4	—
KS (Surface water of Kuroshio)	20.0~25.0	26.0~30.0	34.4~34.8	34.0~34.7
EK (Modified Surface Water of Kuroshio in the ECS)	15.0~20.0	—	34.3~34.5	—
EU (Subsurface Water of the ECS)	—	14.0~22.0	—	33.6~34.3
KU (Kuroshio Subsurface Water in the ECS)	—	16.0~23.0	—	34.6~35.0
KM (Kuroshio Subsurface-Intermediate Mixed Water in the ECS)	12.0~16.0	12.0~16.0	34.4~34.6	34.4~34.6
KI (Kuroshio Intermediate Water in the ECS)	5.0~12.0	5.0~12.0	34.2~34.4	34.2~34.4
KD (Kuroshio Deep Water in the ECS)	<5.0	<5.0	>34.4	>34.4

Integrated from: Qiu et al., 1984; Miao et al., 1987; Li et al., 1989b; Li and Yuan, 1992; Zhang et al., 1996; Li and Su, 2000.

© Subsurface Water of the ECS (EU), © Kuroshio Subsurface-Intermediate Mixed Water in the ECS (KM), © Kuroshio Intermediate Water in the ECS (KI), and © Kuroshio Deep Water in the ECS (KD).

As shown in Figure 2B, in summer, the surface layer of the BS, the YS and the ECS is classified into 8 water masses: ① BY, ② BS, ③ YS, ④ Y, ⑤ YE, ⑥ EF, ⑦ ES and ⑧ KS. There are 10 water masses in the bottom layer: ① BY, ② BS, ③ Y, ④ YS Cold Water

Mass (YC), ⑤ EF, ⑥ EU, ⑦ Kuroshio Subsurface Water in the ECS (KU), ⑧ KM, ⑨ KI and ⑩ KD.

From Figure 2A, one can see that due to strong vertical mixing in winter, the surface and bottom water masses in the BS and the YS are basically the same. The water with low-temperature and low-salinity is distributed in the coastal area, while the mixed water is distributed in the central portion. EF occupies the coastal water west of the YS and the ECS. YE is distributed in the offshore

water area between the YS and the ECS. E_S , E_K and K_S are distributed in the surface layer of the ECS from near to far, with the temperature and salinity gradually increasing, i.e., the temperature ranges from 13.0~17.0°C to 15.0~20.0°C, and then to 20.0~25.0°C, while the salinity ranges from 33.8~34.4 to 34.3~34.5, then to 34.4~34.8. E , EU , KM , KI and KD are distributed in the bottom layer from near to far.

In summer (Figure 2B), the extent of B_S or Y_S reduces, and the BY recedes to the two sides, presenting a narrow zonal distribution. Y almost covers the surface layer of the whole YS and even the BS. In the warm half year, the ocean temperature is gradually increased by solar radiation and the salinity is reduced by precipitation in the upper layer, which intensifies the thermocline and forms the vertical overlapping pattern of Y and Y_C water masses in most sea areas of the YS (Li and Su, 2000). Y_C is widely distributed below the thermocline in the bottom layer of the YS (Zhao, 1985), and characterized by low temperature within a range of 6.0~15.0°C (He et al., 1959; Guan, 1963; Li and Yuan, 1992). YE , E_S and K_S are distributed in the surface layer, and the temperature and the salinity increase from near to far with the salinity ranging from 32.0~33.0 to 33.5~34.2, then to 34.0~34.7. EU , KU , KM , KI and KD are distributed in the bottom layer from near to far.

It is worth mentioning that thermohaline properties of EK in winter look similar to those of KU in summer, but their formation mechanisms are different. KU belongs to the offshore water system, while EK belongs to the mixed water system influenced by the Taiwan Warm Current, the Tsushima Current and the mixed water on the ECS shelf. In summer, the upper EK water mass is completely modified and integrated into E_S , while the lower part is integrated into EU (Li and Su, 2000).

As a typical water mass in the YS, Y_C forms and matures in spring, weakens in autumn and renews in winter year after year (Zhu et al., 2017). Y_C has three low temperature centers: the northern YS cold center, the eastern and western cold centers in the southern YS as shown as shaded areas in Figure 2B (Weng et al., 1988; Yu et al., 2006). The average location of the cold center in the northern YS is near 38°14'N, 122°12'E, where the temperature range is about 4.0~7.4°C, and the salinity range is about 31.9~32.8 (Weng et al., 1988). Previous studies have also shown that the boundary of Y_C is controlled by tidal mixing (Zhao, 1985). In addition, the sea-air heat flux in the previous winter has a decisive influence on the intensity of Y_C (Zhu et al., 2017).

Water masses in the Taiwan Strait

The observational data usually did not cover the whole TS, so the study of water mass in the TS was carried out relatively

late compared with that in other areas of the China seas (Table 1). According to the seasonal variations of temperature, salinity and water mass structure by Li et al. (1990); Weng et al. (1992), (Hu et al., 1999a; Hu et al., 1999b; Hu et al., 2003; Hu et al., 2011; Hu et al., 2020), Xiao et al. (2002), and Jan et al. (2006), the TS can be classified into 9 main water masses: Min-Zhe Coastal Water (MZCW), Upwelling Water (UW), Mixed China Coastal Water (MCCW), Zhujiang River Diluted Water (ZJW), Northern Taiwan Mixed Water (NTMW), SCS Surface Water (SCSSW), SCS Water (SCSW), Kuroshio Branch Water (KBW), and Subsurface Kuroshio Branch Water (SB-KBW). According to previous research, the distribution of water masses in the TS is shown in Figure 3, and the temperature and the salinity ranges of individual water mass are summarized in Table 3. In the previous literatures, the water masses in winter (December to February of the following year) and summer (June to August) were relatively complete, while the distribution of water masses in spring or autumn was mainly described qualitatively. Therefore, Figure 3 only shows the distributions of the water masses in winter and summer.

According to Figure 3 and Table 3, MZCW, with low temperature and low salinity, is distributed above 20 m near the northwestern coast of the TS. Weng et al. (1992) and Xiao et al. (2002) pointed out that MZCW exists in autumn, winter and spring, but disappears in summer. However, Jan et al. (2006) found that sometimes MZCW still exists in June.

MCCW appears from autumn to the next spring (October-May), and is distributed between MZCW and KBW. Its temperature and salinity are also between the two, i.e., the MCCW distribution mainly depends on the extents of MZCW and KBW. In winter, the northbound KBW meets the southbound MCCW near the middle strait. The weakening of the northeasterly monsoon in March further causes the retreating of MCCW and the spreading of KBW. In May, KBW extends northward to its maximum extent, covering almost the entire strait. However, KBW disappears in summer and is replaced by SCSW and SCSSW. SCSSW and SCSW are predominant in the entire TS in summer, and are distributed 0~20 m and 20~120 m of the southern TS, respectively from summer to winter. The temperature and salinity ranges of SCSSW in summer are 25.7~30.5°C and 31.4~34.3, respectively.

UW is characterized by low temperature and high salinity. In summer, it is distributed in the upwelling zone along the coasts of eastern Guangdong and southern Fujian, northern Fujian and south of the Taiwan Bank. The mean core values of temperature and salinity in summer are 21.9°C and 34.4 (Xiao et al., 2002; Hu et al., 2003; Hu et al., 2011). In other seasons, UW may also appear around the Taiwan Bank (Hu et al., 2003).

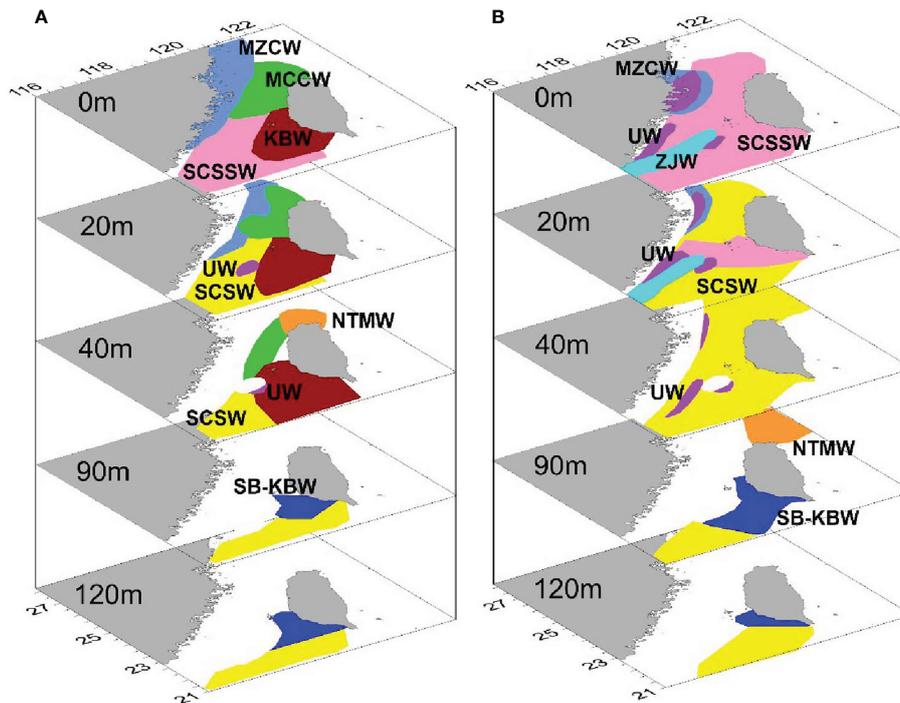


FIGURE 3 Water mass distribution in the Taiwan Strait in (A) winter and (B) summer. Light blue-MZCW, Green-MCCW, Violet-UW, Orange-NTMW, Pink-SCSSW, Yellow-SCSW, Dark Red-KBW, Blue-SB-KBW, Bright blue-ZJW. (Redrawn and integrated from: Weng et al., 1992; Xiao et al., 2002; Hu et al., 2003; Jan et al., 2006; Hu et al., 2011; Hu et al., 2020).

Because of prevailing southwesterly monsoon in summer, the diluted water from the Zhujiang River Estuary extends eastward to the Taiwan Bank and forms ZJW with a thickness of more than 10 m. The

temperature and salinity ranges are 27.6~29.1°C and 30.0~31.7, respectively.

NTMW and SB-KBW are two water masses in the lower layer of TS. NTMW is distributed near the northeastern

TABLE 3 Ranges of temperature, salinity, depth range of water masses in the Taiwan Strait in summer and winter.

		MZCW (Min-Zhe Coastal Water)	UW (Upwelling Water)	NTMW (Northern Taiwan Mixed Water)	ZJW (Zhujiang River Diluted Water)	MCCW (Mixed China Coastal Water)	SCSSW (SCS Surface Water)	SCSW (SCS Water)	KBW (Kuroshio Branch Water)	SB-KBW (Subsurface Kuroshio Branch Water)
Summer	T (°C)	23.1~25.2	21.8~22.4	15.9~24.7	27.6~29.1	—	25.7~30.5	20.0~31.1	—	15.0~26.9
	S	32.5~33.7	34.3~34.4	34.2~34.8	30.0~31.7	—	31.4~33.4	32.6~34.7	—	33.9~34.9
	D (m)	0~40	0~170	30~125	0~10	—	0~40	0~90	—	>50
Winter	T (°C)	<14.0	—	17.1~23.1	—	15.6~19.8	17.3~20.8	18.3~20.8	19.0~26.3	15.5~24.8
	S	<31.0	—	34.1~34.7	—	32.4~33.9	33.4~33.9	33.4~33.9	33.7~34.9	34.1~34.9
	D (m)	—	—	0~100	—	0~70	—	—	0~125	50~150

T is temperature, S is salinity, and D is depth range. Integrated from: Li et al., 1990; Weng et al., 1992; Xiao et al., 2002; Jan et al., 2006; Hu et al., 2011.

corner of Taiwan Island all year round. As affected by the Kuroshio, it is characterized by high temperature and high salinity, and is located at the depths of 40~90 m with the depth varying greatly from season to season. **SB-KBW** appears throughout the year at the depth around 100 m in the southeastern TS.

Finally, it is worth mentioning that the **KBW** in spring, autumn and winter (Jan et al., 2006) is actually similar to the upper warm water in the southern TS (Weng et al., 1992; Xiao et al., 2002; Hu et al., 2011), while the upper warm water in the southern TS in summer is classified into two water masses, **SCSW** and **SCSSW**, by Jan et al. (2006). In addition, the **SB-KBW** described in Jan et al. (2006) is similar to the lower warm water of the southern TS (Weng et al., 1992; Xiao et al., 2002) or the subsurface water mass (Hu et al., 2011). The characteristic values of individual mass listed in Table 3 are derived from the combined statistics of the similar water masses mentioned above.

Water masses in the South China Sea

The SCS is a semi-enclosed marginal sea of the Northwest Pacific, connecting with the Pacific Ocean mainly through the Luzon Strait. As affected by the frequent Pacific water intrusion, abundant runoff, seasonal monsoon wind and complex basin topography, water masses in the SCS are characterized by complex structure and seasonal variation. Since most studies focused on the water masses of the whole SCS in winter (December to February of the following year) and summer (June to August), the 3-D distribution diagrams only show the classifications in winter and summer. As listed in Table 1, most of investigators classified the whole SCS into 10 main water masses by clustering analysis, corresponding analysis, discriminant analysis, T-S similarity and other methods. These water masses are: Diluted Water (**F**), SCS Surface Water (**S**), Surface-Subsurface Mixed Water (**M**), SCS Subsurface Water (**U_S**), Northwest Pacific Subsurface Water (**U_P**), Kuroshio Surface Water (**KS**), Subsurface-Intermediate Mixed Water (**UI**), Intermediate Water (**I**), Deep Water (**D**) and Bottom Water (**B**). Figure 4 integrates distribution of the SCS water masses above 2000 m. Table 4 lists statistics of the temperature and salinity ranges (or core values) of individual water mass.

From Figure 4, in summer, with increased runoff and enhancement of the southwesterly monsoon, **F** extends eastward and westward from the Zhujiang River Estuary at the same time, forming a zonal distribution along the coast of Guangdong with the salinity lower than 31.7. The extent gradually shrinks to the coast west of the Zhujiang River Estuary in winter. **S** occupies most of the upper SCS from surface to about 50 m (or 100 m in some areas) in winter and

summer. **M** is the mixed water mass between **F** and **S**, or between **S** and **U_S/U_P**, so the temperature and salinity are between them with a depth to about 100 m. **KS** appears in the surface and 50 m layer west of the Luzon Strait, with the temperature and salinity ranging from 19.0-26.3°C, 33.7-34.9 in winter and ranging from 25.4-29.7°C, 34.5-34.8 in summer.

U_S and **U_P** exist in both winter and summer. **U_S** is mostly distributed in the range of 100~300 m with a salinity of up to 34.7. Under the influence of upwelling along the coasts of the eastern Guangdong, southern Fujian and eastern Hainan Island (Hu and Wang, 2016), **U_S** can be found in the shallow water above 20 m in summer (Zhu et al., 2019). **U_P** shows relatively high temperature and high salinity properties. In summer, **U_P** is only distributed in the 100~200 m layer west of the Luzon Strait in the forms of “loop” or “extending” without further intrusion into the SCS (Hu et al., 2000). However, **U_P** presents a distribution pattern with several continuously distributed eddies at 175 m in winter (Zhu et al., 2019), which would be the signature of the nonlinear Rossby waves originating from the Pacific and entering the northern SCS through the Luzon Strait (Zheng et al., 2011; Hu et al., 2012; Xie et al., 2016; Xie et al., 2017; Zheng et al., 2017; Zhu et al., 2019).

UI is mainly located at a depth range of 200~700 m. **I** is located at 500~800 m, which dominates the whole SCS at the 500 m layer, while gradually shrinks northward to the northern SCS at 600-700 m (Li et al., 2004). **D** appears between 1000~2500 m, and **B** is located below 2500 m (figure not shown).

Figure 5 is a T-S diagram based on the observational data of the winter cruise in the northern SCS in 2010 (Zhu et al., 2019), to partly illustrate the T-S distribution and separation of typical water masses in winter. It is only for the northern SCS, not representative of the whole SCS.

It's worth noting that Xie et al. (2011) and Gao et al. (2020) classified the **I** into two water masses: the SCS Intermediate Water (called **SCSIW** in Xie et al. (2011) or **SIW** in Gao et al. (2020)), and the Northwest Pacific Intermediate Water (called **NPIW** in Xie et al. (2011) or **WPIW** in Gao et al. (2020)). However, the exact boundary of these two water masses is uncertain, so we can only temporarily classify them as one, the Intermediate Water (**I**).

Summary

In this paper, the previous results of water mass classification in the China seas are summarized according to the analytical method and the research area. 3-D visualization technologies are used to draw schematic diagrams, which show spatial distribution of water masses in individual seas. Meanwhile, core values or ranges of the temperature and the salinity of individual water mass are integrated. The major results are summarized as follows.

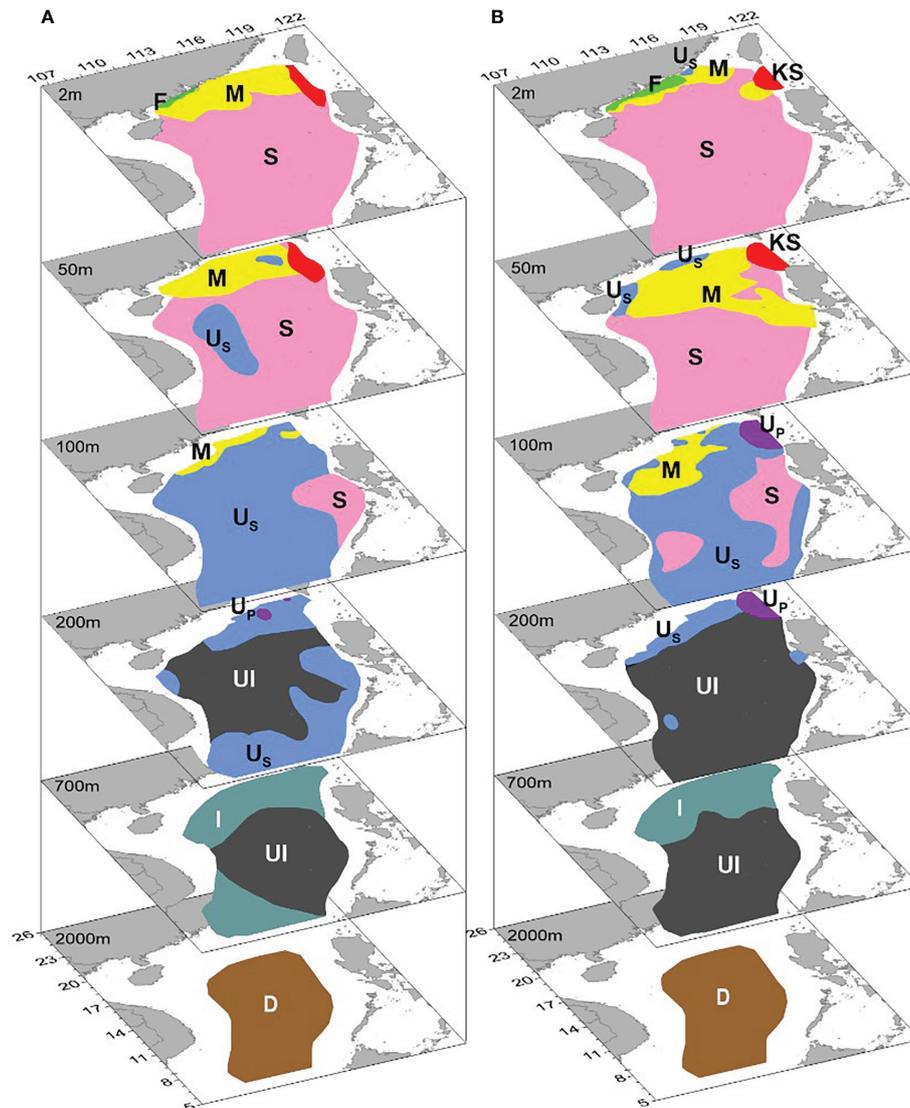


FIGURE 4

Water mass distribution in the South China Sea in (A) winter and (B) summer. Green: Diluted Water (F); Pink: SCS Surface Water (S); Yellow: Surface-Subsurface Mixed Water (M); Blue: SCS Subsurface Water (U_s); Violet: Northwest Pacific Subsurface Water (U_p); Red: Kuroshio Surface Water (KS); Black: Subsurface-Intermediate Mixed Water (UI); Moss green: Intermediate Water (I); Brown: Deep Water (D). (Redrawn from Li et al., 2002a; Li et al., 2002b; Li et al., 2004; Jan et al., 2006; Zhu et al., 2019).

(1) In winter, there are 14 water masses in the surface and bottom layers of the Bohai (BS), the Yellow Sea (YS) and the East China Sea (ECS): BY, B_s, Y_s, Y, YE, E_F, E_s, E, EK, EU, KS, KM, KI and KD. In summer, there are 14 water masses in the surface and bottom layers of the BS, YS and the ECS: BY, B_s, Y_s, Y, Y_C, YE, E_F, E_s, EU, KS, KU, KM, KI and KD. Compared with that in winter, there is neither EK in the surface layer nor E in the bottom layer, while there are KU and Y_C in the bottom layer in summer.

(2) The Taiwan Strait (TS) is classified into 9 water masses: MZCW, UW, MCCW, ZJW, NTMW, SCSSW, SCSW, KBW and SB-KBW. MZCW exists in four seasons. KBW reaches its maximum range northward in spring, and disappears or is replaced by SCSW and SCSSW in summer. MCCW appears from autumn to the following spring, and NTMW is distributed at the northeast corner of Taiwan Island all year round, with its depth range varying seasonally. UW and ZJW are water masses frequently appearing in summer. SB-KBW

TABLE 4 The ranges of temperature and salinity of water masses of the SCS in summer and winter.

Water Mass	Summer		Winter	
	T (°C)	S	T (°C)	S
F (Diluted Water)	27.4~32.0	<31.7	17.2~19.4	<31.0
M (Surface-Subsurface Mixed Water)	22.9~30.8	32.1~34.2	19.6~22.5	31.8~34.3
S (SCS Surface Water)	22.3~31.9	33.2~34.6	21.0~29.5	32.6~34.6
U _S (SCS Subsurface Water)	15.7~22.2	34.4~34.7	14.8~21.8	34.5~34.7
UI (Subsurface-Intermediate Mixed Water)	11.0~15.6	34.4~34.7	10.5~14.9	34.5~34.6
I (Intermediate Water)	5.5~11.1	34.4~34.5	5.3~10.4	34.4~34.5
D (Deep Water)	2.4~5.5	34.5~34.6	2.4~5.2	34.5~34.6
B (Bottom Water)	2.4~2.4	34.6~34.6	2.3~2.4	34.6~34.6
KS (Kuroshio Surface Water)	25.4~29.7	34.5~34.8	19.5~26.3	33.7~34.5
U _P (Northwest Pacific Subsurface Water)	15.9~24.9	34.7~34.9	19.4~20.4	34.7~34.9

Integrated from: Li et al., 2002b; Jan et al., 2006; Xie et al., 2011; Zhu et al., 2019; Gao et al., 2020.

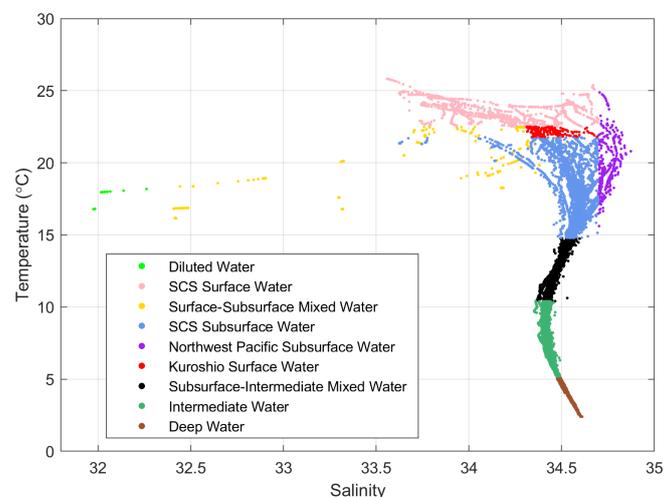


FIGURE 5

T-S diagram based on the observational data of the winter cruise in the Northern SCS in 2010. Data is from Zhu et al. (2019).

is stable throughout the year at the southeastern TS below 100 m.

(3) The whole South China Sea (SCS) in winter and summer is classified into 10 water masses: **F**, **S**, **M**, **U_S**, **U_P**, **KS**, **UI**, **I**, **D** and **B**. **F** and **S** are strong in summer and autumn. Among them, **M** has the widest range in spring. **KS** is distributed above 50 m at the exit of the water exchange channel between the SCS and the Pacific Ocean. **U_S** is distributed at 100~300 m and rises up to 20 m in summer. In winter and spring, **U_P** intrudes the SCS at the form of pulsed nonlinear Rossby waves with the widest distribution in spring, and is distributed in the 100~200 m layer

west of the Luzon Strait only in the form of “loop” or “extending” in summer.

After years of studying, systematic results have been obtained on the concept and definition, theory and method, law and characteristics of the water masses in the China seas. The development of new methods, such as T-S similarity method and density-spicity diagram, for water mass analysis is also one of the future research directions. We hope to attract more people to join in the study of water mass, by developing more new methods, expanding the multi-parameter classification of water mass and combining with numerical

results. What is more, it is necessary to enhance studying the water mass in spring and autumn in the future, so as to obtain a more complete distribution of water mass in the China seas, and to further reveal the formation and variation of each water mass.

Author contributions

JZ collected the references and wrote the manuscript by integrating the comments and suggestions from JH and QZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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