Ocean thermal energy resources in the South China Sea

Fen Dong[1,a*], Dashu Li[2,b], Qiang Liu[1,c], Qingyang He[1,d] and Yiping Zhang[1,e]

dongfen@cnooc.com.cn *, liuqiang1@cnooc.com.cn, heqy5@cnooc.com.cn, zhangyp41@cnooc.com.cn, 2059570871@qq.com

[1]CNOOC Research Institute Ltd., Beijing, 100028, China
[2]China University of Petroleum, Beijing, 102249, China

Abstract: Ocean thermal energy is an important marine renewable energy. The development and utilization of ocean thermal energy resources can effectively alleviate the energy problems and environmental pollution problems caused by conventional energy shortage. Based on GODAS data set and new wave energy assessment formula, this paper estimates the OTEC resources in the South China Sea with Nihous' method. The temperature difference in the South China Sea is large with most areas over 18℃ even in winter except the shallow coastal, so the South China Sea can be considered as a suitable place for the development of OTEC plants. The horizontal distribution of temperature difference is low in the north while high in the south. Annual OTEC net power density in the South China Sea ranges from 300 to 1200 kW.km-2. In the area with the depth less than 1000m, net power density increases unevenly with increasing water depth, ranging from 300 to 900 kW.km-2. The variation gradient between the areas with 1000m and 4000m depth is small. Compared with other regions in the world, the South China Sea is relatively rich in the thermal energy. Suitable water depth for OTEC development in the South China Sea is relatively homogeneous, mainly concentrated between 720m and 770m, and the average value is about 750m.

Keywords: OTEC, Resource assessment, Suitable water depth.

1 INTRODUCTION

Marine renewable energy is an important part of renewable energy. The total marine renewable energy is 76.6 TW in theory, in which the ocean temperature difference energy is the largest part, with about 40 TW reserves in the world (Goto S, 2011).

Ocean Thermal Energy refers to the thermal energy stored in the temperature difference between the surface seawater and the deep seawater, which can be used to realize thermal cycle and generate electricity. In addition, it can also produce fresh water, provide the cold source of air conditioning and develop the aquatic industry. In 1881, D' Arsonval first formulated the concept of Ocean Thermal Energy Conversion (OTEC) (D' Arsonval J-A, 1881). In 1979, the world's first real closed-loop OTEC device — "MINIOTEC" has been built in Hawaii; In 1981 and 1990, 50~100 kW closed cycle units were built and operated successfully in Nauru Island and Kyushu, Japan) (LIU W M, 2012). Now manufacture and sea trail on thermal energy conversion device at 50 KW are being carried out in China.

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The key technological challenges to commercial-scale application of marine thermal energy is Ocean Thermal Energy Conversion (L.A. Vega, 2012). At present, researchers have carried out a series of studies on OTEC technique, including cycle working fluid (Li, 2017 and Wu, 2015), thermodynamic cycle of OTEC (Ahmad, 2011 and LI, 2016). Another kind of research focuses on estimating thermal energy reserves, since estimates of Ocean Thermal Energy Conversion resources is the basic and premise for development planning and site selection.

Nihous (2005) proposed an Order-of-Magnitude model to estimate the worldwide OTEC resources in 2005. He indicates that about 3x109 kW (3 TW) may be available at most. Though the estimate is much smaller than values currently available in the technical literature, the order-of-magnitude estimate still represents a staggering amount. Nihous (2007) improved his study with a simple one-dimensional time-domain model of the thermal structure of the ocean, raising the estimated maximum steady-state OTEC production from 3TW to 5TW. Rajagopalan and Nihous (2013) recognized that "Given the magnitude of OTEC deployment corresponding to maximal net power production (wcw=60 m year-1), there is virtually no chance that this additional, hypothetical forcing would occur within a time frame immediately relevant to Global Warming (say, within the 21st Century)." OTEC net power density values range between 500 and 1000 kW km-2 at wcw=60 m per year if OTEC flows had no effect on the thermal structure of the ocean. Leland (2010) characterized the local bathymetry, water properties, thermal structure, the seasonal variations of the OTEC resource in southeastern Florida by measurements data. Rauchenstein et al. (2011) assessed the annual and seasonal averages of the temperature gradient between the sea surface and water at 1000 m depth in southeastern Florida with assimilation data by the 3-dimensional, data-assimilative hindcast/forecast HYCOM+NCODA model. Devis-Morales et al. (2014) analyzed the characteristics of thermal energy resources and environmental conditions of several typical sites in the Colombian sea area using the reanalysis data. Wu and Jiang (1988) estimated the ocean thermal energy capacity in China according to the seawater depth and empirical formula, indicating that the thermal energy reserves in the South China Sea are large and can be utilized all year round. Shi et al. (2011) took a review of the investigation and study of marine energy resources in China in 2011, indicating that OTEC resource in Yellow Sea, East China Sea and South China Sea were about 14.63 x 1018 ~ 15.19 x 1018 kJ and Xisha is the most suitable test site for early development. Yan (2017) analyzed the temporal and spatial characteristics of the thermal energy in the Pacific Ocean and the sea surrounding China based on SODA data, and calculated the coefficient of variation of thermal energy. The results show that in China thermal energy resources in the South China Sea and the east of Taiwan are the most abundant, where energy is stable and can be exploited effectively all year round. Wang (2009) and Ni (2013) both expounded the analysis methods, distribution, reserves, evaluation and site selection of thermal energy resources in detail and systematically.

Previous studies on OTEC reserves evaluation have obtained some generally accepted conclusions：1) Global OTEC reserves are on the scale of TW, and the suitable areas for OTEC development are concentrated in the tropical and subtropical seas; 2) OTEC resource in the South China Sea is rich, where it is suitable for large-scale mining. Although existing research have estimated the distribution of thermal energy resource in China, most of them are simplified in calculation and lack of sufficient data. In this paper, we propose new results of the OTEC resources assessment in the South China Sea based on Global Ocean Data Assimilation System (GODAS) dataset and the method of calculating gross electrical power by Nihous et al (Nihous, 2007). In order to provide reference for site selection and exploitation of ocean thermal energy, we present suitable water depth in exploitation and characteristics of thermal energy resources in the South China Sea.

2 DATA AND MODEL DESCRIPTION

2.1 Data description

Temperature data were obtained via the NOAA Physical Sciences Laboratory's web site (https://psl.noaa.gov/data/gridded/) from the Global Ocean Data Assimilation System (GODAS). GODAS is a real-time ocean analysis and a reanalysis with various horizontal resolutions of 0.333 degree latitude x 1.0 degree longitude. 40 vertical layers are in the model, with respective thicknesses of 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125, 135, 145, 155, 165, 175,185, 195, 205, 215, 225, 238, 262, 303, 366, 459, 584, 747, 949, 1193, 1479, 1807, 2174, 2579, 3016, 3483, 3972, 4478m, from the ocean surface to the seafloor. The dataset were counted as mean monthly matrices, and the available variables include temperature, u v-component of current, salinity.

Terrain data were obtained via NOAA' s ETOPO1, which is a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry.

In this paper, we choose the data range from January 1981 to December 2020, 40 years totally. The study area in this paper ranges from 2° N to 24 ° N and 106° E to 123° E, as shown in Fig. 1.

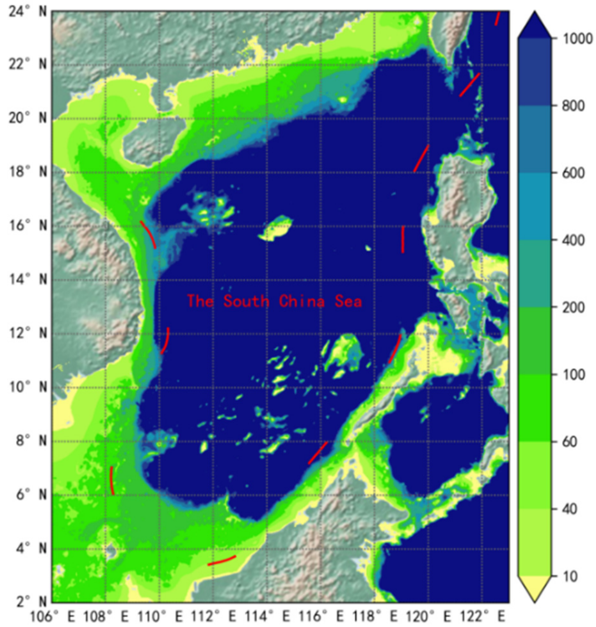

Figure 1: Study area and water depth (m).

2.2 Model description

According to Jiang's study (Jiang and Wu, 2016), the upper homogeneous layer is about 45m in the South China Sea. With actual engineering technology, Surface temperatures were usually taken at 20 m depth. In this paper, we take the weighted average of temperature at depth of 5m and 15m as the temperature of OTEC warm seawater (TW).

In the area where the water depth is less than 800m, the seabed temperature is taken as the temperature of OTEC cold seawater (Tc) when calculating the temperature difference. The water temperature at the depth of 800m which is available by interpolating the temperature of depth more than 800m is regarded as the cold water temperature. It is noted that since the paucity of temperature data at 800m for GODAS, the cubic spline interpolation algorithm (Arun and L. K, 1992) is used to obtain the temperature between 500m and 900m at an interval of 5m by interpolating the temperature of depth at 459m, 584m, 747m and 949m in the vertical direction.

The assessment of OTEC resources model used this paper is first proposed by Nihous et al. (Nihous, 2005). A standard OTEC process was proposed for modeling purpose, ΔT is distributed between the major components of a power plant: one half of the temperature difference (ΔT) across a power producing turbine, and the balance to allow surface seawater to cooling and deep seawater to warming. In this "emperature ladder", ΔT/16 in either evaporator or condenser is imposed to maintain the exchange of heat. In his formulas for OTEC power, the gross electrical power can be expressed as：

$$P_g = \frac{3Q_{cw}\rho C_p \gamma \varepsilon_{tg}}{16(1+\gamma)T_{ww}} \Delta T^2 \tag{1}$$

Where ΔT is the temperature difference between the surface and deep level, ρ is an average seawater density ($1025kg/m^3$), cp is the specific seawater enthalpy (4.096kJ.℃), ε_{tg} is the total efficiency of turbine generator (0.75), γ is the ratio of OTEC surface seawater flow rate over OTEC deep seawater flow rate. γ is usually set as 1~2 based on a typical system in that warm water is easier to access the system than the cold water (Nihous, 2005).

It can be seen from Eq.(1) that OTEC power is proportiona to the temperature difference between surface and deep level. Most designs typically require about 30% of Pg to run the plant at design conditions. It can be verified that at design conditions, the net power Pnet expressed below is maximal near the design value γ=2 as γ varies (Nihous, 2005 and 2007).

$$p_{net} = \frac{Q_{cw}\rho c_p \varepsilon_{tg}}{8T_{ww}} \left\{ \frac{3\gamma}{2(1+\gamma)} \Delta T^2 - 0.18\Delta T^2_{design} - 0.12\left(\frac{\gamma}{2}\right)^{2.75} \Delta T^2_{design} \right\} \tag{2}$$

Rajagopalan and Nihous (2013) adapted above formulas by a fixed value of wcw allow an estimate of the state of the ocean when the effects of distributed OTEC flow singularities are included. From the modified temperature field in the OTEC region, the OTEC net power density Pnet can be written as:

$$P_{net} = w_{cw}\frac{3\rho c_p \varepsilon_{tg}\gamma}{16(1+\gamma)}\frac{\Delta T^2}{T_w} - P_{pump} \quad (3)$$

$$P_{pump} = w_{cw}\, 0.3\frac{\rho c_p \varepsilon_{tg}\gamma}{4\,(1+\gamma)} \quad (4)$$

where w_{cw} is the OTEC equivalent deep seawater vertical velocity(m/s), Tw is the absolute temperature of OTEC warm seawater, In this paper the design value γ is set as 1.5. Ppump is the pumping power density , which is equivalent to 30% of the gross power density at standard conditions (ΔT=20℃，TW=300K)

3 RESULTS AND DISCUSSION

3.1 Seasonal variation of ocean thermal

Temperature difference is the critical factor of OTEC power. Due to the seasonal variation characteristics of solar radiation, ocean thermal derived from solar radiation shows clear seasonality. This paper takes April, July, October and January as the representative months of spring, summer, autumn and winter to analyze the ocean thermal distribution characteristics in 40 years.

As shown in Fig.2, the horizontal distribution of temperature difference in the South China Sea is low in the north while high in the south. Time distribution shows seasonal variation: high in summer, low in winter, spring and autumn is the transition season of temperature change. Temperature difference of most areas in spring, summer and autumn is greater than 20°C (Figure 2a~2c), and the area with high temperature difference greater than 25 °C increases in summer (Figure 3b). The temperature difference weakens obviously from autumn to winter, decreasing more than 3°C than in most areas. Therefore, we should pay more attention to the stability of winter power generation for OTEC system.

In general, the temperature difference in the South China Sea is large with most areas over 18°C even in winter except the shallow coastal. The temperature difference around Xisha Islands ranges from 21~24°C; the temperature difference around Zhongsha Island ranges from 23~26°C; the temperature difference around Nansha Islands is greater than 23°C. Nihous et al. proposed that the OTEC can generate net power output when temperature difference is larger than 11 °C with design temperature difference available for OTEC process at 20 °C (Nihous, 2005). Considering the current techniques, OTEC is commonly considered a viable energy source where the temperature difference exceeds approximately 18°C between surface and deep waters, and a high-quality resource where the temperature difference greater than 20°C (Li and Zhang, 2017). Comparing with other regions in China or world, the South China Sea can be considered as a suitable place for the development of OTEC plants.

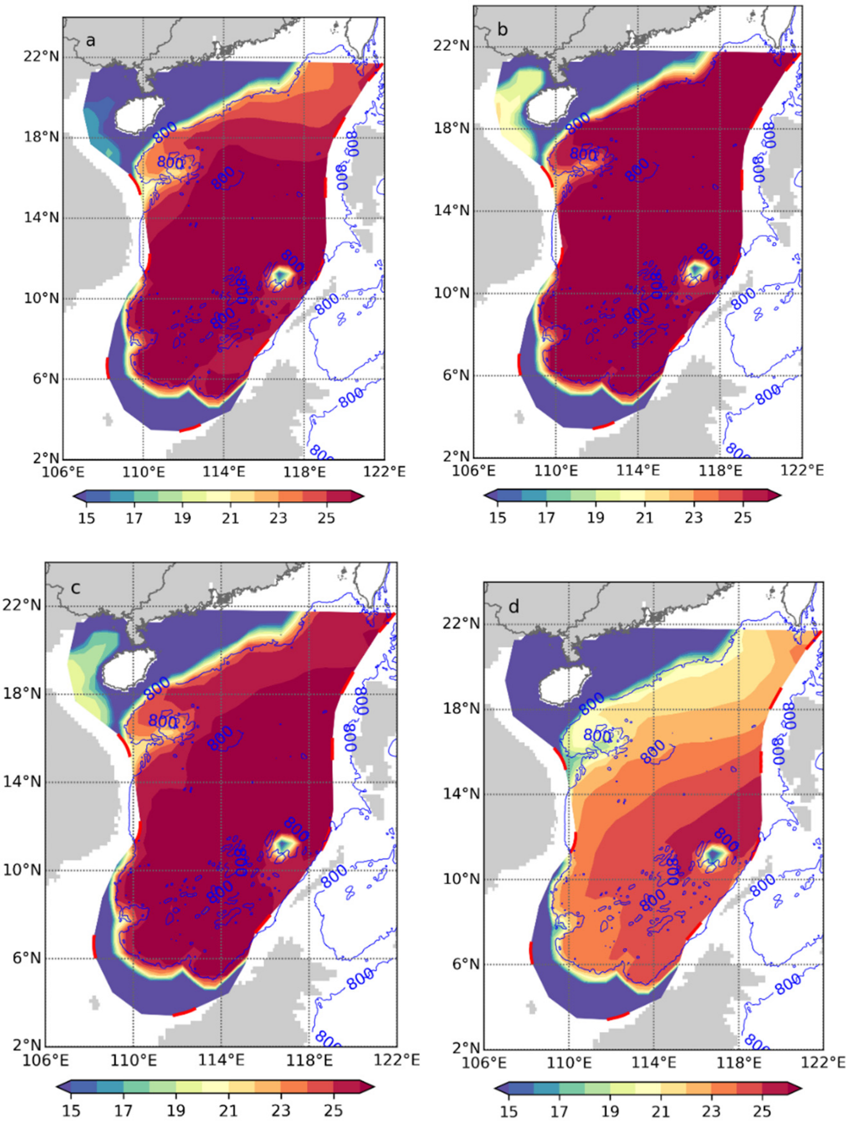

Figure 2: Distribution of average temperature difference of the South China Sea in April(a), July(b), October(c), January(d) (Blue contour: water depth, m).

3.2 Temperature of sea surface and deep layer

The principle of OTEC is producing mechanical work in a Rankine cycle operated between warm surface seawater and cold deep seawater. Surface warm seawater (24~28℃) provides the high temperature needed for an low boiling point working fluid such as ammonia to gasify; deep cold seawater (4~6℃) provides the low temperature needed for the exhausted steam to complete a thermodynamic cycle (Su and Zeng, 2012). Hence, the variation characteristics of the temperature of sea surface and deep layer water are crucial to the stability of OTEC power generation.

The annual average, monthly maximum and monthly minimum temperature of the surface seawater in the past 40 years are depicted in Figure 4. The average annual temperature of the South China Sea surface water ranges from 24℃ to 30℃, which shows a growing tendency from the Hainan Island to the Nansha Islands along the southeast direction (Figure 3a). The spatial distribution of maximum temperature of the surface seawater is relatively homogeneous, which is above 30℃ in most areas (Figure 3b). As shown in Figure 4c, the minimum temperature ranges from 22℃ to 27℃. The minimum temperature in the north of 15°N is greater than 24 ℃, where can be considered suitable for providing the high temperature needed for OTEC system. In the areas around Dongsha Islands and Xisha Islands at the depth less than 800m, the minimum temperature of the surface seawater is less than 22℃, this shows the warm water in these locations is difficult to achieve the appropriate conditions for OTEC in cold seasons.

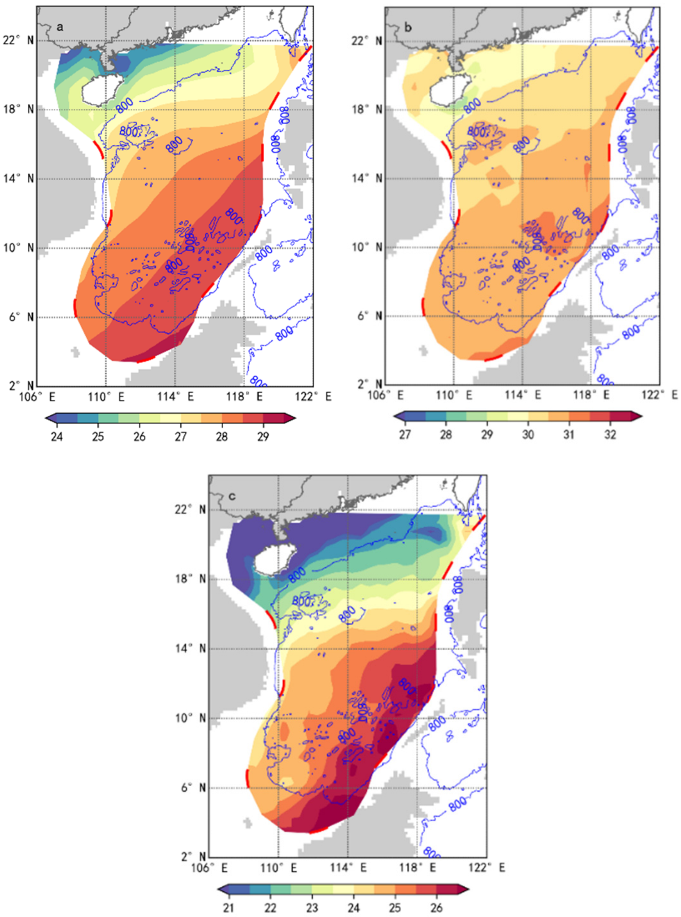

Figure 3: Annual mean temperature(a), monthly maximum temperature(b) and monthly minimum temperature(c) of surface seawater (Blue contour: water depth, m)

The role of deep cold seawater in the thermodynamic cycle of OTEC is chiller fluid. With OTEC technology, the temperature of deep water uesd to condense the working fluid should be at least less than 6 ℃ (Su and Zeng, 2012). As shown in Fig.4, the temperature of deep layer in the coastal regions is higher than 15℃. In most areas, the annual mean temperature of the deep layer is about 5℃, the maximum ranges from 5.5℃ to 6.5℃, and the minimum is less than 5℃. Overall, the cold water of most areas in the South China Sea can be accessible by the current techniques.

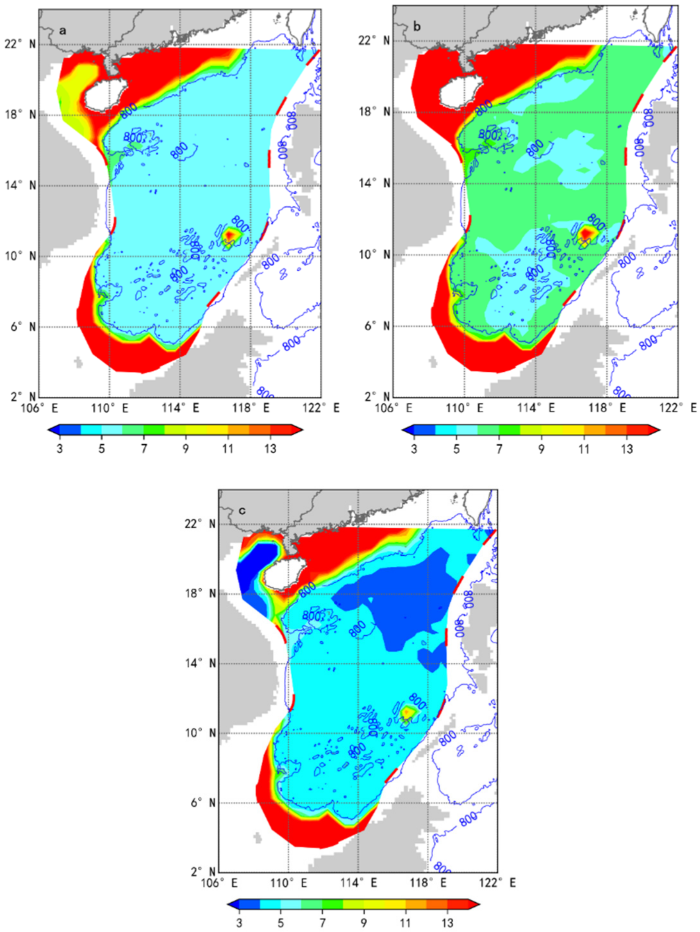

Figure 4: Annual mean temperature(a), monthly maximum temperature(b) and monthly minimum temperature(c) of deep seawater (Blue contour: water depth, m)

3.3 Annual OTEC net power density

From Equation(2), the net power generation of OTEC would grow linearly as a Function of cold water vertical velocity. Nihous proved that the maximal value of W_{cw} is 60m per year if OTEC flows had no effect on the ocean's thermal structure (Krishnakumar and Nihous, 2013). Fig.5 shows OTEC net power density in the South China Sea, computed with the data in Fig.1

and Equation (2). Values in most area rangs between 900 and 1200 kW.km^{-2}. Compared with other regions in the world, the South China Sea is relatively rich in the thermal energy.

As shown in Fig.5, annual OTEC net power density in the western of Hainan at 50m depth is about 500~600kW·km^{-2}. Annual OTEC net power density of the South China Sea is obviously divided into four regions along the northwest-southeast direction: 300~900 kW·km^{-2}, 900~1000 kW·km^{-2}, 1000~1100 kW·km^{-2} and 1100~1200 kW·km^{-2}. The area where values between 300 and 900 kW.km^{-2} is mainly in the north with depth less than 1000m, and the net power density increases unevenly with increasing water depth. The variation gradient between 1000m and 4000m depth is small. OTEC net power density increases with the decreasing of latitude because the south area is closer to the equator and receives more direct solar radiation energy.

Considering power consumption and construction cost, the suitable location of OTEC plant should be near the islands. OTEC net power density is about 600~800 kW·km^{-2} around Dongsha Islands, about 1000 kW·km^{-2} around Sansha city, about 1000~1100 kW·km^{-2} around Xisha Islands and Zhongsha Islands and about 1100~1200 kW·km^{-2} around Nansha Islands, Huangyan Island, YongShu reef and AnDu Beach.

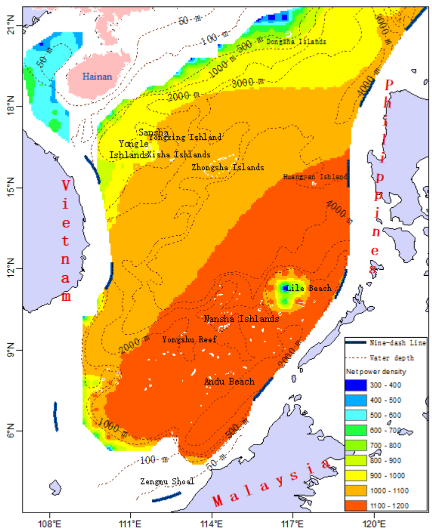

Figure 5 Annual OTEC net power in the South China Sea(kW·km-2).

3.4 Suitable water depth for OTEC developmentSuitable water depth for OTEC development

Considering the current techniques, OTEC is commonly considered exploitable where the temperature difference exceeds 18°C between surface and deep waters, and the temperature of deep water uesd to condense the working fluid should be at least less than 6 ℃. As shown in Fig2 and Fig.4, in most areas, temperature difference exceeds 20 ℃ and the temperature of cold water is about 5°C. In order to provide more guidance for the site selection of OTEC plants, suitable water depth is proposed in this paper. Suitable water depth refers to the depth when temperature difference exceeds 18 ℃ and average temperature is 6℃, where OTEC can be utilized by current techniques.

Fig.6 plots the contours of suitable water depth in the South China Sea. Due to small temperature gradient in deep levels, the distribution of suitable water depth is relatively homogeneous, ranging from 720m to 770m. The magenta line at 750m in this figure can be seen as dividing line. Values around Dongsha Islands and Xisha Islands range between 720m and 750m, values around Yongle Islands are about 750m, values around Nansha Islands range between 750m and 780m, values around Huangyan Island and Lile Beach range from 730m to 750m.

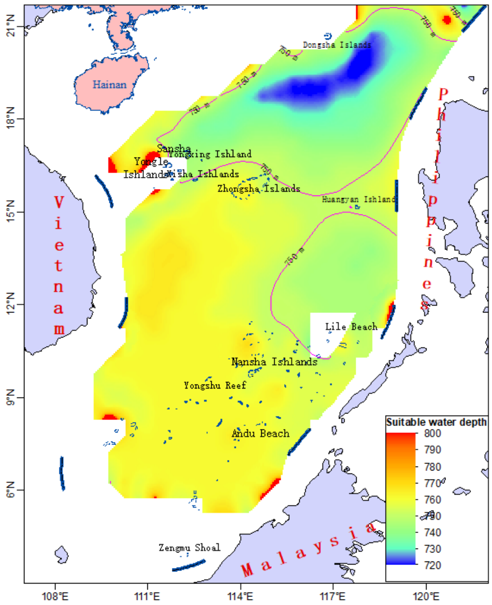

Figure 6 Suitable water depth for OTEC development in the South China Sea.

4 CONCLUSIONS

In this study we use the GODAS monthly average marine dataset to estimate the Ocean thermal energy resources in the South China Sea with a new method proposed by Nihous et al. We analyze the temporal and spatial variation of temperature difference, the distribution of temperature of surface water and cold water respectively, and the suitable water depth for OTEC development is. The conclusions can be listed as following:

1) The horizontal distribution of temperature difference is low in the north while high in the south. Time distribution shows seasonal variation: high in summer, low in winter, spring and autumn is the transition season of temperature change. In general, the temperature difference in the South China Sea is large with most areas over 18℃ even in winter except the shallow coastal, so the South China Sea can be considered as a suitable place for the development of OTEC plants.

2)Annual OTEC net power density in the South China Sea ranges from 300 to 1200 kW.km-2. In the area with the depth less than 1000m, net power density increases unevenly with increasing water depth, ranging from 300 to 900 kW.km-2. The variation gradient between the areas with 1000m and 4000m depth is small. Compared with other regions in the world, the South China Sea is relatively rich in the thermal energy.

3)Suitable water depth for OTEC development in the South China Sea is relatively homogeneous, mainly concentrated between 720m and 770m, and the average value is about 750m..

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