The control strategy and low power consumption of Deep FuXing

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1. Introduction

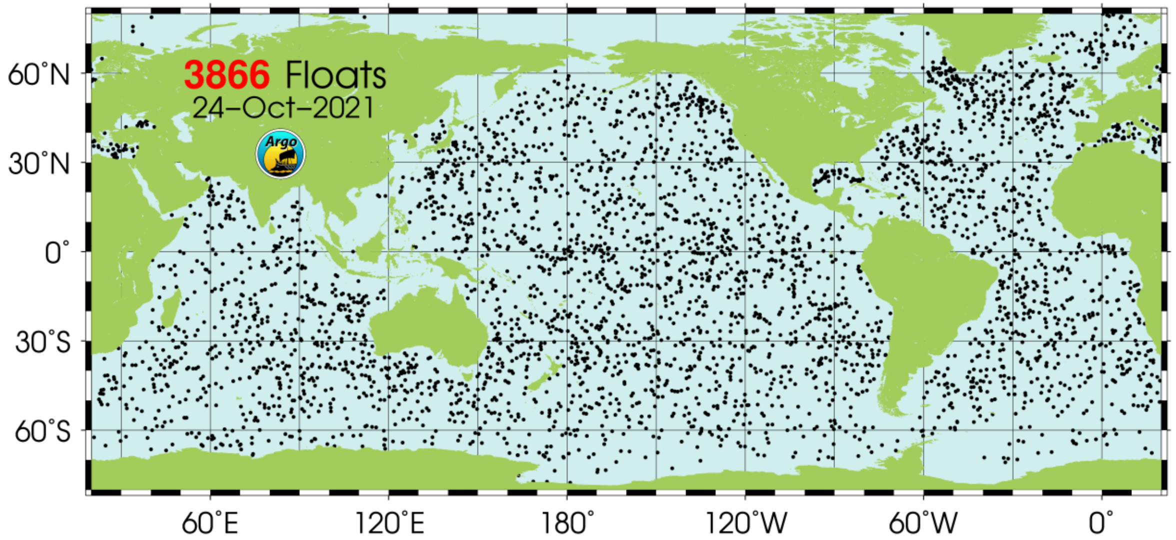


Figure 1. Array for Real-time Geostrophic Oceanography(Argo)

Figure 2. Positioning navigation and timing under water

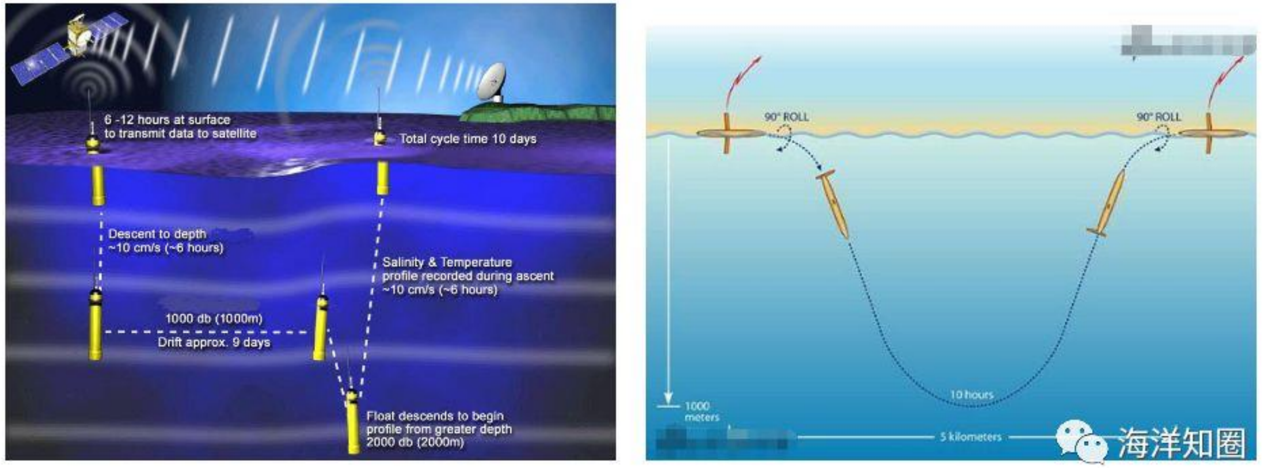


Figure 3. Joint Observation

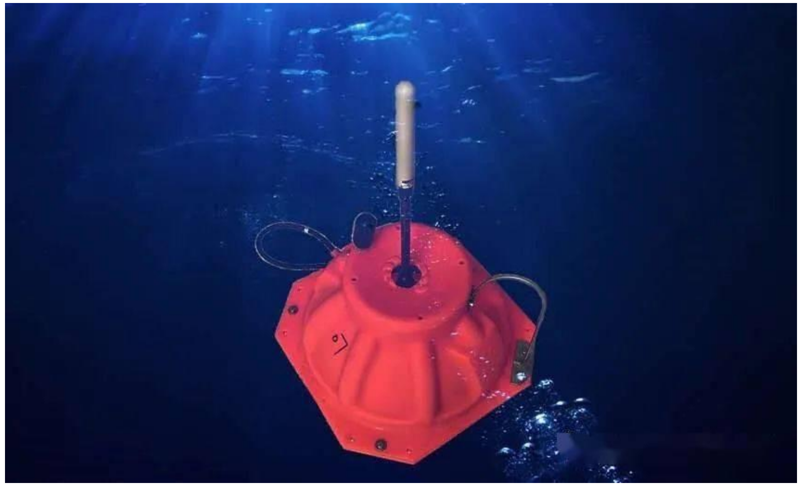


Figure 4. Submarine seismic detection

1. Introduction

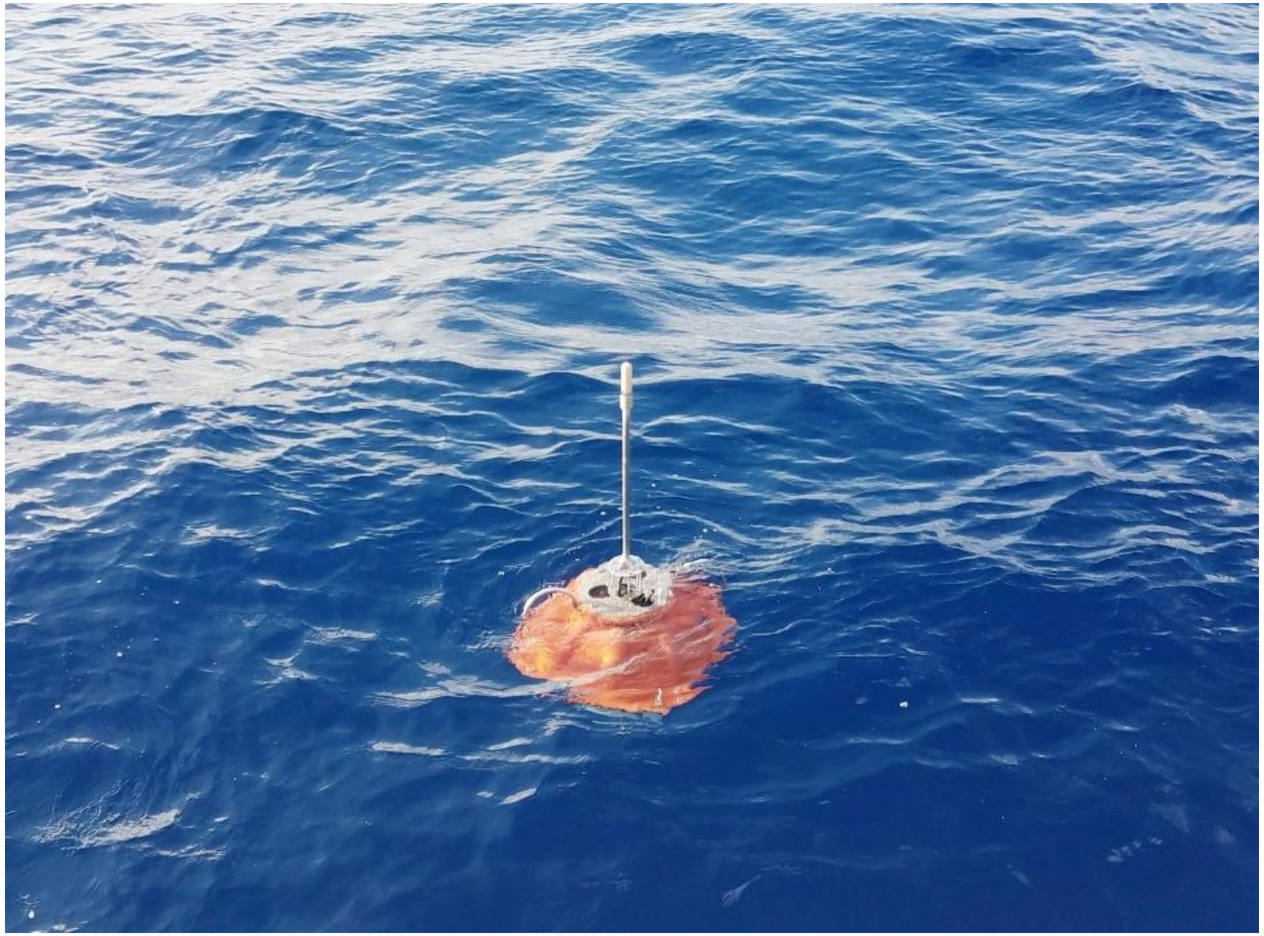


Figure 5. Deployment of Deep FuXing in August 2018 at South China Sea

Deep FuXing, which is a deep Argo over 4000 meters depth, is designed by Tianjin University and Pilot National Laboratory for Marine Science and Technology (Qingdao).

- Target depth: 4000 meters
- Dive cycles: 100 (ten-day cycle)
- Mass: smaller than 56 kg
- Carrying capacity: over 8 kg
- Telemetry: Beidou or Iridium

1. Introduction

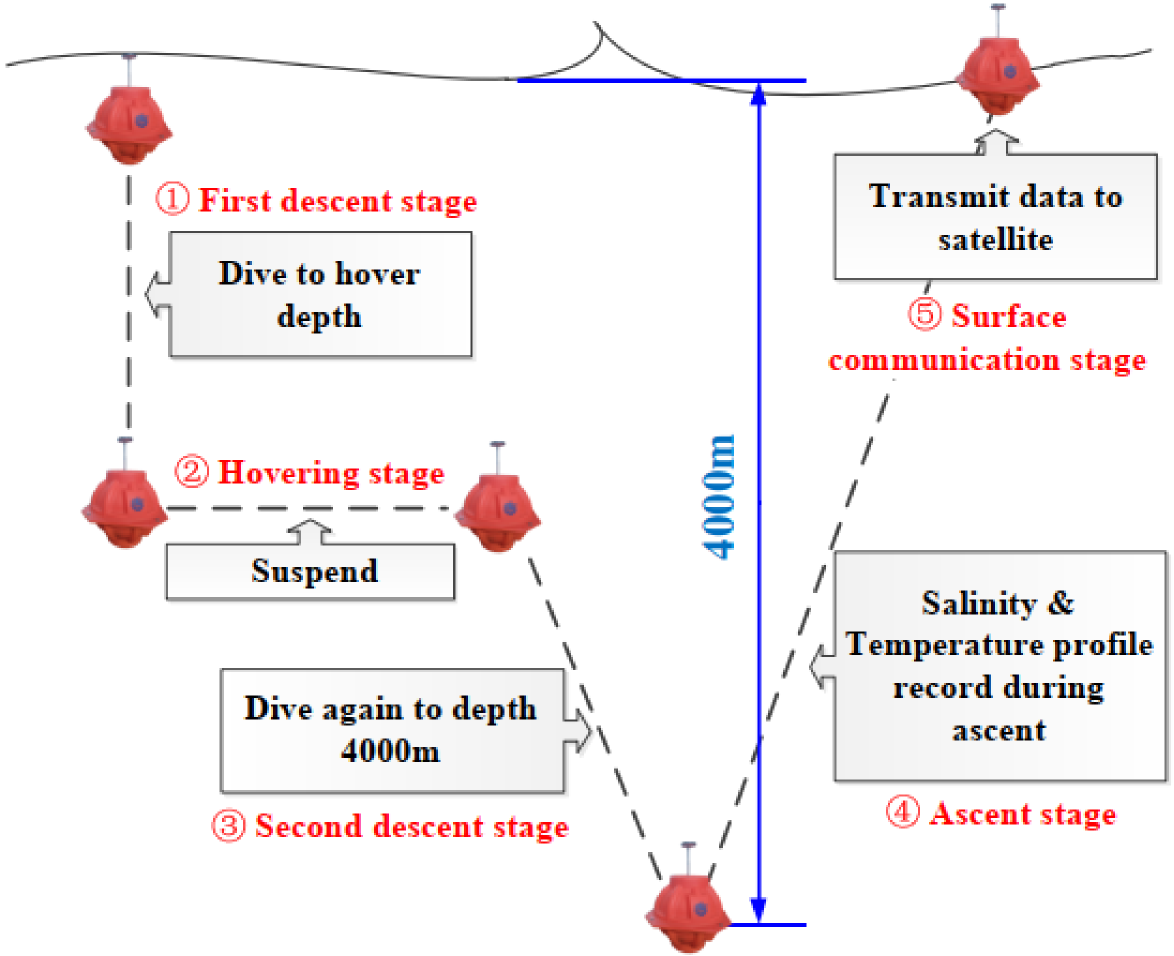


Figure 6. The working process of the deep-sea self-sustaining profile buoy

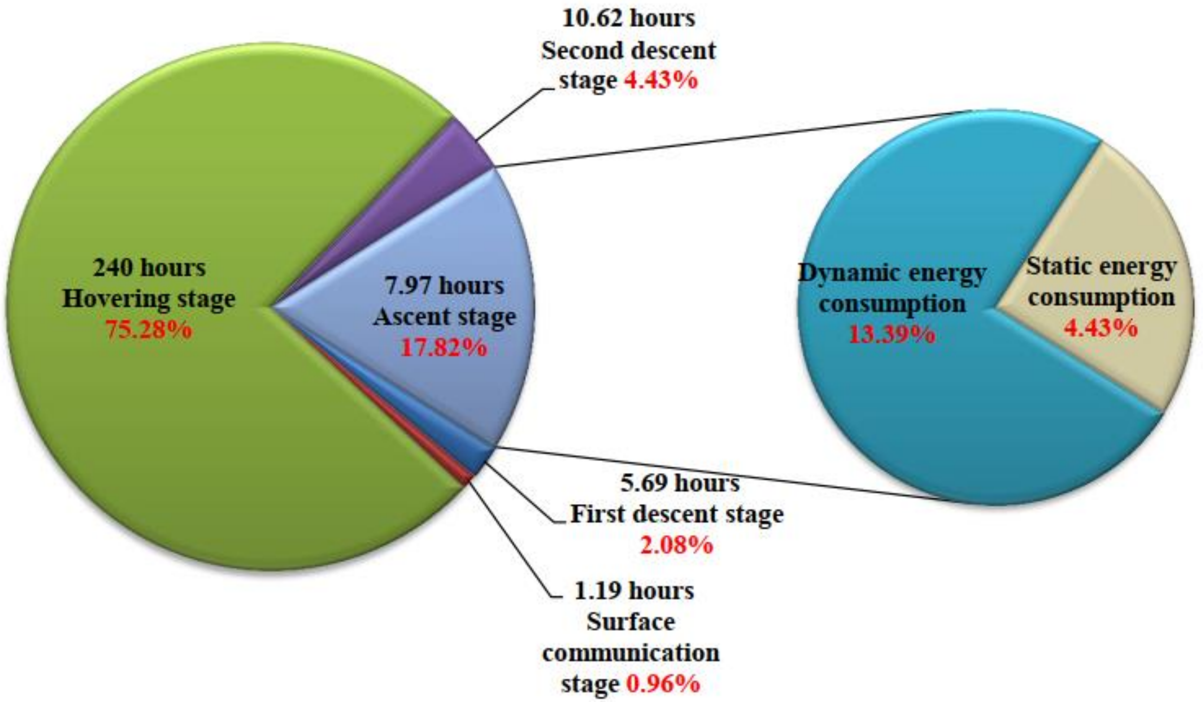


Figure 7. The energy consumption of each working stage.

1. Introduction

Table1. The running states of devices and sensors of Deep FuXing in the whole working stage

Devices and Seneors	First Descent	Hovering	Second Descent	Ascent	Surface Communication
CTD sensor	●	●	●	●	●
Steering engine	◖	◖	◖	○	○
Oil pump motor	○	◖	○	◖	○
GPS module	○	○	○	○	●
Comet module	○	○	○	○	●
Embedded control system	●	⊙	●	●	●

● running, ○ not running, ◖ running if necessary, ⊙ Standby mode.

2. Control & Oil Draining Strategy

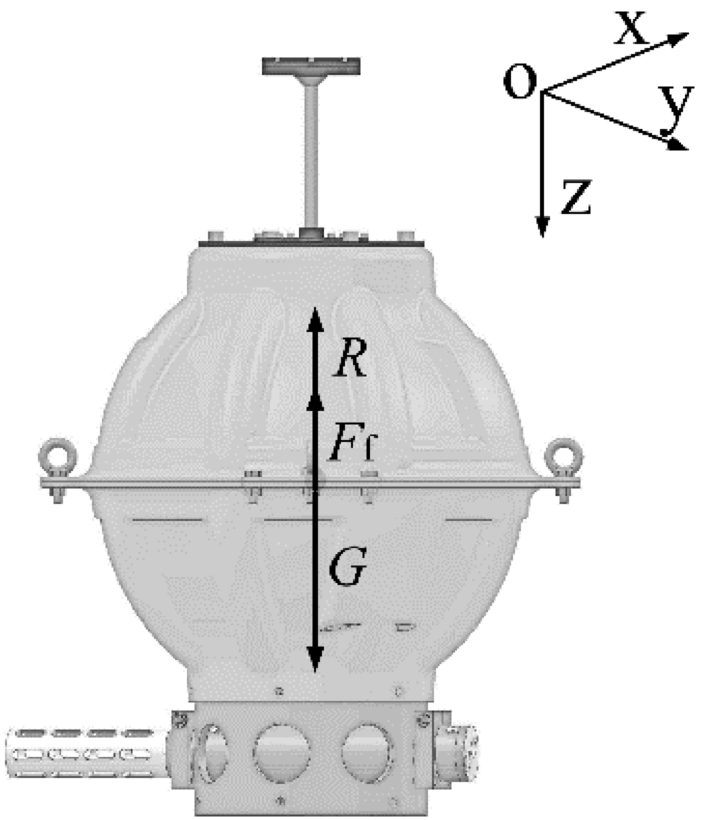


Figure 8. The force analysis of the deep-sea self-sustaining profile buoy in the ascent stage

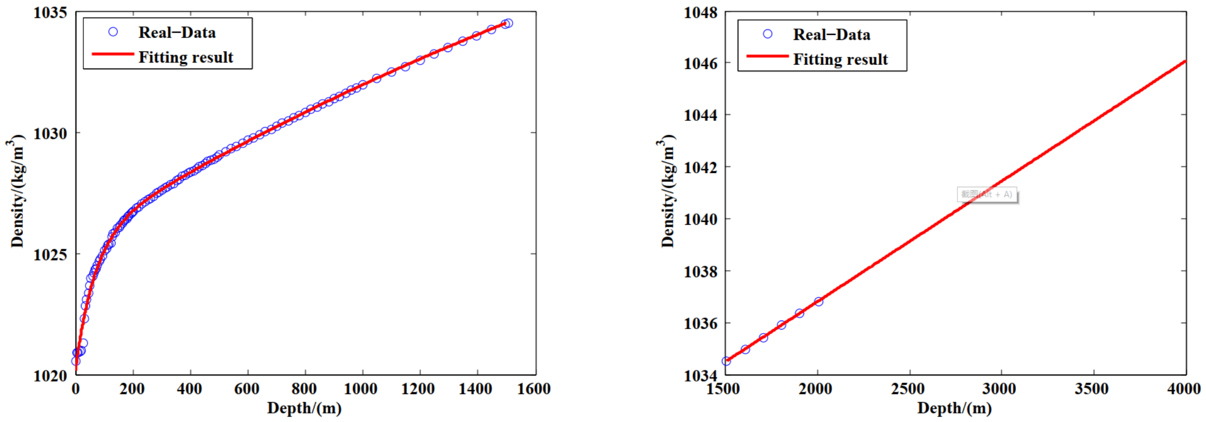
Buoyancy: $F_f = -\rho g(V_{oil} + V_B)$

Resistance: $R = -\frac{1}{2}(C_D A_D + C_f A_f)\rho \boldsymbol{v}|\boldsymbol{v}|$

Resultant force: $\sum F = mg - F_f - \boldsymbol{R}$

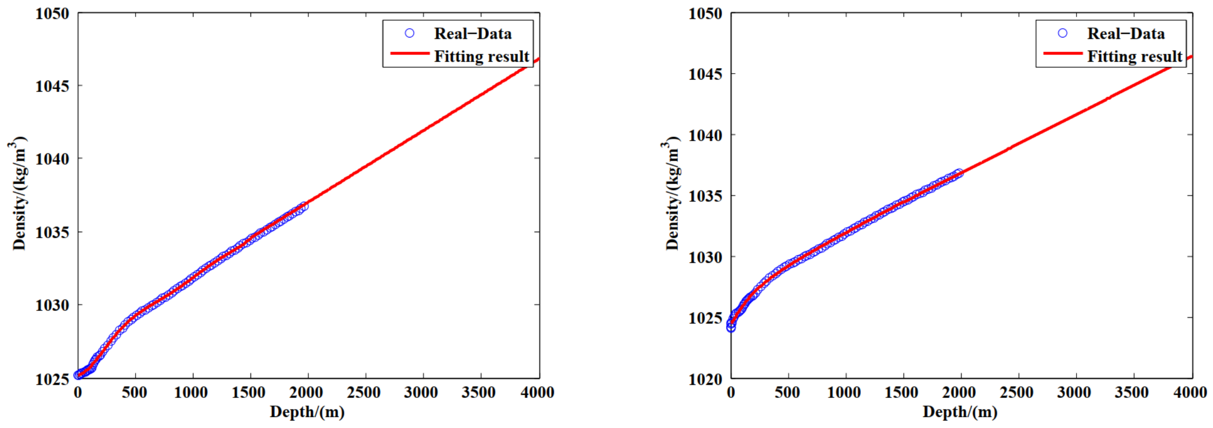
Kinetic Equation:
$$\begin{cases} a(t) = \dfrac{\sum F(t)}{m} \\ \boldsymbol{v}(t) = \boldsymbol{v}(t-1) + a(t) \\ h(t) = h(t-1) + \boldsymbol{v}(t) \end{cases}$$

2. Control & Oil Draining Strategy



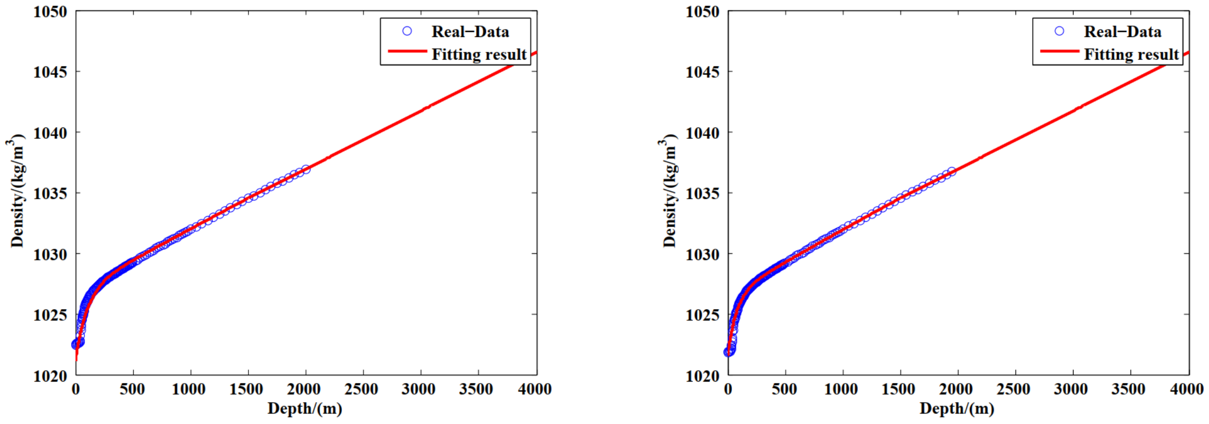
(a)0-1500m (b)1500-4000m

Figure 9. The fitting result of the density data at 18.035 N and 114.849 E



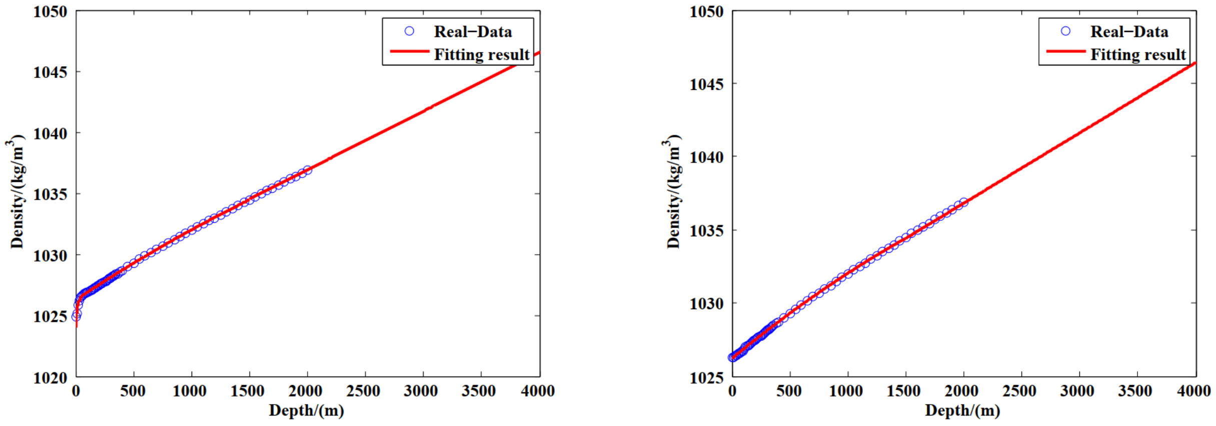
(a)summer (b)Winter

Figure 10. The fitting result of the density data in the southern hemisphere



(a)summer (b)Winter

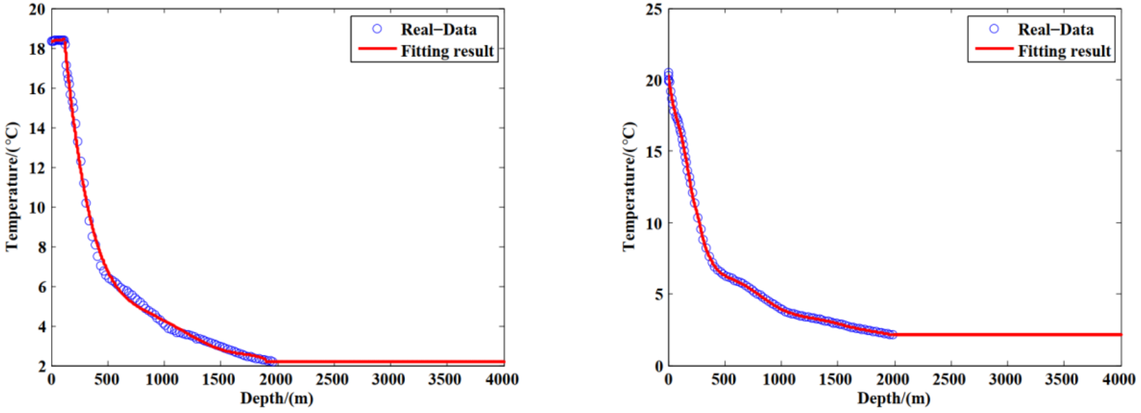
Figure 11. The fitting result of the density data in the equator area



(a)summer (b)Winter

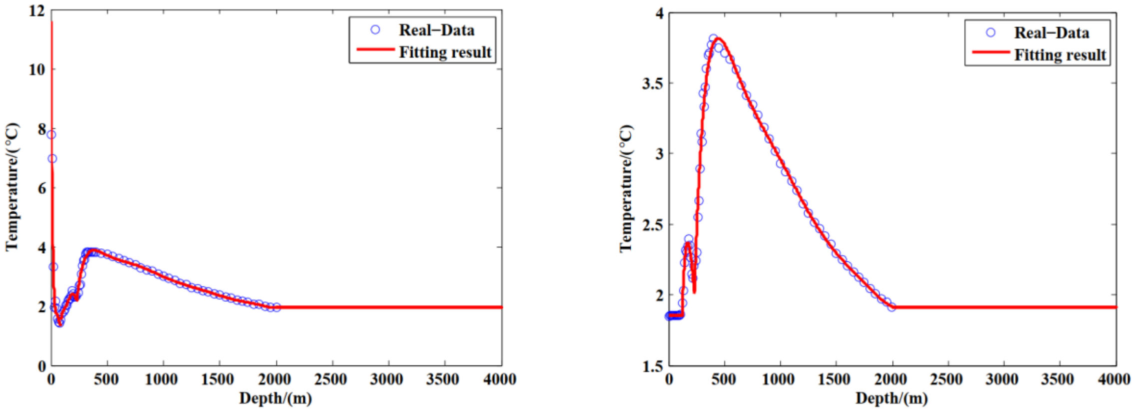
Figure 12. The fitting result of the density data in the nouthern hemisphere

2. Control & Oil Draining Strategy



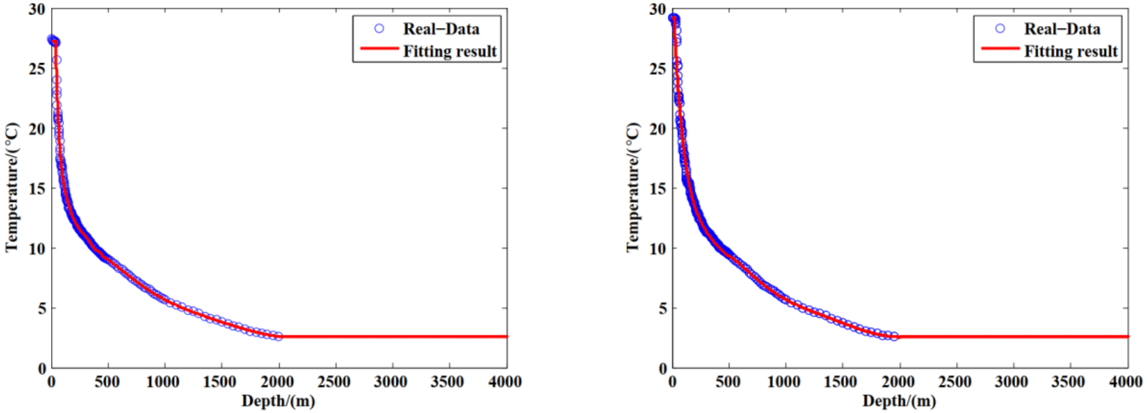
(a) summer (b) Winter

Figure 13. The fitting result of the temperature data in the southern hemisphere



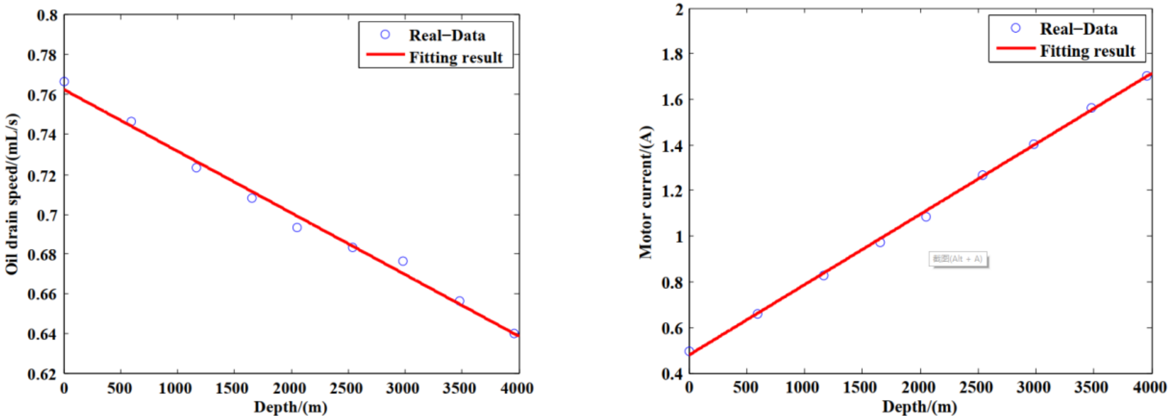
(a)summer (b)Winter

Figure 14. The fitting result of the temperature data in the nouthern hemisphere



(a)summer (b)Winter

Figure 15. The fitting result of the temperature data in the equator area



(a)Oil drain speed (b)Motor Current

Figure 16. The fitting effect of the oil draining speed and motor's operating current

2. Control & Oil Draining Strategy

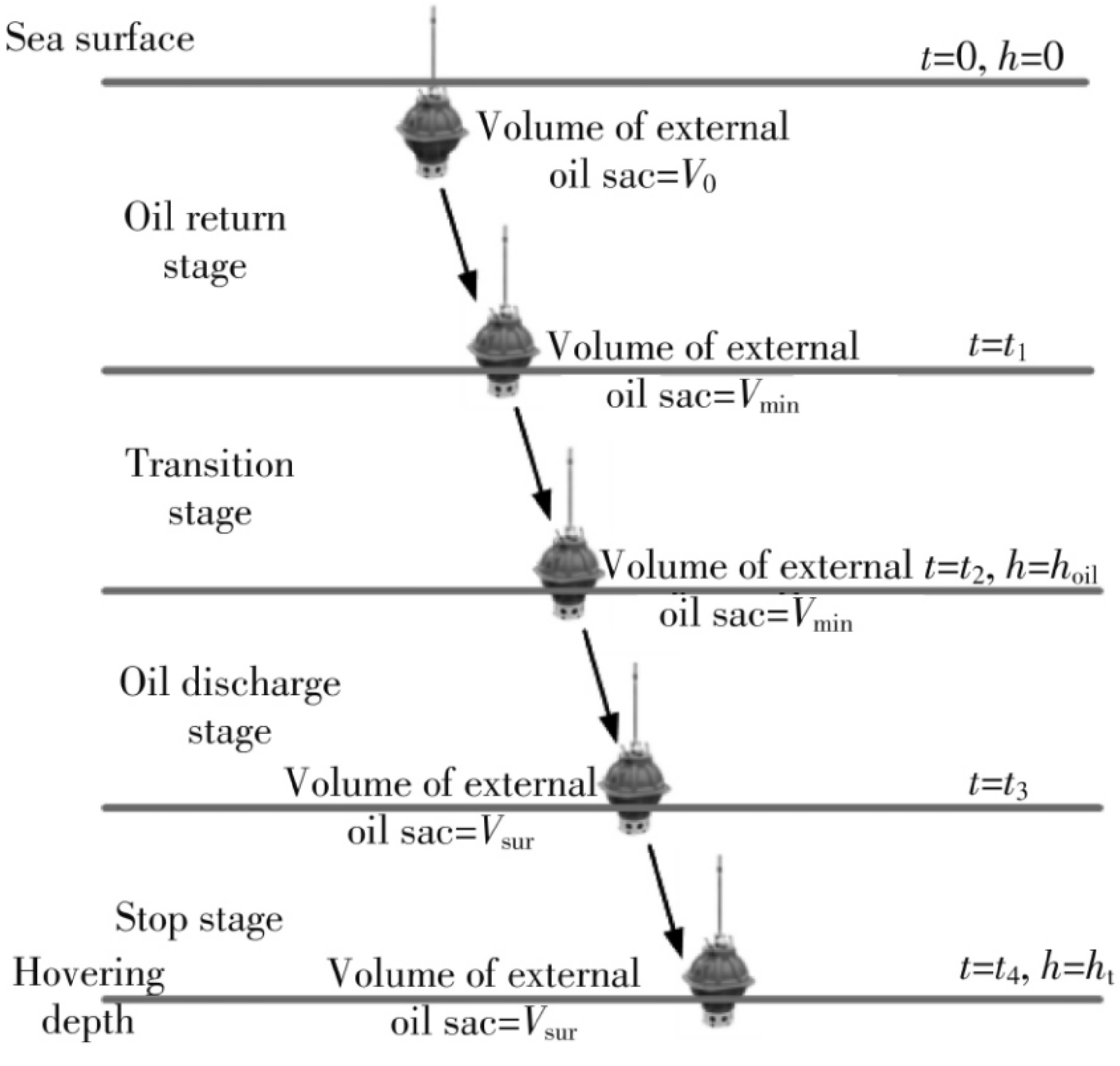


Figure 17. Motion planning of dive process before hovering

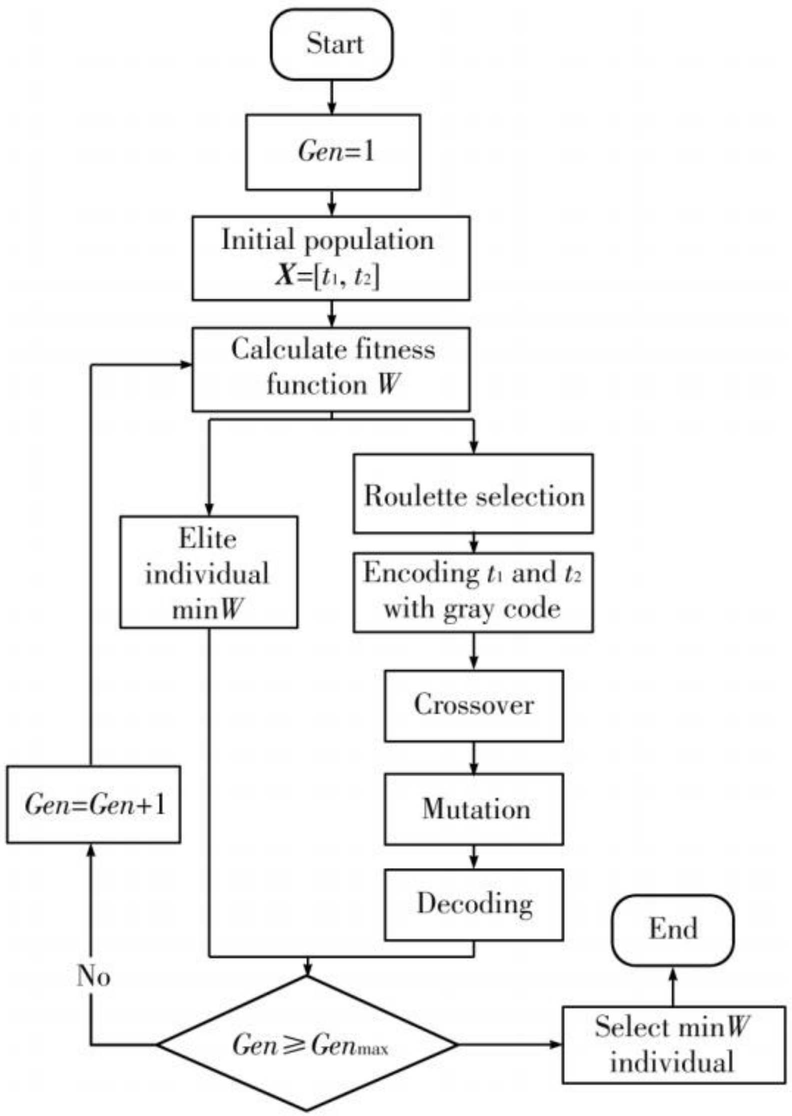


Figure 18. Flow chart of genetic algorithm

2. Control & Oil Draining Strategy

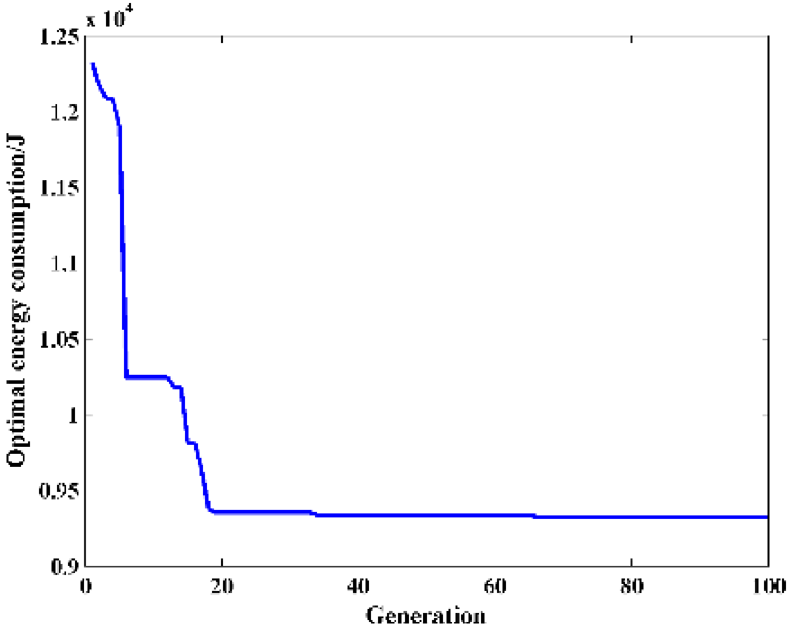


Figure 19. Hovering depth=1000 m

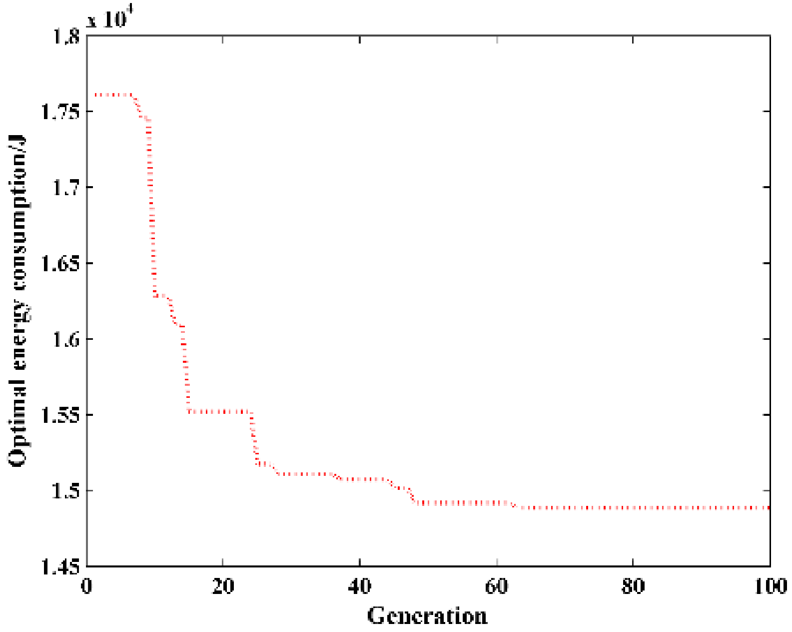


Figure 20. Hovering depth=2000 m

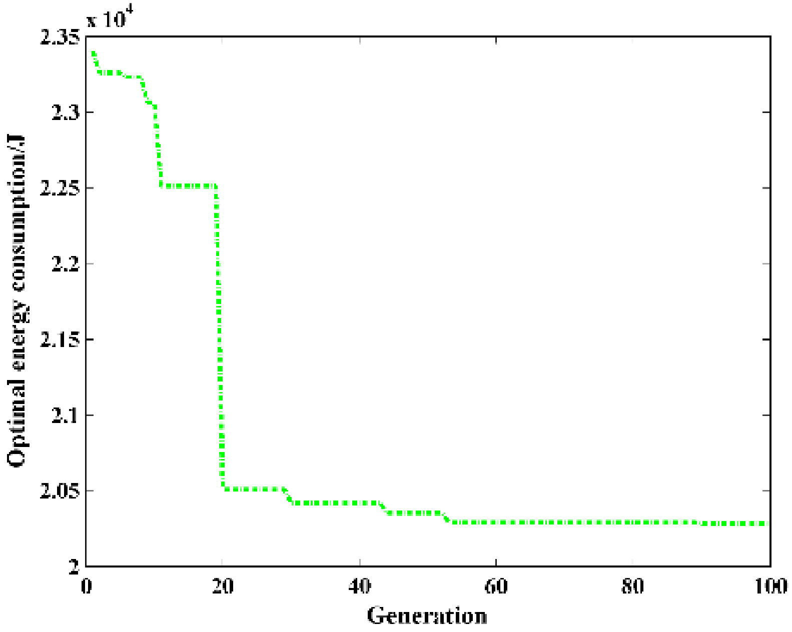


Figure 21. Hovering depth=3000 m

2. Control & Oil Draining Strategy

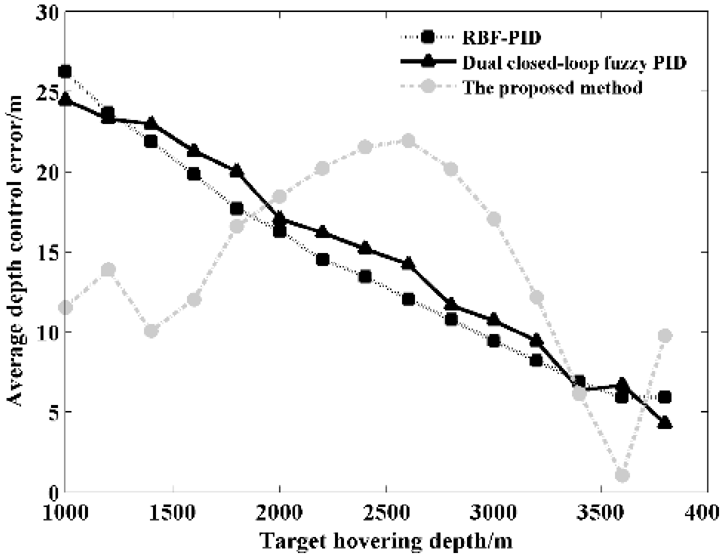


Figure 22. Average depth control error

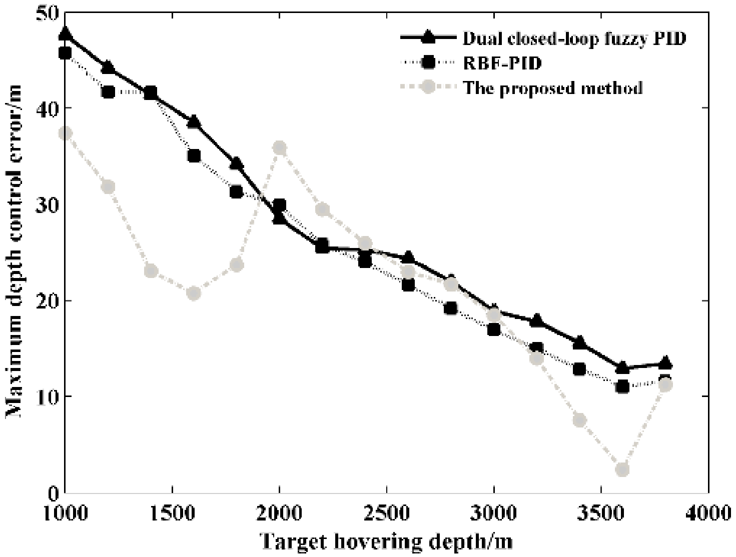


Figure 23. Maximum depth control error

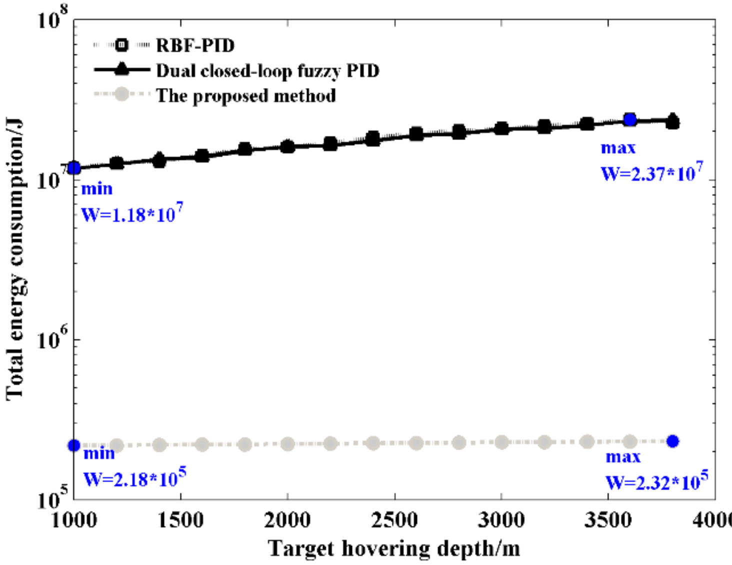


Figure 24. Semi-logarithmic graph of total energy consumption of three control methods

2. Control & Oil Draining Strategy

One-time Oil Draining Control Model

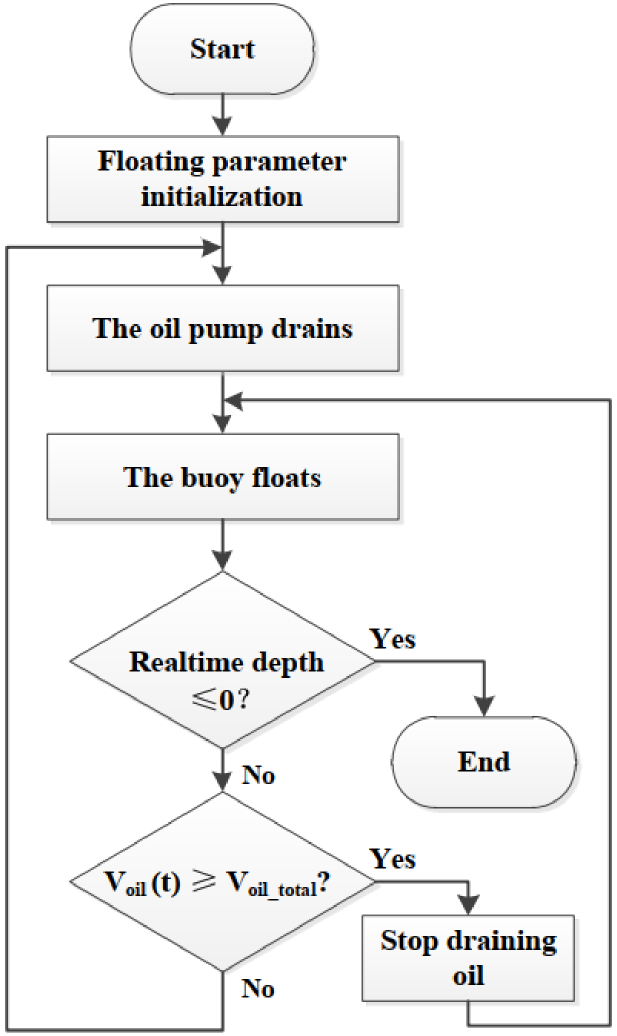


Figure 25. One-time oil draining control mode

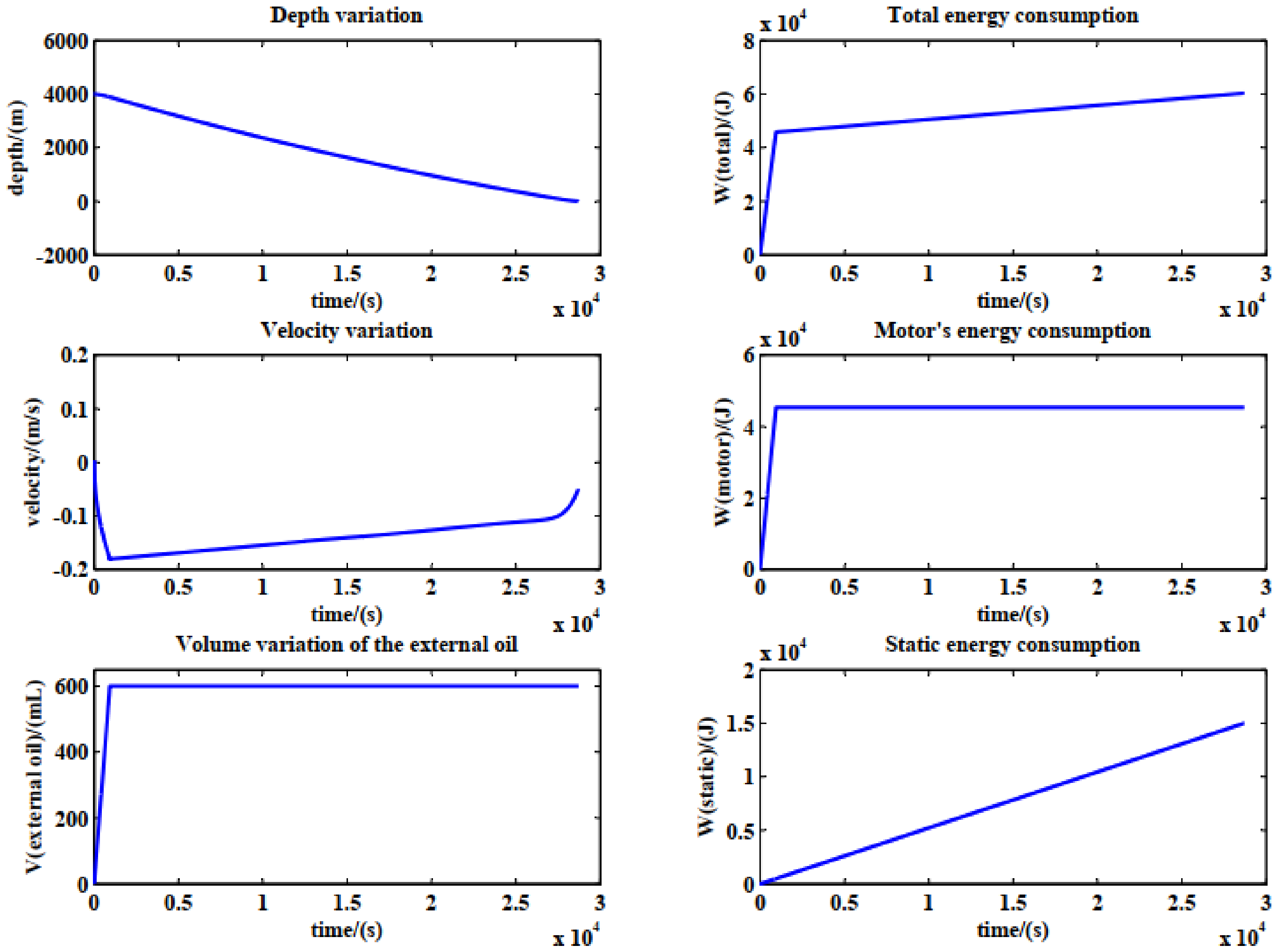


Figure 26. Ascent stage of the one-time oil draining method

2. Control & Oil Draining Strategy

Stage Quantitative Oil Draining Control Model

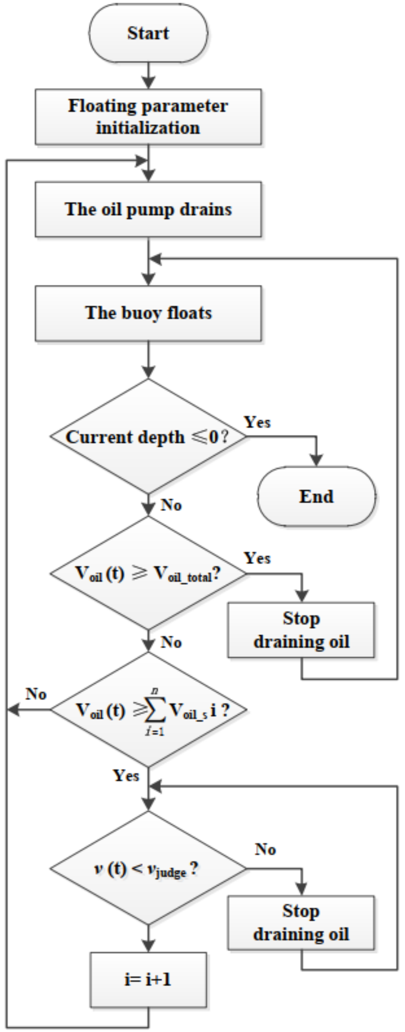


Figure 27. Stage quantitative oil draining

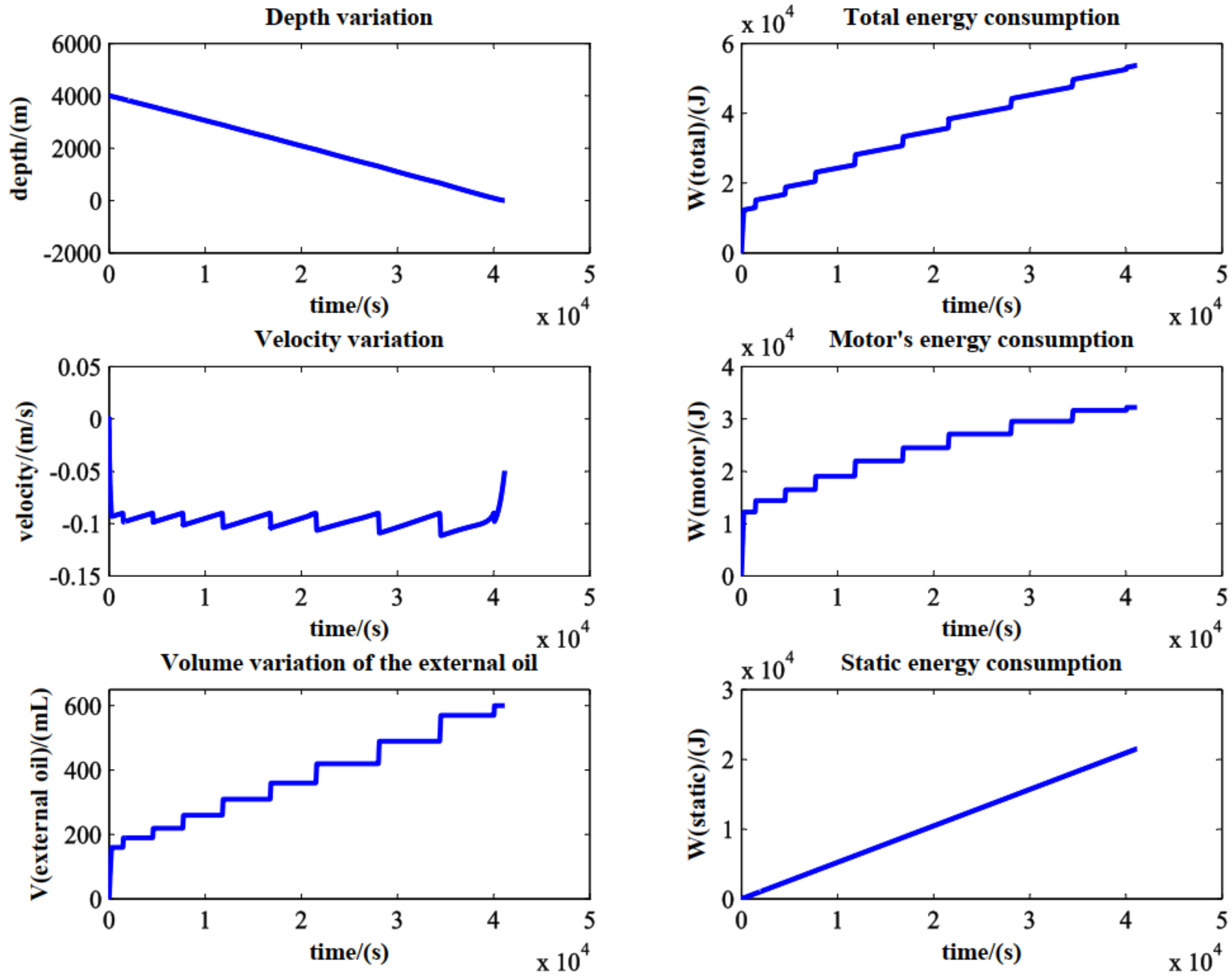
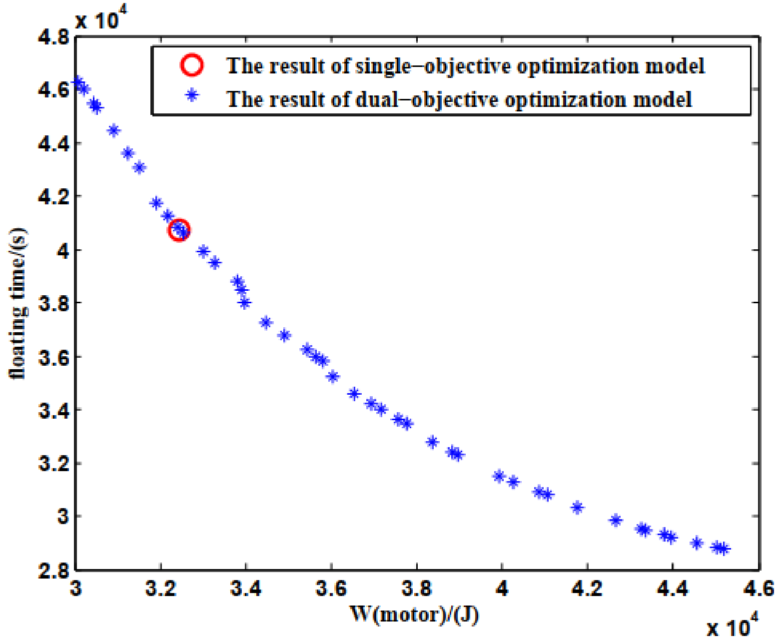


Figure 28. Ascent stage optimized by the NSGA-II method

2. Control & Oil Draining Strategy

Table2. The optimization effect of the NSGA-II method compared with pre-optimization

	Before Optimization	After Optimization	Optimal Ratio
V_{oil_s} (mL)	[600]	[160,30,30,40,50,50,60,70,80,30]	–
v_{judge} (m/s)	–	0.9	–
t (s)	28,704	40,699	–
W_{static} (J)	15,007.51	21,278.95	–
W_{motor} (J)	45,325.47	32,198.96	28.9%
W_{total} (J)	60,332.98	53,716.84	11.0%



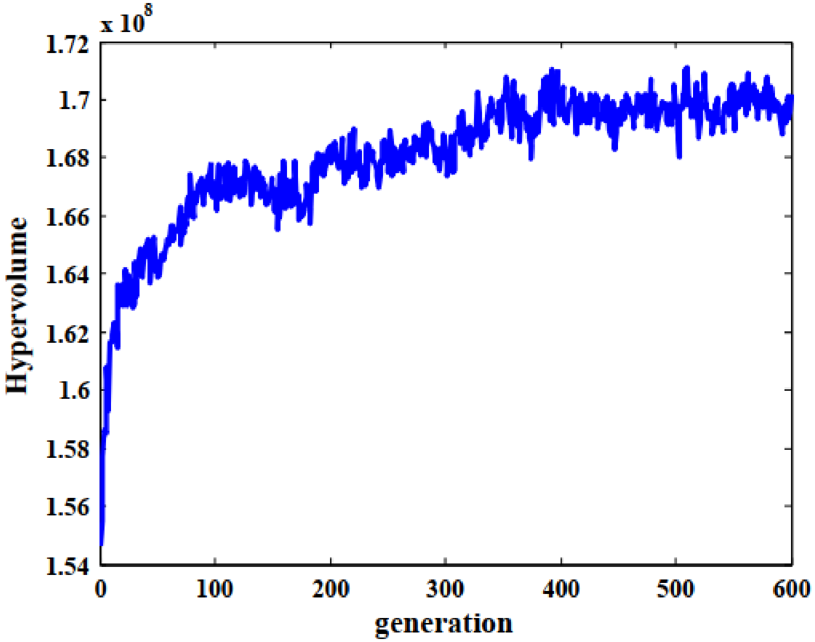


Figure 29. Optimal results of multi-objective optimization model.

3. hardware-in-the-loop simulation system

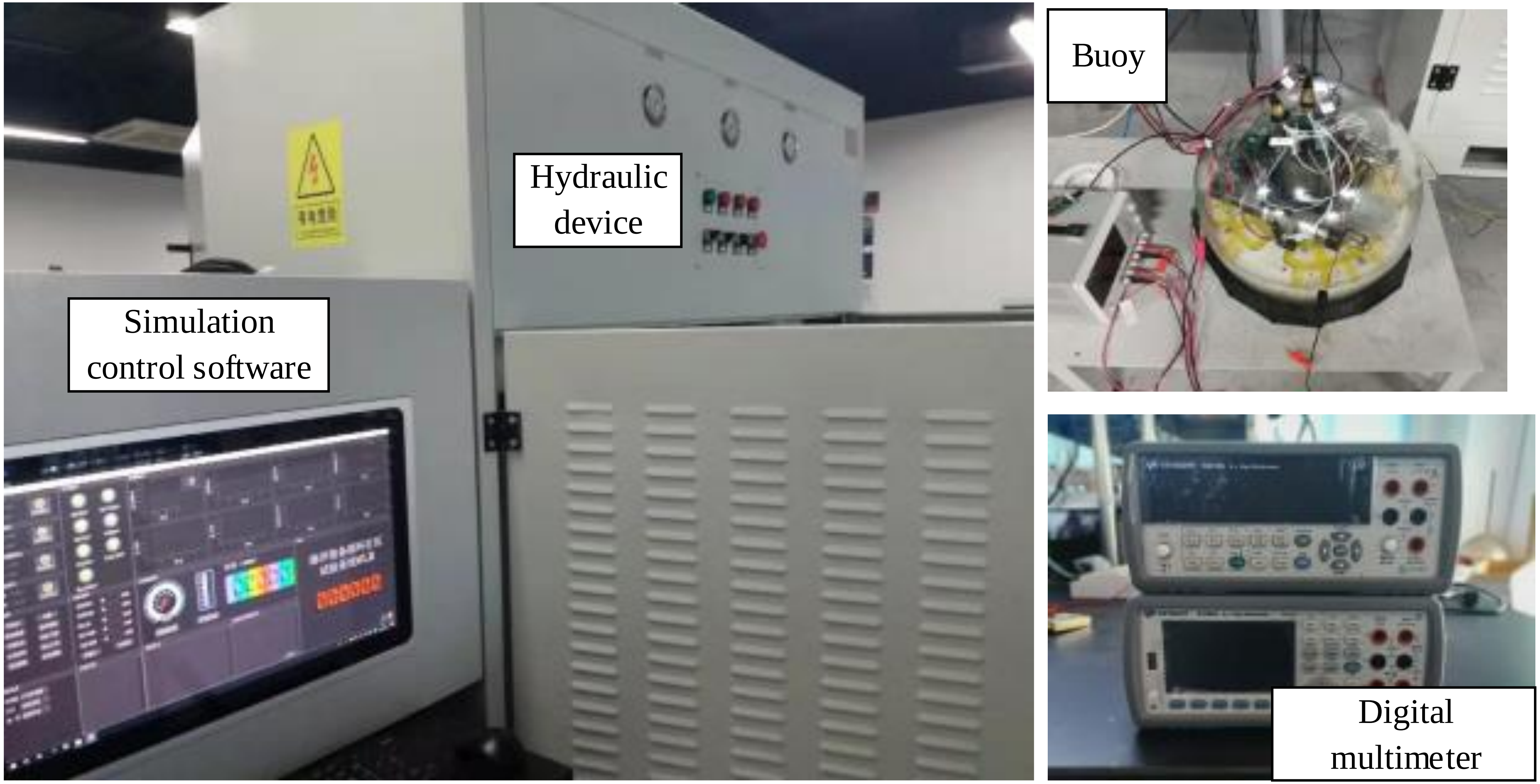


Figure 30. Hardware-in-the-loop simulation system

3. hardware-in-the-loop simulation system

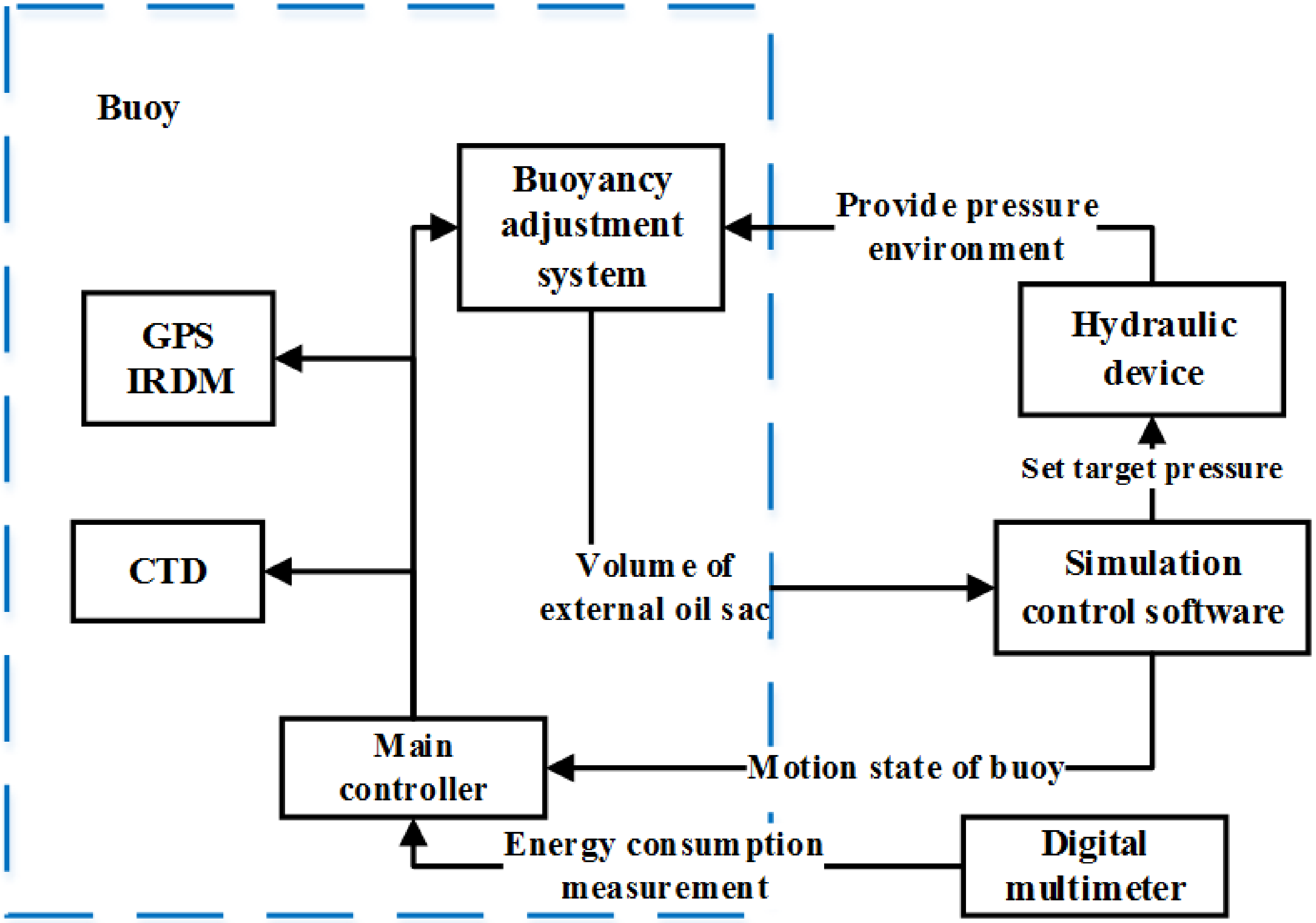


Figure 31. Relationship Structure of hardware-in-the-loop simulation system

Figure 32. Simulation system

3. hardware-in-the-loop simulation system

Figure 33. Hardware-in-the-loop simulation software

3. hardware-in-the-loop simulation system

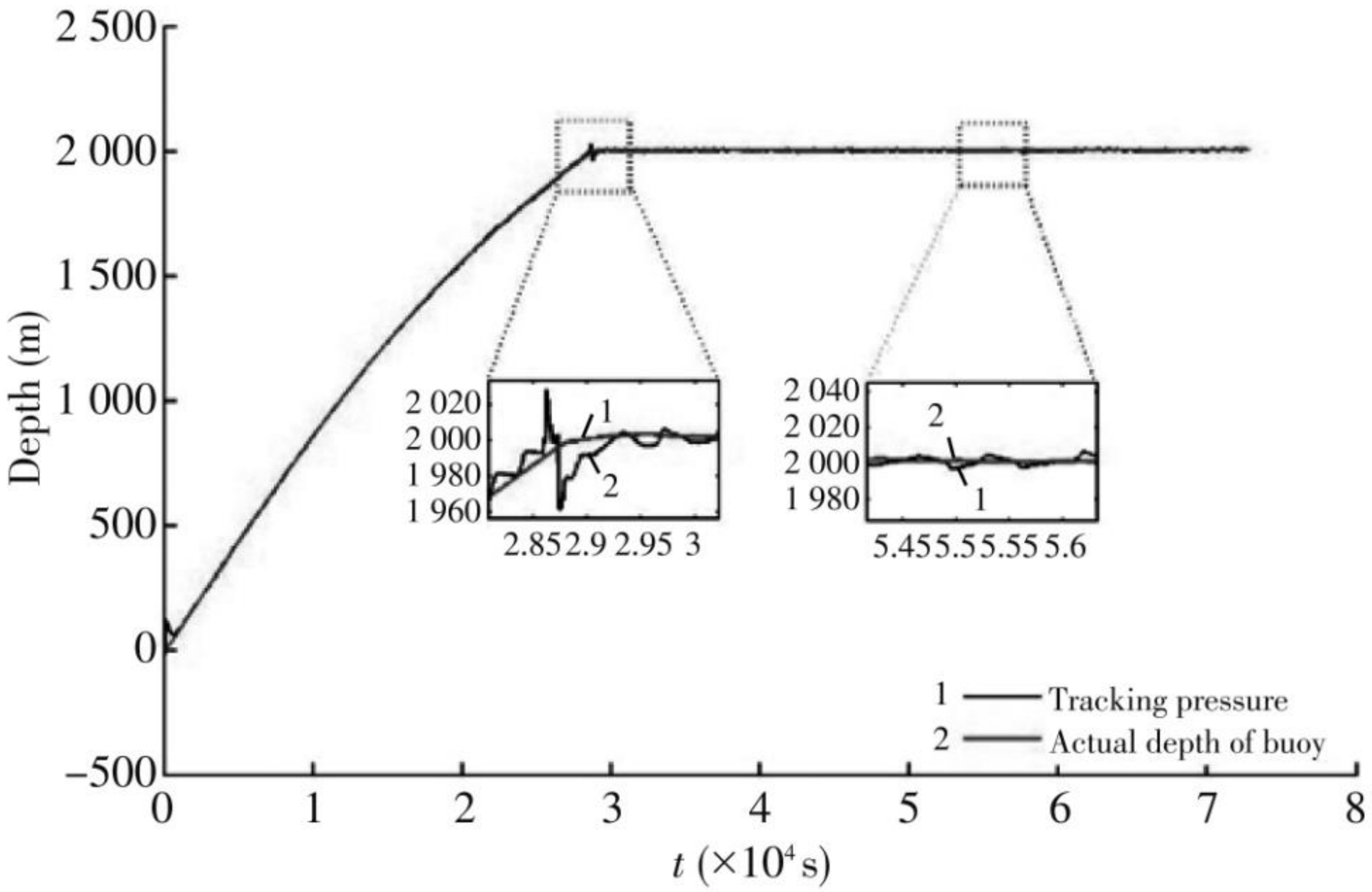


Figure 34. Depth variation of buoy in experiment

The target hovering depth of the experiment was The 2000 m. For the convenience of the experiment Hovering time was 12H. And the ocean data were used for the fitting curves.

4. Device Application

2018.01
Offshore test in South China Sea

2018.02
1500 meters test in South China Sea

2018.07
3500 meters test in South China Sea

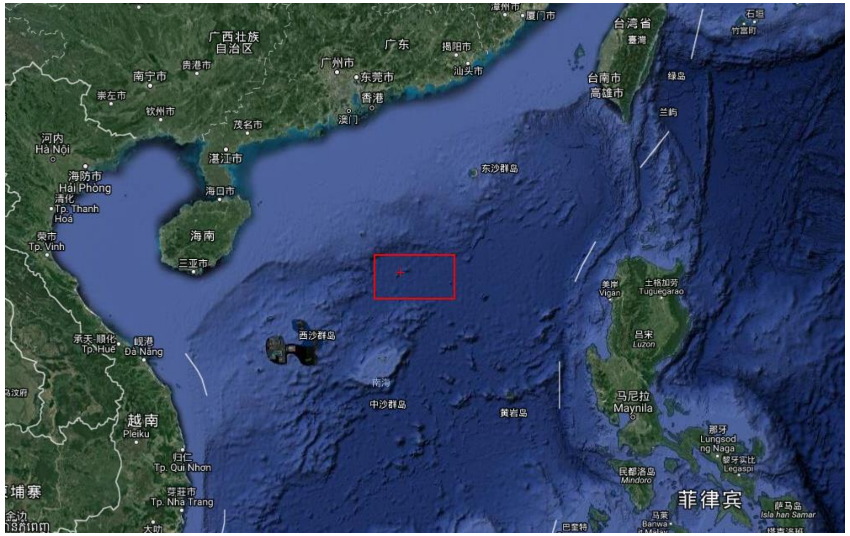
2019.03
Extreme environmental test in Western Pacific

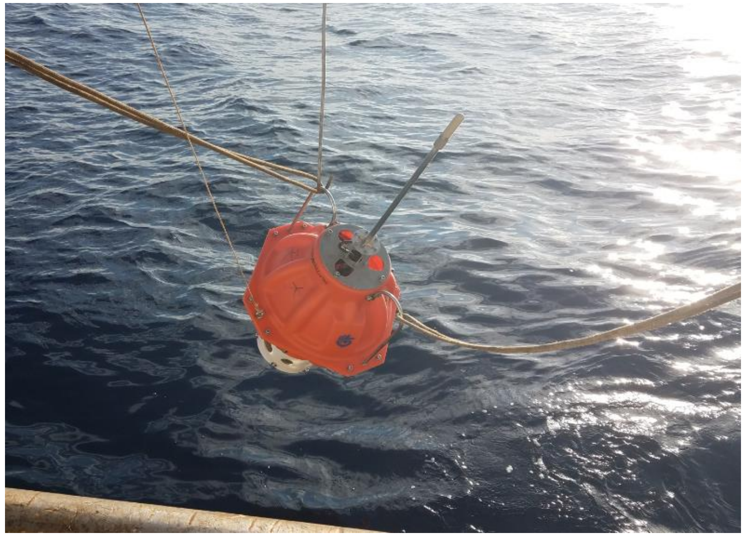
2019.08
4000 meters test in Western Pacific

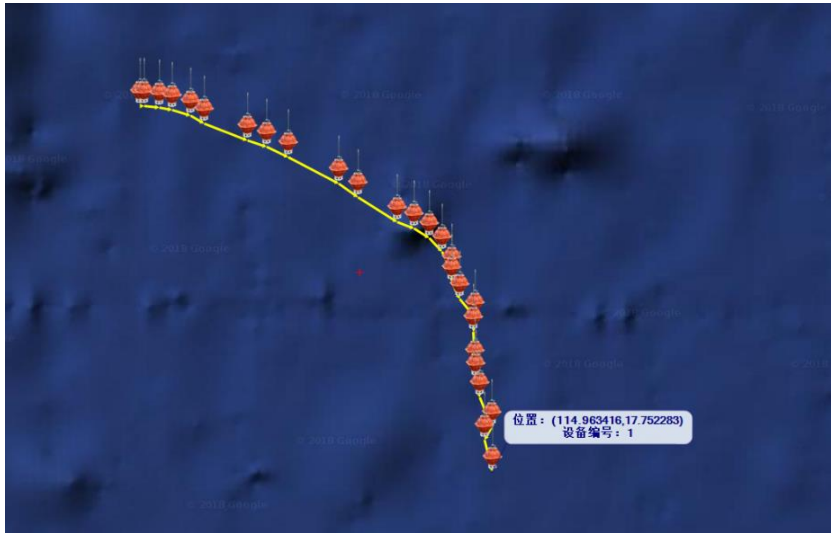
2021.10
Deployment in Indian Pacific

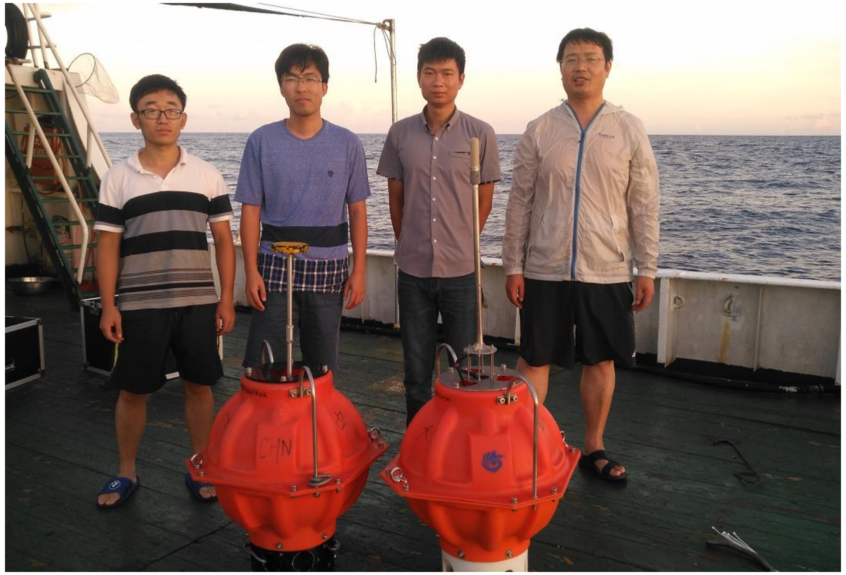
4. Device Application

3500 meters test in South China Sea







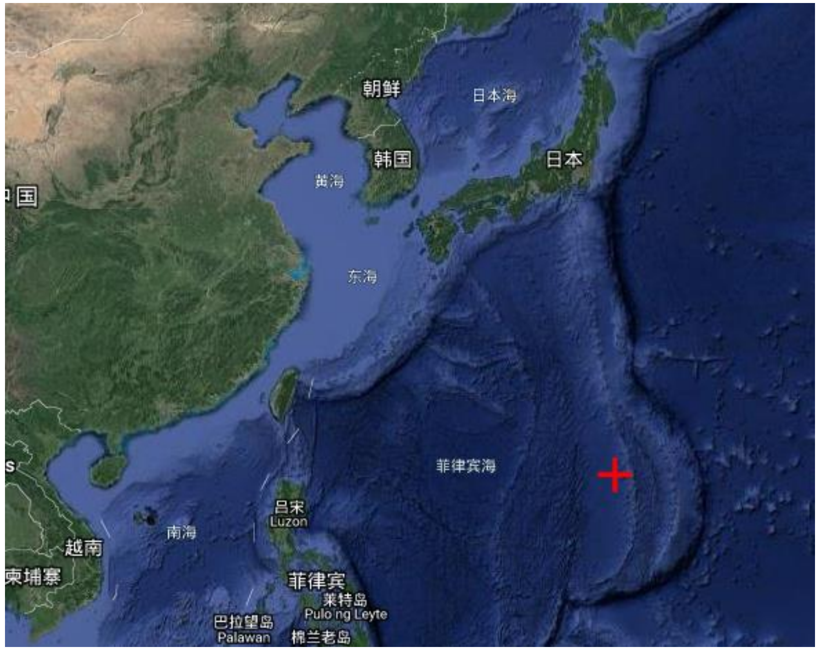


From July 24th to August 8th, 26 cycles has been operated, including 11 cycles over 2000 meters and 4 cycles over 3000 meters. The maximum diving depth is 3550.3 meters, and the satellite transmission success rate reaches 99.9%.

4. Device Application

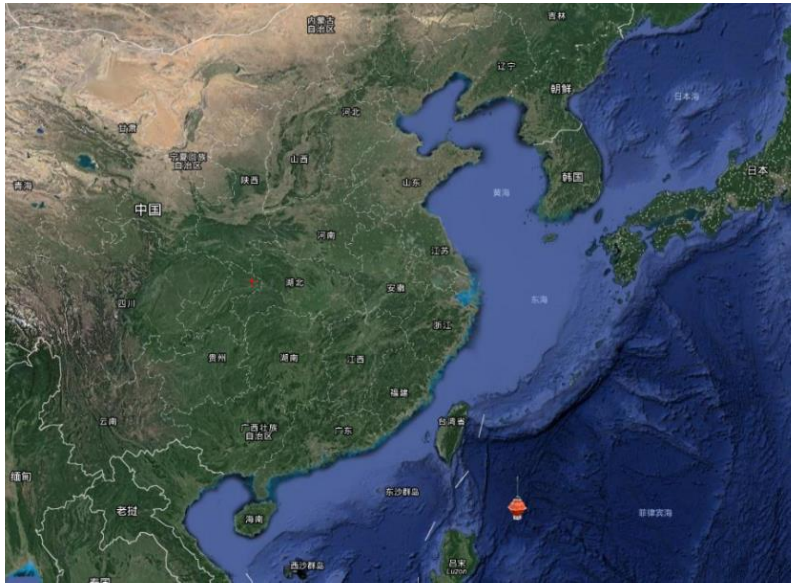
Deep FuXing - 5, which carried a pressure sensor, has been mounted on a cable, and dived from 4080 to 4180. The testing position is the western of Pacific with 4214 meters depth (N19.005897, E142.002541).

From March 13th to 20th, 110 cycles from 4080 to 4180 has been operated. The characteristics of the hydraulic system, pressure house, and control module is verified under the extreme condition.

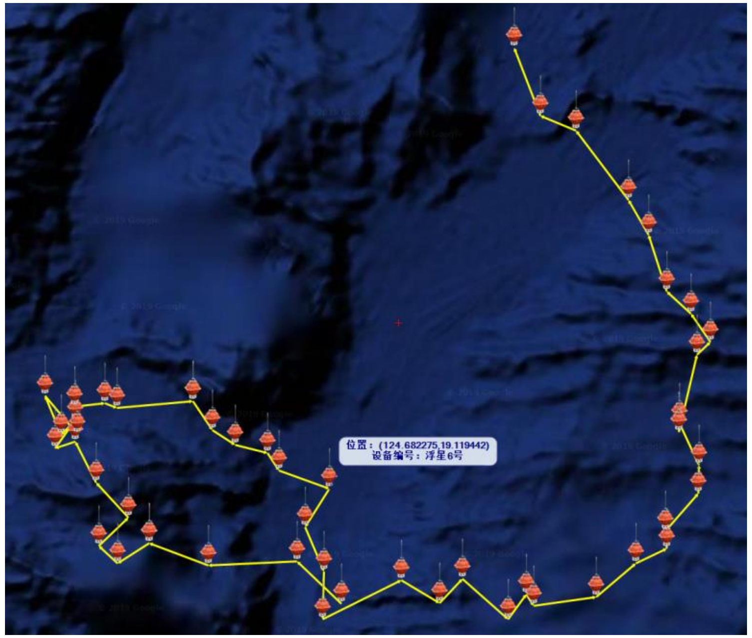


4. Device Application

4000 meters test in Western Pacific



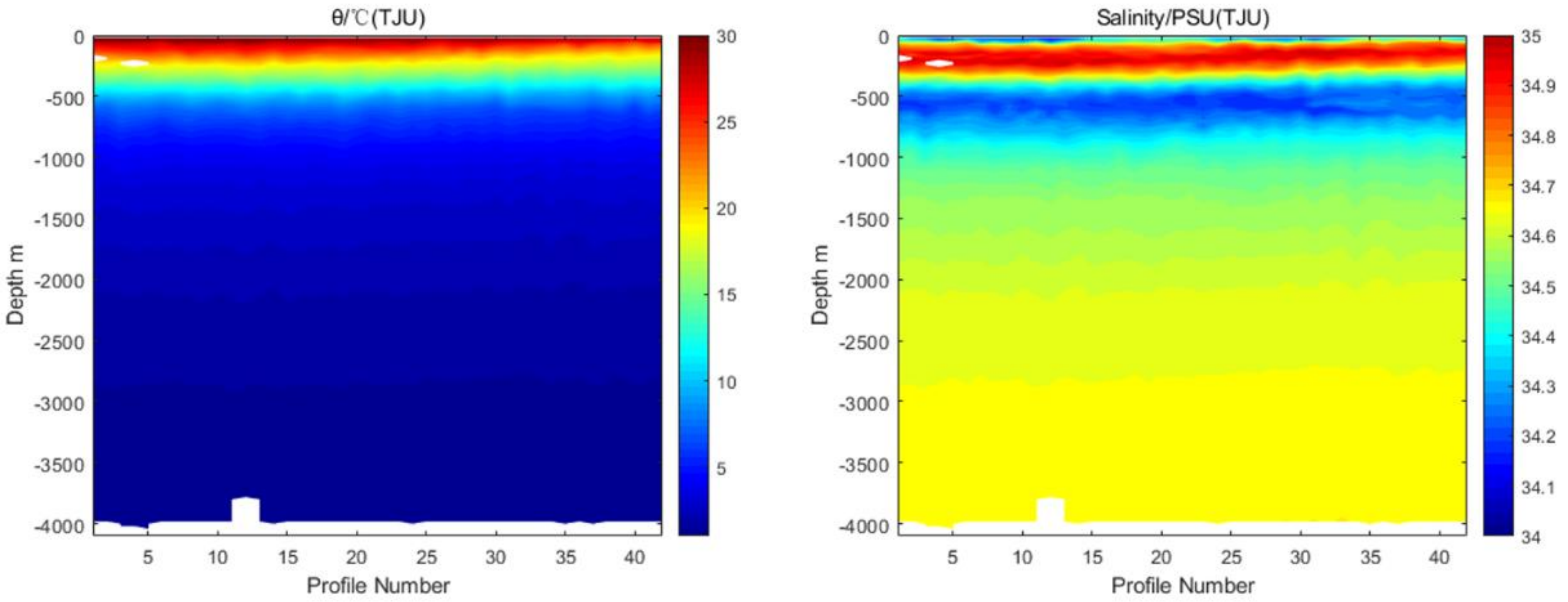
Deep FuXing - 6, which carried a CTD sensor from the National Ocean Technology Center (NOTC), has been deployed. The deployment position is the western Pacific with 5000 meters depth (N19.003888, E124.648790).



From August 8th to September 10th, 48 cycles over 4000 meters has been operated, and the maximum diving depth is 4082.9 meters. Using the CTD sensor, profile data of temperature and salinity are measured.

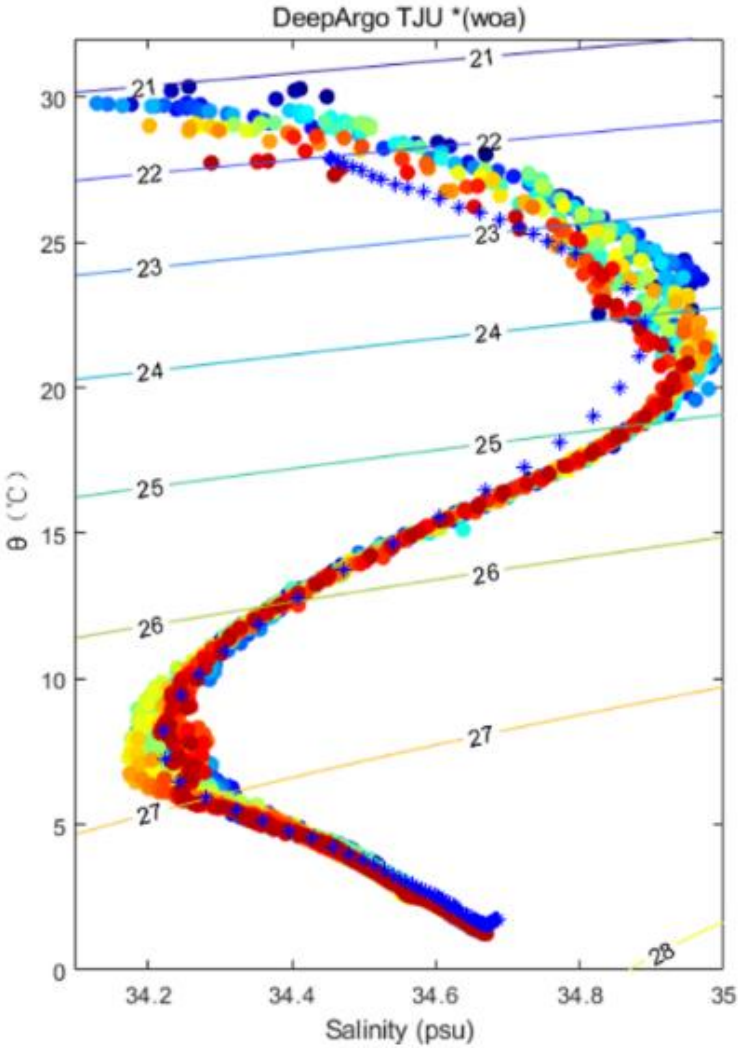
4. Device Application

4000 meters test in Western Pacific



As can be seen from the temperature and salinity heat maps, the temperature and salinity data of 48 profiles aren’t drifting obviously. The temperature and salinity of the data vary greatly in the mixed layer and thermocline layer, but have a good consistency in the gradient layer and deep sea isothermal layer. The range of salinity data also accords with the characteristics of ocean water.

4. Device Application



The temperature is basically consistent with WOA2018, and the salinity is within 0.01PSU compared with WOA2018. The data quality is good and meets the observation requirements of the international Argo plan, which verifies the performance of the buoy in real sea conditions.

Deep FuXing

1. The stage quantitative oil draining control mode can replace the one-time oil draining mode as an optimization scheme for ascent stage. Then the energy consumption model of Depth control process was established to find the Optimal energy consumption control method by Genetic algorithm.
2. Deep Argo is one of the important part for deep sea survey, We will continue to optimize Deep FuXing and look forward to entry into the Argo program.
3. A 6000 meters Deep FuXing has been assembled last quarter, and it will be deployed next year.

That’s all, Thank you.