Yale-NUIST Center on Atmospheric Environment

Variation of Water Temperature and the dominant thermal stratification and vertical mixing process involved in a large，shallow lake

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Outline

- Introduction
- Material and method
- Result and Discussion
- Conclusion
- Further work

Introduction

Part 1:Why concentrating on thermal stratification

1.Temperature is one of the most important environmental conditions of lake which has a great impact on biological decomposition, metabolism and lake biological production. (Wang,1980).

2.In the studies of the temperature distribution in lake, the thermal stratification problem has obtained great attention.

3.Thermal stratification limits the vertical transport of oxygen and other dissolved gases which influences the supply of biological nutrient supply and results uncertainty in studying Lake flux(Nurnberg, G.K.: 1984;Schladow, S.G. and Hamilton, D.P.: 1995);It will trap plankton (such as cyanobacteria) in eutrophic area near surface on sunny days. Thus the risk of the outbreak of water quality problems just increases (JC Patterson et al. 1984;BS Sherman et al.1994;SA Condie et al. 1997;M Bormans et al. 1998). It also affects the release and accumulation of phosphorus, iron, manganese and other elements in the sediment, which affects the chemical properties of Lake water(Courtney D.Giles: 2016).

Part2: Present situation of studies on lake's thermal stratification

1.Being different from many deep lakes which are dimictic, shallow lakes commonly show variation of temperature in diurnal scale.

2.Most studies have focused on the simulation work (DUNCAN E.FARROW:2003; C.R.CHU:2010), analysis on short-term case (N.V.Tuan:2009; ZHAO Qiaohua) , the law of energy change of the internal mechanism(N.R., Samal:2014), upwelling of the vertical circular (Toshiyuki Godo:2001; Franziska P the oschke:2015) and the law of entrainment(A. Chai:1991; N.V.Tuan:2009).

3.Changing pattern of thermal stratification based on long-term data (not less than one year) from large, shallow freshwater lake(just like Taihu) gets less focus.

Part3: Criteria for determining the depth of mixed layer

1.Mixing is considered as an opposite process to stratifying and is used to quantitively determine the extent of it in many researches.

2.Several methods have been designed to determined a proper Hmld(depth of mixed layer).However, each of them has been limited in some certain conditions(Kara A B， 2000).

3.Choosing or designing a criteria to seek Hmld in Taihu must be a meaningful job.

Part4: Influential factors of stratifying-mixing state

1.The thermal stratification process of lake water is affected by water salinity, specific heat, algal blooms, turbidity, water surface heat flux exchange and other meteorological factors.

2.This research also aim to find which factors influence the stratifying-mixing state of Taihu obviously and subsequently summarize how they take their effect based on determining the Hmld.

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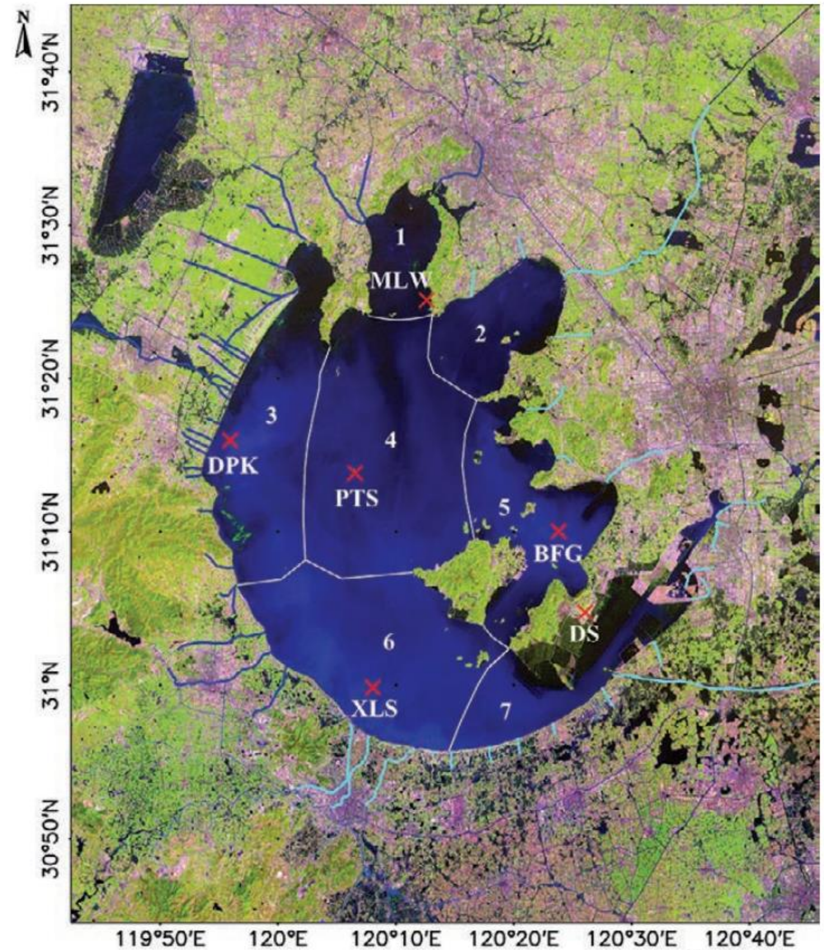
Material and method

Data Source

Site	PTS
Location	31.2323° N/ 120.1086° E (center part)
Period	2015:Jan,April,July, October
Mean Depth	2.8



Observation System

<table>
<tr><th>System</th><th>Instrument</th><th>Data</th></tr>
<tr><td rowspan="3">Campbell EC150</td><td>sonic anemometer/thermometer (model CSAT3 ,Campbell Scientific）</td><td rowspan="6">Air Temperature
Sensible Heat
Latent Heat
Upward Longwave Radiation
Downward Longwave Radiation
Upward Shortwave Radiation
Downward Shortwave Radiation
Wind Speed
Wind Direction
Water Temperature(0.2m,0.5m, 1.0m,1.5m,bottom)</td></tr>
<tr><td>open-path H_2O/CO_2 analyzer</td></tr>
<tr><td>four-way net radiometer (model CNR4， Kipp & Zonen B. V.）</td></tr>
<tr><td rowspan="2">Automatic Weather Station</td><td>anemometer and wind vane (model 05103; R M Young Company）</td></tr>
<tr><td>air temperature and humidity probe (model HMP155A,Vaisala,Inc.）</td></tr>
<tr><td>Water Temperature Chain</td><td>temperature probes (model 109-L, Campbell Scientific)</td></tr>
</table>

Other Data	Source
Weather analysis data	Korea Meteorological Administration(KMA)

Collection System

System	Data Logger	Frequency	Interval
EC System	datalogger (model CR 3000, Campbell Scientific)	10Hz	half-hourly intervals
Other	datalogger (model CR1000, Campbell Scientific)	1Hz	

Quality Control

<table>
<tr><th>Data</th><th>Type of Error</th><th>Processing Method</th></tr>
<tr><td>Sensible Heat</td><td>Abnormal value</td><td>stdTs>0.5|threshold<-50|>100 →NaN</td></tr>
<tr><td>Latent Heat</td><td>Abnormal value</td><td>stdh2o>1.2|threshold<-100|>500 →NaN</td></tr>
<tr><td>Radiation</td><td>Abnormal value</td><td>Downward Shortwave Radiation<5
Downward Shortwave Radiation →NaN
Upward Shortwave Radiation →NaN</td></tr>
<tr><td>Wind Speed</td><td>Missing Value(NaN)</td><td>Interpolation or → NaN</td></tr>
<tr><td>Water Temperature</td><td>Missing Value(-9999)</td><td>Interpolation</td></tr>
</table>

Method

Criteria to get a Hmld can be divided to two main categories: subjective method and objective method. Subjective method mainly ask to artificially determine a ΔT(difference criteria) or a $\Delta\frac{\partial T}{\partial Z}$ (gradient criteria)from surface when objective method commonly refers to curvature criteria which ask to find the largest $\frac{\partial^2 T}{\partial z^2}$ to catch the base of mixed layer.

Table Commonly used ILD and MLD Criteria(cited from Kara A.B,2000)

Temperature–Based Criterion		Density–Based Criterion	
Author	ΔT	Author	$\Delta\sigma_t$
Thompson [1976]	SST–0.2°C	*Miller* [1976]	$0.125\,\sigma_t$
Lamb [1984]	SST–1.0°C	*Levitus* [1982]	$0.125\,\sigma_t$
Price et al. [1986]	SST–0.5°C	*Lewis et al.* [1990]	$0.13\,\sigma_t$
Kelly and Qiu [1995]	SST–0.5°C	*Spall* [1991]	$0.125\,\sigma_t$
Martin [1985]	SST–0.1°C	*Sprintall and Tomczak* [1992]	$0.5\,(\partial\sigma_t/\partial T)$
Wagner [1996]	SST–1.0°C	*Huang and Russell* [1994]	$0.125\,\sigma_t$
Obata et al. [1996]	SST–0.5°C	*Ohlmann et al.* [1996]	$0.5\,(\partial\sigma_t/\partial T)$
Monterey and Levitus [1997]	SST–0.5°C	*Monterey and Levitus* [1997]	$0.5\,(\partial\sigma_t/\partial T)$

Due to a low salinity in Taihu, ILD and MLD can be regarded as identical value. Thus merely using water temperature is enough to seek a Hmld.

In order to match the observation system which has only 5 layers in Taihu. Objective method is not chosen due to its high demand on vertical resolution. Nor the maximum angle method(Peter C.,2011).

Kara's subject method is taken to determine the Hmld in Taihu. Here is the flow chart of it.

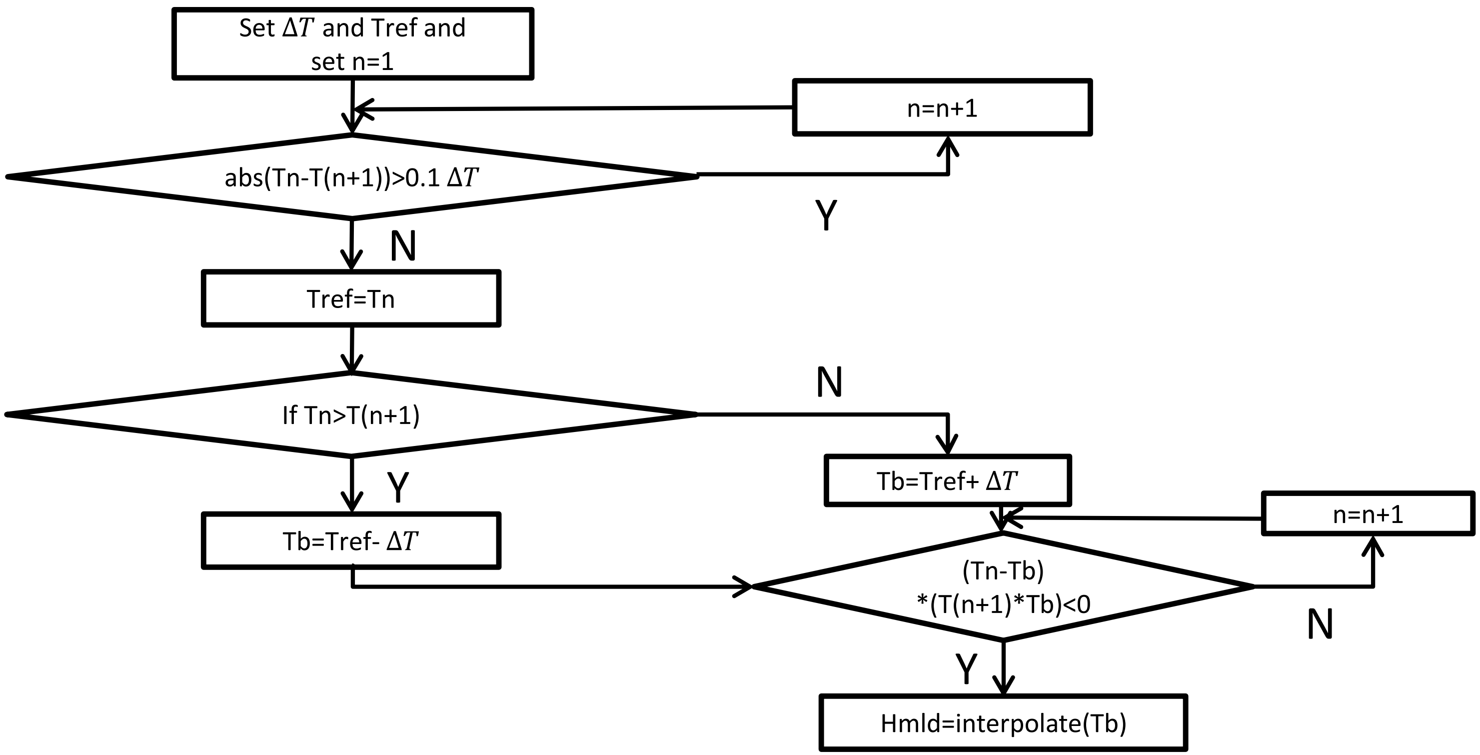


Fig 1. Flow Chart of Kara's subject method

If no suitable pair of Tn and T(n+1) is found in the first loop, the original value of Tref near the surface should be used. If no suitable Tb is found, The whole layer should be considered as mixed layer.

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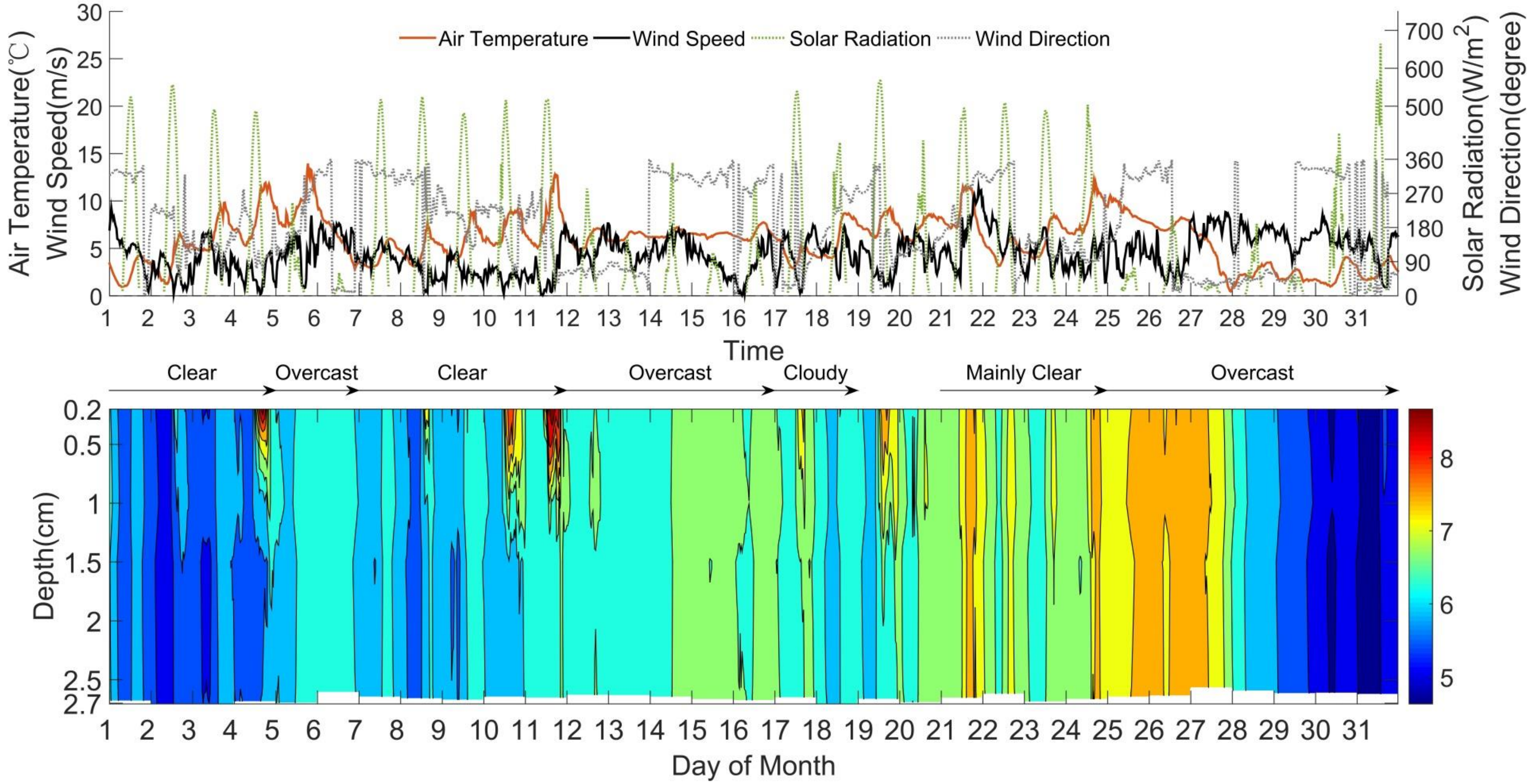
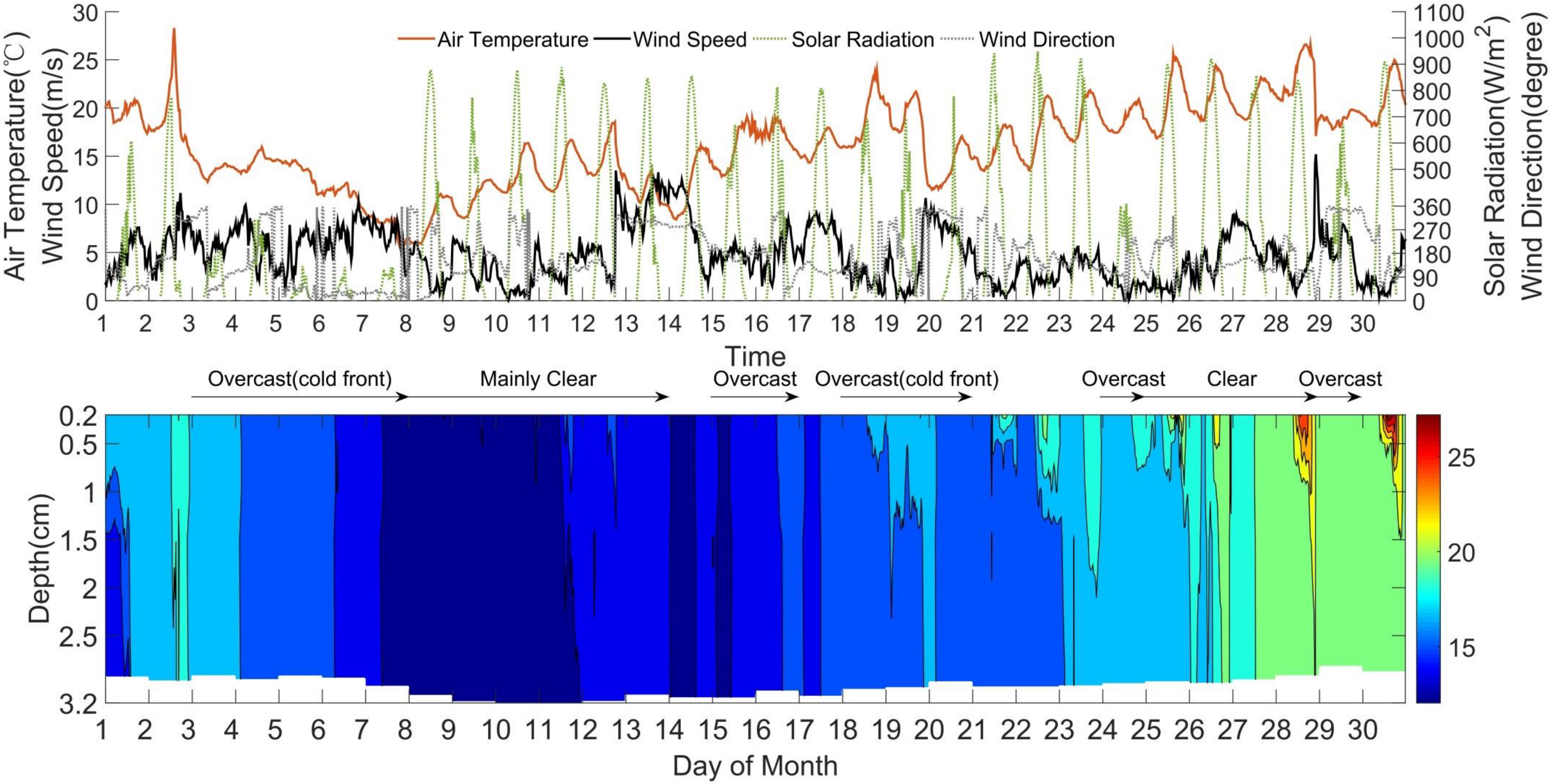
Result and Discussion

Part 1:Seasonal variation characteristics of water temperature

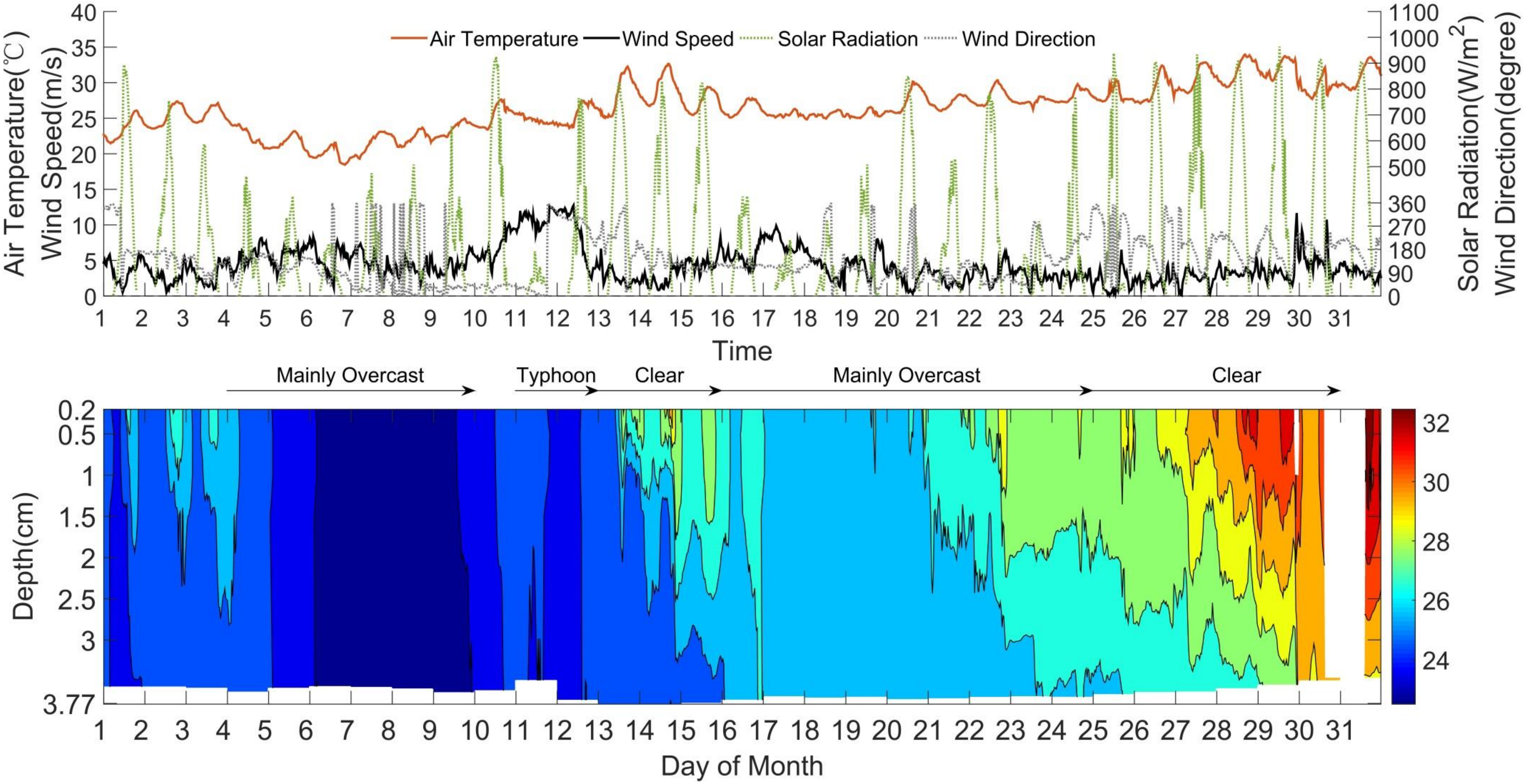


a



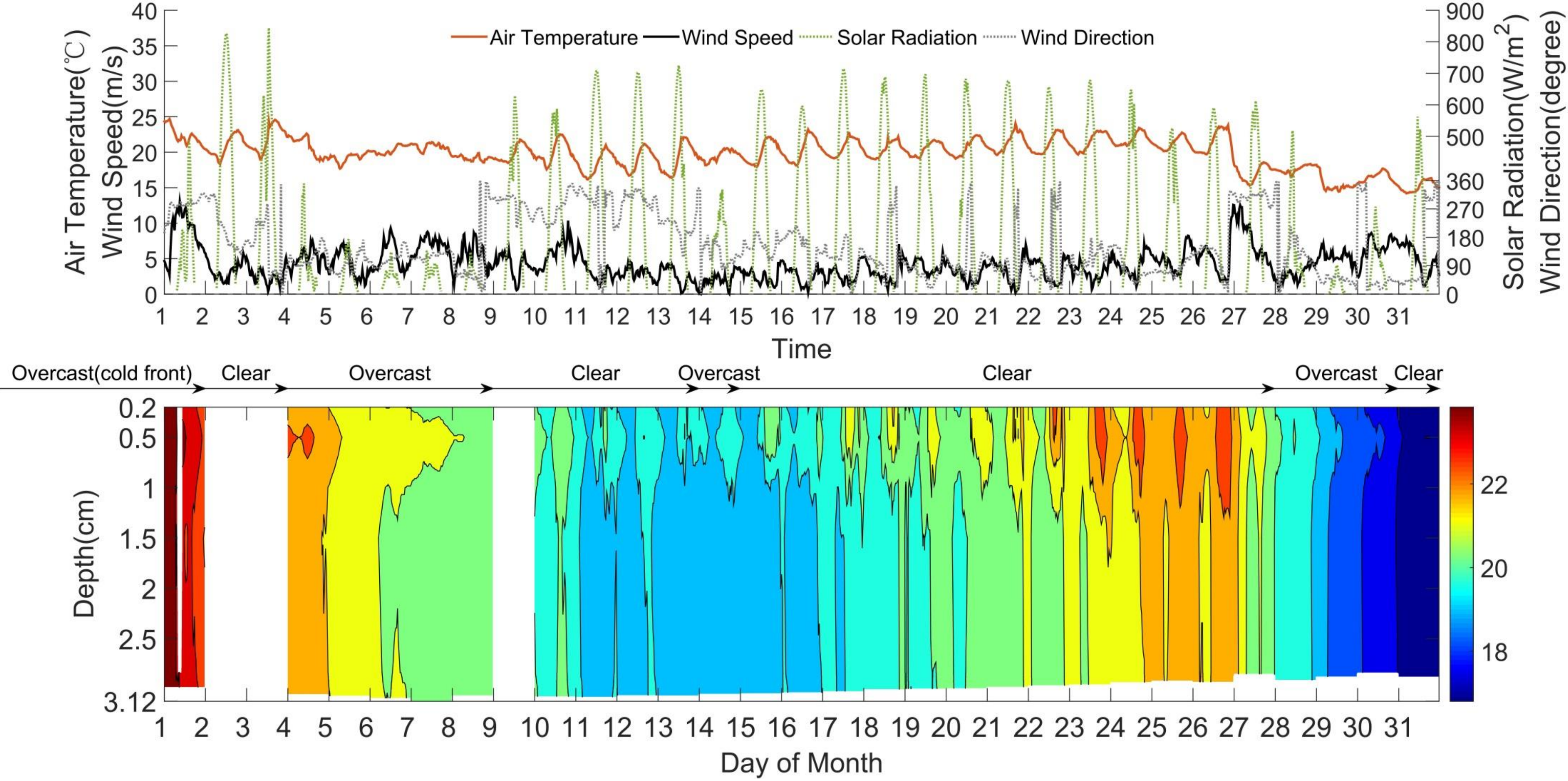
Air Temperature
Wind Speed
Solar Radiation
Wind Direction
Air Temperature(℃)
Wind Speed(m/s)
Solar Radiation(W/m2)
Wind Direction(degree)
Time
Overcast(cold front)
Mainly Clear
Overcast
Overcast(cold front)
Overcast
Clear
Overcast
Depth(cm)
Day of Month

b



Air Temperature
Wind Speed
Solar Radiation
Wind Direction
Air Temperature(℃)
Wind Speed(m/s)
Solar Radiation(W/m2)
Wind Direction(degree)
Time
Mainly Overcast
Typhoon
Clear
Mainly Overcast
Clear
Depth(cm)
Day of Month

c



d

Fig 2. variation characteristics of water temperature in **a.** January which represents Winter, **b.** April which represents Spring, **c.** July which represents Summer and **d.** October which represents fall. They are coupled with basic Meteorological elements which include air temperature, wind speed, wind direction and solar radiation.

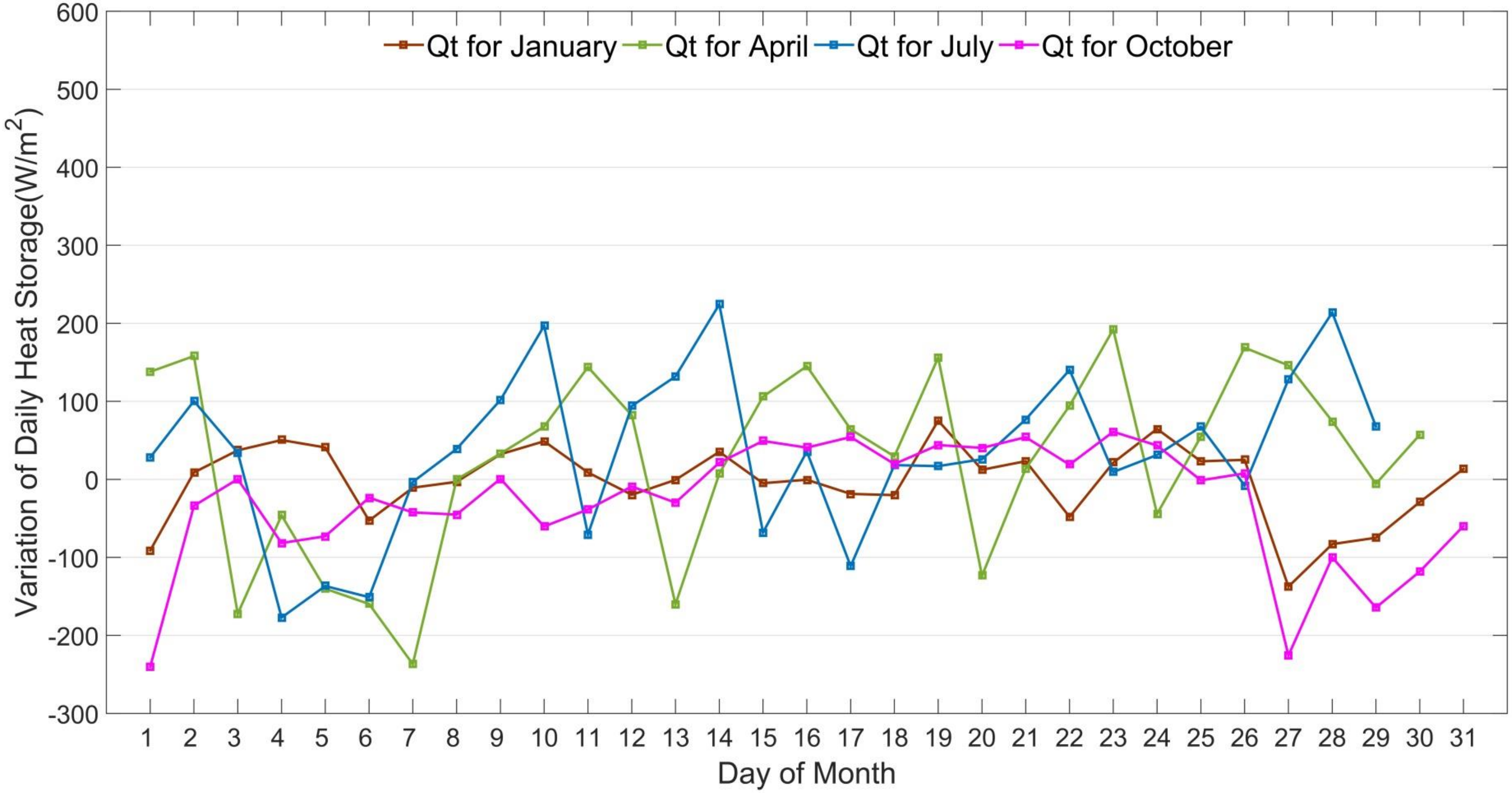
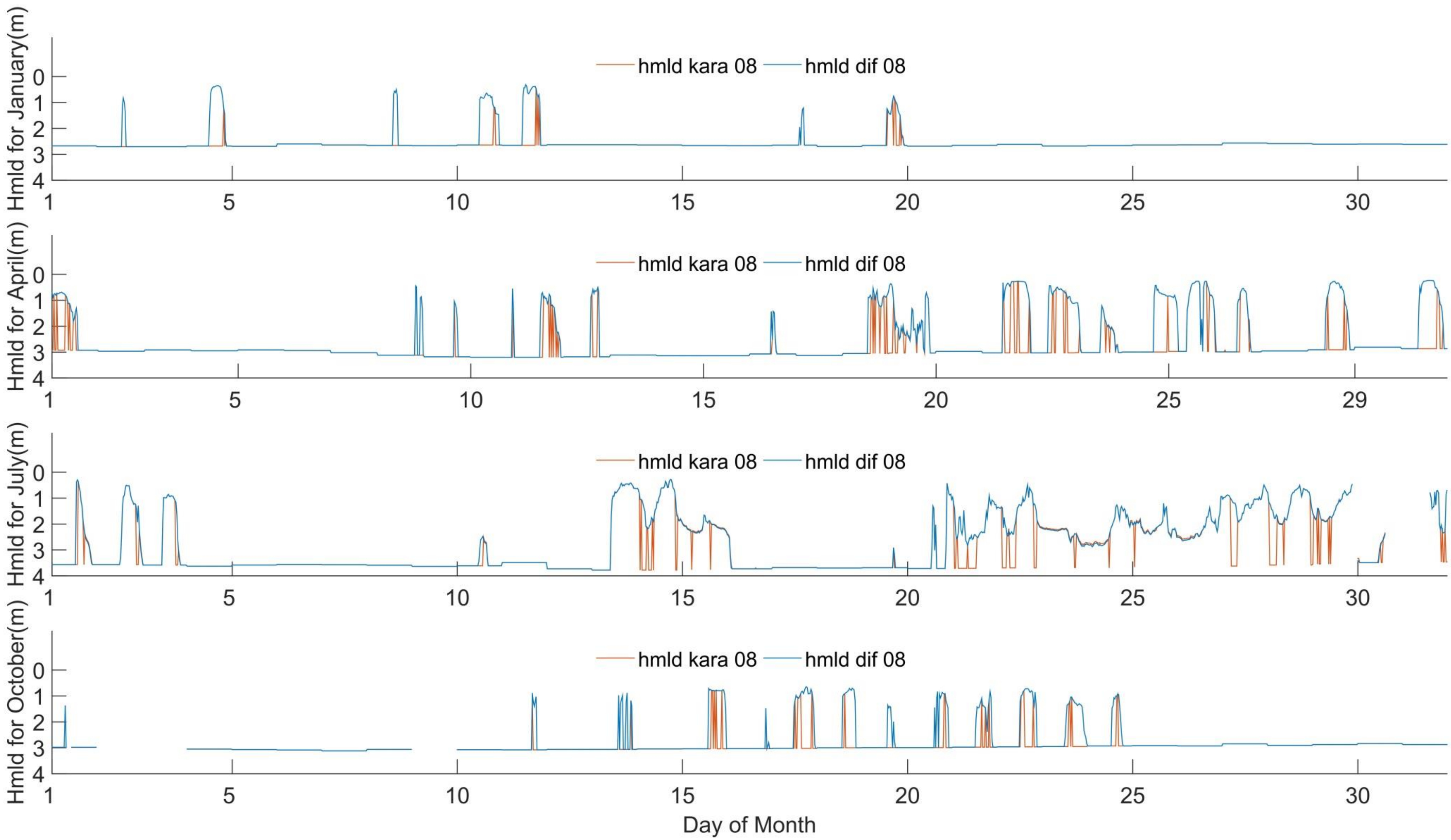


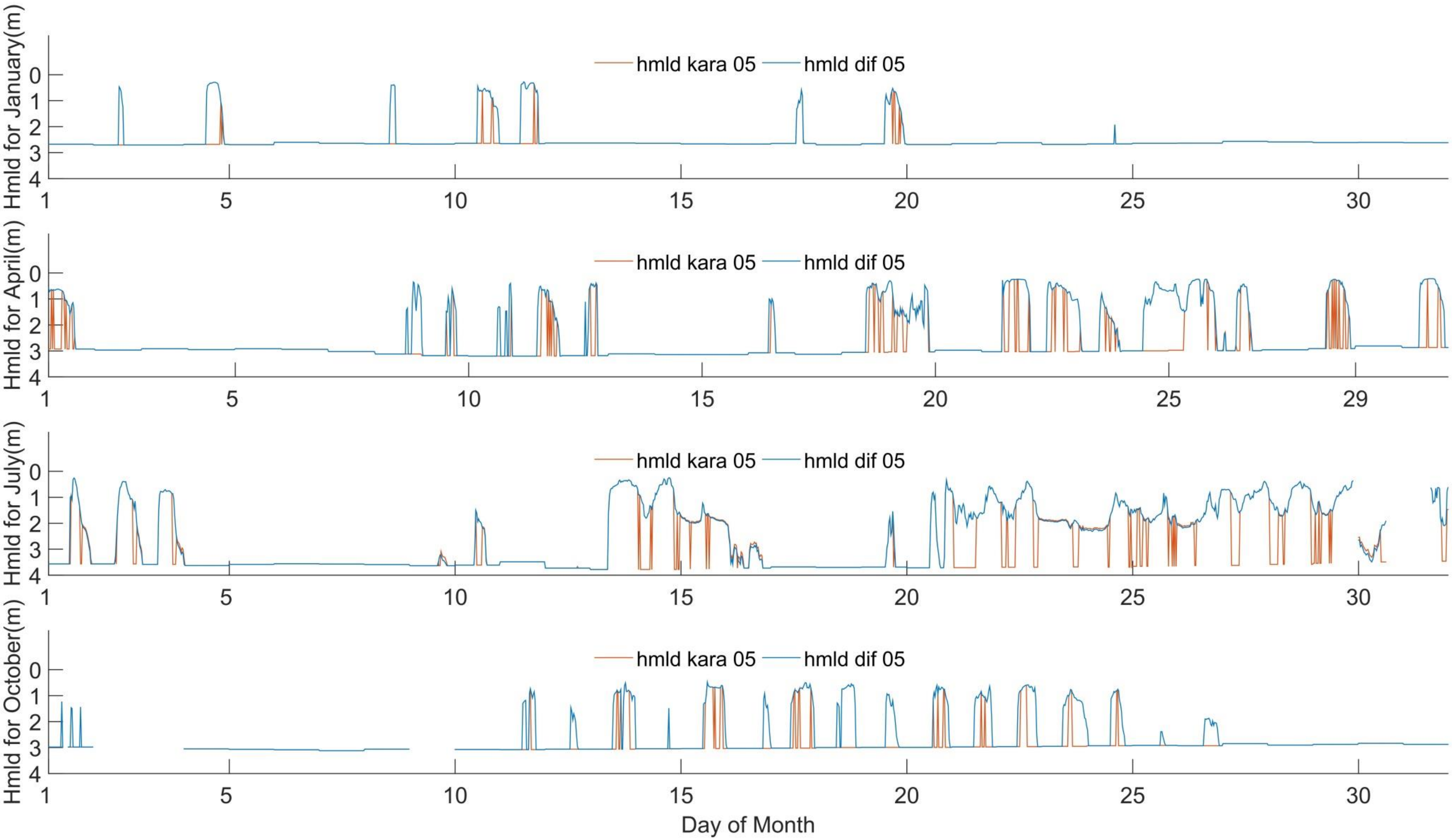
Fig 3. Variation of daily heat storage for four seasons.

Part 2:Discussing the method for searching Hmld in Taihu

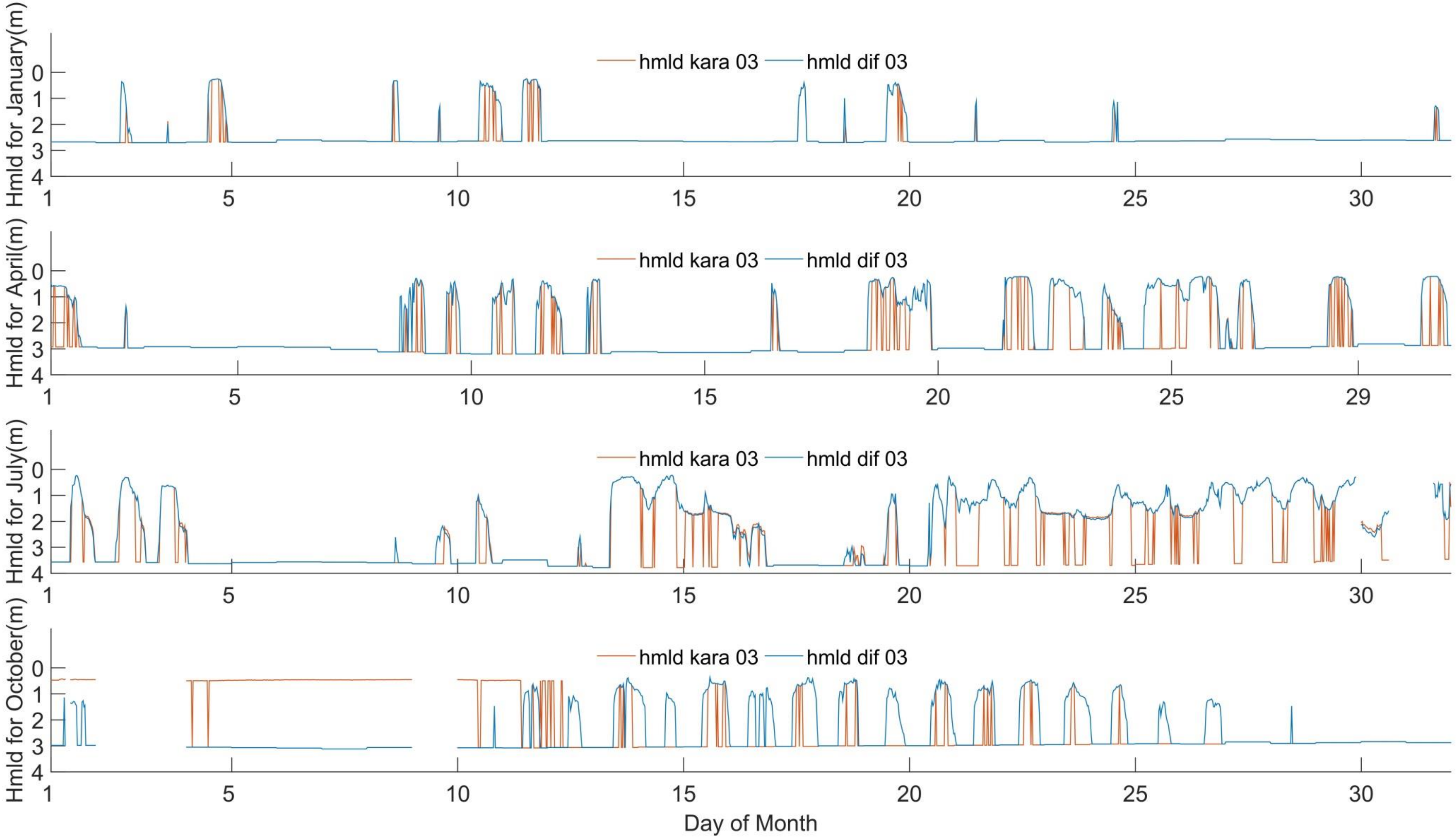
Method	Criteria	Advantages
Kara's definition (introduced in Material and method section)	ΔT=0.8,0.5,0.3	1.Good at handle the problem of inversion layer and cool skin phenomenon. 2.Good at fitting into system with low vertical resolution of water temperature.
Improved difference method (Tb=Ts-ΔT, interpolant is also used in improving this traditional method)	ΔT=0.8,0.5,0.3	Good at fitting into system with low vertical resolution of water temperature after improving it.


Hmld for January(m)
hmld kara 08
hmld dif 08
Hmld for April(m)
hmld kara 08
hmld dif 08
Hmld for July(m)
hmld kara 08
hmld dif 08
Hmld for October(m)
hmld kara 08
hmld dif 08
Day of Month

a


hmld kara 05
hmld dif 05
Hmld for January(m)
Hmld for April(m)
Hmld for July(m)
Hmld for October(m)
Day of Month

b



c

Fig 4. Comparison between two chosen methods when searching Hmld in four seasons. **a**, **b**, **c** are when ΔT is 0.8, 0.5, 0.3, respectively.

1.The Hmld from Kara's method lack continuity when compared with improved difference method. This difference is more obvious when ΔT gets lower.
2.When ΔT=0.3, Kara's method shows strong stratification from October 4th to 8th whereas the other one gets mixed layer to bottom.

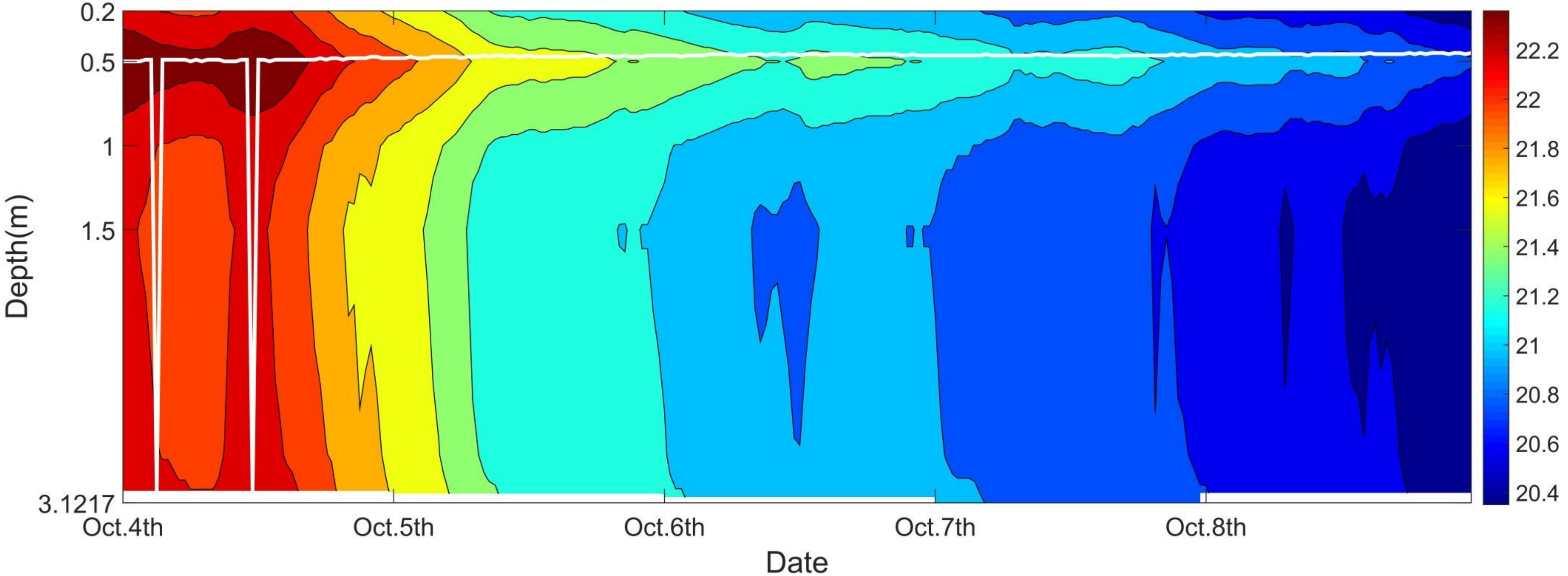


Fig 5. Water temperature and Hmld from October 4th to 8th. It can be seen that the low Hmld which indicates seemingly stratification is due to the algorithm in Kara's method to handle inversion layer.

It’s reasonable to select the improved difference method to search Hmld in Taihu’s observation system since Kara’s method shows poor consequence because of finding a strong stratification in overcast day and the lack of continuity.

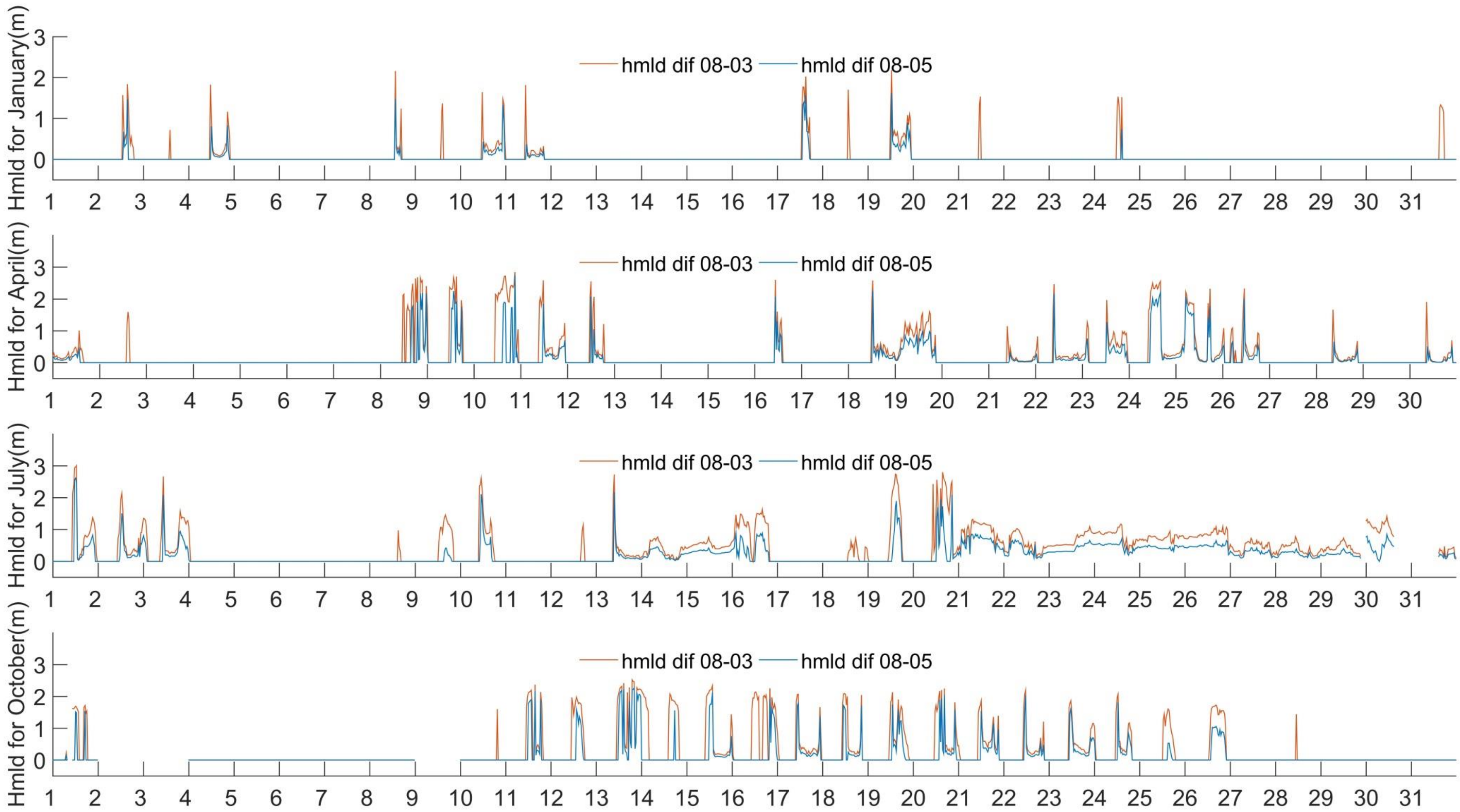


Fig 6. Comparison of using different ΔT in improved difference method.

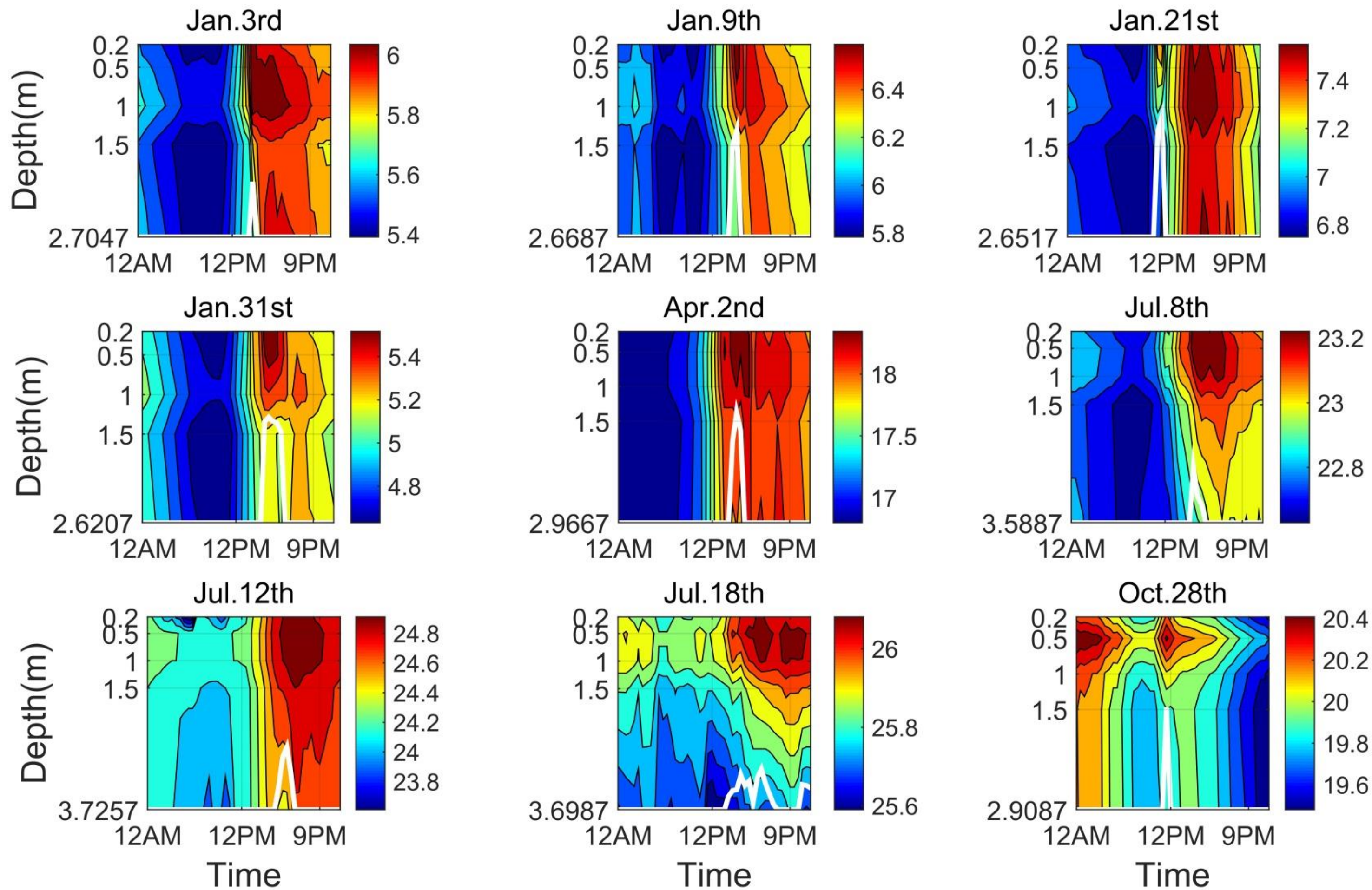


Fig 6. The daily characteristic of the dates when using ΔT=0.3 results in unique stratification

It's reasonable to select the ΔT=0.3 in improved difference method to search Hmld in Taihu's observation system and apply it to further works.

Part 3:Analyzing how the most influential factors take their effect on the stratifying-mixing process

Based on the general characteristic of water temperature and thermal stratification combined with different elements such as solar radiation, air temperature, heat flux, wind speed and wind direction and a reliable way of determining Hmld, it’s necessary to quantitively analyzing the relationship between these factors and the stratifying-mixing process, as well as the law behind it.

The analysis on a case

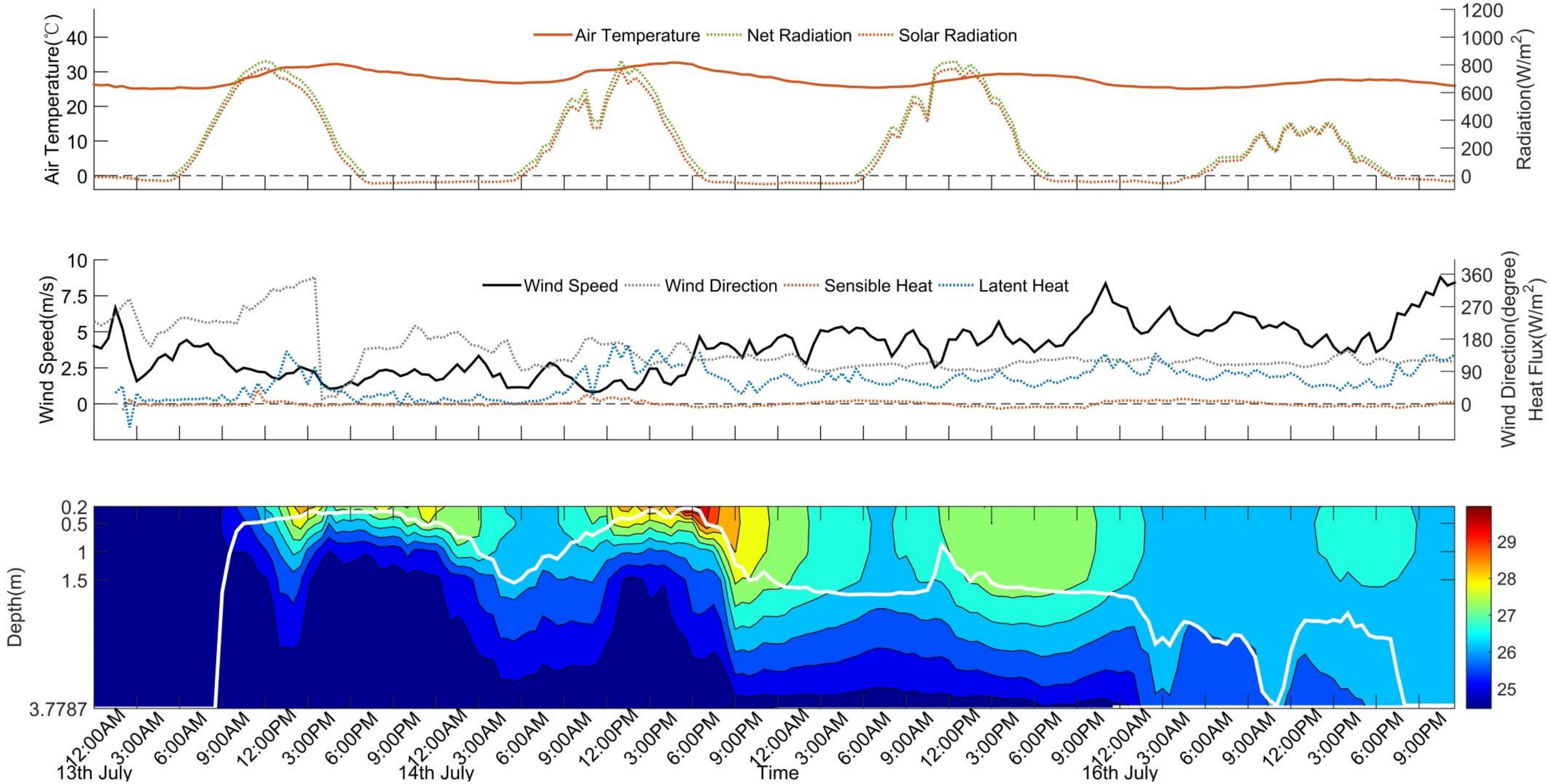


Fig 6. The water temperature, heat flux, radiation, air temperature, wind speed, wind direction and calculated Hmld from Jul.13 to Jul.16.

The analysis on different types of wind speed&solar radiation

Element	Season	Threshold(average value)
Solar radiation	Spring	344.58 W/m^2
	Summer	297.38 W/m^2
	Fall	276.92 W/m^2
	Winter	193.92 W/m^2
Wind speed	Spring	4.71 m/s
	Summer	4.27 m/s
	Fall	4.18 m/s
	Winter	4.38 m/s

Number of Days	Strong&Strong	Strong&Weak	Weak&Strong	Weak&Weak
Spring(30)	6	10	8	6
Summer(28)	3	10	9	6
Fall(27)	4	13	7	3
Winter(31)	6	12	10	3

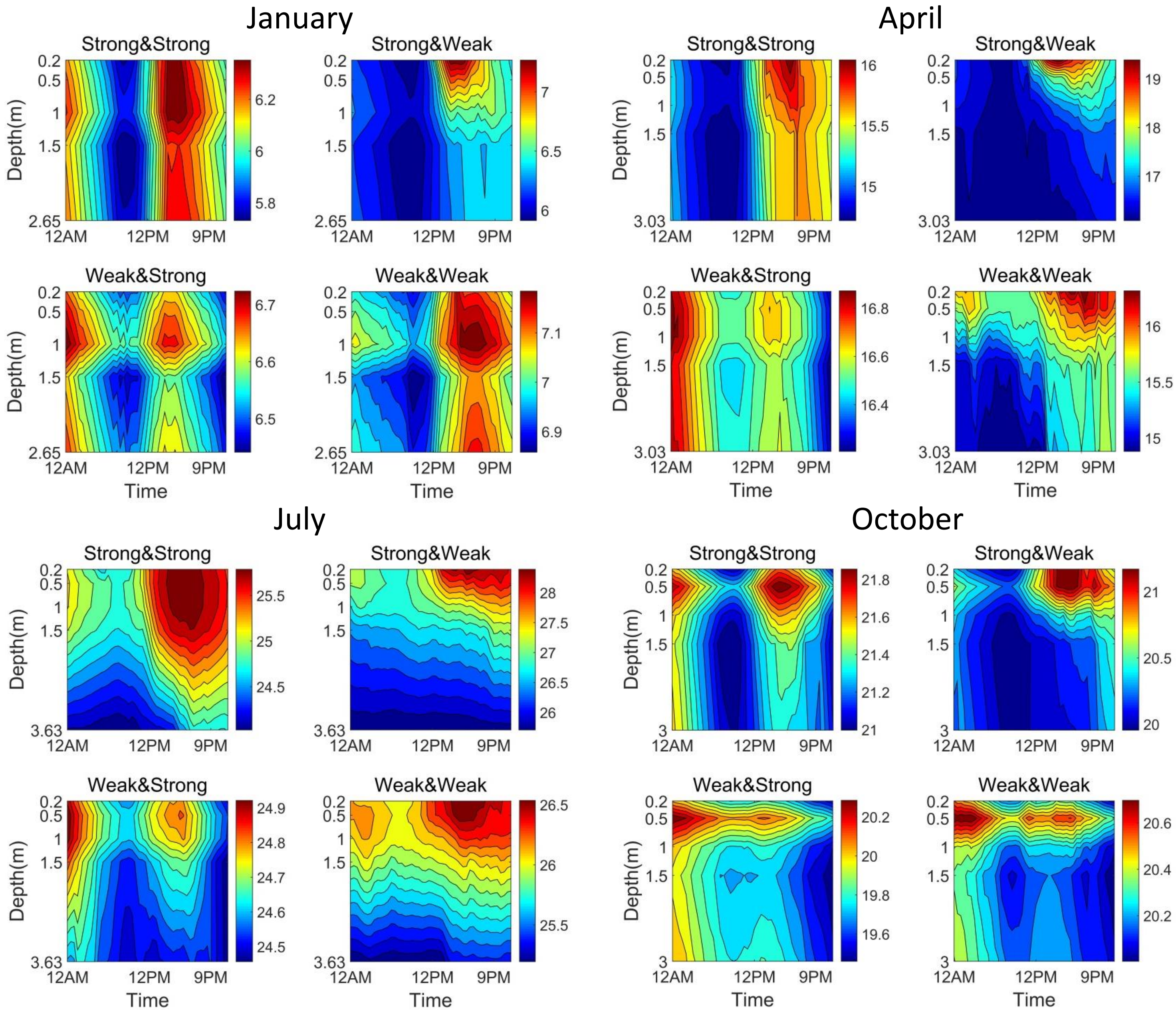


Fig 7. The diurnal variation of water temperature under the condition of different types of solar radiation and wind speed in four seasons.

The law of how solar radiation and wind speed affect Hmld

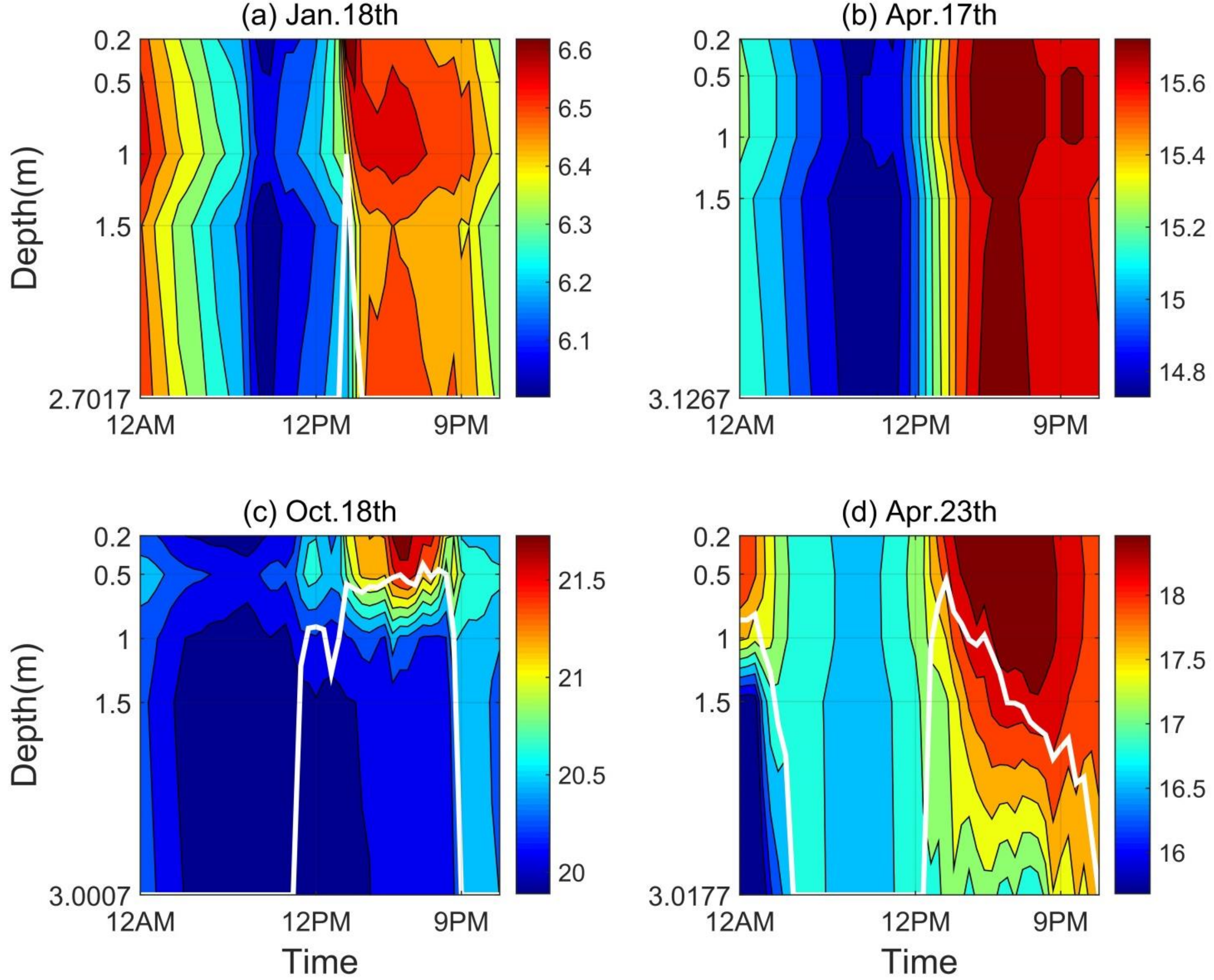


Fig 7. Four typical daily characteristics of diurnal variation of water temperature. **a.** sudden overturning in daytime. **b.** mixing during the whole day. **c.** sudden overturning at night. **d.** stratification disappears slowly without sudden overturning.

Date	Mean Daily Solar Radiation(W/m²)	Mean Daily Wind Speed(W/m²)	Mean Daily Hmld (m)	Mean Daily Relative Hmld (%)	Start Time of Stratification	End Time of Stratification	Hmld Before Sudden Overturning	Wind Speed During Overturning
1.2	321.322	2.41941	2.01179	74.3547	12.5	19	NaN	NaN
1.3	258.648	4.56741	2.67205	98.7942	13.5	14.5	1.987	4.083
1.4	278.593	1.79932	1.29433	48.248	11	22	NaN	NaN
1.8	296.285	2.37127	1.97322	74.2463	13	17	0.3454	2.177
1.9	276.736	2.84318	2.55332	95.6778	13.5	15	1.303	2.906
1.10	282.726	1.82967	1.32805	50.2353	11	24	1.308	2.41
1.11	298.959	1.05909	1.08101	40.7671	10	20.5	0.6623	6.367
1.17	305.678	3.13164	1.90468	71.9109	12.5	17.5	0.5759	5.148
1.18	201.728	4.72011	2.59397	96.0138	13	14.5	1	4.853
1.19	336.159	2.04764	1.56237	58.699	11.5	23	1.704	5.427
1.21	275.523	5.30117	2.52625	95.2703	10.5	12	1.115	8.29
1.24	242.009	3.61465	2.38132	89.4335	11.5	15	1.143	5.033
1.31	274.644	3.23823	2.33388	89.0565	14.5	17.5	1.47	4.927
4.1	268.661	5.35023	1.69133	57.8298	0	16	NaN	NaN
4.2	299.79	6.89223	2.80904	94.6867	13.5	15.5	1.633	9.68
4.8	481.916	2.41133	2.1977	70.5143	11	24.5	0.7093	6.505
4.9	308.197	3.54419	1.98001	62.1927	11	18.5	1.589	3.4
4.10	420.511	0.790111	1.85719	58.0976	10.5	23	0.7614	5.361
4.11	469.969	3.03318	1.46561	45.7764	9	23	1.959	5.612
4.12	473.401	4.20326	1.88642	59.309	11	19	0.3607	12.33
4.16	354.881	5.10621	2.51019	81.7208	10	14.5	NaN	NaN
4.18	313.525	2.39375	1.67094	54.719	11.5	NaN	NaN	NaN
4.19	264.08	1.12072	1.07691	35.4637	NaN	21	1.423	9.45
4.21	485.159	1.62857	1.19639	39.5024	9	25.5	1.069	3.238
4.22	528.778	2.34654	1.12024	36.9879	8.5	27.5	1.919	3.945
4.23	507.464	4.183	2.06886	68.5581	12	23.5	NaN	NaN
4.24	204.939	1.44921	1.36502	45.597	9.5	NaN	NaN	NaN
4.25	499.04	1.33896	0.554142	18.6287	NaN	25	NaN	NaN
4.26	539.079	4.01204	1.58158	52.9016	9.5	19	NaN	NaN
4.28	481.113	2.67971	0.952498	32.7131	8	21.5	1.527	14.19
4.30	530.953	1.54993	0.864909	30.1292	8	22	1.265	6.494
7.1	386.385	2.67093	1.94512	54.5668	10	23.5	NaN	NaN
7.2	325.879	2.04966	1.84732	51.8084	10	26.5	NaN	NaN
7.3	254.568	2.26363	1.68996	47.1967	8.5	25	NaN	NaN
7.8	198.456	3.82397	3.52825	98.3164	14.5	16.5	NaN	NaN
7.9	216.912	4.00655	3.09441	85.1595	12	20.5	2.987	6.169
7.10	448.434	6.63107	2.59802	71.9539	9.5	18.5	NaN	NaN
7.12	300.109	8.36132	3.61144	96.9342	15.5	18	NaN	NaN
7.13	450.296	2.4778	1.35448	35.8454	6	NaN	NaN	NaN
7.14	394.408	1.89487	0.702422	18.599	0	23.5	NaN	NaN
7.15	424.257	4.36847	1.58791	42.1906	0	23.5	NaN	NaN
7.16	200.715	4.9211	2.60466	69.9301	NaN	20	2.547	6.16

Date	Mean Daily Solar Radiation(W/m²)	Mean Daily Wind Speed(W/m²)	Mean Daily Hmld (m)	Mean Daily Relative Hmld (%)	Start Time of Stratification	End Time of Stratification	Hmld Before Sudden Overturning	Wind Speed During Overturning
7.18	95.9596	3.54875	3.52622	95.3377	13	19.5	NaN	NaN
7.19	180.151	4.65145	2.72297	73.8198	10.5	18.5	1.438	7.982
7.20	446.488	1.92883	2.29222	61.6575	9.5	NaN	NaN	NaN
7.21	251.326	2.02507	1.17334	31.6463	0	23.5	NaN	NaN
7.22	421.274	2.91479	0.869347	23.5553	0	23.5	NaN	NaN
7.23	108.947	2.74775	1.70879	46.4009	0	23.5	NaN	NaN
7.24	227.589	2.85666	1.32925	36.0263	0	23.5	NaN	NaN
7.25	300.797	1.80659	1.35194	36.9719	0	23.5	NaN	NaN
7.26	403.386	2.18583	1.3171	36.2772	0	23.5	NaN	NaN
7.27	424.684	2.82683	0.846177	23.345	0	23.5	NaN	NaN
7.28	532.476	3.28386	0.809406	22.5797	0	23.5	NaN	NaN
10.11	411.538	2.47492	1.96054	63.7022	10.5	20	1.31	3.241
10.12	394.129	3.32148	2.16344	70.6853	10.5	18	NaN	NaN
10.13	375.719	2.26428	1.79756	58.6736	10.5	28	NaN	NaN
10.14	176.241	1.84552	2.44719	80.3235	14	20	1.5	3.034
10.15	370.588	2.22228	1.47933	48.6354	9.5	25	0.5156	4.62
10.16	331.759	1.8648	2.08246	68.6676	10	25	NaN	NaN
10.17	407.252	2.30516	1.44506	47.8391	9.5	23.5	1.222	5.13
10.18	387.09	2.11424	1.56054	52.0066	10	21	0.9592	4.861
10.19	371.388	3.78733	1.97471	65.941	11	22	NaN	NaN
10.20	346.839	2.15804	1.80479	60.3273	11	25	1.182	4.912
10.21	377.131	2.2792	1.67183	56.1456	10	21.5	1.329	4.816
10.22	354.334	2.40048	1.4834	50.0697	10	21.5	1.007	4.823
10.23	380.104	2.71488	1.66813	56.4767	11	25	NaN	NaN
10.24	315.151	2.983	1.7666	60.2796	11	20	2.043	6.4
10.25	287.784	3.74222	2.32695	79.8086	12	19	NaN	NaN
10.26	333.355	4.43078	2.27812	77.7869	12.5	22	1.914	9.9
10.28	169.963	2.65665	2.84614	97.8504	10.5	11.5	NaN	NaN

This table doesn't include these cases which keep mixed layer to bottom during the whole day. Notice that sometimes a strong stratification could last for more than one day due to a slow mixing at night and a heating up by solar energy in another day. This is more obvious in Summer.

Since solar radiation influences Hmld greatly at daytime whereas the vertical convection take part in the mixing process at night when there is no shortwave radiation. The discussion should be divided into two categories according to the time.

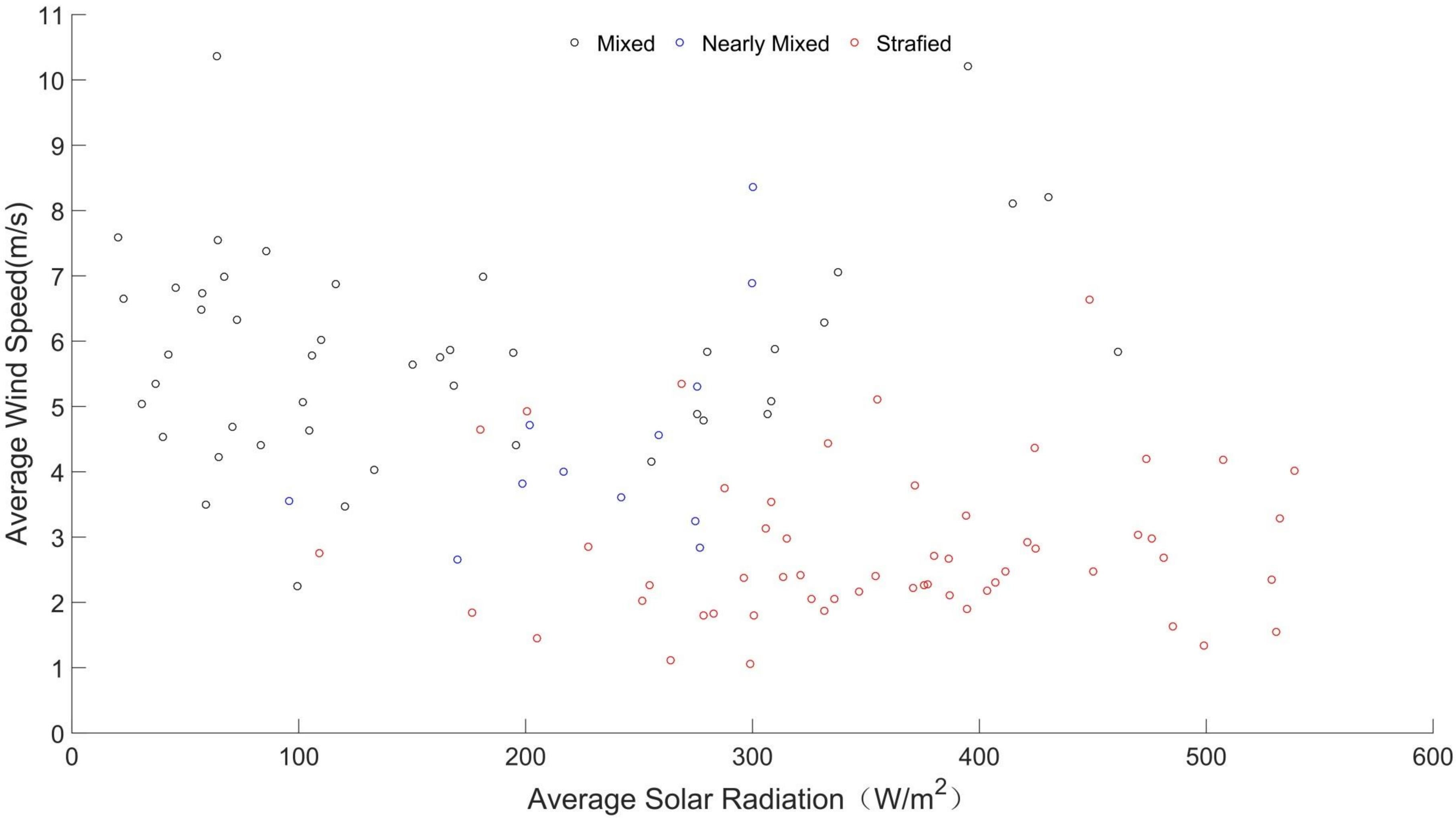


Fig 7. The distribution of different sates of stratifying-mixing process in daytime. Black points represent the whole mixing condition(relative Hmld=100%), blue points represent states that 85%<=relative Hmld<100% and red points represent stratification that Hmld<85%.

It can be seen that at daytime, the higher the solar radiation, the stronger the wind speed needed to mix up the lake. For a commonly clear day with a mean solar radiation equal to $300W/m^2$, the threshold of wind speed may be 4m/s. This value may exceed 5m/s in summer when water body is intensively heated up by solar radiation and may also be less than 3m/s in Winter.

Number of Days	Whole Mixing	Stratification	Overturning in Daytime	Lowest Wind Speed for Overturning at Night
Spring(30)	12	18	0	3.238m/s
Summer(28)	6	22	0	6.16m/s
Fall(27)	10	17	0	3.034m/s
Winter(31)	18	13	5	2.177m/s

1.The overturning in daytime only appears in winter all of which break relatively weak stratification. The wind speed needed to overturn in daytime (munimum=2.906m/s) is larger than that at night.
2.Whole mixing is less likely to emerge in summer and more frequent in winter.
3.The largest wind speed needed to break stratification at night appears in summer and the weakest wind needed is in winter.

Conclusion

1. Obvious thermal stratification commonly appears in clear days. However, the water body always gets mixed during cold front passage, typhoon when a strong wind exists. The mixing state also appears in other overcast days.
2. The improved difference method has better performance when being used in Taihu's environment than Kara's method which lacks continuity in determining Hmld and gets unacceptable values when there is a inversion of temperature. The improved method is more acute in catching weak stratification when take 0.3 as ΔT .
3. Being the most important meteorological elements in affecting the stratifying-mixing process, solar radiation and wind speed have totally opposite impacts.

4. In daytime, the stronger the solar radiation, the larger the wind speed is required to mix up the whole water body.
5. Sudden overturning appears mainly at night. It is less strict for wind to broke an existed stratification during daytime than that at night when the lowest value of wind speed required to mix up the whole water body is 3.238m/s, 6.16m/s, 3.034m/s and 2.177m/s in Spring, Summer, Fall and Winter, respectively.

Further Work

1. Compare the same characteristics between Taihu and others lakes that are different in salinity, turbidity, water depth or biochemical environment.
2. Compare more methods for calculating Hmld from other studies or models and evaluate the consequences.
3. More quantitively analyze the relationship between meteorological elements and Hmld.

Thank You