Yale-NUIST Center on Atmospheric Environment

Variations and Mechanism of Thermal Stratification in a Eutrophic Lake

富营养化湖泊热力分层规律和机理的研究

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OUTLINE

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- **Research Progress**
- **Research Contents**
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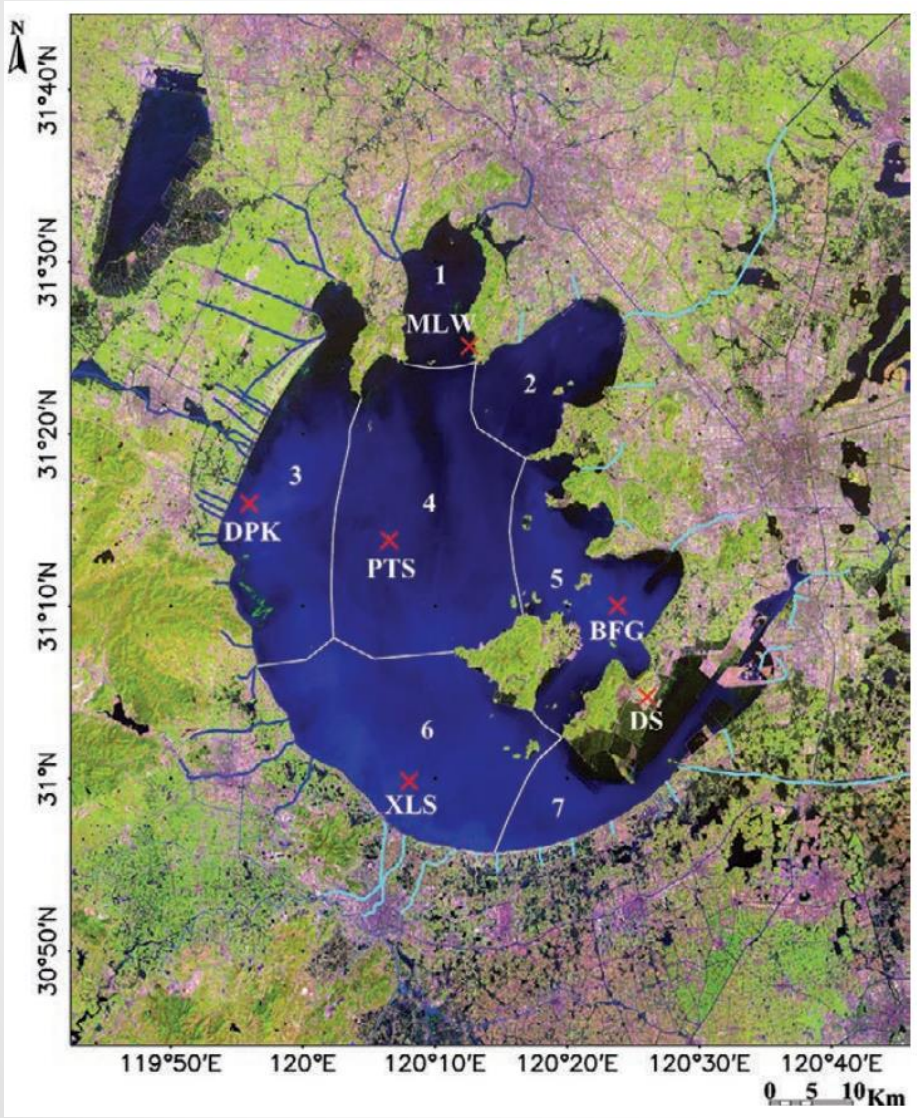
BACKGROUND

The phenomenon of thermal stratification in the body of a lake has attracted widespread attention.

1. Thermal stratification is a stable state that circumscribes the vertical convection, limiting the supply of nutrients and altering the chemical property of lakes.
2. The thermal structure of a lake not only indicates the response of the lake to atmospheric forcing, but also plays an important role in changing the local climate. It can be a useful variable for improving numerical weather forecasts.
3. By trapping planktons in the surface layer where sunlight is abundant, the risk of water quality problems is increased. Thermal stratification is a reliable predictor of algae bloom, especially in eutrophic lakes.

BACKGROUND



1. Lake Taihu is located in the urban agglomeration in the Yangtze River Delta.
2. The surrounding administrative units, Jiangsu, Zhejiang, Anhui, and Shanghai are all intensively urbanized areas.
3. Lake Taihu is not only an important source of water and food supply, but also affects the surrounding weather.
4. However, Lake Taihu is super eutrophic, with nearly annual algae events. Studying the thermal stratification in Lake Taihu helps the water pollution treatment and water resource management.

RESEARCH PROGRESS

1. The geographical position and the depth of a lake determine its thermal structure. Simultaneously, thermal stratification is influenced by several external factors: salinity, specific heat, algal blooms, turbidity, heat flux and meteorological elements.
2. As for most deep lakes in the temperate zone, greater heat storage leads to sustained stability, which causes the temperature to vary over a long cycle. Dominated by the seasonal variation of solar radiation, deep lakes are classified as dimictic type and the warm monomictic type.
3. In shallow lakes, the heat storage is not large enough to maintain thermal stratification for more than 24 hours, which leads rapid changes in daily scale. External factors become more influential. The pattern of stratification in shallow lakes must have particular characteristics.

RESEARCH PROGRESS

4. To date, studies of thermal stratification and the relevant physical and chemical processes in deep lakes are relatively mature.
5. Current research on similar topics in shallow water involve mainly model simulations, analyses of short-term cases and research on mechanisms related to internal waves, the vertical circulation that emerges during upwelling, and the entrainment law in mixing lakes.
6. However, studies based on long-term data (longer than one year) to characterize features of thermal stratification in eutrophic, shallow lakes are still limited.

RESEARCH PROGRESS

7. It is important to quantify the strength of stratification by determining the mixed layer depth (MLD).
8. Two practical techniques for MLD determination are used: the subjective method and the objective method. The former commonly involves the difference criterion ($\Delta \mathbf{T}$ ($\Delta \boldsymbol{\rho}$)) and the gradient criterion ($\frac{\partial \mathbf{T}}{\partial \mathbf{z}}$ ($\frac{\partial \boldsymbol{\rho}}{\partial \mathbf{z}}$)), which is effective but empirical. The latter commonly refers to the curvature criterion ($\frac{\partial^2 \mathbf{T}}{\partial \mathbf{z}^2}$($\frac{\partial^2 \boldsymbol{\rho}}{\partial \mathbf{z}^2}$)), which is objective but demands high vertical resolution.
9. All the methods have their own advantages and limitations.

RESEARCH CONTENT

1. How does the water temperature in Lake Taihu varies diurnally and seasonally? How does it respond to various weather characteristics?

Content: Sum up the diurnal and seasonal patterns and compare them with those of other lakes. Find how thermal stratification react to weather change.

2. How should the thermal stratification in Lake Taihu be quantified? Furthermore, what are the main factors that control it? How does the thermal stratification in Lake Taihu typically change with these dominant factors under different conditions?

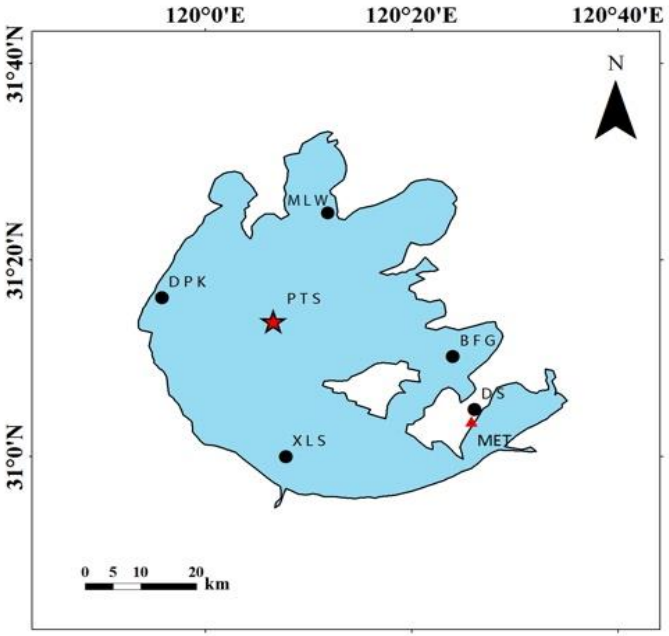
Content: Come up with a suitable MLD criteria for Lake Taihu, use it on finding dominant factors, and quantify their relationship.

3. As Lake Taihu is shallow, what mechanism underlies the switch of its thermal stratification (from being stable to being unstable)?

Materials and Methods

1. Sites

选取位于湖中央的平台山通量观测站，建站日期2013年6月，湖中心平均水深2.8m。



2. Instruments

System	Height	Instrument
Campbell EC150	8.5m	sonic anemometer/thermometer (model CSAT3，Campbell Scientific）
		open-path H2O/CO2 analyzer
		four-way net radiometer (model CNR4，Kipp & Zonen B. V.）

Materials and Methods

System	Instrument
Automatic Weather Station	anemometer and wind vane (model 05103; R M Young Company）
	air temperature and humidity probe (model HMP155A， Vaisala, Inc.）

System	Instrument	Height
Water Temperature Observation System	temperature probes （model 109-L, Campbell Scientific)	0.20, 0.50, 1.00, and 1.50 m, and sediment temperature at the depth of ~0.10 m below the water column

System	Data
Dongshan Weather Station	Cloud Fraction and Weather Condition

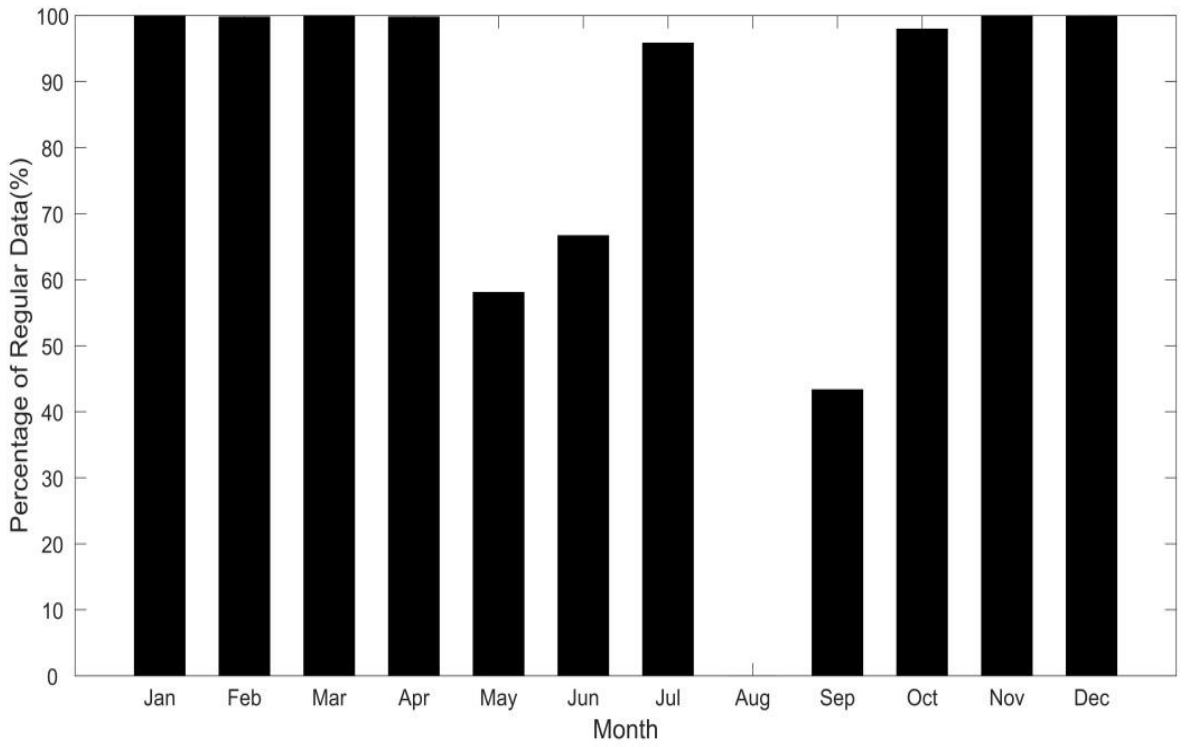
3. Collection

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

4. Quality Control

Nighttime shortwave radiation is set to 0; Removing spikes (Vickers et al); Coordinate Rotation (Lee et al); WPL correction (Webb et al); etc.

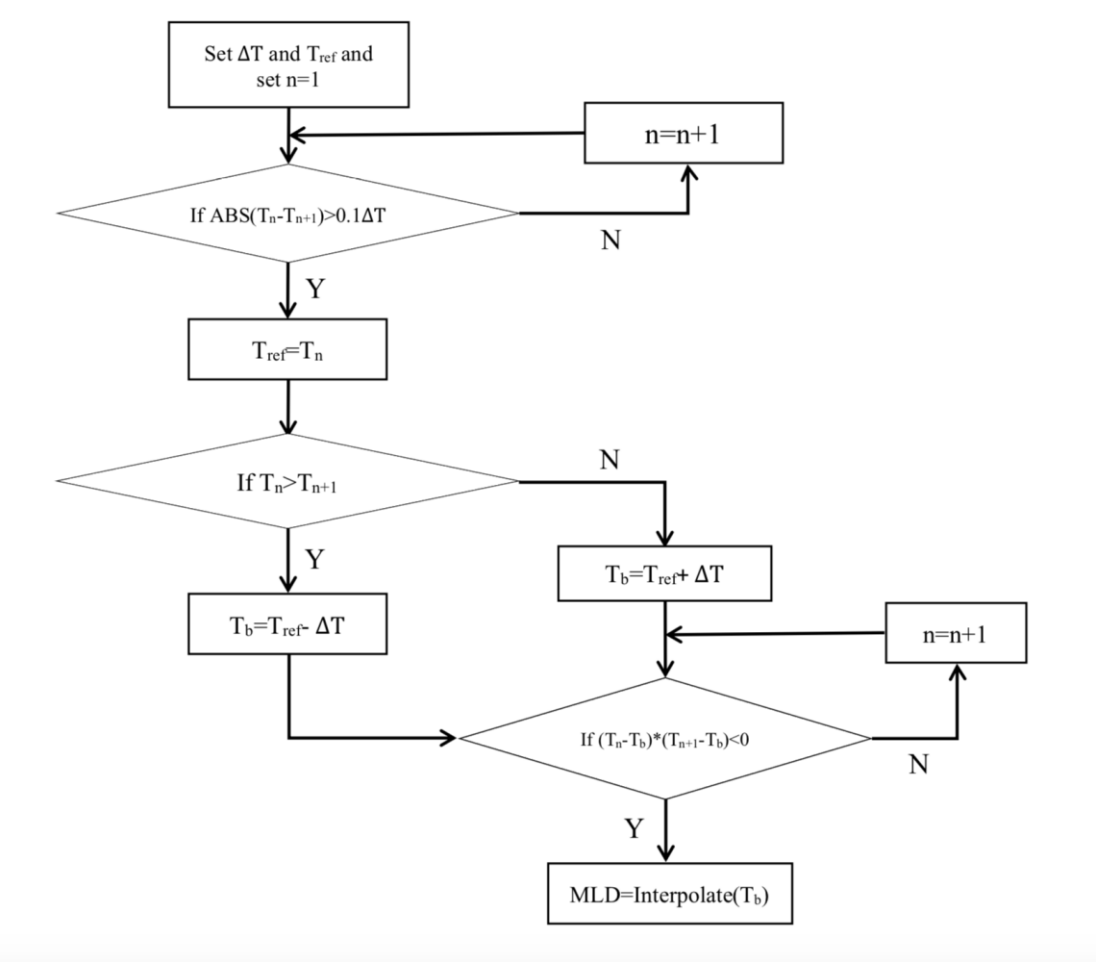
Field Maintenance Log:



January, April, July and October are picked to represent Winter, Spring, Summer and Fall, respectively.

5. Criterion for MLD

Kara's Optimal Criteria



Traditional Difference Criteria

$$\mathrm{MLD} = \frac{(T_b - T_n)}{T_{n+1} - T_n} * (h_{n+1} - h_n) + h_n$$

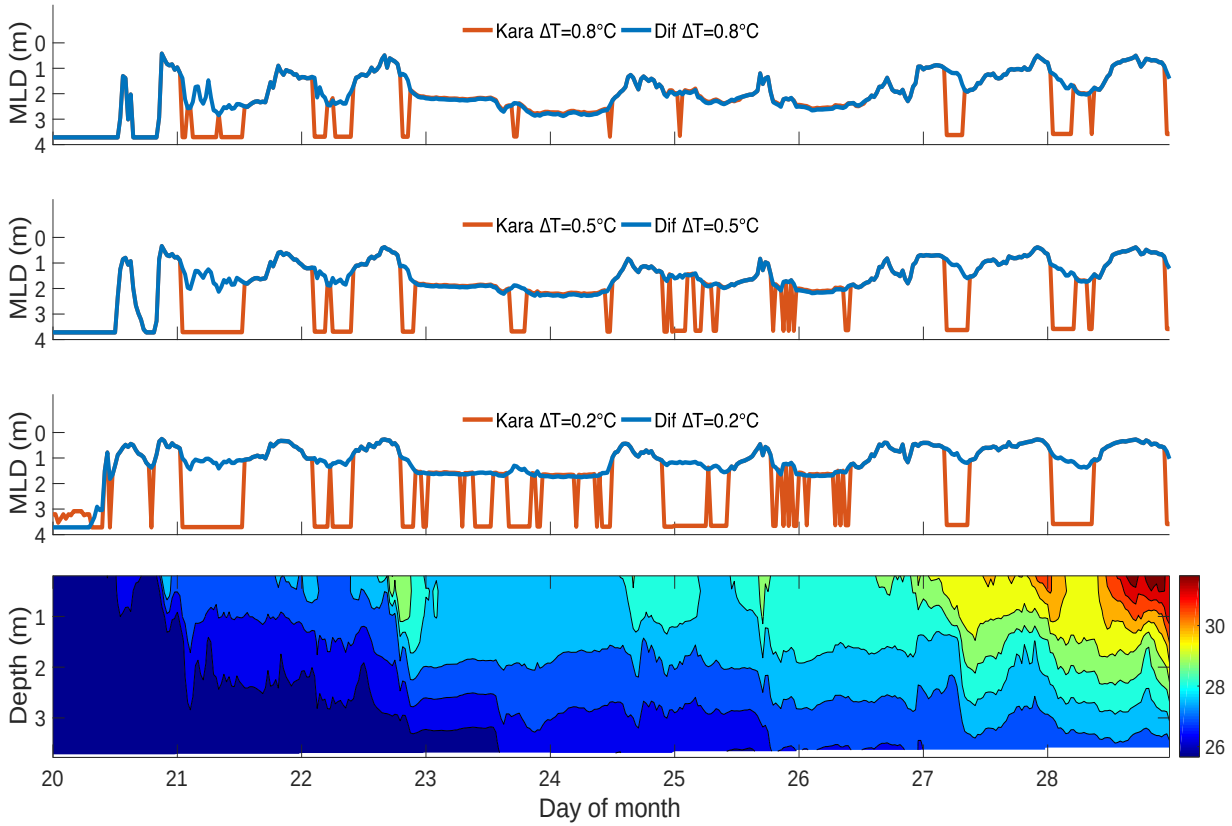


Fig. 1. Two typical differences between Kara's optimal definition and the traditional difference criterion, from July 20 to 28, with ΔT set to 0.8°C, 0.5°C and 0.2°C and the coupled water temperature.

Kara's optimal criteria lacks stability and continuity!

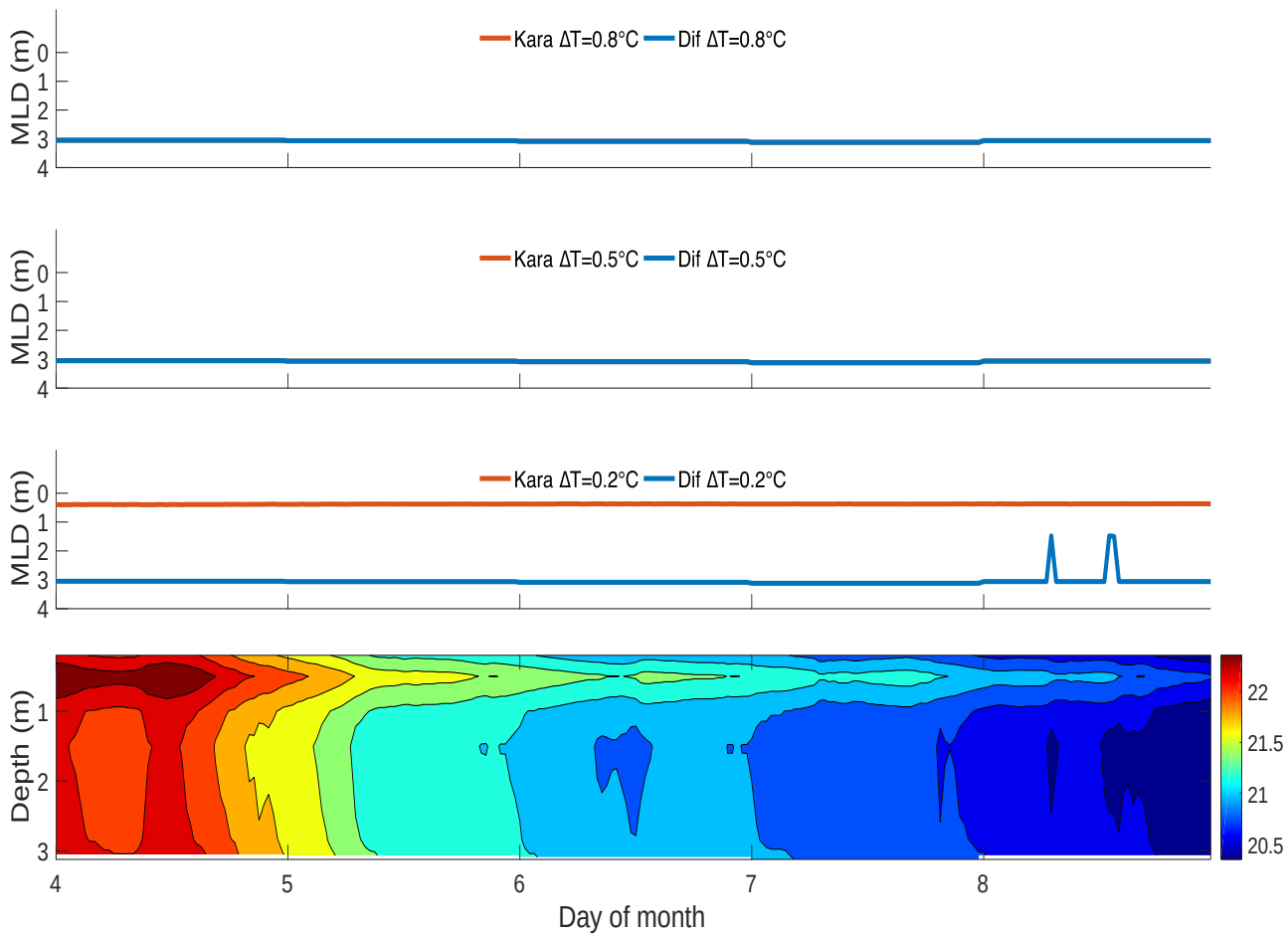


Fig. 2. Two typical differences between Kara's optimal definition and the traditional difference criterion, from October 4 to 8, with ΔT set to 0.8°C, 0.5°C and 0.2°C and the coupled water temperature.

Kara's optimal criteria is unable to cope with the weak inversion layer in Lake Taihu!

Reason: When the temperature difference of the inversion layer is smaller than ΔT, the algorithm is unable to find a place for T_b as the lower part of the lake is still stratified. As a result, the MLD is improperly set to the maximum depth, leading to a lack of MLD continuity in time. Second, the temperature difference of the inversion layer is slightly larger than ΔT from October 4 to 8. This result causes a low value of MLD although vertical mixing is still quite strong in the whole water column.

Conclusion: The traditional difference criterion gives more stable results for Lake Taihu and is more suitable to use with better continuity and fewer errors.

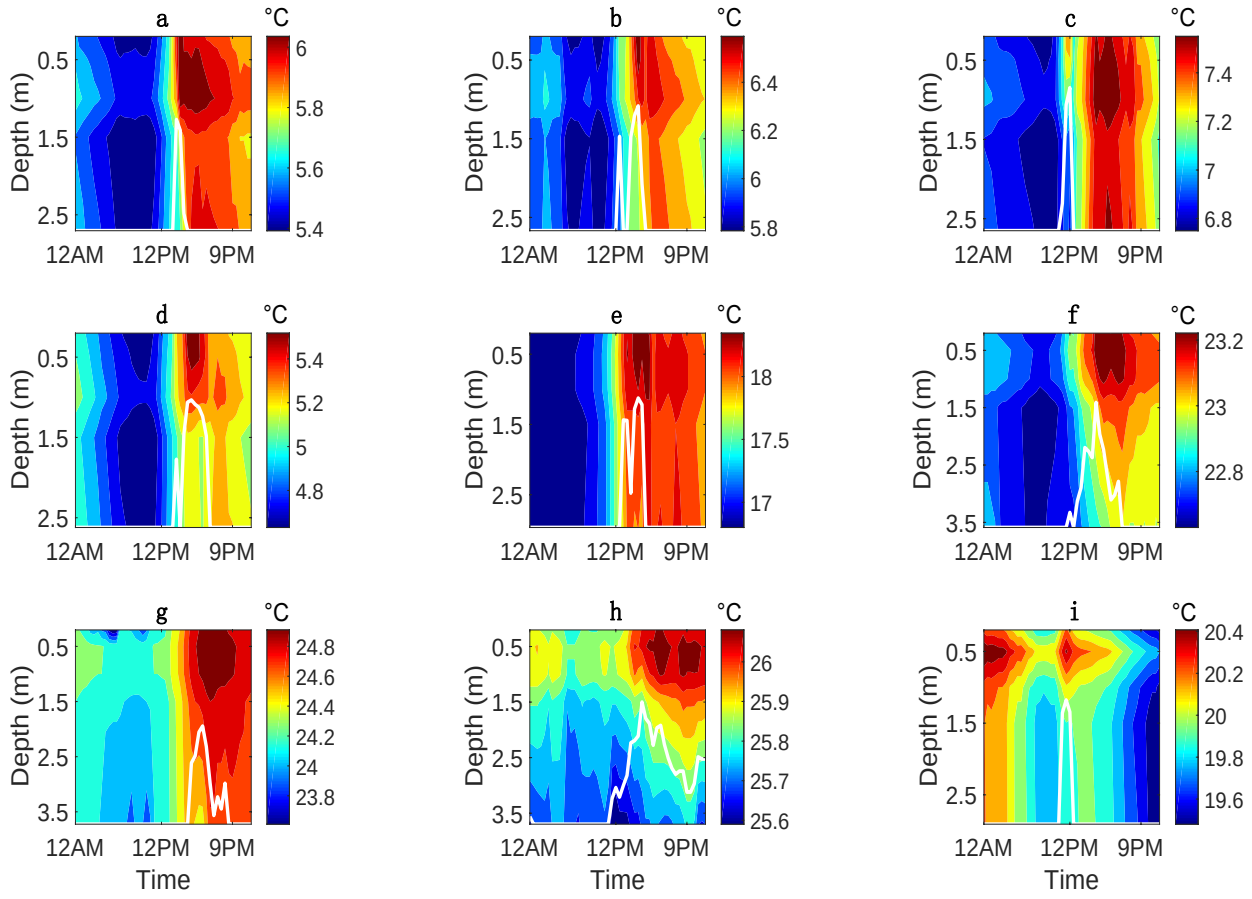


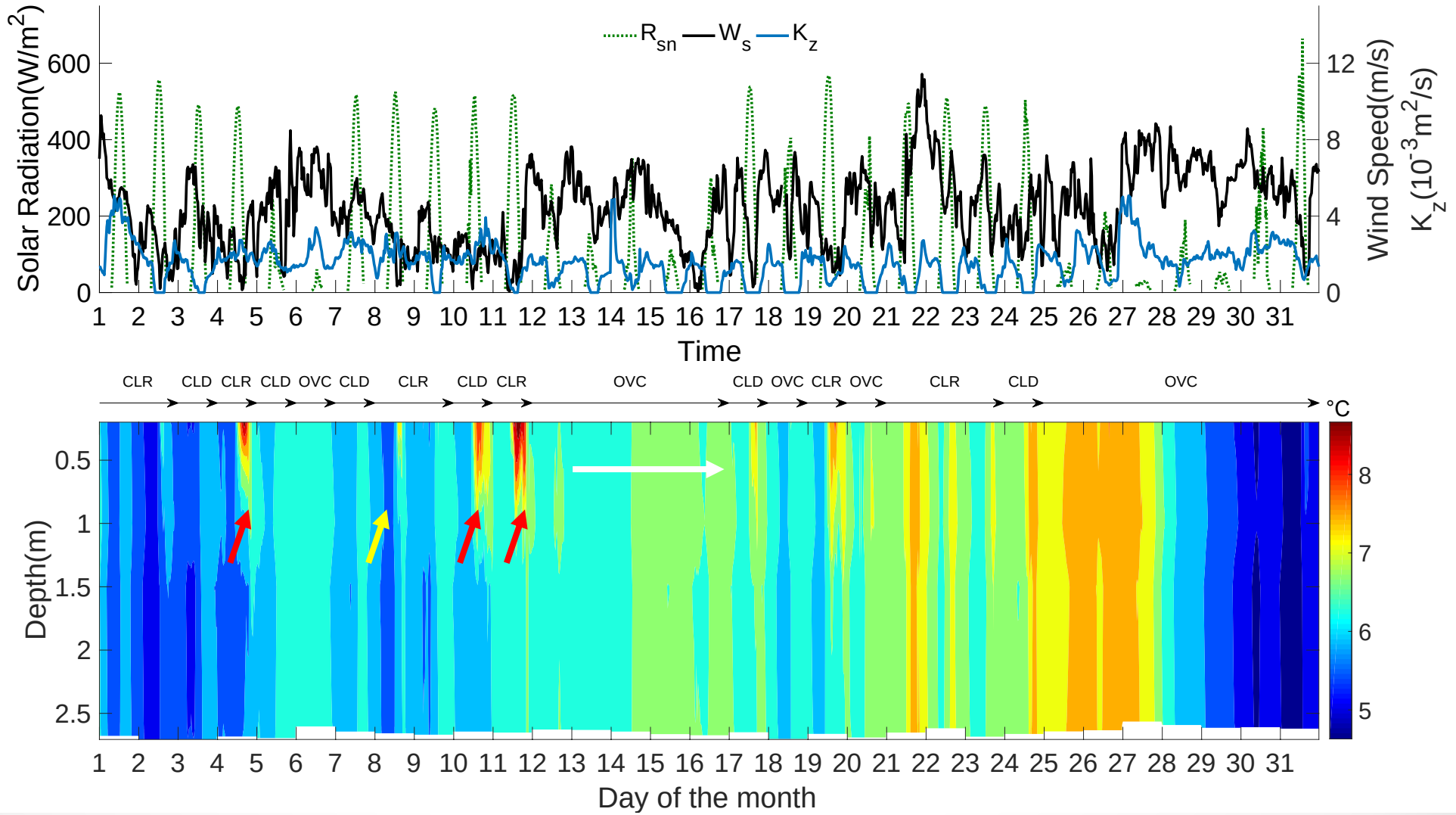
Fig. 3. Cases of water temperature and the MLD partly chosen from the daily patterns in which the wholly mixed state is shown with ΔT=0.8°C and ΔT=0.5°C, while thermal stratification is found with ΔT=0.2°C, including January 3 (a), 9 (b), 21 (c) and 31 (d), April 2 (e), July 8 (f), 12 (g), and 18 (h) and October 28 (i).

In some cases, we find that thermal stratification (MLD < maximum depth) does not appear with ΔT = 0.5°C or ΔT = 0.8°C, but occurs only when Δ*T* = 0.2°C. As a transition between stable and unstable state, weak stratiication is highlighted by using Δ*T* = 0.2°C.

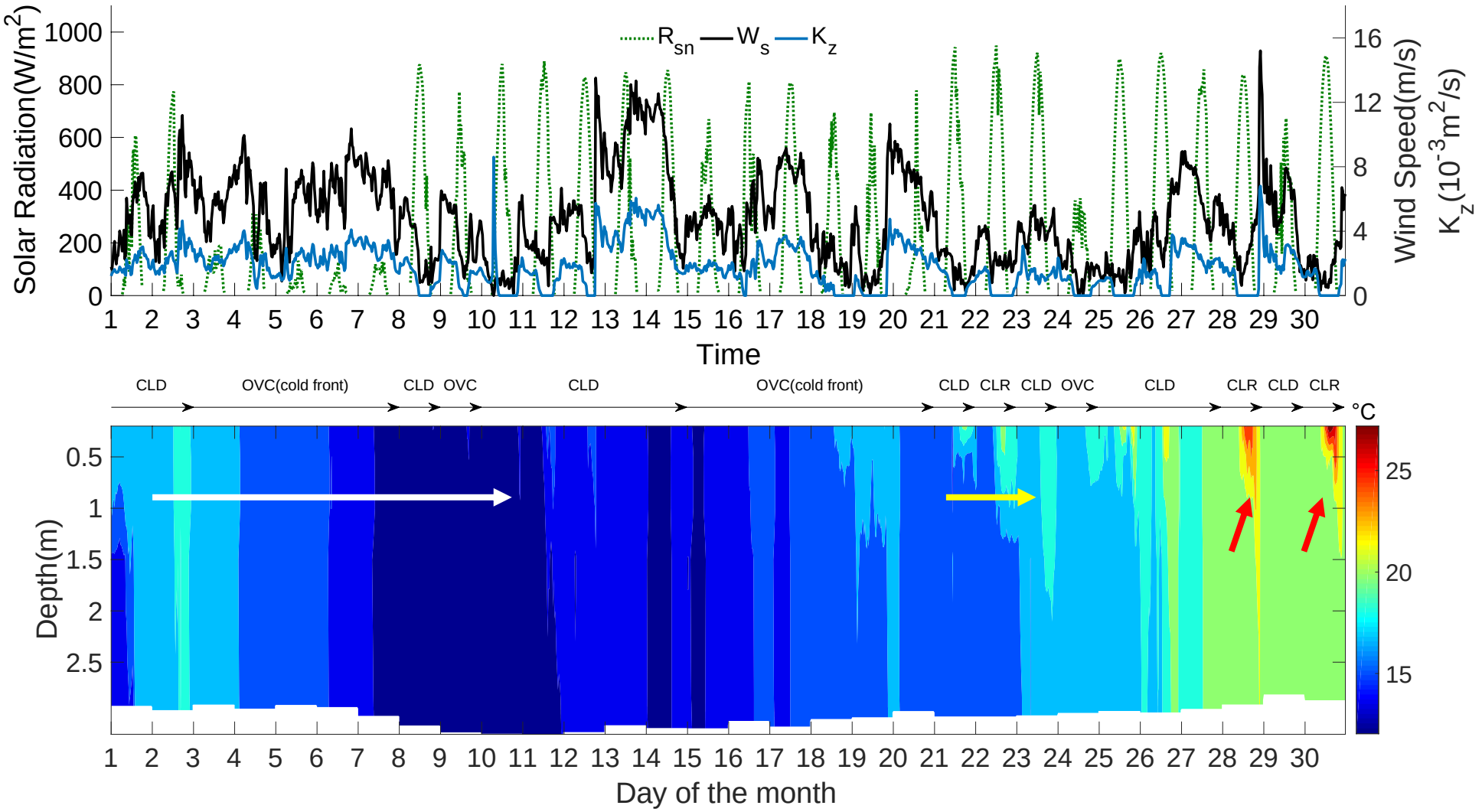
Conclusion: The traditional difference criterion with Δ*T* = 0.2°C is applied in studying thermal stratification and vertical mixing processes in Lake Taihu.

RESULTS AND DISCUSSION

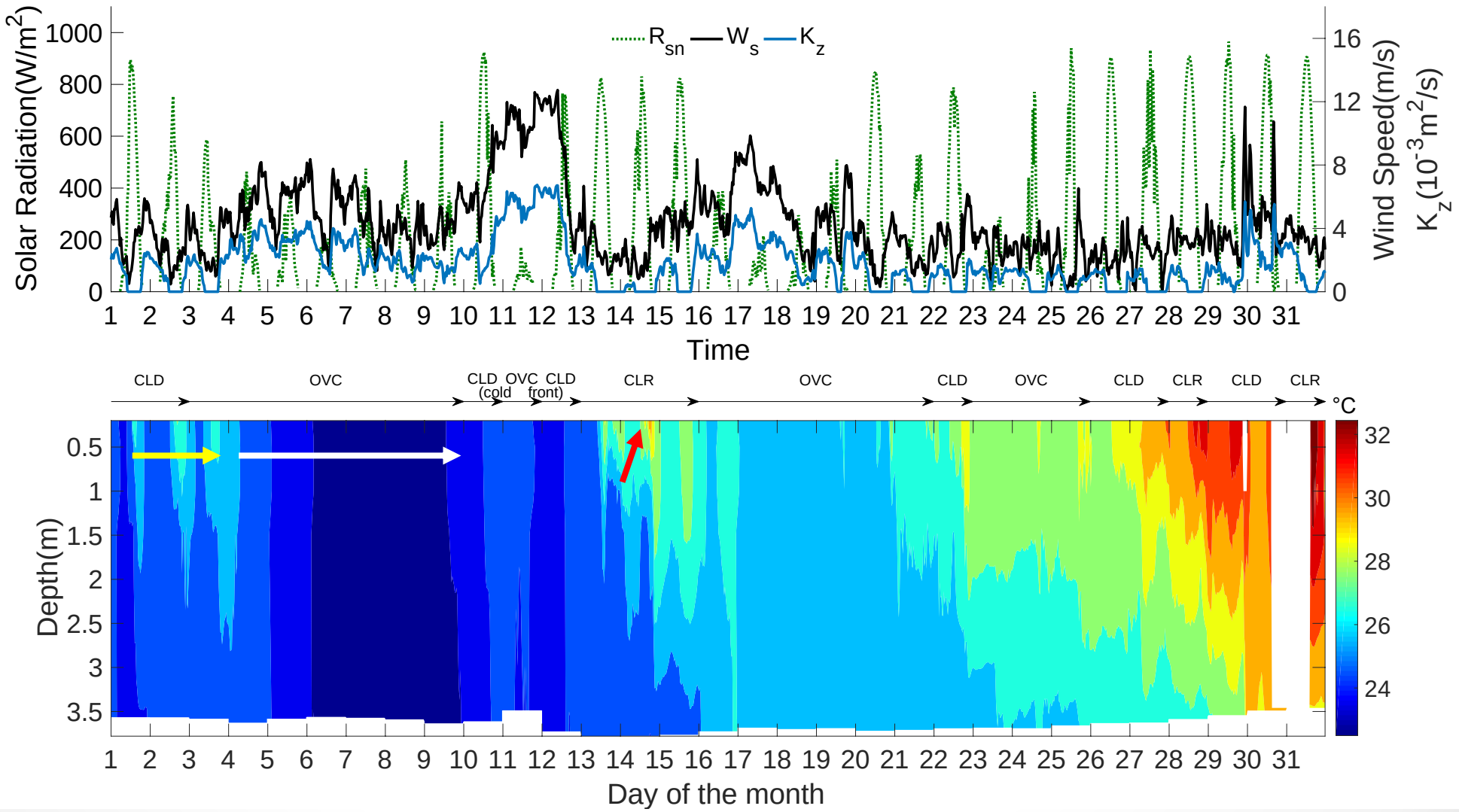
(a)



(b)


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLD
OVC(cold front)
CLD OVC
CLD
OVC(cold front)
CLD CLR CLD OVC
CLD
CLR CLD CLR
°C
Depth(m)
Day of the month

(c)


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLD
OVC
CLD OVC CLD
(cold front)
CLR
OVC
CLD
OVC
CLD
CLR
CLD
CLR
°C
Depth(m)
Day of the month

(d)

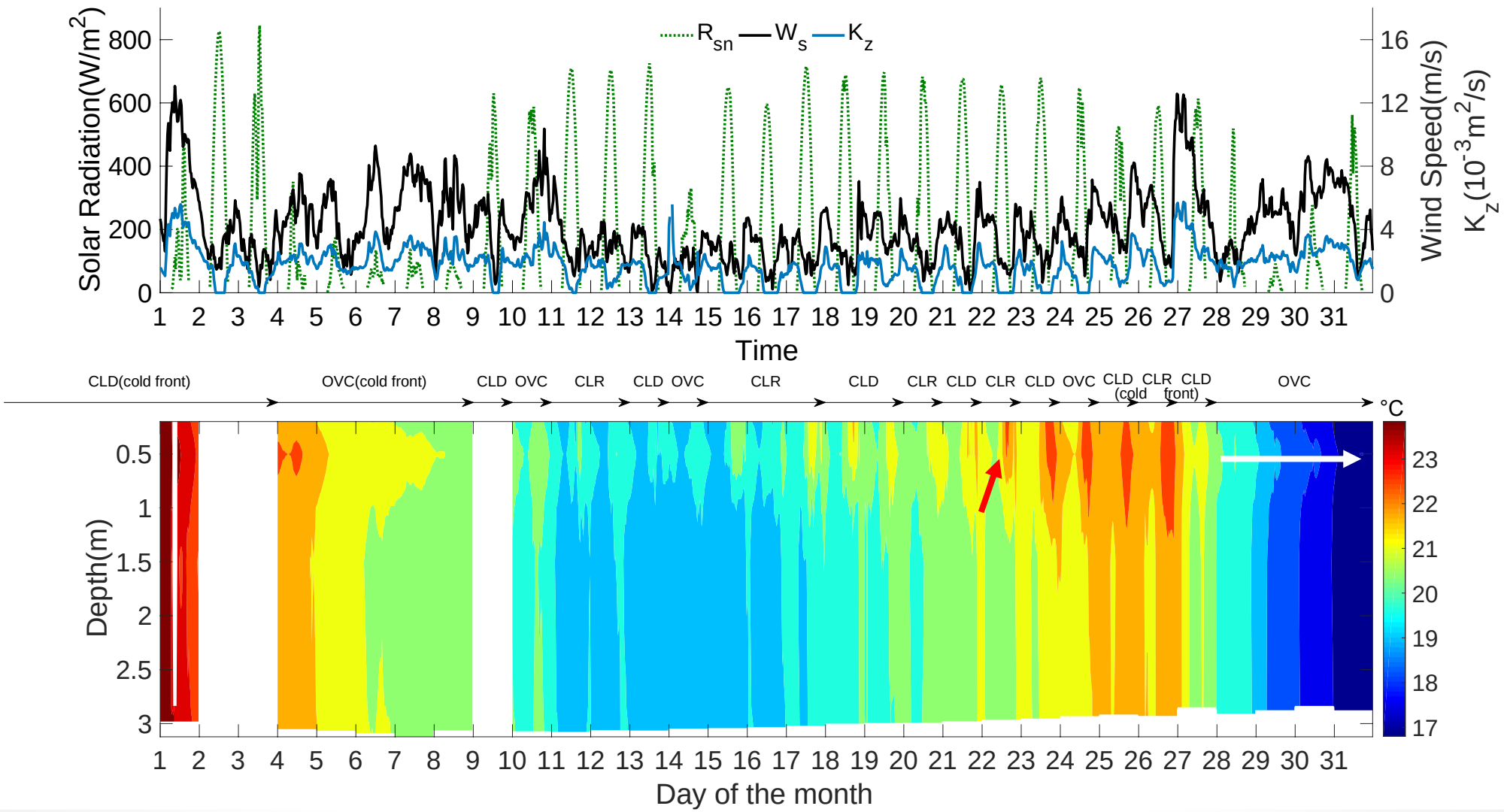


Fig. 4. The vertical distribution of water temperature in four seasons coupled with solar radiation (R_{sn}, which is net shortwave radiation here), wind speed (W_s) and turbulent diffusivity (K_z) at the same period.

General Characteristics of Thermal Stratification in Lake Taihu at 2015

Diurnal:

Strong Stratification

Weak Stratification

Characteristic 1: **Stratifying in day and mixing at night.**

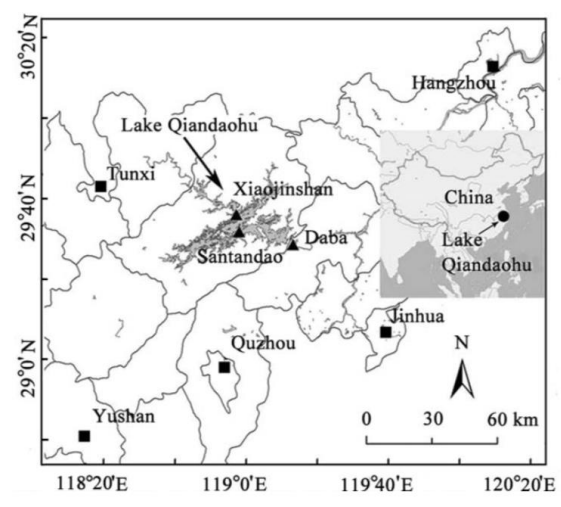
No Stratification → **Characteristic 2:** **The temperature of different depths change in the same manner.**

Seasonal:

- **Strong in spring and summer, weak in fall.**
- **Long-lasting thermal stratification (>1 day) in summer due to sustained surface heat flux.**

Comparing With Other Lakes

Deep Lake：
Lake Qiandaohu



Term	Lake Qiandaohu	Lake Taihu
Depth	30m in average	1.9m in average
Positon of thermal stratification	1. Thermocline 2. Varying	1. Fixed at the surface and stretching downward.
Cycle of thermal stratification change	1. Monomictic 2. 1-year-cycle	1. Warm polymicitc 2. 1-day-cycle or a few days.
Strength of thermal stratification	1. <1°C/m	1. Usually stronger than 1°C/m，the peak is 5°C/m。
Response to external factors	1. Reacting more slowly when it’s deeper.	1. Consistent manner for the whole layer.

Shallower Lake: Lake Müggelsee (to the east of Berlin)

Term	Lake Müggelsee	Lake Taihu
Depth	4.9m in average	1.9m in average
*Position of thermal stratification	1. Varying	1. Fixed
Cycle of thermal stratification change	1. Polymictic	1. Warm Polymictic
*Long-lasting stratification	1. In each seasons, lasting from 1 week to a few months.	1. Only in summer, lasting for 1 week.

Analysis:

(1) Depth

The greater depth of Lake Müggelsee leads to a varying thermal stratification position. It has characteristics for both deep lake and shallow lake.

(2) Location

The higher latitude (20 degree more than Lake Taihu) means a colder climate. Lake surface temperature is 10 °C lower and the thermal stratification is weaker.

(3) Fetch

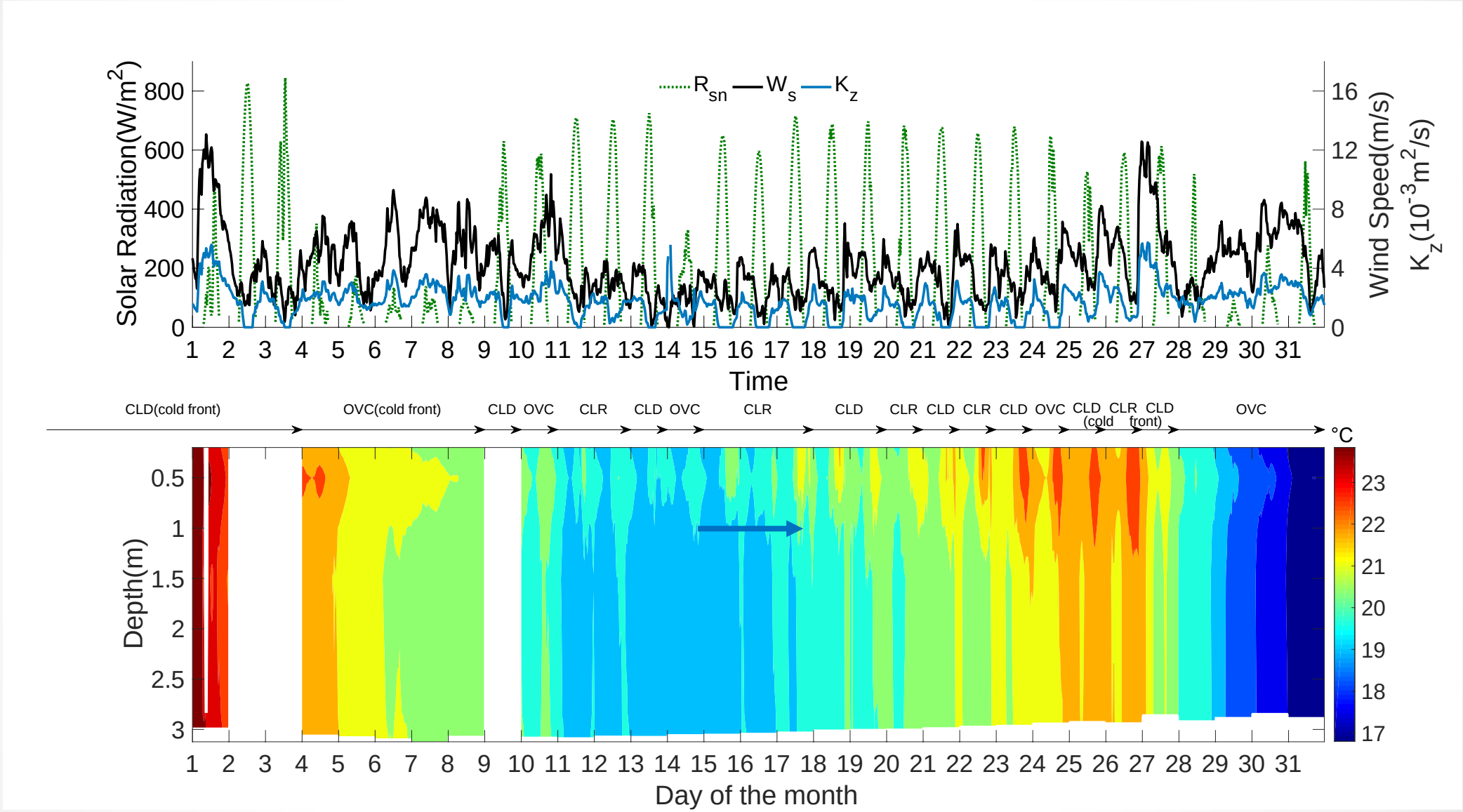
less fetch of Lake Müggelsee (7.9 km^2) than Lake Taihu (2400 km^2) may account for its longer-lasting stratification.

Analysis on The Factors That Influence Thermal Stratification

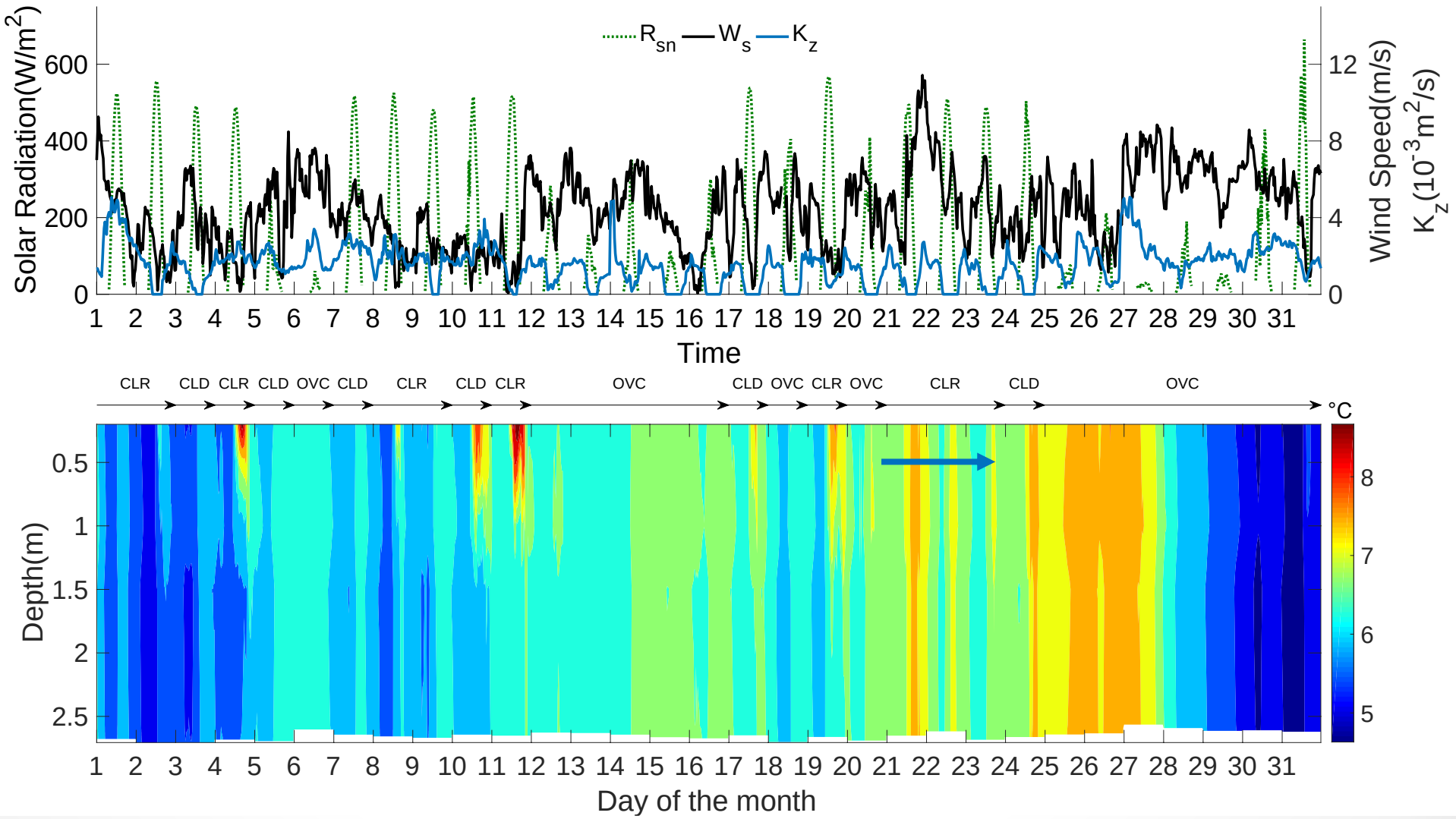
1.Weather Condition and Thermal Stratification

Clear Day： **Strongest stratification, weak stratification（Oct. 15-17）and entire mixing state (Jan. 21-23).**

Oct.


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLD(cold front)
OVC(cold front)
CLD OVC
CLR
CLD OVC
CLR
CLD
CLR CLD CLR CLD OVC
CLD CLR CLD (cold front)
OVC
°C
Depth(m)
Day of the month

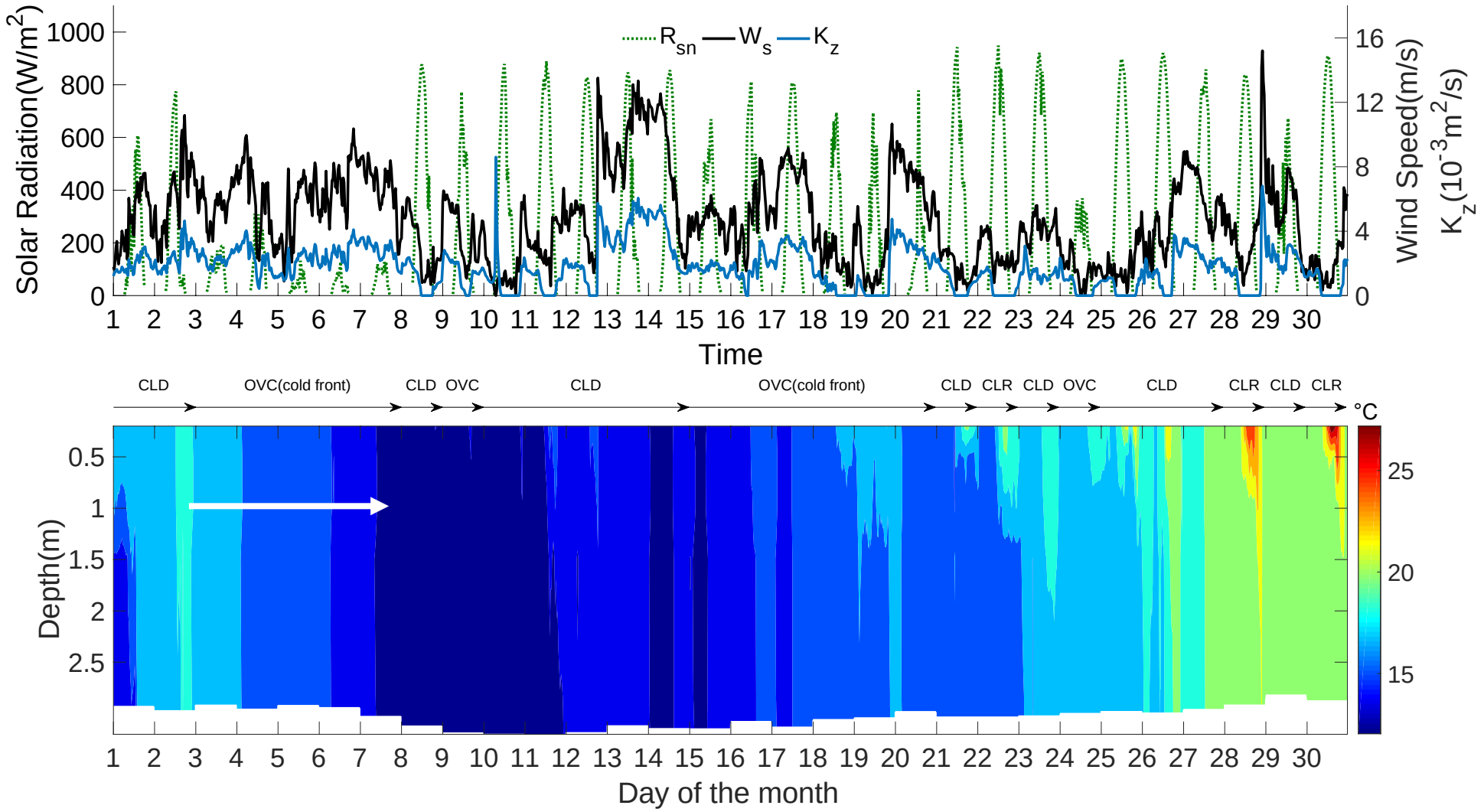
Jan.


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLR CLD CLR CLD OVC CLD CLR CLD CLR OVC CLD OVC CLR OVC CLR CLD OVC
°C
Depth(m)
Day of the month

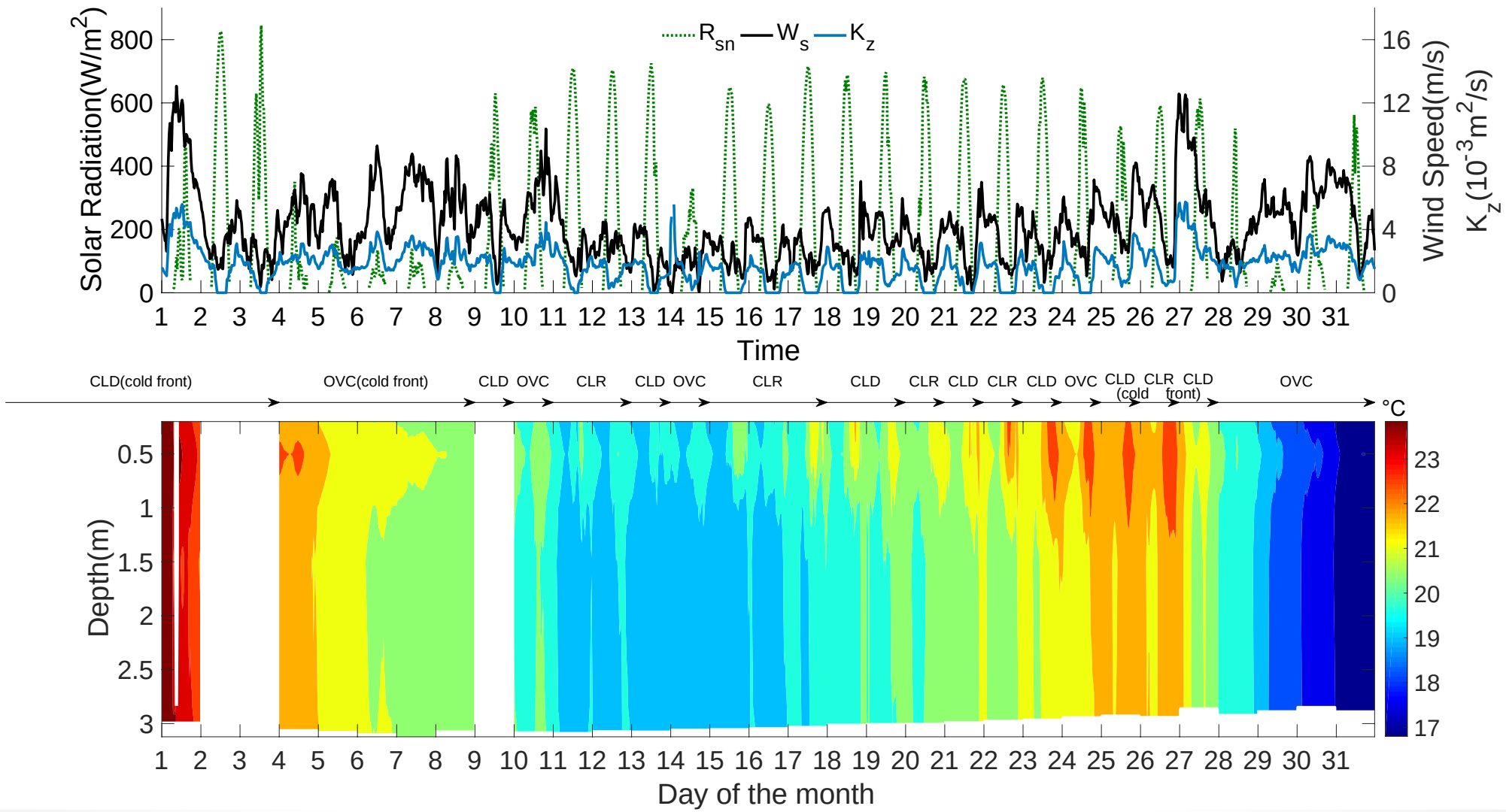
Overcast Day: **No stratification. Cold fronts (Apr. 3-7, 15-20, Jul. 11, Oct. 4-8) are followed by mixing state for a few days.**

Cloudy Day: **Less strong stratification than clear day and less mixing state than overcast day. More weak stratification.**

Apr.


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLD
OVC(cold front)
CLD OVC
CLD
OVC(cold front)
CLD CLR CLD OVC
CLD
CLR CLD CLR
°C
Depth(m)
Day of the month

Oct.


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLD(cold front)
OVC(cold front)
CLD OVC
CLR
CLD OVC
CLR
CLD
CLR CLD CLR CLD OVC
CLD (cold
CLR CLD front)
OVC
°C
Depth(m)
Day of the month

2. Specific factors and thermal stratification

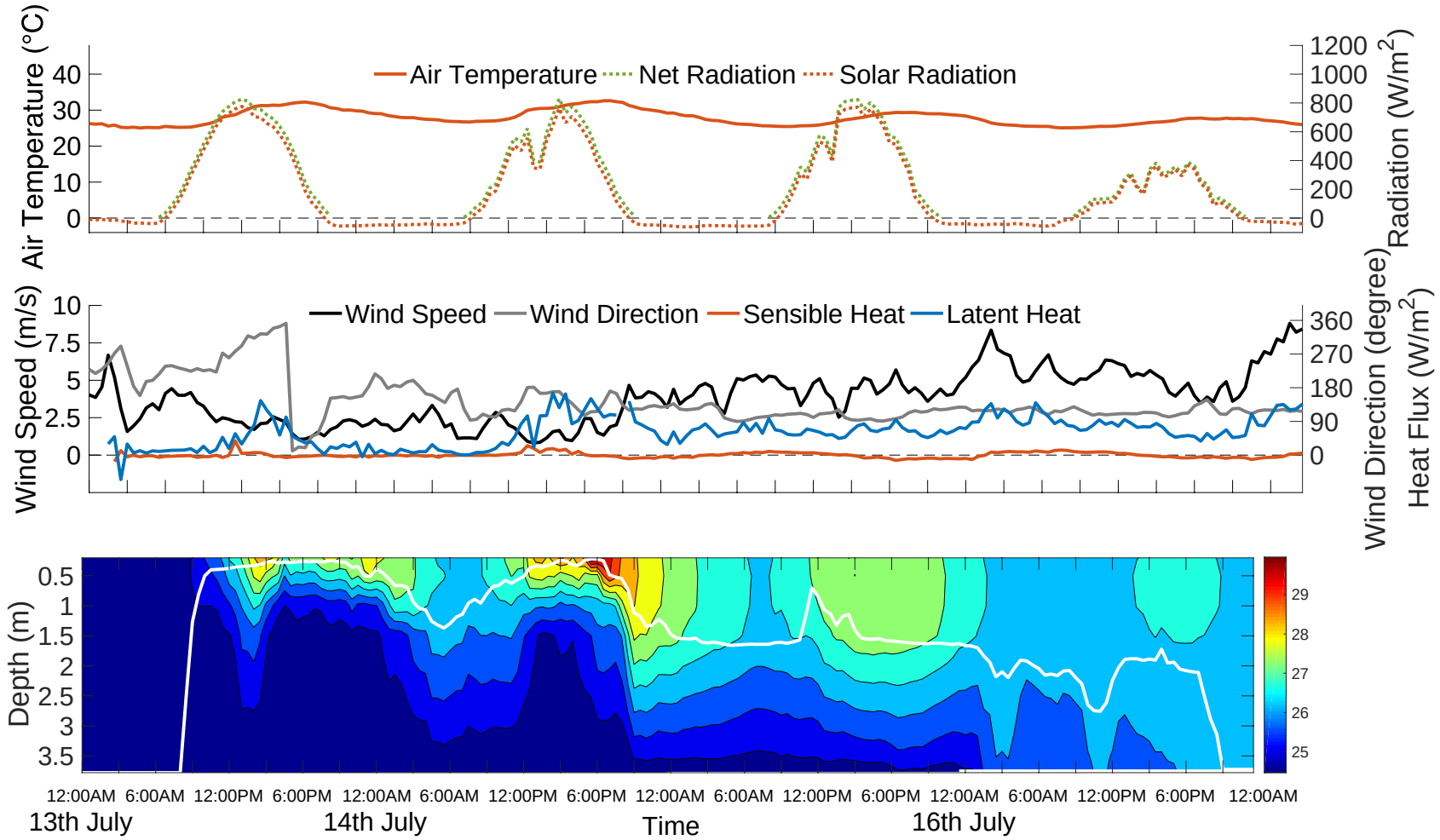


Fig. 5. Meteorological factors, heat fluxes and MLD during Jul. 13-16.

Solar Radiation:

(1) Stronger solar radiation leads to stronger thermal stratification.

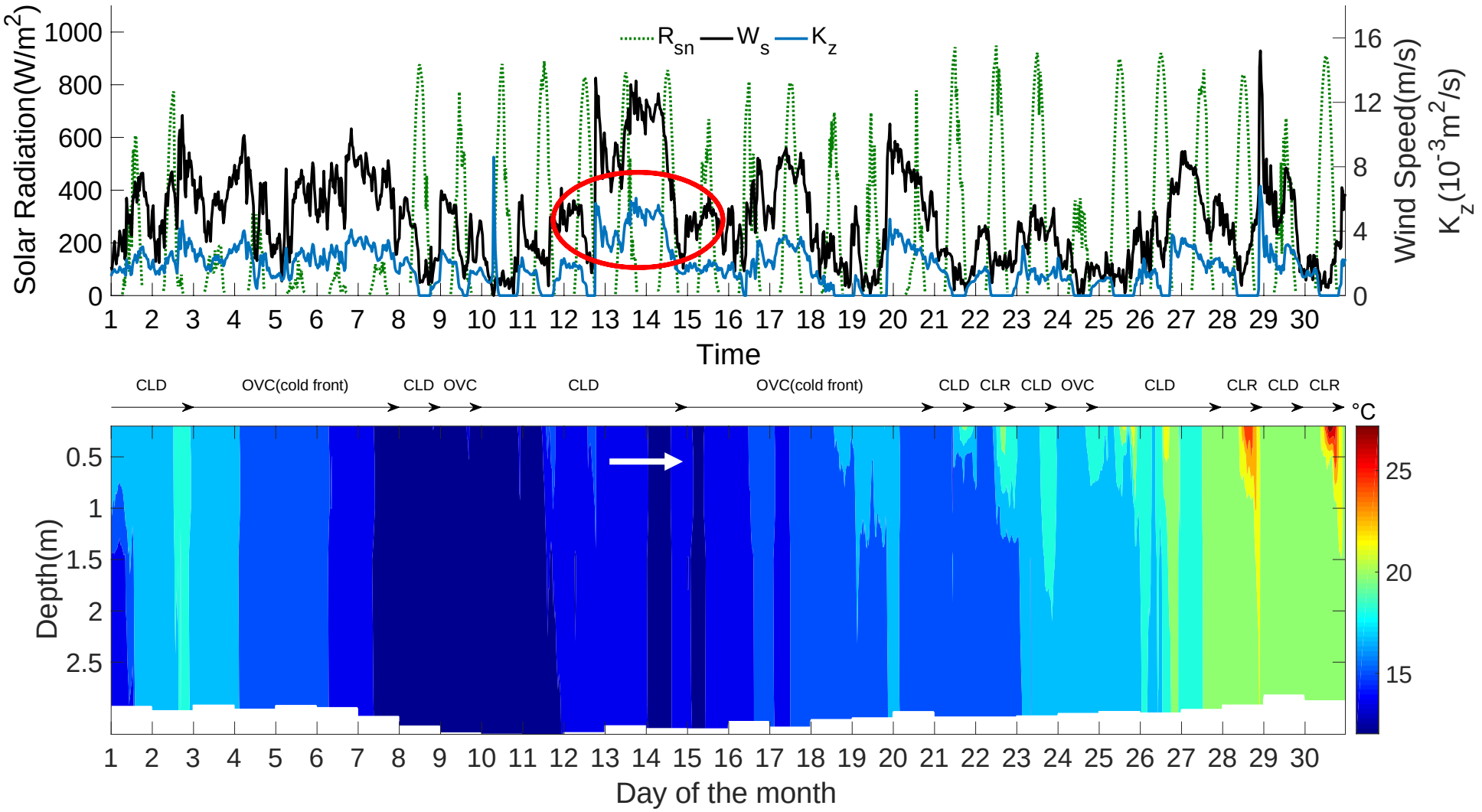
(2) Slow response of thermal stratification to solar radiation. (3h lag on peak)

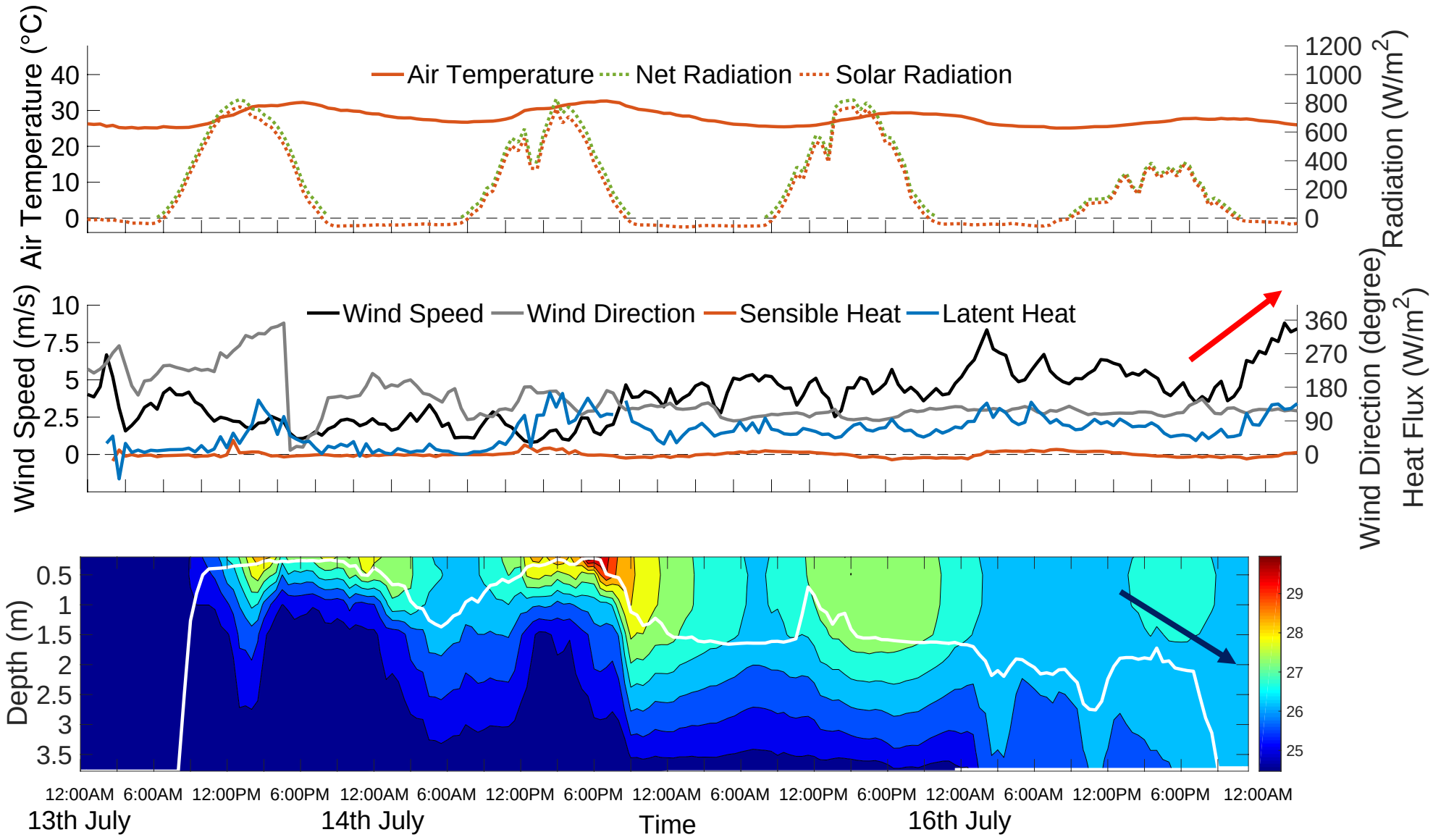
Wind Speed:

(1) Intensive Mixing: Due to the strong wind, high K_z still occurs when solar radiation is strong (Apr. 13-14).

(2) Quick response (Jul. 16)

Apr.


Solar Radiation(W/m2)
Wind Speed(m/s)
Kz(10-3m2/s)
Rsn
Ws
Kz
Time
CLD
OVC(cold front)
CLD OVC
CLD
OVC(cold front)
CLD CLR CLD OVC
CLD
CLR CLD CLR
°C
Depth(m)
Day of the month


Air Temperature (°C)
Air Temperature
Net Radiation
Solar Radiation
Radiation (W/m2)
Wind Speed (m/s)
Wind Speed
Wind Direction
Sensible Heat
Latent Heat
Wind Direction (degree)
Heat Flux (W/m2)
Depth (m)
12:00AM 6:00AM 12:00PM 6:00PM 12:00AM 6:00AM 12:00PM 6:00PM 12:00AM 6:00AM 12:00PM 6:00PM 12:00AM 6:00AM 12:00PM 6:00PM 12:00AM
13th July
14th July
Time
16th July

Heat Flux:

(1) Daytime: Net radiation is slightly lower than solar radiation. They change consistently, which means solar radiation contributes the most of net radiation.

(2) Nighttime: Net radiation (-50W/m^2) and latent heat(30-100W/m^2) take the heat away. This free thermal convection is not so strong as that driven by wind mixing.

(3) Sensible heat can be ignored.

Other Factors:

Wind speed and air temperature have no noticeable impact on thermal stratification.

Conclusion:

Solar radiation and wind speed are dominant factors.

Representative Response of Thermal Stratification to Dominant Factors

1. Categorical Analysis

Factors	Season	Threshold（average）
R_{sn}	Spring	344.58 W/m^2
	Summer	297.38 W/m^2
	Fall	276.92 W/m^2
	Winter	193.92 W/m^2
W_s	Spring	4.71 m/s
	Summer	4.27 m/s
	Fall	4.18 m/s
	Winter	4.38 m/s

Daily average R_{sn} > threshold and daily average W_s < threshold is categorized as Type 1, Daily average R_{sn} < threshold and daily average W_s > threshold is categorized as Type 2. The water temperature in Type 1 and Type 2 is averaged seasonally.

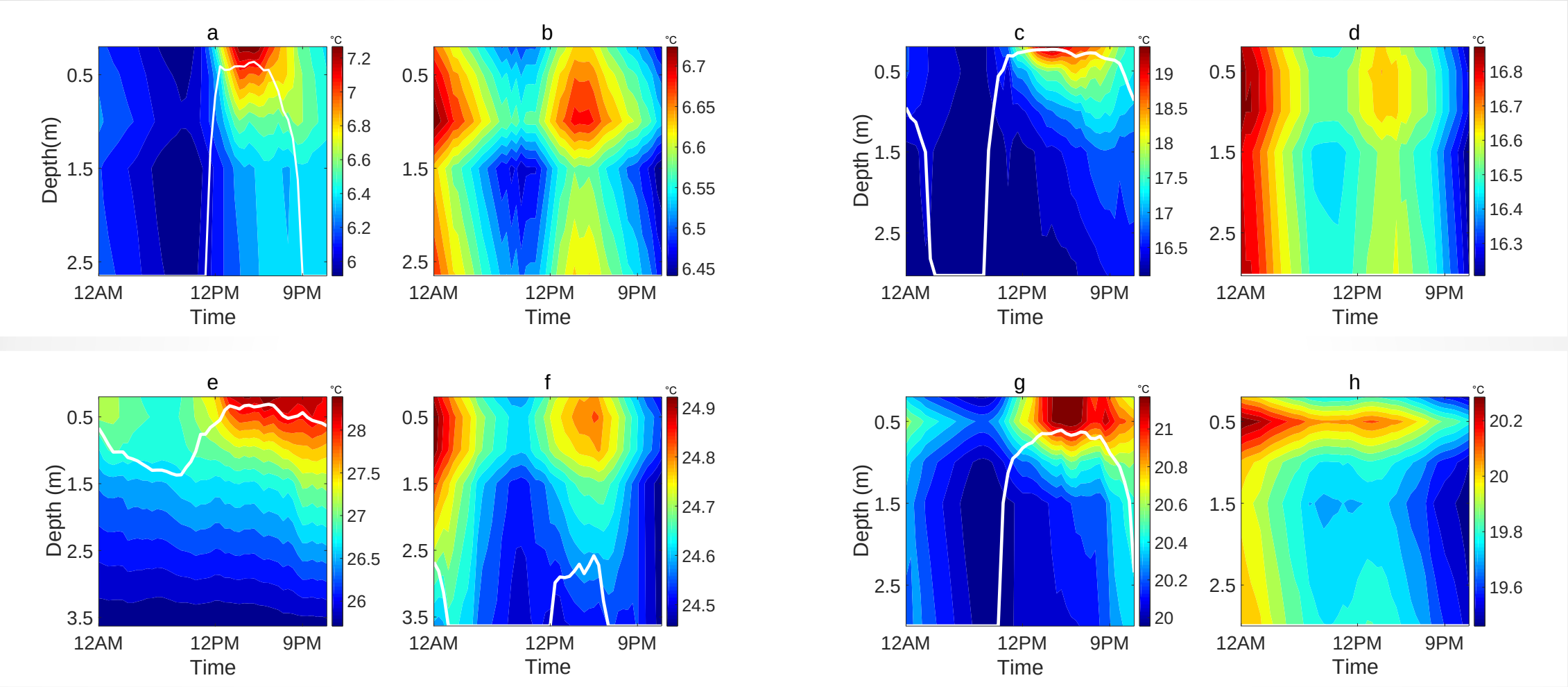


Fig. 6. The average response of water temperature and MLD to Type 1 (high R_{sn} and low W_s) and Type 2 (low R_{sn} and high W_s) conditions at the PTS site in the four seasons in 2015. Type 1 is shown in a (January), c (April), e (July) and g (October). Type 2 is shown in b (January), d (April), f (July) and h (October). (The monthly average maximum depths are used in the four seasons.)

（1）Lake Taihu stratifies in Type 1 and mixes in Type 2.

（2）Inversion Layer: In Type 2, R_{sn} is so weak that surface layer loses more energy than the middle layer does.

（3）Warm Region at Bottom: The sediment is a heat sink in summer due to sustained heat transport, but becomes a heat source in other seasons. This energy balance accelerates the mixing in colder seasons.

2. Quantitative Analysis:

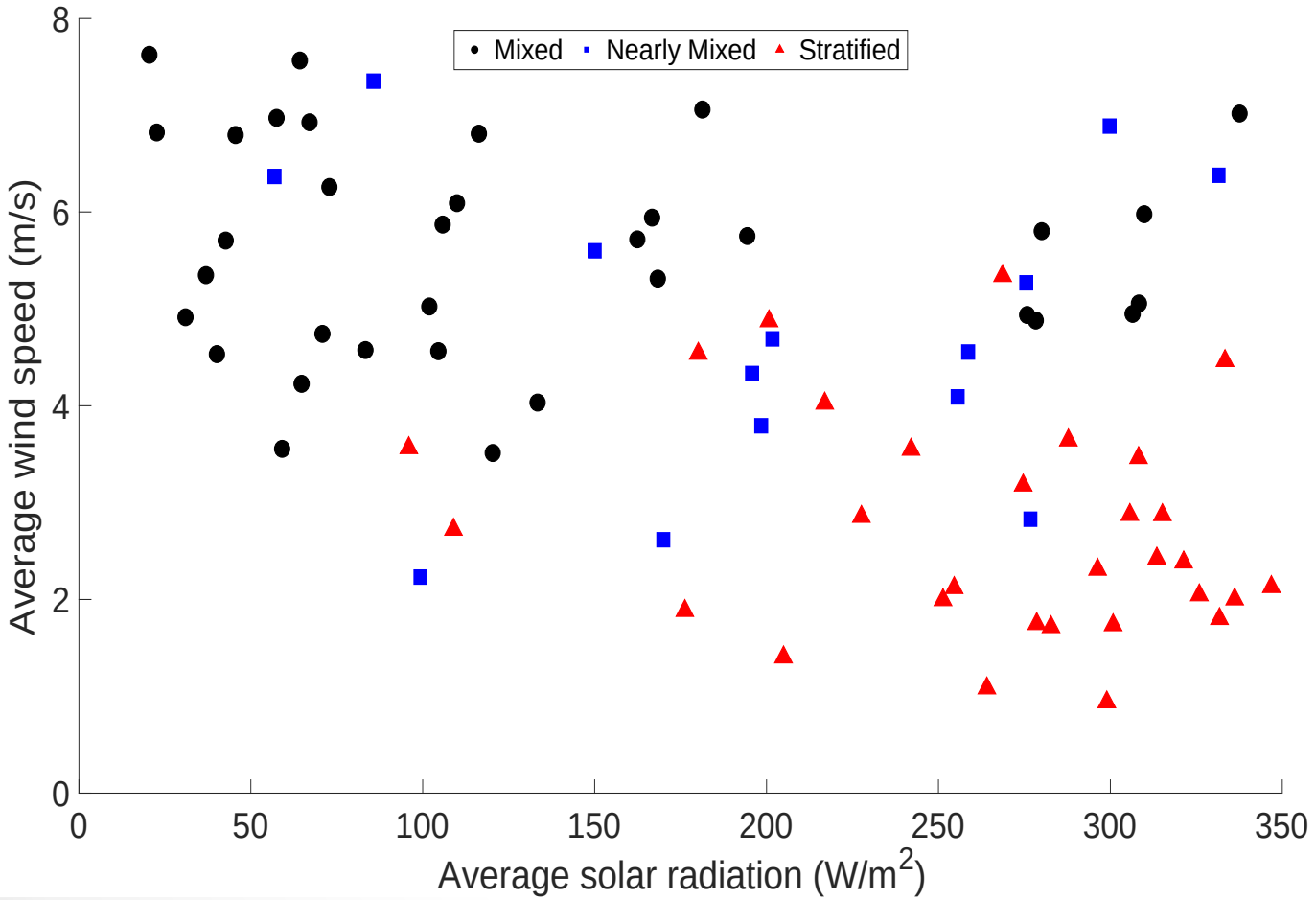


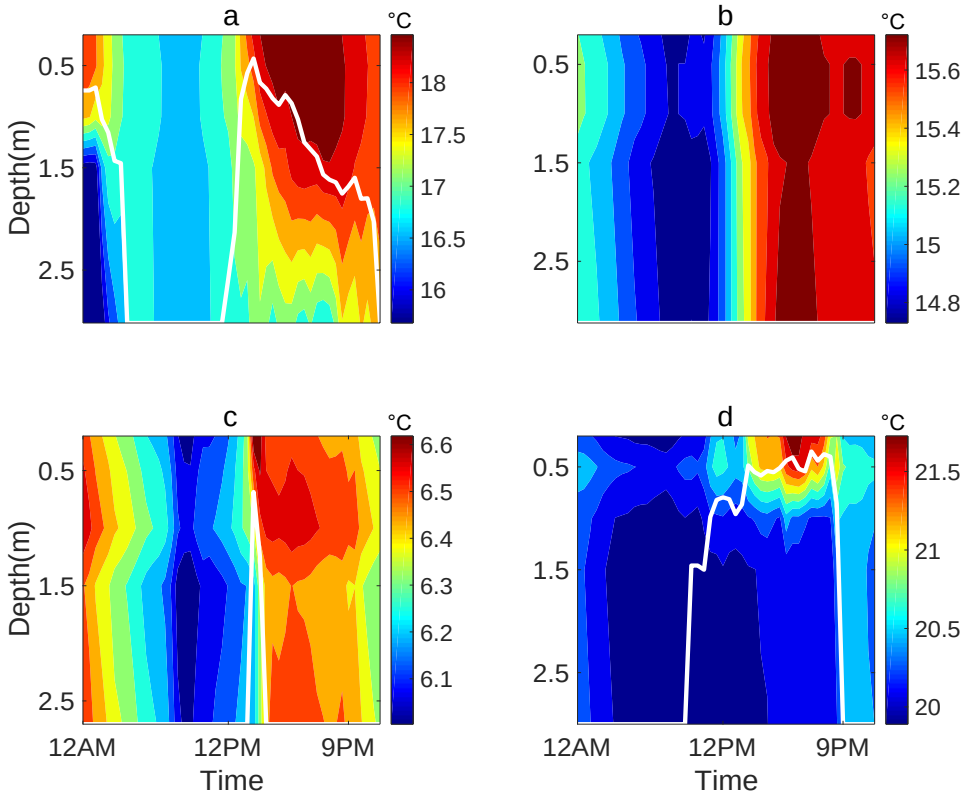
Fig. 7. Thermal stratification with different strengths and the corresponding R_{sn} and W_s. Black points refer to the wholly mixed state with average RMLD of 100%. Blue squares refer to the nearly mixed state with average RMLD between 85% and 100%. Red triangles refer to the stratified state with average RMLD lower than 85%.

1. When R_{sn} increases, W_s must be higher to offset the stronger stratifying effect to maintain the thermal structure.

2. From Fig. 6 when R_{sn} is 100 W m^{-2} and 200 W m^{-2}, the thresholds are approximately 2-3 m s^{-1} and 4-5 m s^{-1}, respectively. When R_{sn} is higher than 300 W m^{-2}, the threshold can exceed 6 m s^{-1}.

The Mechanism Underlying Thermal Stratification Switch

1. Typical cases



Wind-induced convection

≠

Thermal free convection

Fig. 8. Four typical cases for changes in water temperature and the MLD: Thermal stratification slowly decreases on April 23 (a). No thermal stratification appears on April 17 (b). Developed thermal stratification suddenly disappears in daytime on January 18 (c). Developed thermal stratification suddenly disappears in nighttime on October 18 (d).

2. The Law of Wind-induced Convection

Season	Whole Mixing	Stratification	Convection in Daytime			Convection in Nighttime		
			NoD	Values		NoD	Values	
Spring (31 days)	10	20	4	MLD	1.22 m	11	MLD	0.29 m
				W_s	4.04 m s^{-1}		W_s	2.04 m s^{-1}
Summer (28 days)	4	24	1	MLD	2.33 m	4	MLD	0.78 m
				W_s	4.46 m s^{-1}		W_s	3.91 m s^{-1}
Fall (27 days)	7	20	2	MLD	1.23 m	17	MLD	0.42 m
				W_s	2.77 m s^{-1}		W_s	1.91 m s^{-1}
Winter (31 days)	17	14	6	MLD	0.85 m	7	MLD	0.30 m
				W_s	2.43 m s^{-1}		W_s	2.41 m s^{-1}

Conclusions and Prospect

1.Conclusions

(1) Lake Taihu stratifies in daytime and mixes in nighttime. It's thermal stratification is stronger in spring and summer but weaker in fall.

(2) Lake Taihu is warm polymictic. It's variation of thermal stratification is lower than that of deep lakes in seasonal scale, but is more intensive in daily scale. Polymictic lakes differ with each other due to location, depth and fetch.

(3) Traditional difference criteria（$\Delta T = 0.2°C$）is better than Kara's optimal criteria to use in Lake Taihu。

(4) Thermal stratification responds obviously to weather condition, being strongest in clear days, weaker in could days and disappears in overcast days. Lake Taihu cools down via net radiation and latent heat, which mix the lake slower than the wind do.

(5) Solar radiation and wind speed are two dominant factors. The stronger solar radiation, the stronger thermal radiation. The stronger wind, the stronger mixing. When solar radiation is weak, surface inversion layer and bottom warm region occur. They accelerate the mixing. Quantitative relationship between solar radiation and wind speed is found: stronger wind is needed to offset the stratifying effect when solar radiation gets stronger.

(6) Wind-induced convection is the main mechanism of thermal stratification switching. It's a good supplement of the thermal free convection theory. It's easier to happen at night than in the day, frequent in winter and fall but rare in summer.

2. Innovation

(1) Long-term data.

(2) Comparing with lakes with different depths, location and geomorphology.

(3) Strict comparison between reliable MLD criterion.

(4) Dominant factors and mechanism of thermal stratification change are found. This is helpful on understanding the thermal and dynamic processes in lakes, as well as on the improvement of the models.

3. Prospective

(1) Better data quality is needed to strengthen the conclusion.

(2) Focusing on PTS station, we did not consider the algae, macrophytes and surrounding environment. Other sites are worth picking to do the similar research.

(3) To exactly improve modeling work, a formula which depicts the quantitative relationship between solar radiation and wind speed is necessary.

(4) To get intuitional understanding on wind-induced convection, 3D flow field is needed in modeling working.

(5) To help with water resource management, it's important to answer the question "how does thermal stratification influence algae bloom?"

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