Yale-NUIST Center on Atmospheric Environment

Temporal dynamic of thermal diffusivity in water based on a k-ε model

Zhang Zhen, Cheng Xin

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Outline

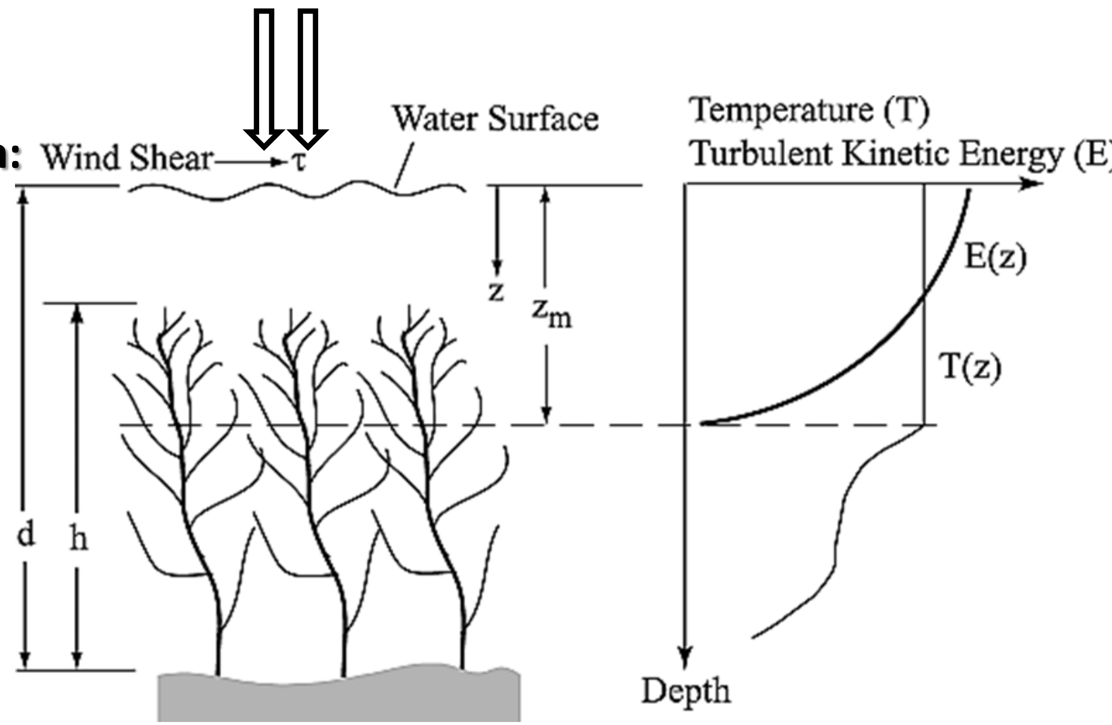
- Background
- Physical mechanism
- Model and Data
- Parameter optimization
- Preliminary results
- Conclusions
- On-going works

Background

- Shallow lakes have unique physical and biological characteristics that lead to strong interactions between biological, chemical and physical processes.
- Vertical turbulent mixing is an important role in lakes, which controls the temperature profile and the distribution of DO, nutrients and phytoplankton.
- While the importance of submerged macrophytes in shallow lake systems has been well documented, there is a lack of mechanistic relationship to include macrophytes in models.

Physical mechanism

Production of TKE
- **Natural convection:** vertical heat transfer
- **Forced convection:**



	Heat flux	***Stratification***	***TKE***
	Positive	Stable	Restraint
	Negative	Unstable	Production

Figure 1 Parameterization of one-dimensional water column model with submerged macrophytes

Model and Data

- k-ε model: one-dimensional equation for transport and dissipation of kinetic energy produced by wind, coupled to heating at the water surface.

Heat transfer equation: $$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) + \frac{H}{\rho c_P}$$

TKE equation: $$\frac{\partial E}{\partial t} = \frac{\partial}{\partial z}\left(K_z \frac{\partial E}{\partial z}\right) + K_z \alpha g \frac{\partial T}{\partial z} - 0.05 P C_D E^{\frac{2}{3}}$$

K ε

- Data: acquired from The Taihu Eddy Flux Network, mainly in the BFG site (2012-2015).

Parameter optimization

Table 1 Model parameter values

Parameter	Description	Nominal Value (units)
K_{wc}	light attenuation coefficient for water	2 m^{-1}
K_m	specific light attenuation coefficient for macrophytes	0.02 $m^2 gDW^{-1}$(Westlake [1964])
P	macrophyte biomass density	? $gDWm^{-3}$
MH	macrophyte stand height	2m in the Summer
d	water depth	Summer: 2m; Fall: 1.8m; Others: 1.6 m
C_k	mixing length coefficient	0.1(Herb [2005])
C_D	drag coefficient	1.0 (Finnigan [2000])
K_h	hypolimnetic diffusivity	0.03 $m^2 d^{-1}$(Herb [2005])
C_w	wind correction coefficient	1.0
nz	number of discrete depth increments	50
Δt	time increment	30min

Table 2 Comparison of Statistical data between observed and predicted water temperature (20cm, 50cm) with different Biomass density parameter in August, 2012-2015

ME (°C)	2012		2013		2014		2015	
	20cm	50cm	20cm	50cm	20cm	50cm	20cm	50cm
500gDWm^{-3}	0.8	1.5	0.9	1.3	0.6	0.8	0.8	1.0
300gDWm^{-3}	0.8	1.2	0.8	1.1	0.6	0.7	0.8	1.0
100gDWm^{-3}	0.7	0.8	0.7	0.7	0.6	0.5	0.6	0.6
50gDWm^{-3}	0.6	0.7	0.6	0.6	0.5	0.5	0.6	0.6
40gDWm^{-3}	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.5
20gDWm^{-3}	0.6	0.6	0.5	0.5	0.4	0.4	0.5	0.5
10gDWm^{-3}	0.6	0.6	0.6	0.6	0.4	0.4	0.5	0.5
0gDWm^{-3}	0.7	0.7	0.7	0.7	0.5	0.4	0.6	0.5

RMSE(°C)	2012		2013		2014		2015	
	20cm	50cm	20cm	50cm	20cm	50cm	20cm	50cm
500gDWm^{-3}	1.0	1.5	1.1	1.6	0.8	1.0	1.0	1.3
300gDWm^{-3}	1.0	1.2	1.0	1.4	0.8	0.9	1.0	1.1
100gDWm^{-3}	0.8	0.8	0.8	0.9	0.7	0.6	0.8	0.8
50gDWm^{-3}	0.8	0.7	0.8	0.8	0.7	0.6	0.7	0.7
40gDWm^{-3}	0.7	0.6	0.8	0.8	0.7	0.6	0.7	0.7
20gDWm^{-3}	0.6	0.6	0.6	0.6	0.6	0.5	0.6	0.6
10gDWm^{-3}	0.7	0.6	0.7	0.7	0.6	0.5	0.6	0.6
0gDWm^{-3}	0.8	0.7	0.9	0.9	0.6	0.5	0.7	0.6

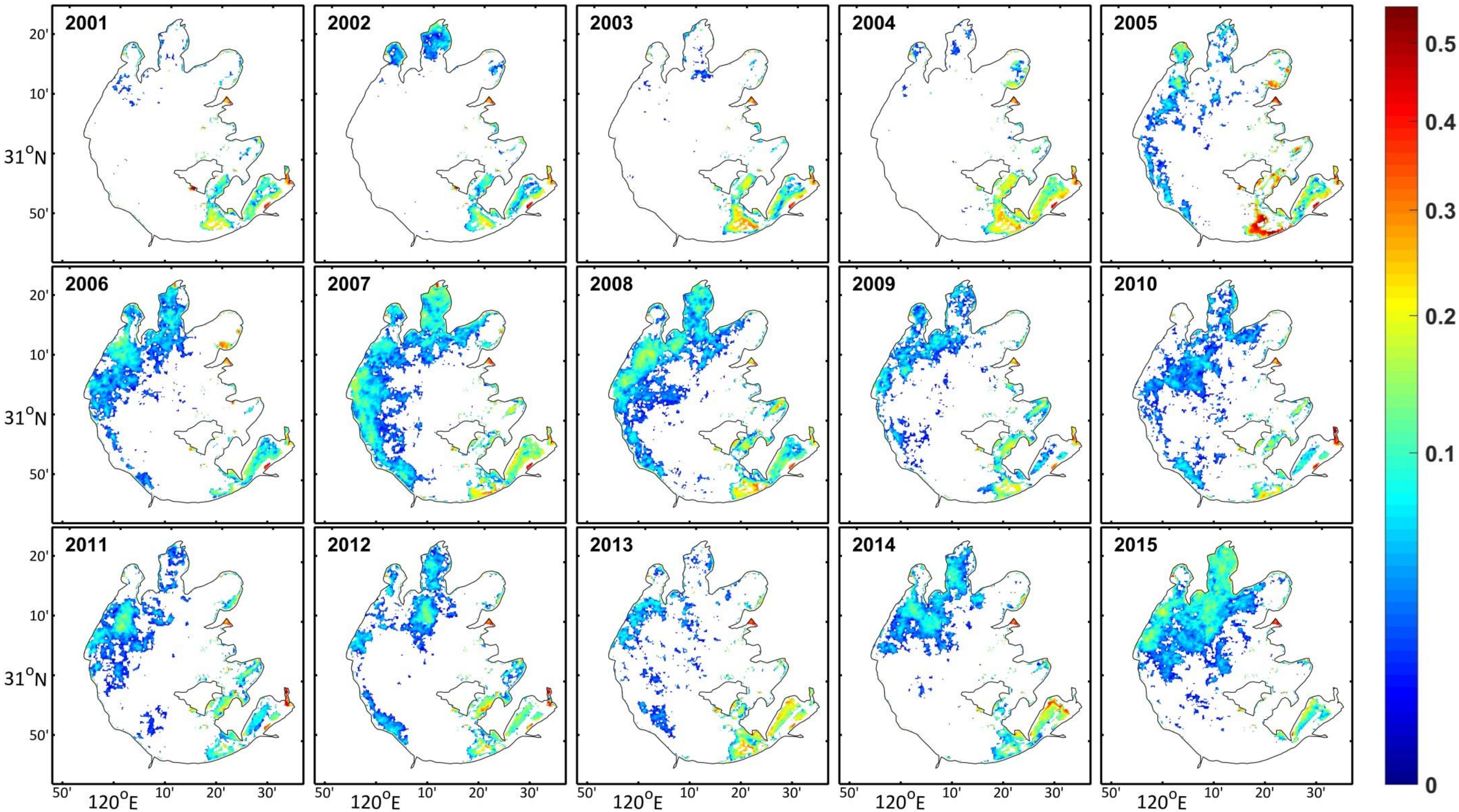


Figure 2 interannual NDVI spatial distribution of Lake Taihu from 2001 to 2015

Table 3 Parameter values adjustment relied on four–years averaged month's NDVI value

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NDVI	-0.09	-0.04	-0.06	-0.02	0.02	0.05	0.10	0.15	0.09	0.03	-0.04	-0.09
B(2012)	0	0	0	0	3	7	14	20	12	4	0	0
B(2013)	0	0	0	0	3	7	14	20	12	4	0	0
B(2014)	0	0	0	0	2	5	10	16	9	4	0	0
B(2015)	0	0	0	0	2	4	8	12	7	3	0	0
MH	1.2	1.2	1.2	1.2	1.6	1.6	1.6	2	1.8	1.6	1.2	1.2

NDVI: Normalized Difference Vegetation Index B: Biomass density MH: macrophyte height

Preliminary results

- Temperature Performance(Case: 2012, 2014)
  - Comparison between measured and predicted T_w
  - Predicted temperature profile
- Energy distribution(Case: 2013)
  - Comparison between measured and predicted H, LE, u_*
  - Predicted TKE and K_z (vertical turbulent diffusivity)

Water temperature at depth of 0.2m in 2012

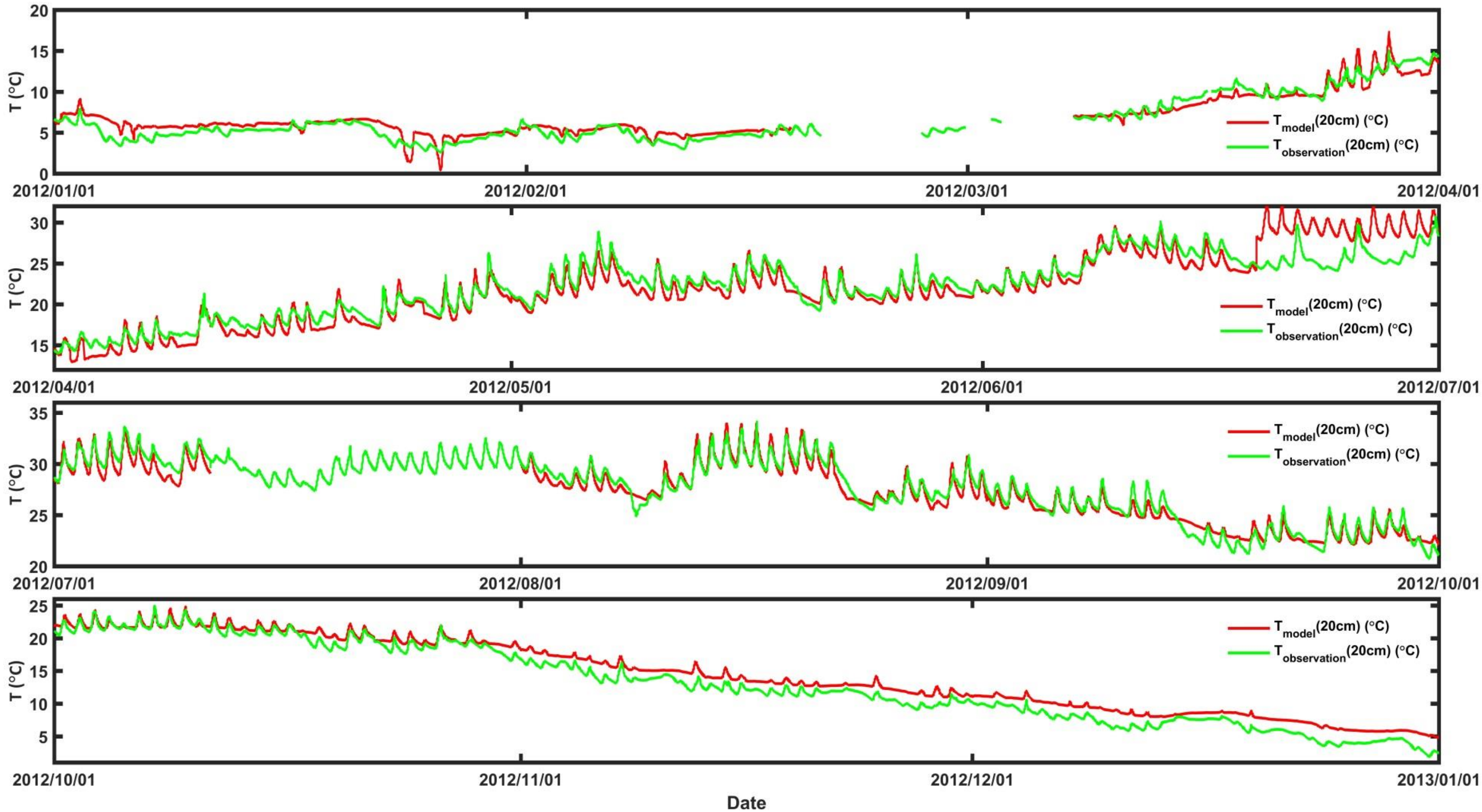


Figure 3a Time series for DOY 1-366(2012) at BFG site: measured water temperature (20cm; green lines) and predicted water temperature (20cm; red lines)

Water temperature at depth of 0.5m in 2012

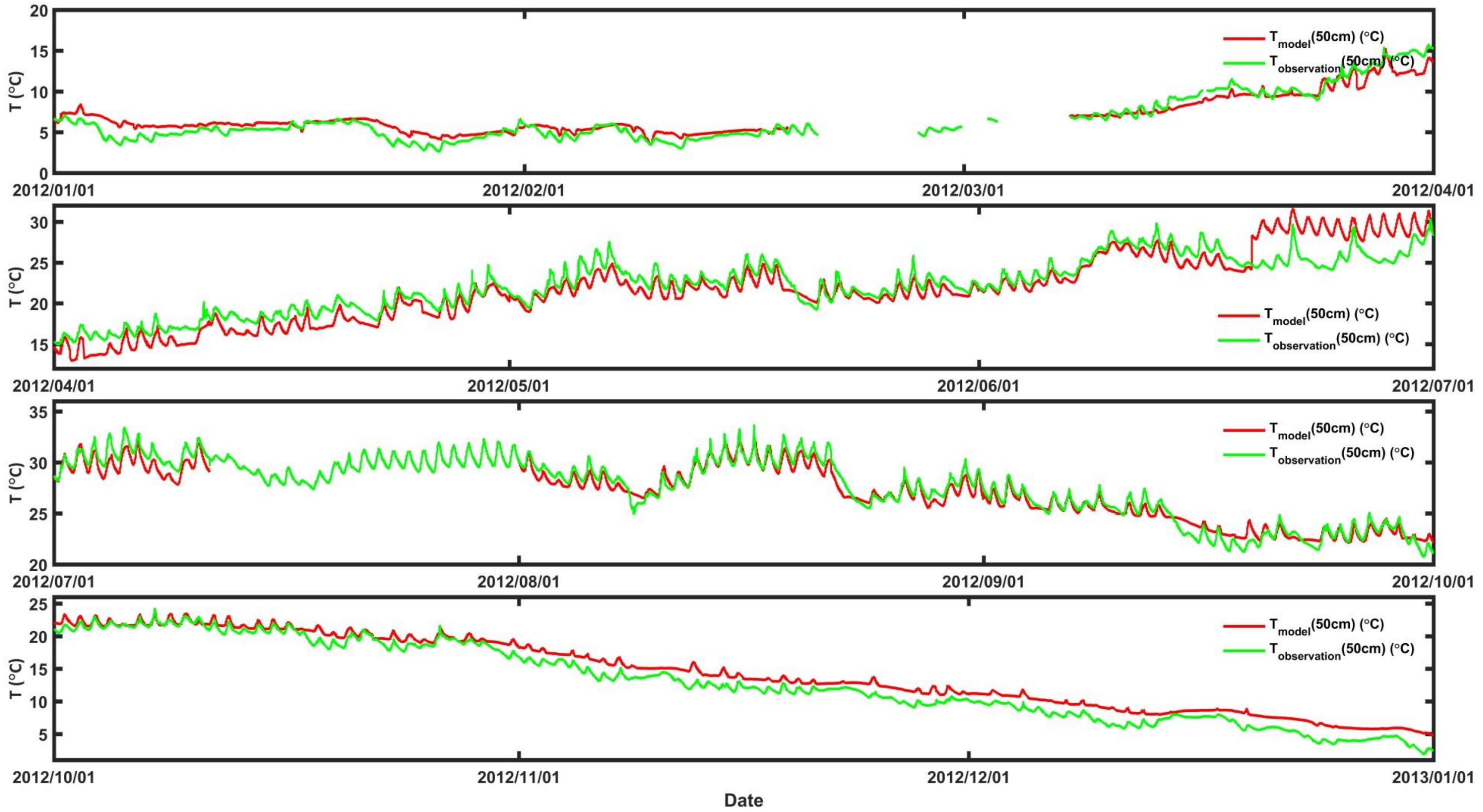


Figure 3b Time series for DOY 1-366(2012) at BFG site: measured water temperature (50cm; green lines) and predicted water temperature (50cm; red lines)

Water temperature at depth of 1.0m in 2012

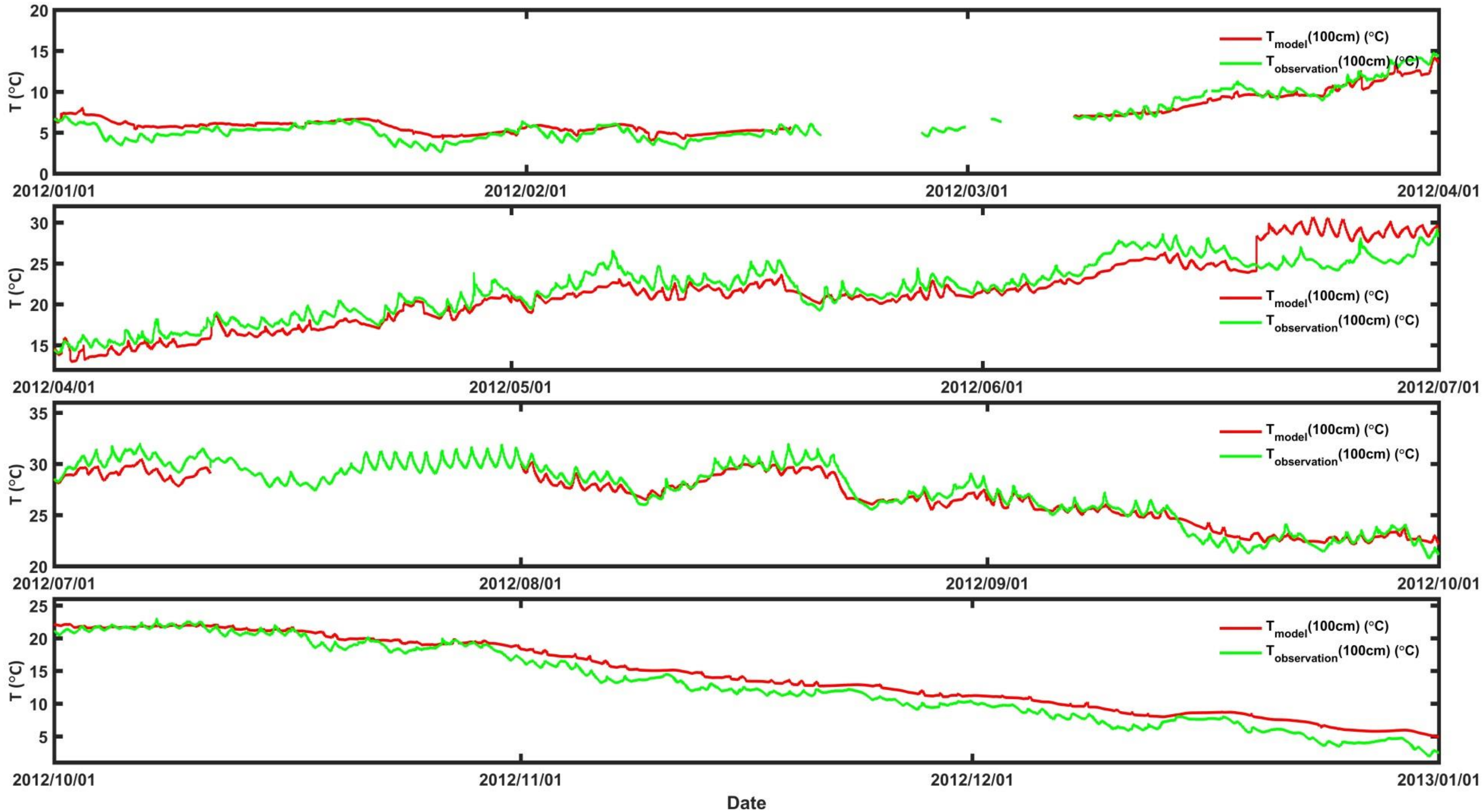


Figure 3c Time series for DOY 1-366(2012) at BFG site: measured water temperature (100cm; green lines) and predicted water temperature (100cm; red lines)

Water temperature at depth of 1.5m in 2012

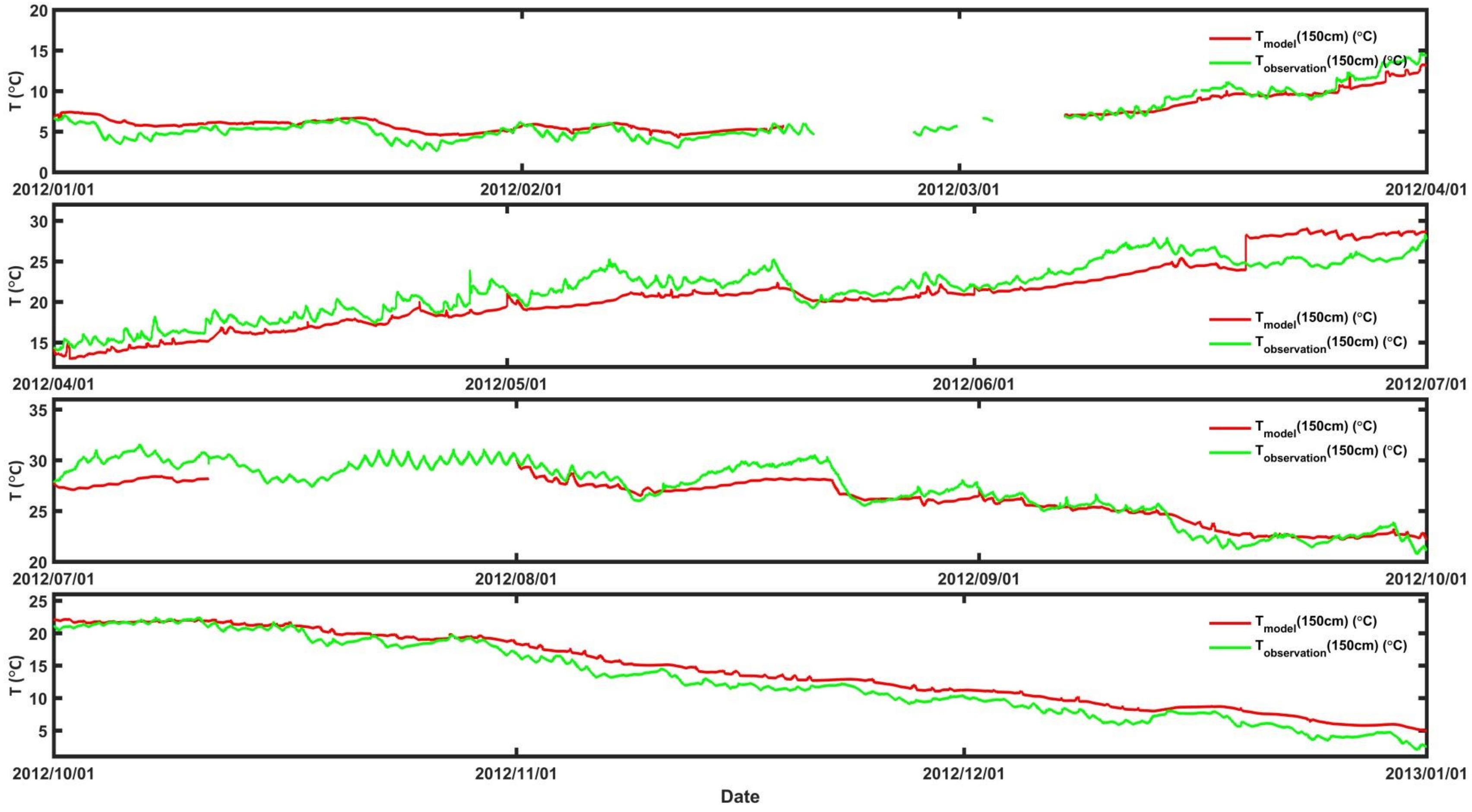


Figure 3d Time series for DOY 1-366(2012) at BFG site: measured water temperature (150cm; green lines) and predicted water temperature (150cm; red lines)

Water temperature profile in 2012

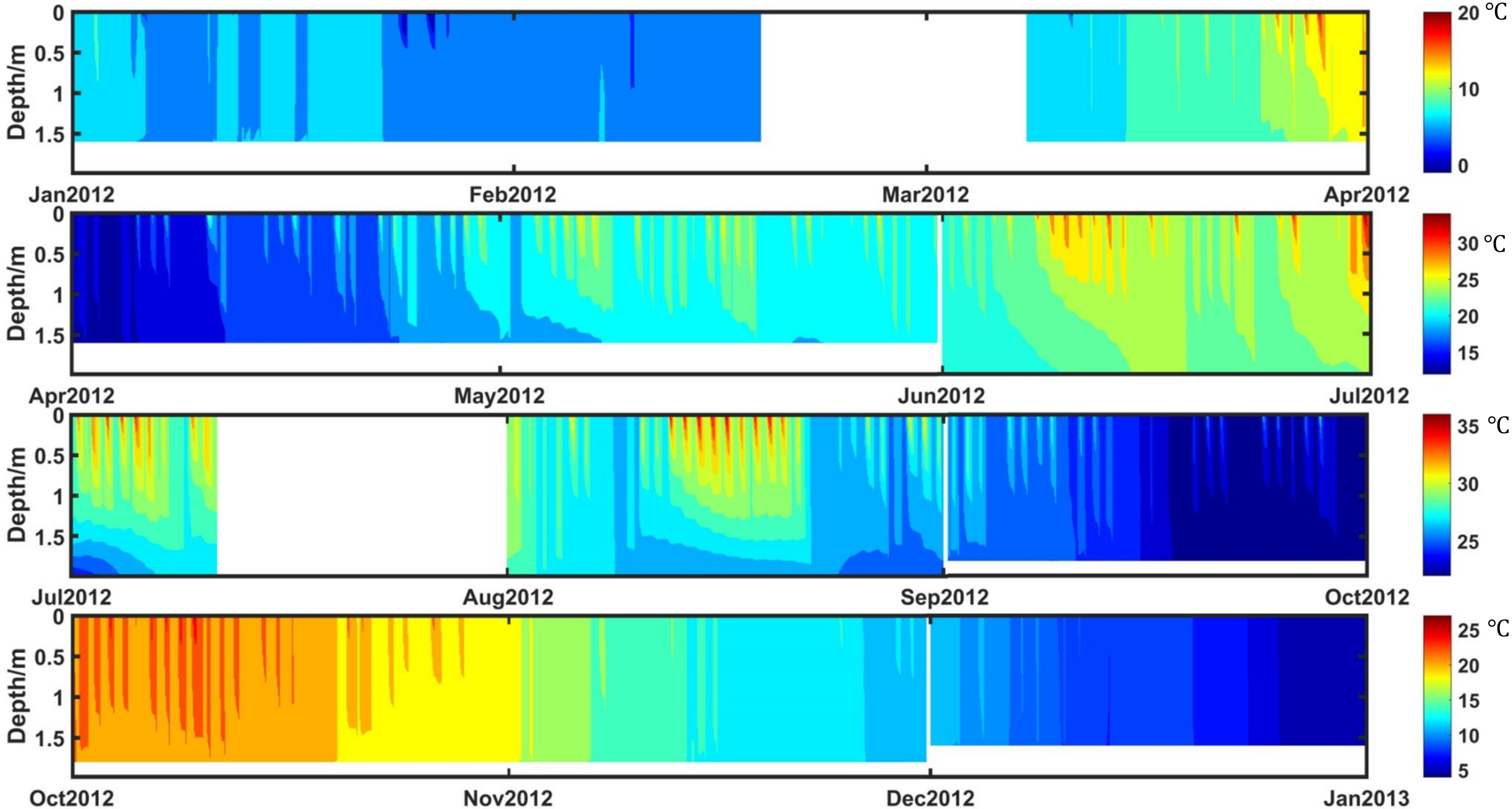


Figure 4 Time series of predicted water temperature profile for DOY 1-366(2012) at BFG site

Water temperature at depth of 0.2m in 2014

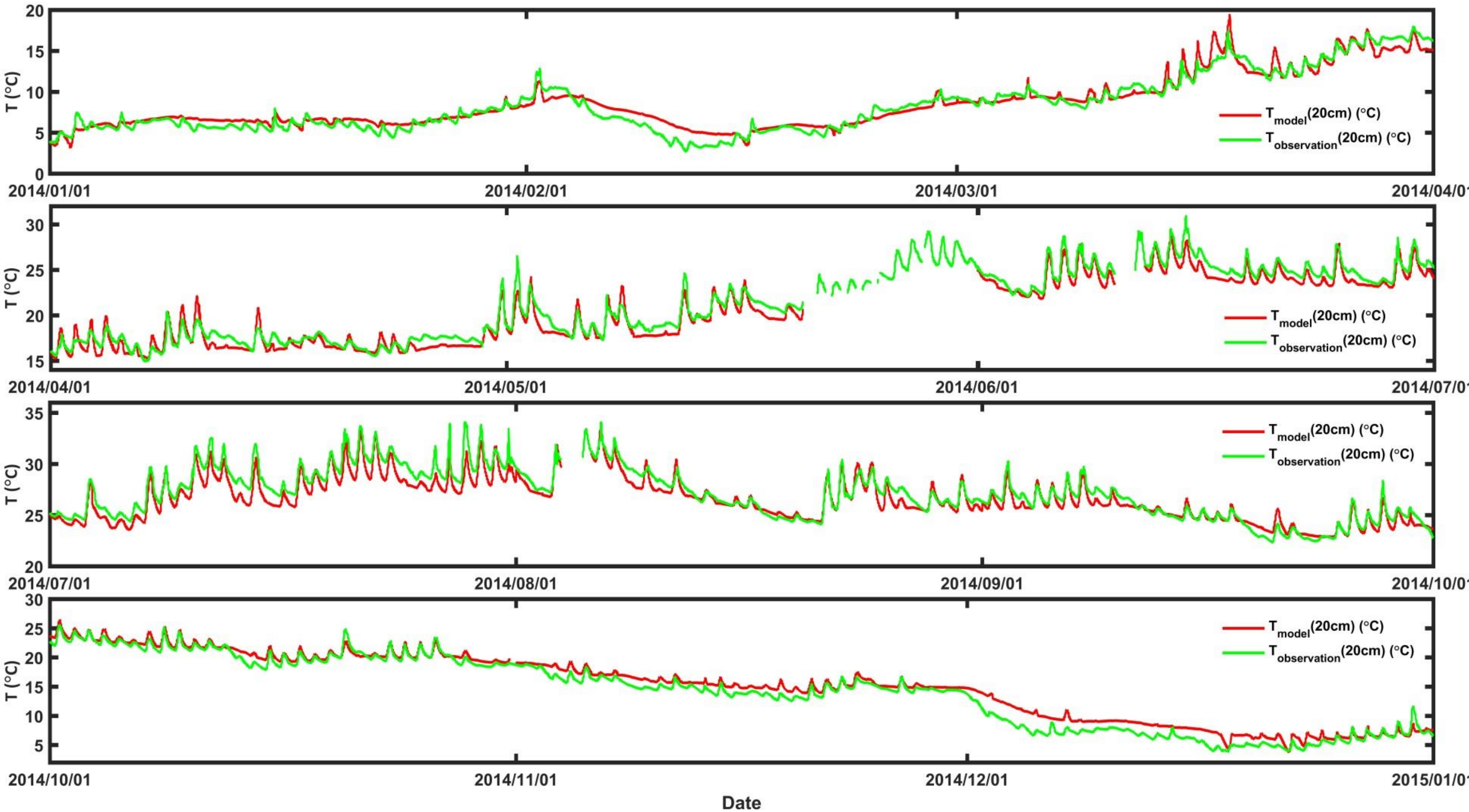


Figure 5a Time series for DOY 1-365(2014) at BFG site: measured water temperature (20cm; green lines) and predicted water temperature (20cm; red lines)

Water temperature at depth of 0.5m in 2014

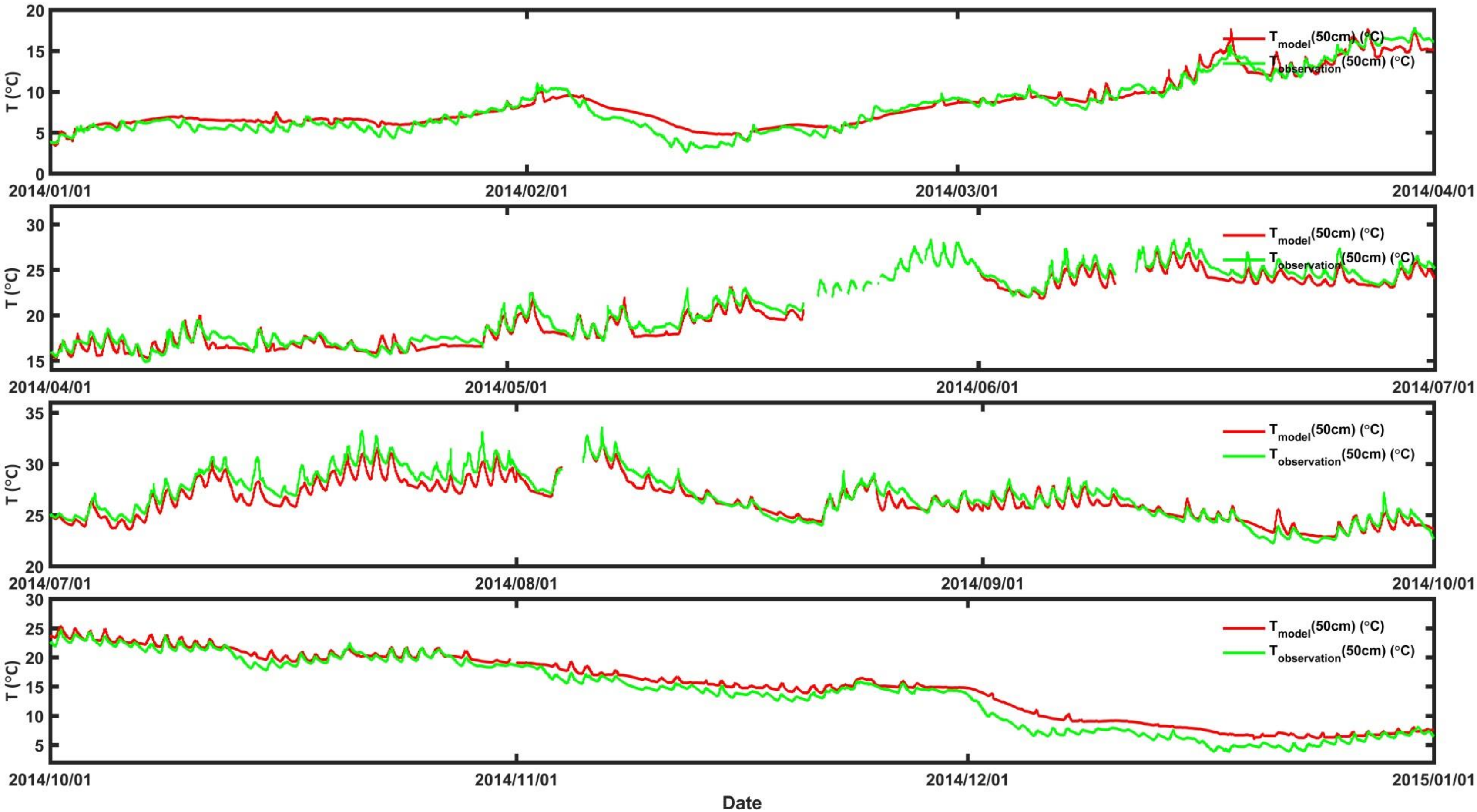


Figure 5b Time series for DOY 1-365(2014) at BFG site: measured water temperature (50cm; green lines) and predicted water temperature (50cm; red lines)

Water temperature at depth of 1.0m in 2014

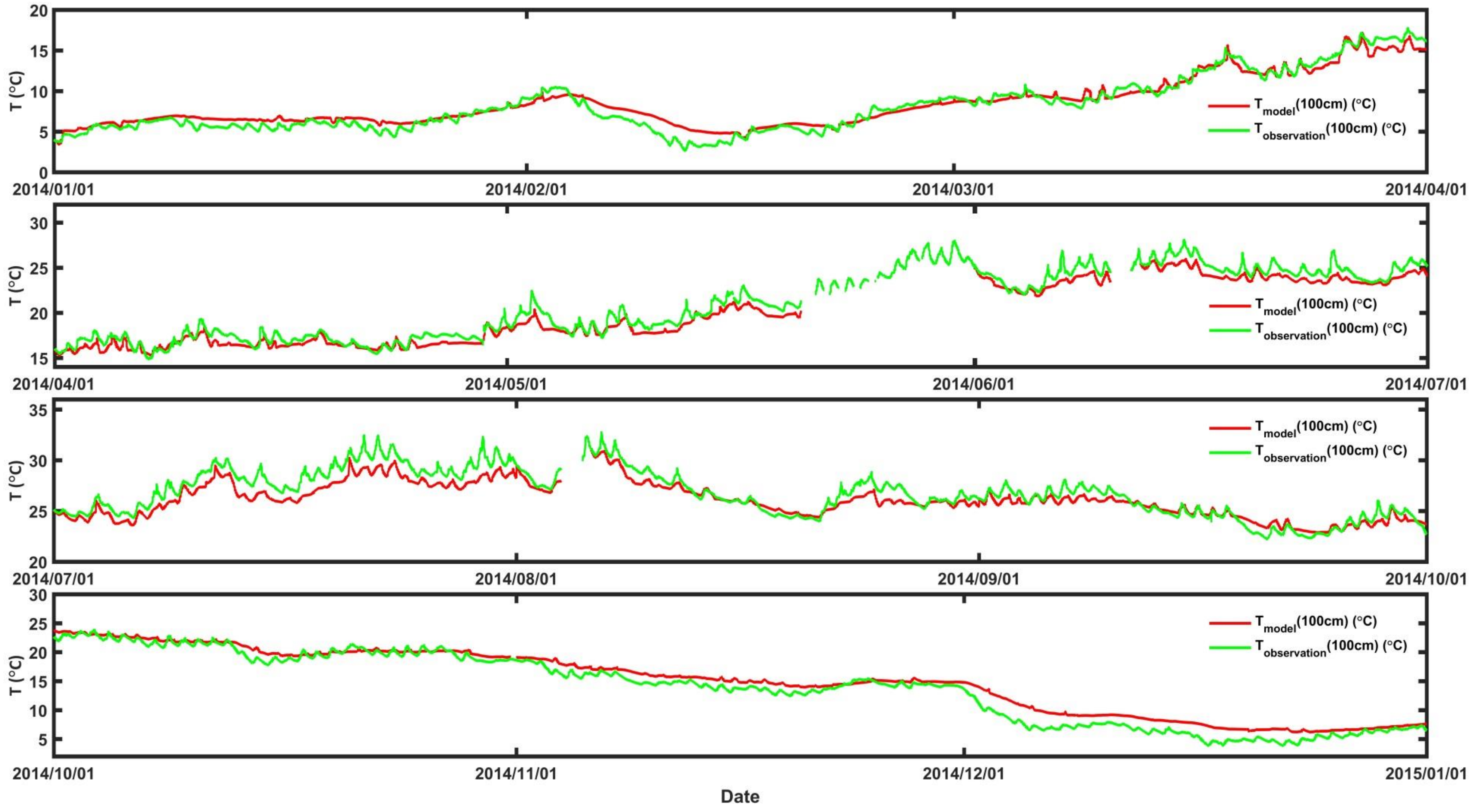


Figure 5c Time series for DOY 1-365(2014) at BFG site: measured water temperature (100cm; green lines) and predicted water temperature (100cm; red lines)

Water temperature at depth of 1.5m in 2014

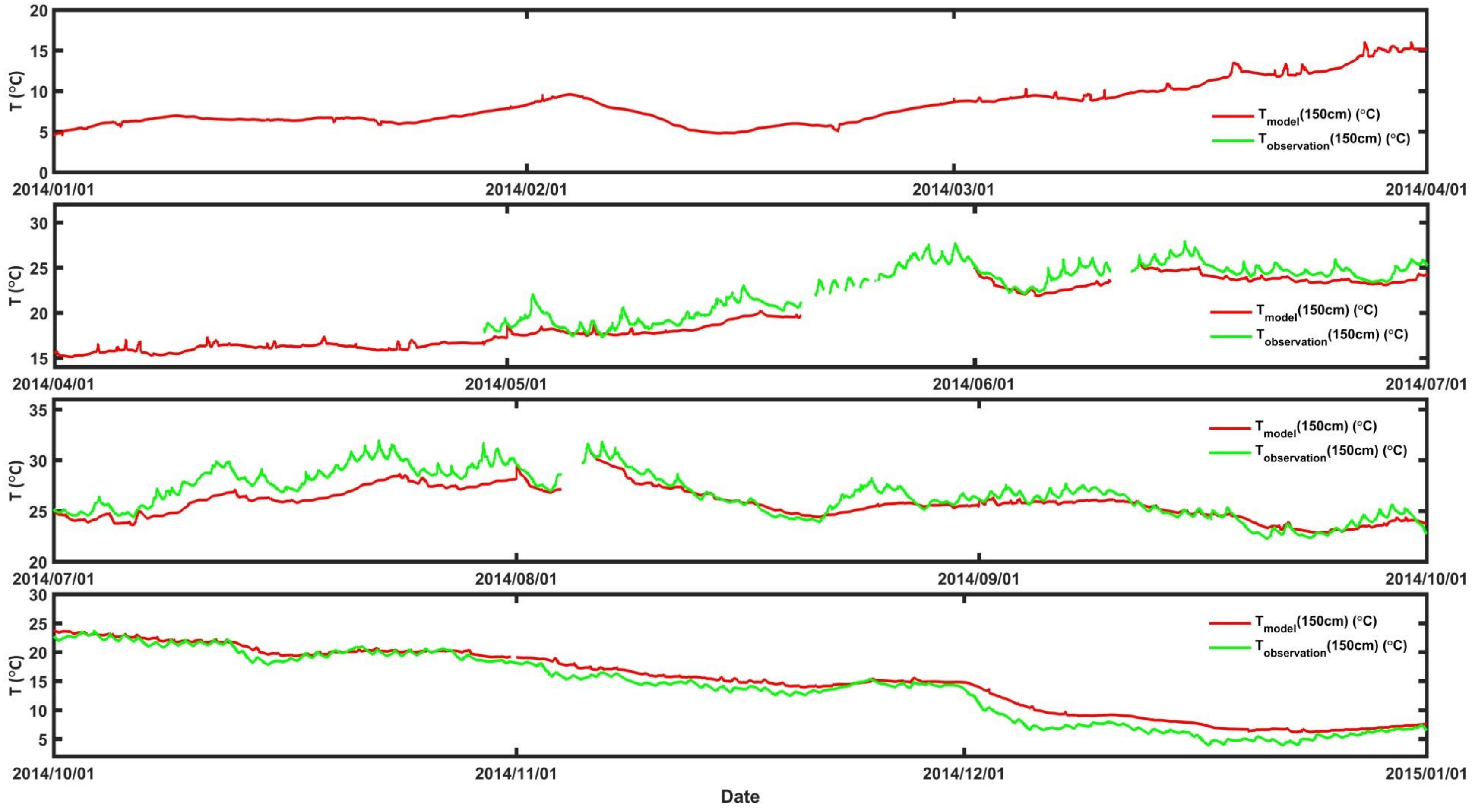


Figure 5d Time series for DOY 1-365 (2014) at BFG site: measured water temperature (150cm; green lines) and predicted water temperature (150cm; red lines)

Water temperature profile in 2014

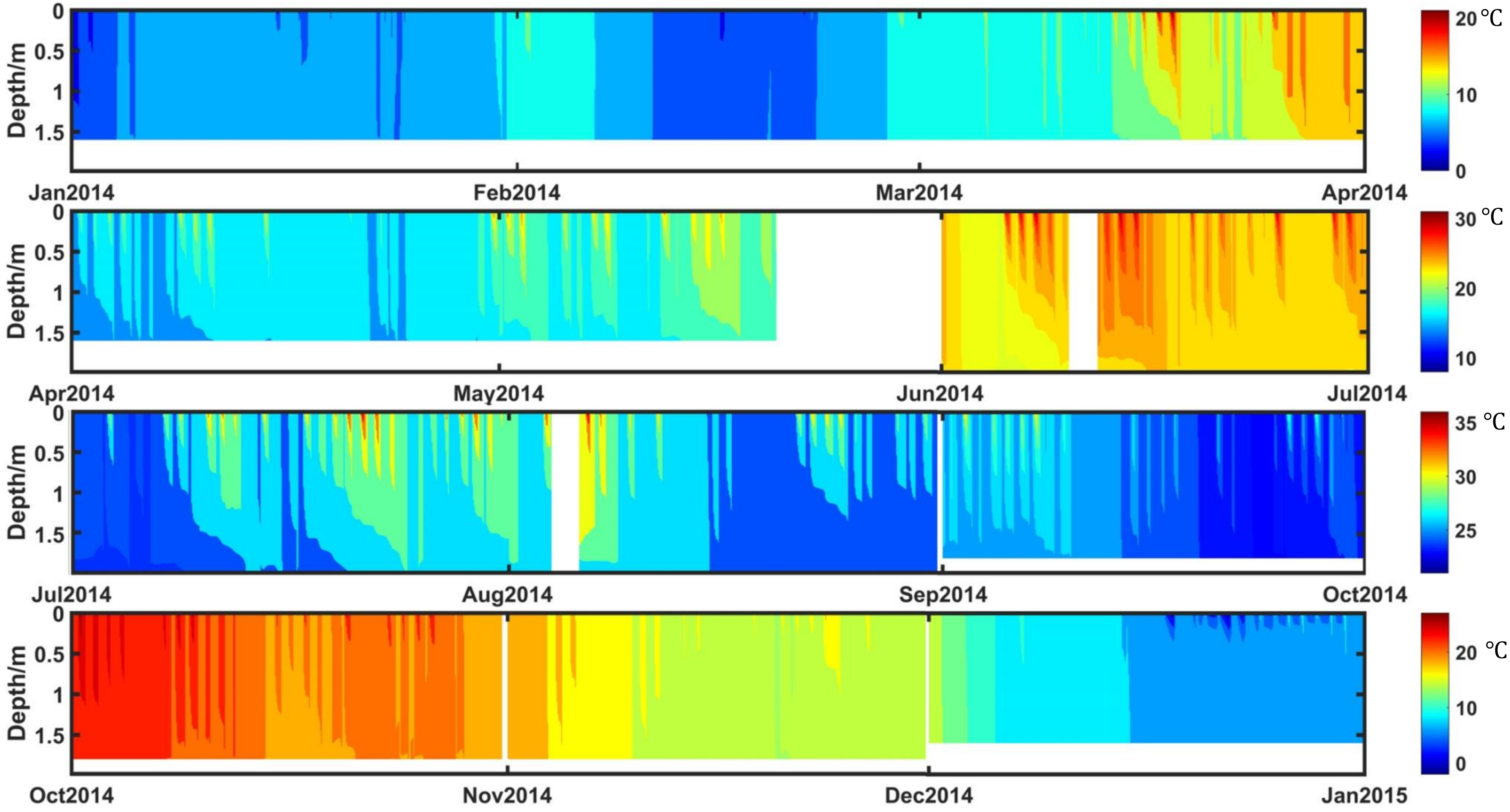


Figure 6 Time series of predicted water temperature profile for DOY 1-365(2014) at BFG site

Table 4 Comparison of Mean errors between observed and predicted water temperature (20cm, 50cm, 100cm, 150cm) in 2012-2015

2012

ME(℃)	20cm	50cm	100cm	150cm
Jan	0.9	0.9	0.9	0.9
Feb	0.4	0.4	0.4	0.4
Mar	0.6	0.5	0.5	0.6
Apr	0.9	1.4	1.1	1.5
May	0.1(?)	1.0	1.2	1.6
Jun	0.8	0.9	1.2	1.6
Jul	0.7	0.7	0.9	1.4
Aug	0.6	0.6	0.6	1.0
Sep	0.6	0.5	0.5	0.5
Oct	0.7	0.7	0.7	0.7
Nov	1.6	1.6	1.6	1.7
Dec	1.5	1.5	1.5	1.5

2013

ME(℃)	20cm	50cm	100cm	150cm
Jan	0.9	0.9	0.9	1.0
Feb	0.7	0.7	0.7	0.8
Mar	0.7	0.6	0.7	1.0
Apr	0.8	0.8	0.9	1.4
May	0.1(?)	0.8	1.1	1.9
Jun	0.2(?)	0.5	1.0	1.3
Jul	1.0	0.9	1.4	2.0
Aug	0.6	0.6	0.9	0.9
Sep	0.8	0.8	0.8	0.9
Oct	0.9	1.0	0.9	1.9
Nov	1.9	2.0	1.9	1.9
Dec	1.4	1.5	1.5	1.5

2014

ME(℃)	20cm	50cm	100cm	150cm
Jan	0.5	0.6	0.6	0.7(?)
Feb	0.9	0.9	0.9	1.0(?)
Mar	0.7	0.6	0.6	1.0(?)
Apr	0.6	0.5	0.6	0.1(?)
May	0.5	0.4	0.5	0.8
Jun	0.7	0.7	0.8	1.0
Jul	1.1	1.0	1.2	1.8
Aug	0.5	0.4	0.6	0.5
Sep	1.0	1.8	0.7	0.6
Oct	0.6	0.7	0.7	0.6
Nov	0.9	1.1	1.1	1.1
Dec	1.6	1.8	1.8	1.8

2015

ME(℃)	20cm	50cm	100cm	150cm
Jan	0.7	0.8	0.8	0.8
Feb	0.7	0.6	0.6	0.7
Mar	0.8	0.8	0.9	1.5
Apr	0.9	0.7	0.7	1.1
May	0.7	0.5	0.6	0.8
Jun	0.6	0.5	0.7	0.9
Jul	0.8	0.7	1.0	1.4
Aug	0.5	0.5	0.6	0.8
Sep	0.4	0.4	0.4	0.4
Oct	0.9	0.9	0.9	0.8
Nov	2.4	1.8	1.8	1.7
Dec	1.4	1.5	1.5	1.5

Sensible heat flux in 2013

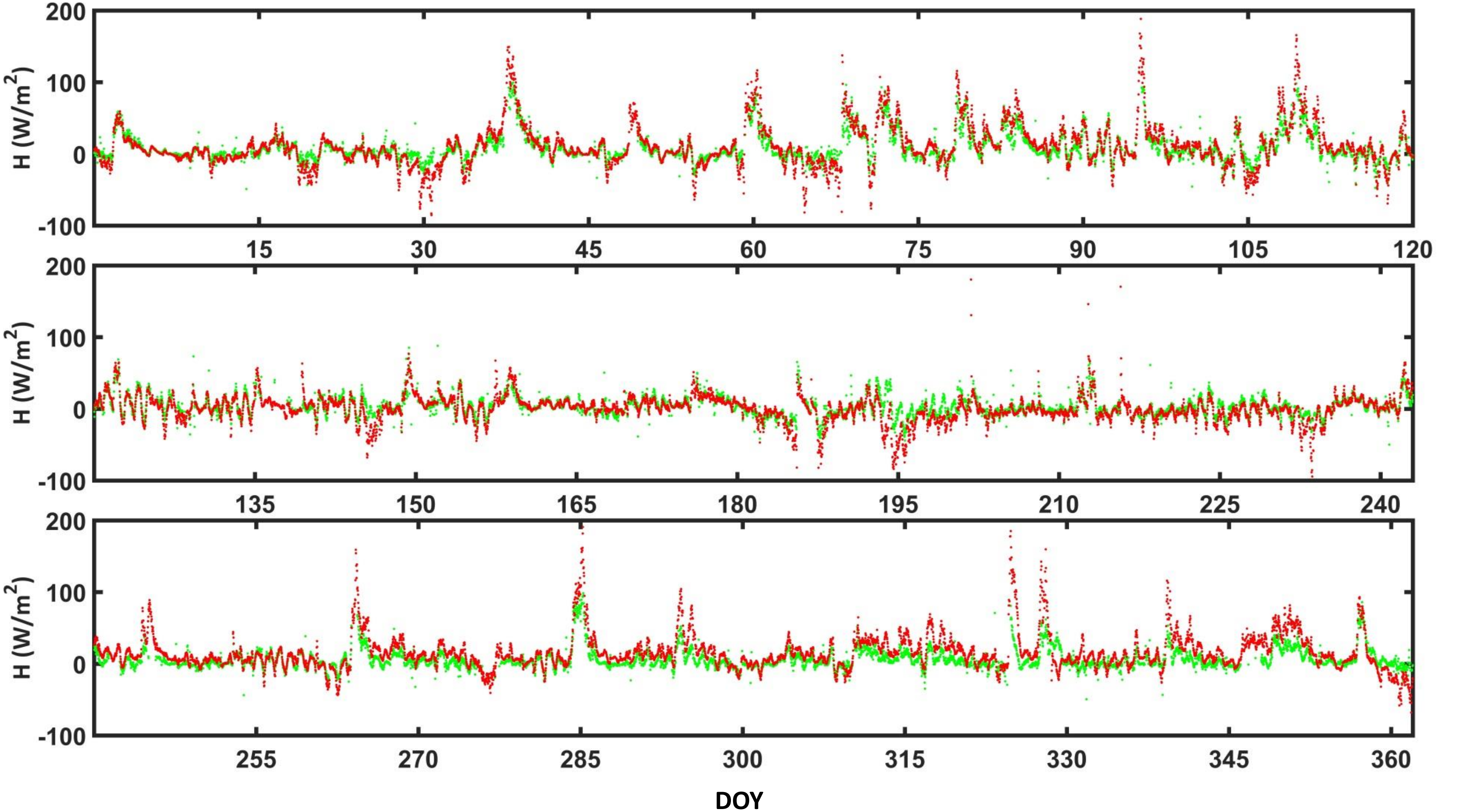


Figure 7 Time series for DOY 1-365(2013) at BFG site: measured Sensible heat flux(green dots) and predicted Sensible heat flux(red dots)

Latent heat flux in 2013

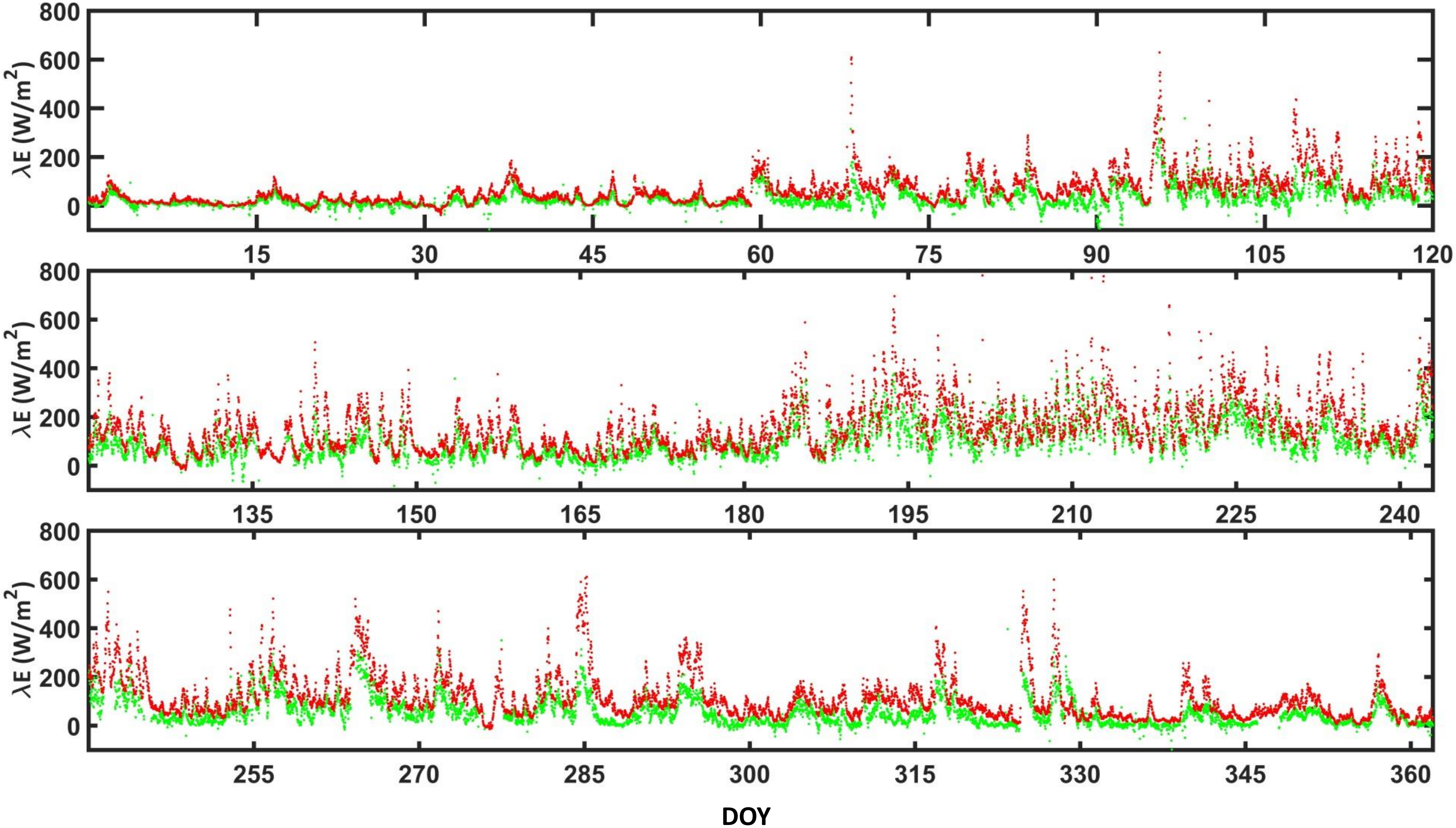


Figure 8 Time series for DOY 1-365(2013) at BFG site: measured Latent heat flux(green dots) and predicted Latent heat flux(red dots)

Shear velocity in 2013

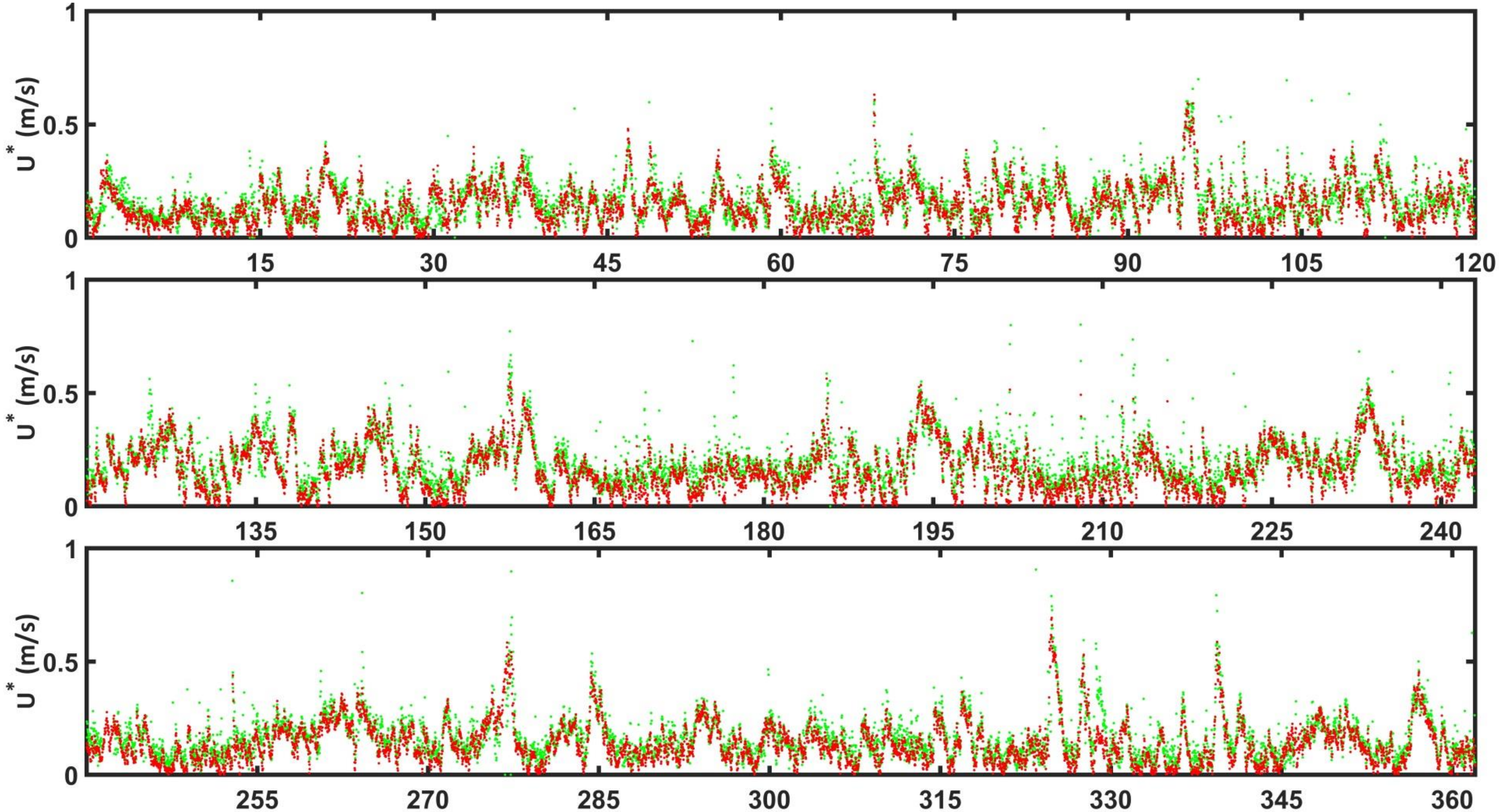


Figure 9 Time series for DOY 1-365(2013) at BFG site: measured shear velocity (green dots) and predicted shear velocity (red dots)

Table 5 monthly mean errors and root-mean-square errors of measured *H*, *LE*, u_* and predicted *H*, *LE*, u_* at BFG site in 2013

	H		*LE*		u_*	
	ME (W/m^2)	RMSE (W/m^2)	ME (W/m^2)	RMSE (W/m^2)	ME (m/s^2)	RMSE (m/s^2)
January	6.1	10.7	12.6	17.0	0.04	0.06
February	5.9	9.3	16.1	22.7	0.04	0.06
March	10.5	15.0	44.6	59.1	0.05	0.07
April	8.5	13.0	61.1	81.4	0.05	0.07
May	5.6	9.4	44.1	63.9	0.04	0.06
June	4.4	7.0	34.8	47.0	0.05	0.07
July	10.3	16.0	56.8	76.8	0.05	0.07
August	6.3	9.4	57.8	79.3	0.04	0.07
September	7.6	10.7	59.2	75.5	0.04	0.06
October	10.7	15.1	69.4	93.0	0.04	0.05
November	14.7	21.4	61.7	78.2	0.04	0.07
December	13.2	17.3	35.8	46.7	0.04	0.05

Water temperature profile in 2013

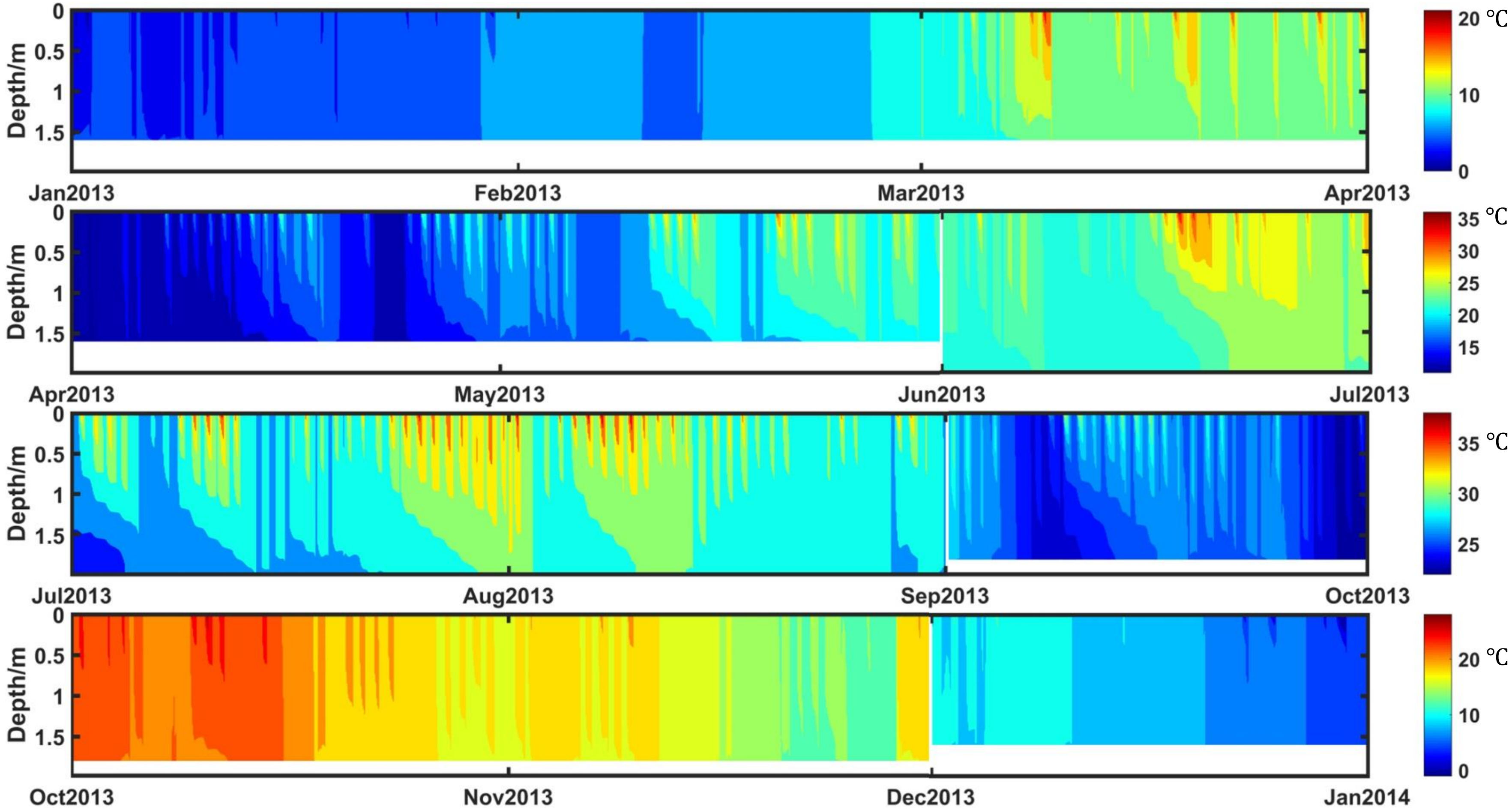


Figure 10 Time series of predicted water temperature profile for DOY 1-365(2013) at BFG site

Turbulent kinetic energy profile in 2013

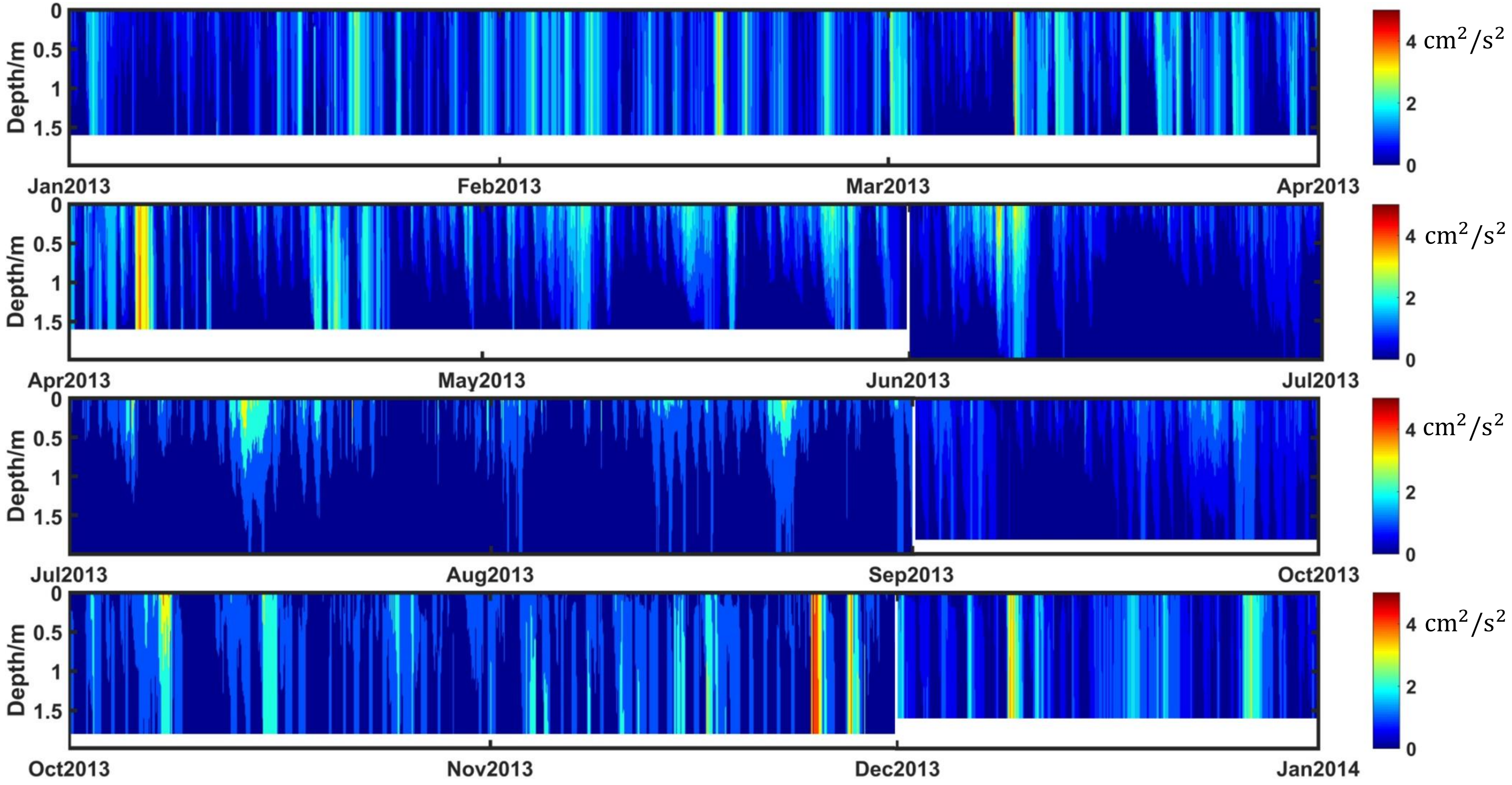


Figure 11 Time series of predicted Turbulent kinetic energy for DOY 1-365(2013) at BFG site

Vertical turbulent diffusivity profile in 2013

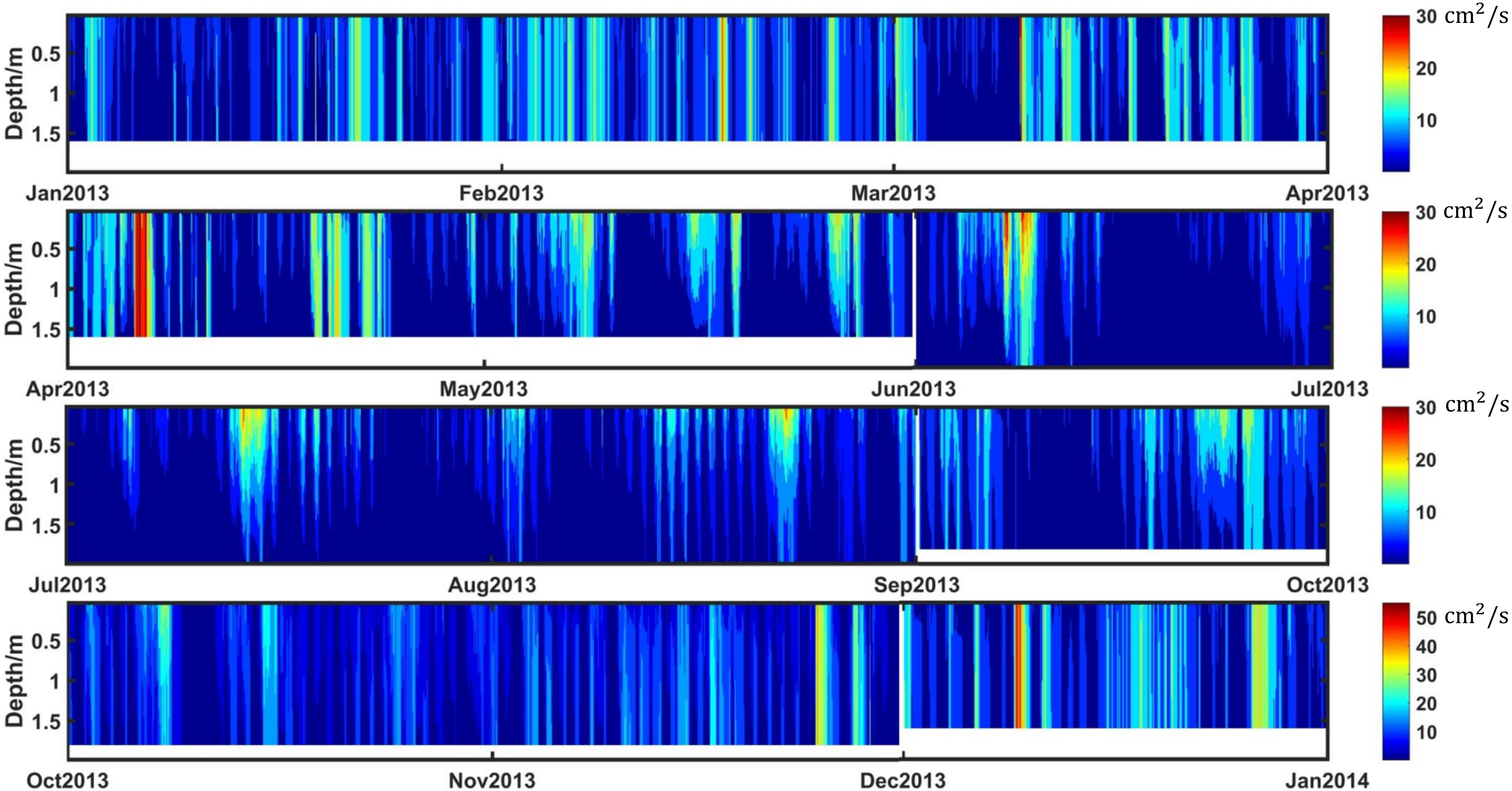


Figure 12 Time series of predicted vertical turbulent diffusivity for DOY 1-365(2013) at BFG site

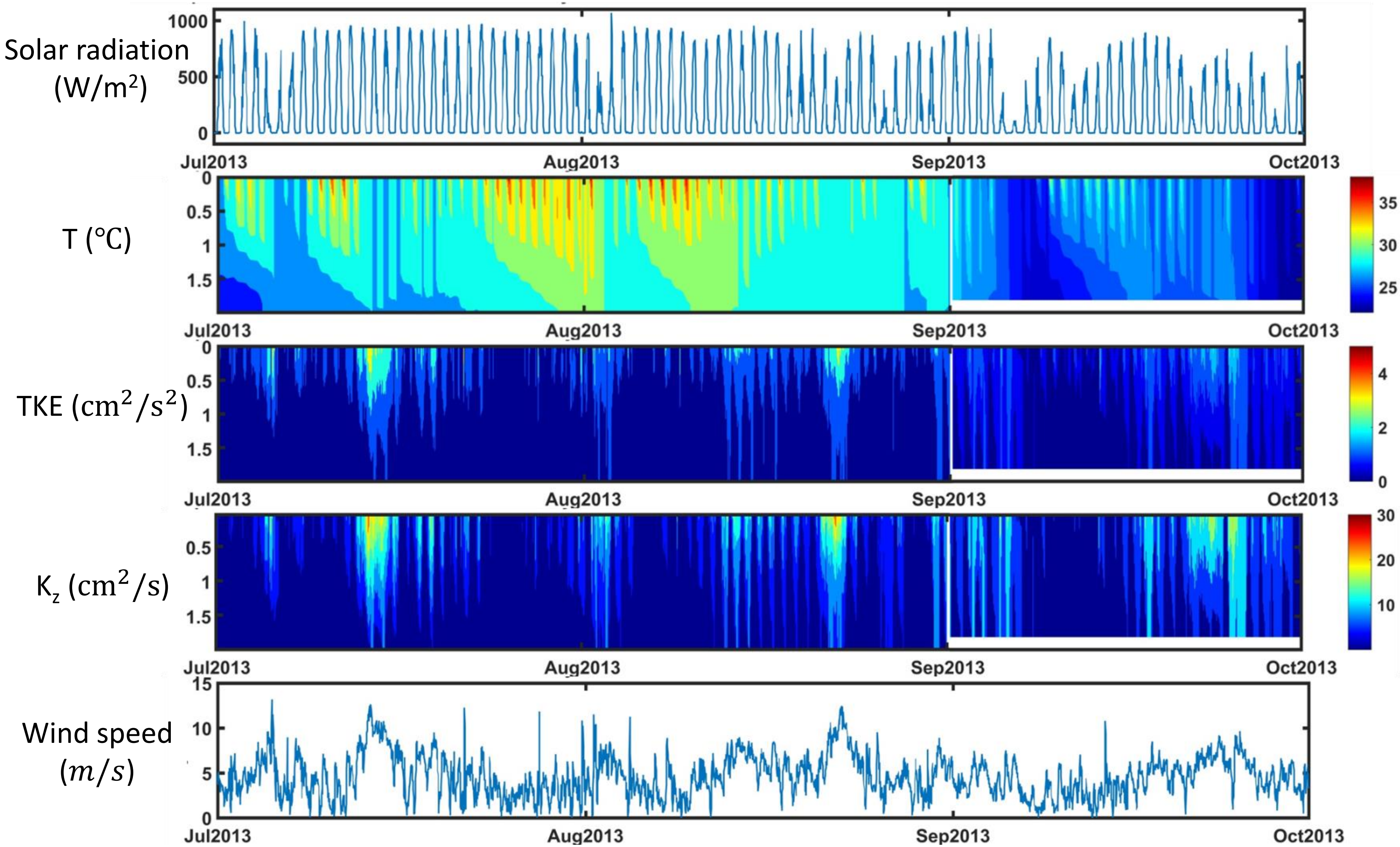


Figure 13 Time series of solar radiation, water temperature profile, turbulent kinetic energy and wind speed for DOY 182-273(2013) at BFG site

Conclusions

- Parameter optimization focus on biomass density related to NDVI variation.
- K-ε model has good performance in water temperature prediction (ME and RMSE are less than 1.0 ℃ under most circumstances), which can also simulate temperature profile, *H*, *LE*, u_* trend well.
- It is doubtful that the result of spring and winter's predicted turbulent kinetic energy (probably because relatively poor T_w performance) and the magnitude of vertical turbulent diffusivity.

On-going works

- Improve the temporal resolution of dynamic water depth.
- Establish precise evaluation System for model in favor of parameter optimization.
- Try to add other module in order to improve the integrity of model.
- Be related to mass transport in shallow lakes with macrophytes.


Thank you
当心触电
Photographer: Cao zhengda