# Seasonal Spatial Patterns of Surface Water Temperature, Surface Heat Fluxes and Meteorological Forcing Over Lake Geneva

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## 1- Introduction and problem statement

In many lakes, surface heat flux (SHF) is the most important component controlling the lake's energy content. Accurate methods for the determination of SHF are valuable for water management, and for use in hydrological and hydrodynamic models. Large lakes, not surprisingly, are subject to spatially and temporally varying meteorological conditions, and hence SHF. Furthermore, the SHF and indeed the entire lake ecosystem is influenced by the lake surface water temperature (LSWT). Although previous studies confirm the SHF variability, they mostly used the point analysis to address this question.

Here, an investigation for estimating the SHF spatial patterns of a large European lake, Lake Geneva (Fig. 1), is reported. We evaluated several bulk formulas to estimate Lake Geneva's SHF based on different datasets. Data sources to run the models included spatio-temporal meteorological data from an operational numerical weather prediction model, COSMO-2, and LSWT from Advanced Very High Resolution Radiometer (AVHRR) satellite imagery.

Models were calibrated at two points in the lake (SHL2 and GE3, Fig. 1) for which regular depth profiles of temperature are available, and which enabled computation of the total heat content variation.

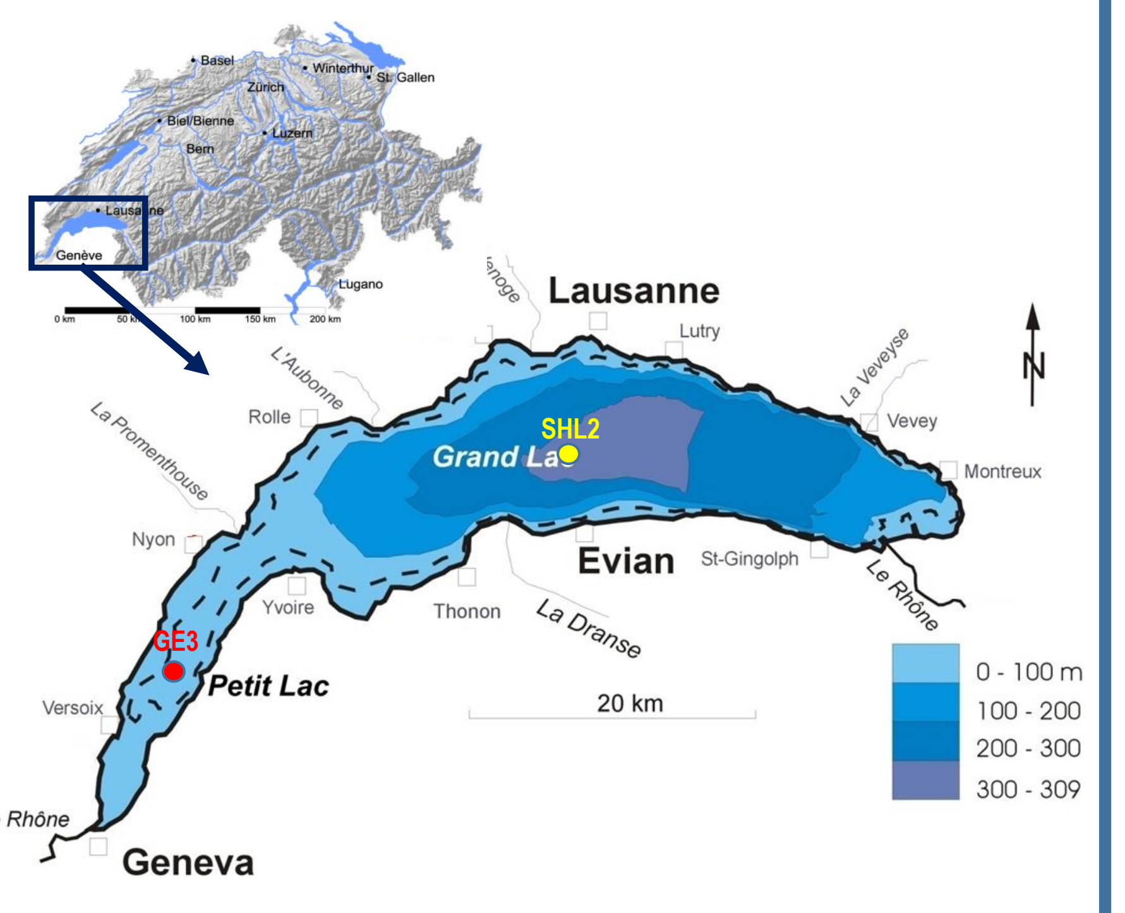


**Figure 1.** Location and bathymetry of Lake Geneva in Switzerland. SHL2 and GE3 are two monitoring points in the lake used for models calibration and verification.

## 2- Methodology

The total heat exchange at the air-water interface is:

$$Q_{tot}(t) \cong \underbrace{Q_{sn}}_{\text{Solar radiation}} + \underbrace{Q_{an}}_{\text{Atmospheric radiation}} - \underbrace{Q_{br}}_{\text{Surface reflection}} - \underbrace{Q_{ev}}_{\text{Evaporation}} - \underbrace{Q_{co}}_{\text{Convection}} = Q_{tot}(\vec{s},\vec{\theta})$$

$$\vec{s} = [\underbrace{T_s(t)}_{\text{AVHRR}}, \underbrace{T_a(t), C(t), \phi_{rel}(t), U_{10}(t), Q_s(t)}_{\text{COSMO-2 model}}]$$

⇨ LSWT, air temperature, cloudiness, relative humidity, wind speed and global radiation, respectively

$\vec{\theta}$: Calibration parameters ⇨ There are 4 calibration factors for each model including: $C_{cloud}$ (cloud type), $C_{an}$ (atmospheric emissivity), $C_{ev}$ or $C_{mur}$ or $C_e$ (depending on selected evaporation model), $C_h$ or γ (depending on selected convection model)

Models calibration was accomplished by minimizing the root mean square error (RMSE) of model/observation heat content:

$$G_{mo}(t) = \int_0^t Q_{tot}(t')\,dt' \Longleftrightarrow G_{obs}(t) = \int_0^H \rho_w C_p T(z,t)\,dz$$

Models were calibrated for the period of 03.2008-12.2010. The best models were then verified for 01.2011-12.2013. The best calibrated model was then selected to calculate the spatial distribution of SHF for the entire period.

## 3- Some examples of input data: Satellite data and meteorological forcing

AVHRR data from the US National Oceanic and Atmospheric Administration (NOAA) have a spatial resolution of about 1 km x 1 km whereas the COSMO-2 model provides hourly meteorological data with a resolution of 2.2 km.

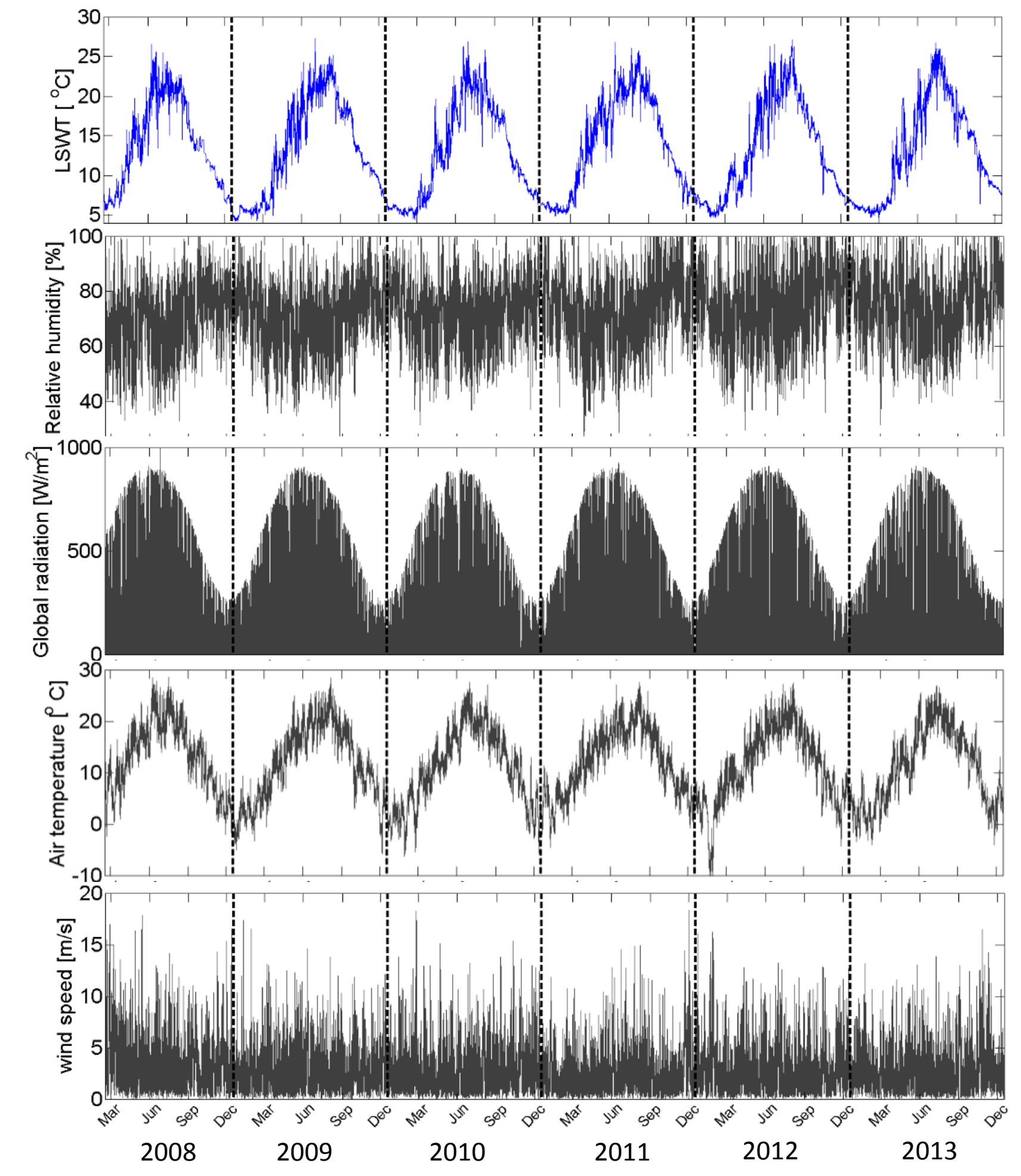


**Figure 2.** LSWT data and hourly meteorological forcing at SHL2 point (cloudiness is not shown).

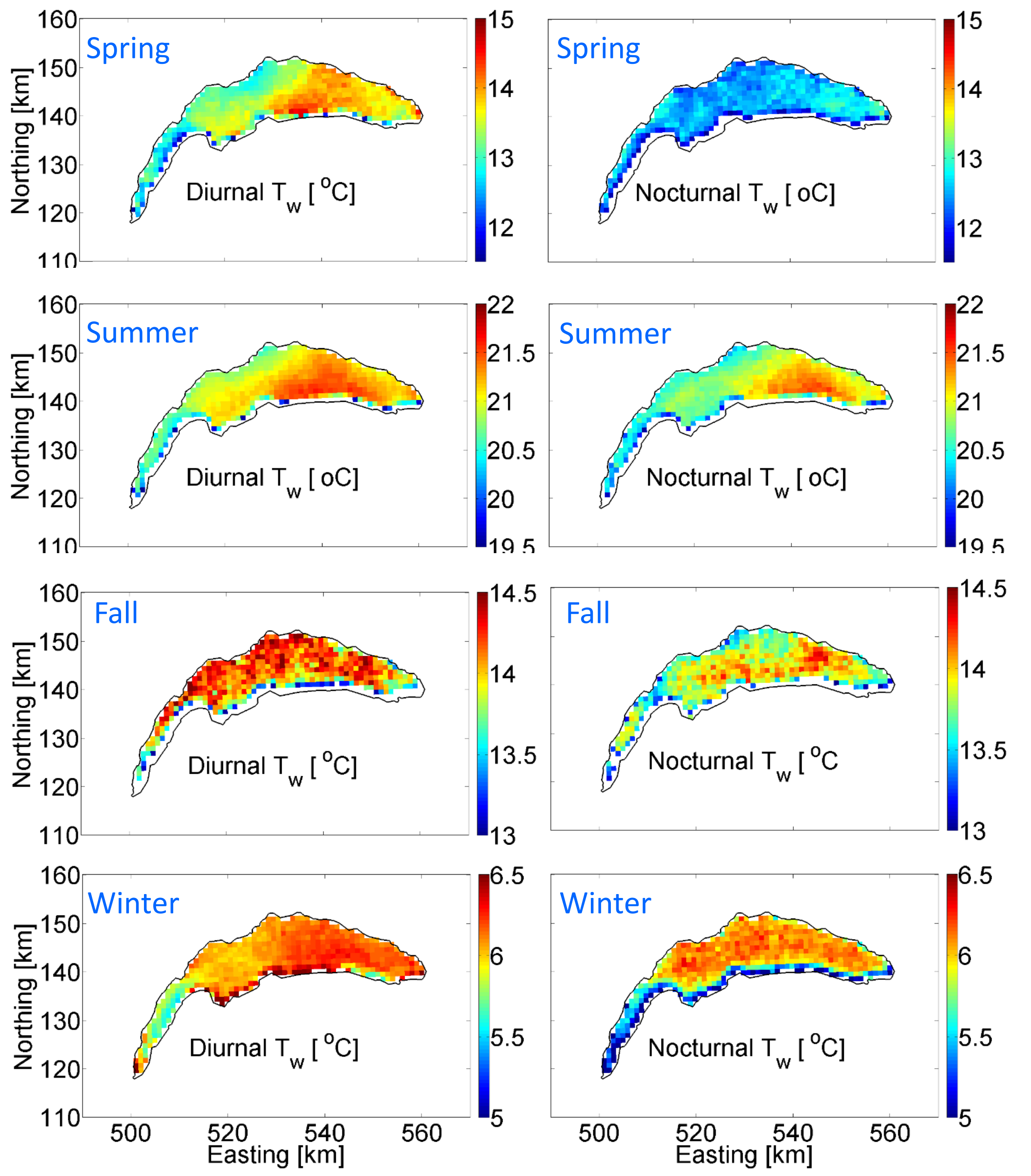
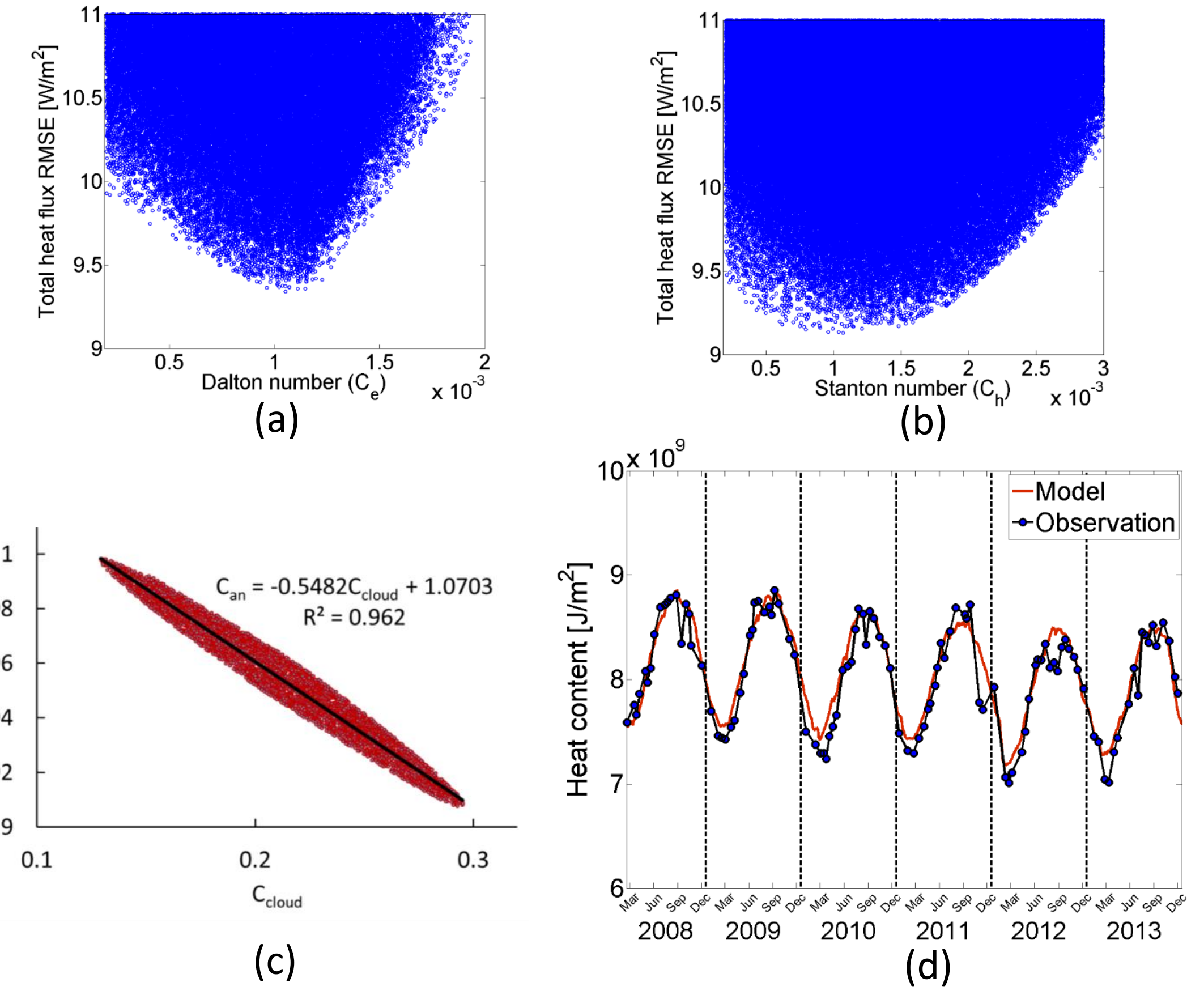


**Figure 3.** Average LSWT seasonal patterns. The observations indicate that, on average, the eastern part of the lake is warmer than the western part.

## 4- Modeling, calibration and verification



(a) (b) (c) (d)

**Figure 4.** Calibration and verification results. (a and b) Examples of Monte Carlo simulation results used to tune the calibration factors, i.e., $C_{e,opt}$ = 0.001146 and $C_{h,opt}$ = 0.001265; (c) correlation between $C_{cloud}$ and $C_{can}$ ; (d) temporal evolution of the lake heat content, e.g., at the SHL2 station, observation vs model results.

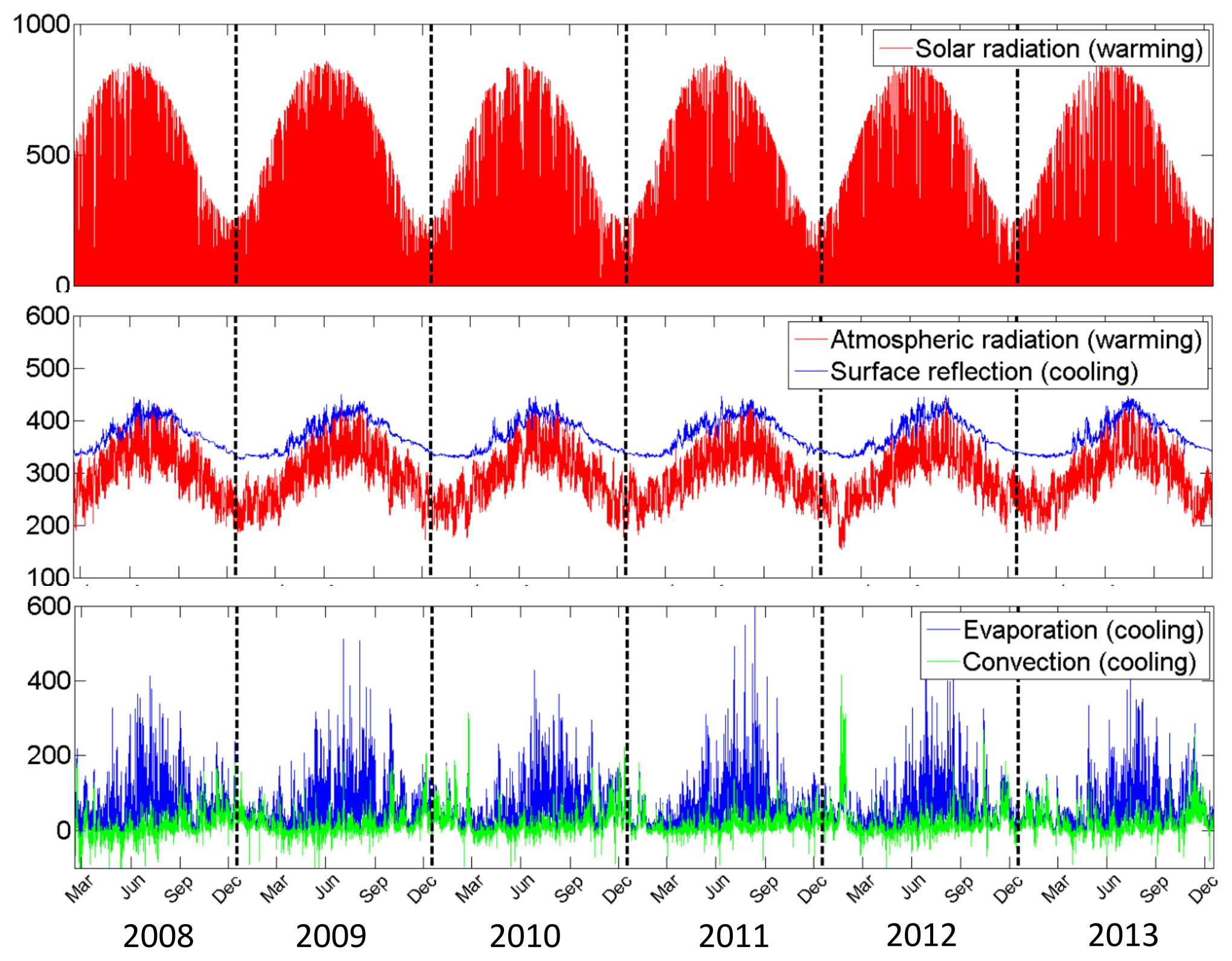


**Figure 5.** Temporal variation of SHF terms, e.g., at the SHL2 station. The results demonstrate that the radiative SHF, on average, are higher than non-radiative terms. However, evaporation, and to some extent convection, show more variation in summer and fall.

## 5- Seasonal heat flux patterns

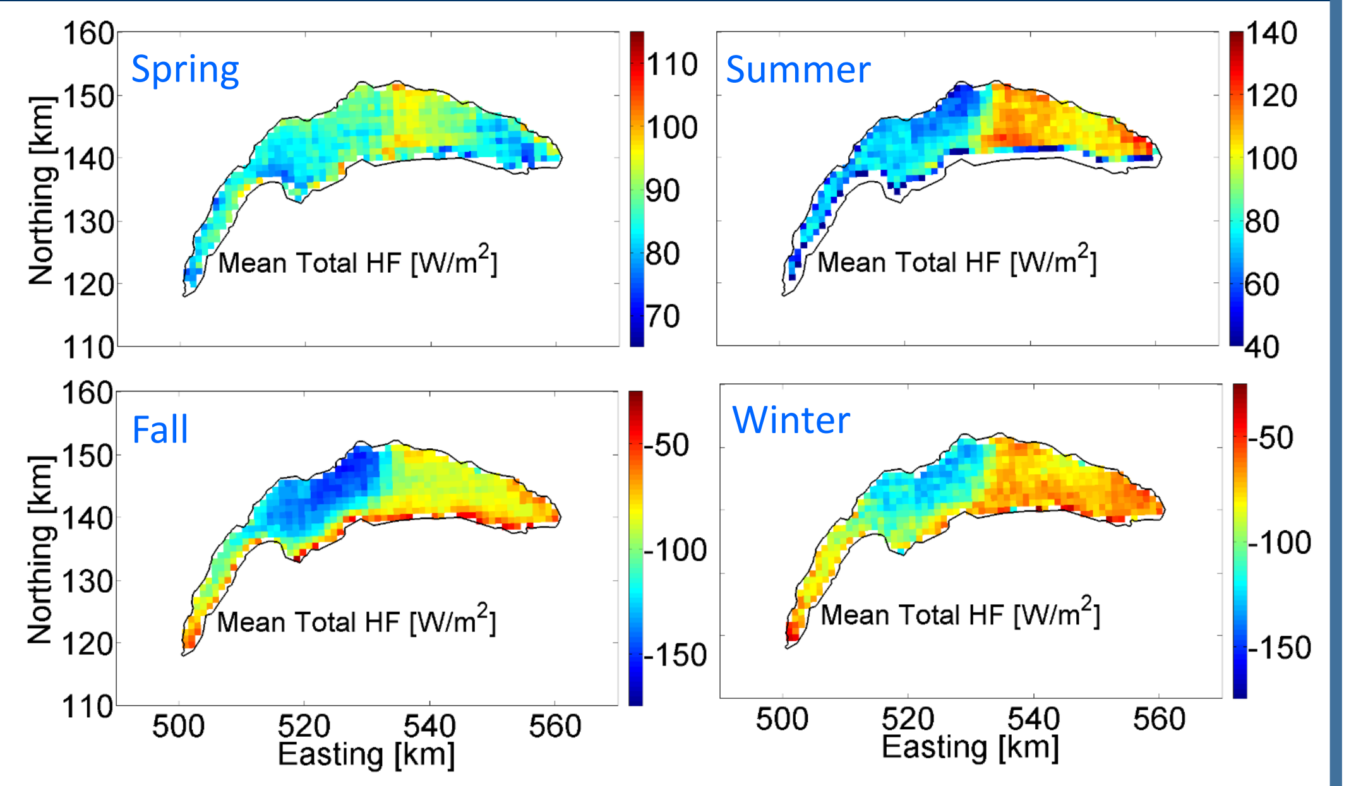


**Figure 6.** Seasonal average total SHF variability over Lake Geneva. The results show the net input energy into the lake is higher in the eastern part than the western part.

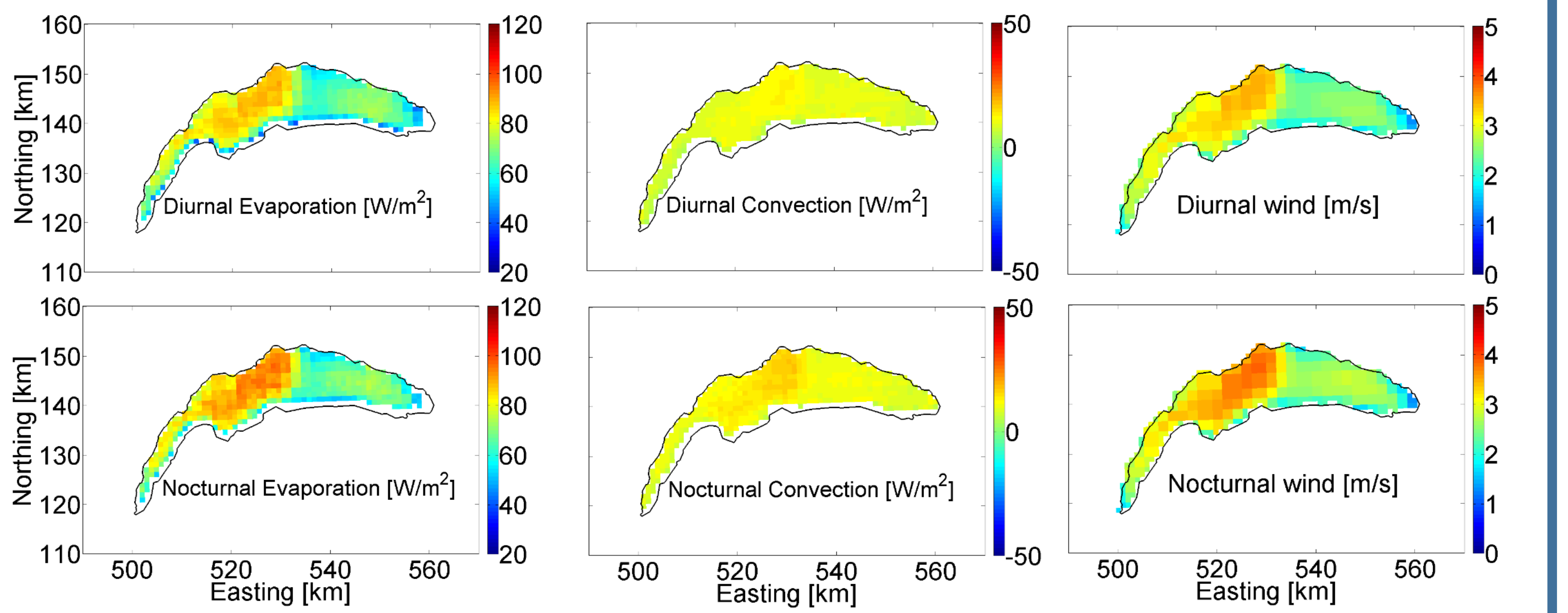


**Figure 7.** Average diurnal/nocturnal evaporation, convection and wind forcing for summertime. The results indicate that the wind pattern is the dominant factor underlying evaporation variability and consequently the total SHF patchiness.

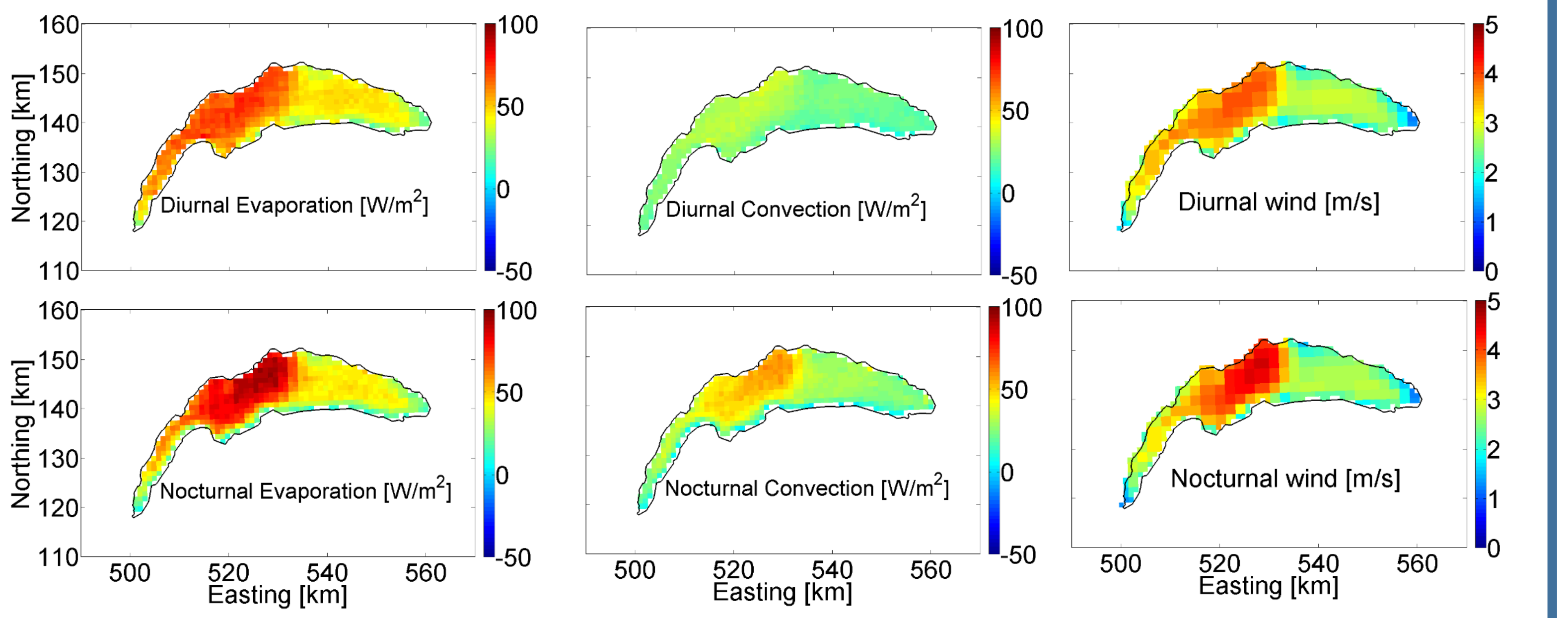


**Figure 8.** Same as Fig. 7 but for Fall. The results show that the convection spatial variability is also notable in this season (especially during night-times).

## 6- Conclusions

- Analysis of the model results shows that evaporative and convective heat fluxes are the dominant terms controlling the spatial pattern of SHF. The former is significant in all seasons while the latter plays a role only in fall and winter.
- Meteorological observations illustrate that wind-sheltering is the main reason for the observed large-scale spatial variability.
- Both modeling and satellite observations indicate that, on average, the eastern part of the lake is warmer than the western part, with a greater temperature contrast in spring and summer than in fall and winter whereas the SHF spatial splitting is stronger in fall and winter. This is mainly due to negative heat flux values (net cooling) and stronger wind forcing, and consequently stronger mixing, in cold seasons.

## References

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