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Observations of positive sea surface temperature trends in the steadily shrinking Dead Sea

Pavel Kishcha[1], Rachel T. Pinker[2], Isaac Gertman[3], Boris Starobinets[1], Pinhas Alpert[1]

[1]School of Geosciences, Tel Aviv University, Tel-Aviv, 69978, Israel
[2]Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742, USA
[3]Israel Oceanographic and Limnological Research, National Institute of Oceanography, Haifa, 31080, Israel

Correspondence to: Pavel Kishcha (pavel@cyclone.tau.ac.il)

Abstract. The steadily shrinking Dead Sea followed by sea surface warming compensates surface water cooling due to increasing evaporation, and even causes the observed positive Dead Sea surface temperature trends. Using observations from Moderate Resolution Imaging Spectroradiometer (MODIS), positive trends were detected in both daytime (0.06 ^{o}C year^{-1}) and nighttime (0.04 ^{o}C year^{-1}) Dead Sea surface temperature (SST) over the period of 2000 – 2016. These positive SST trends were observed in the absence of positive trends in surface solar radiation measured by the Dead Sea buoy pyranometer. Neither changes in water mixing in the Dead Sea nor changes in evaporation could explain surface temperature trends. There is a positive feedback loop between the shrinking of the Dead Sea and positive SST trends, which leads to the accelerating decrease in Dead Sea water levels during the period under study. Note that there are two opposite processes based on available measurements: on the one hand, the measured accelerating rate of Dead Sea water levels suggests a long-term increase in Dead Sea evaporation which is expected to be accompanied by a long-term decrease in sea surface temperature. On the other hand, the positive feedback loop leads to the observed shrinking of the Dead Sea area followed by sea surface warming year on year. The total result of these two opposite processes is the statistically significant positive sea surface temperature trends in both daytime (0.06 ^{o}C year^{-1}) and nighttime (0.04 ^{o}C year^{-1}) during the period under investigation, observed by the MODIS instrument. Our results shed light on the continuing hazard to the Dead Sea and possible disappearance of this unique site.

1 Introduction

The coastal area of the hypersaline terminal lake of the Dead Sea is a unique area of dry land of the lowest elevation on Earth (-420 m a.s.l.). Solar radiation heats this dry coastal area in the daytime and creates a temperature gradient between the uppermost levels of the land and those of the sea. The Dead Sea has been drying up over the last two decades: the water level dropped at the rate of approximately 1 m year^{-1} (Lensky et al., 2005). The Dead Sea drying up is due to the lack of water inflow from the Jordan River; a decreasing tendency in rainfall over the last 40 years (Ziv et al., 2015); and increasing evaporation (Alpert et al., 1979, Shafir and Alpert, 2011). The Dead Sea drying up has led to the shrinking in the Dead Sea water area. Based on satellite imagery from 1972 to 2013, El-Hallaq and Habboub (2014) estimated that the Dead Sea water area shrank on average at the rate of ~2.9 km^2 $year^{-1}$.

Knowledge of the Dead Sea thermal structure has been gained from measured water temperature vertical profiles of over the past 40 years (Gertman and Hecht, 2002; Hecht and Gertman, 2003; Kishcha et al., 2017; Nehorai et al., 2009; Stanhill, 1990). Using regular buoy measurements of Dead Sea water temperature at the depth of 1 m during the ten year period from 1992 to 2002, Hecht and Gertman (2003) detected an increasing statistically significant trend of 0.06 ^oC $year^{-1}$.

Dead Sea surface temperature (SST), which is the main point of our study, is one of the causal factors of water evaporation which affects the Dead Sea water level. There are only a few studies on the Dead Sea SST (Nehorai et al., 2009, 2013; Stanhill, 1990). The above mentioned studies dealt with diurnal, seasonal and interannual variations in SST. O'Reilly et al. (2015) discussed a statistically significant positive trend of 0.34 ^oC per decade in the nighttime surface water temperature in approximately 300 lakes around the world including the Dead Sea (characterized by the statistically significant positive trend of 0.63 ^oC per decade). This was achieved by using both satellite and in situ measurements in the summer season (from July to September) during the 25-year period from 1985 – 2009. They consider that the increase was associated with the interaction among different climatic factors such as increasing surface solar radiation as a result of decreasing cloud cover and increasing air temperature (O'Reilly et al., 2015). To our knowledge, long-term interannual sea surface temperature changes in both daytime and nighttime periods, taking into account all the months of the year, have not been discussed in previous publications.

Our study aims at investigating long-term trends in the Dead Sea SST using the 17-year MODIS period of records (2000 – 2016). This study was carried out on skin surface temperature over land and sea using MODIS data on board the NASA Terra satellite. We found statistically significant positive trends in Dead Sea SST in the absence of positive trends in surface solar radiation which raise questions about the factors contributing to Dead Sea water heating.

2 Method

For the remotely sensed monthly mean temperatures of the Dead Sea used is Collection-6 (C6) of the MODIS Land Surface Temperature (LST) Product: MOD11C3 Level 3 (Wan, 2014). Wan (2014) showed that LST data from Collection-6 are more accurate than those from the previous Collection 5: the mean C6 LST error is within ± 0.6 ^oC which is lower than the mean C5 LST error of ± 2 ^oC. The gridded MOD11C3 data are available at 5 km spatial resolution, two times per day: in the daytime at approximately 10:30 LT and in the nighttime at ~21:30 LT. To study sea surface temperature (SST) trends we used only pixels which covered the Dead Sea (Fig. 1, blue boxes), while all others have been eliminated from the analysis, to avoid thermal contamination. In addition to SST trends, we analyzed similar long-term trends of the skin surface temperature over the land area in the vicinity of the Dead Sea (Fig. 1, red boxes).

To obtain long-term trends of the Dead Sea SST, the above-mentioned MOD11C3 Level 3 monthly data averaged over the Dead Sea (Fig. 1, blue boxes) were deseasonalized by removing 17-year averages from any given month. A similar approach was used in order to obtain long-term trends of the skin surface temperature over the land area (Fig. 1, red boxes). The slope of a linear fit was used to determine Dead Sea surface temperature trends as well as those of skin surface temperature over the land, during the 17-year period under investigation (2000 – 2016). To estimate the significance level (p) value of surface temperature trends, normally distributed residuals of the linear fit were used in a t test (Shapiro and Wilk, 1965; Razali and Wah, 2011). The obtained p values less than 0.05 correspond to statistically significant surface temperature trends at the 95% confidence level.

To study the effect of climatic factors on long-term trends in the Dead Sea SST, we used available pyranometer measurements of surface solar radiation together with measurements of near-surface wind speed from a hydrometeorological buoy, anchored in the Dead Sea (Fig. 1). The measured surface solar radiation (SR) was represented by monthly data of daily average SR and those of daily maximum SR during the 9-year period from 2005 – 2013. The measured wind speed was represented by monthly data of daily averaged near-surface wind speed, during the 10-year period from 2005 - 2014. To estimate long-term trends of above mentioned climatic factors, the same approach was used as for surface temperature trends. In addition, we analyzed yearly data of Dead Sea water levels based on available measurements from 1992 until the present. Taking into account that long-term changes in Dead Sea water levels reflect changes in Dead Sea evaporation, the measurements of Dead Sea water levels were used for the analysis of a possible contribution of long-term changes in evaporation to long-term trends in the Dead Sea SST.

3 Results

3.1 Trends in Dead Sea SST and surface solar radiation

MODIS satellite data of skin surface temperature allowed us to estimate long-term trends in the Dead Sea surface temperature. These data showed a statistically significant positive trend of 0.06 ^{o}C year^{-1} for daytime SST (increase of 1 ^{o}C in SST during the 17 year period under investigation from January 2000 to December 2016) (Fig. 2 a and b; and Table 1). In addition, MODIS data showed a statistically significant positive trend of 0.04 ^{o}C year^{-1} for nighttime SST (Fig. 3 a and b; and Table 1). Note that, in the absence of solar radiation at night, MODIS showed an equal statistically significant positive trend of 0.04 ^{o}C year^{-1} in land skin temperature over the land area in the vicinity of the Dead Sea (Fig. 3 c and d; and Table 1). By contrast to the nighttime period, MODIS data showed the absence of any noticeable trend in daytime land skin temperature (Fig. 2 c and d; and Table 1).

It is noteworthy that this positive daytime SST trend was observed in the absence of positive trend in surface solar radiation, based on pyranometer buoy measurements (Fig. 4). Monthly variations of daily average surface solar radiation (SR) over the 9-year period from 2005 to 2013 revealed even statistically significant negative trend (Fig. 4 a and b, Table 1). Furthermore, the monthly data of daily maximum solar radiation during the same 9-year period revealed no statistically significant trend (Fig. 4 c and d, Table 1).

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3.2 Analysis of factors contributing to the Dead Sea SST trends

The fact that the positive daytime SST trend was observed in the absence of positive trend in surface solar radiation (based on pyranometer measurements from the hydrometeorological buoy anchored in the Dead Sea) indicates that the observed positive trend in the daytime Dead Sea SST cannot be explained by long-term trends in surface solar radiation.

Neither long-term changes in water mixing in the uppermost layer of the Dead Sea under strong winds, nor long-term changes in evaporation could explain the observed phenomenon. Indeed, the monthly data of daily average near surface wind speed (based on buoy measurements during the 10-year period from 2005 to 2014) did not reveal any statistically significant trend (Fig. 5 c and d; Table 1). Furthermore, the observed positive trend in SST could not be explained by a decrease in evaporation. The evaporation process is accompanied by absorption of the latent heat of evaporation, consequently, by a decrease in sea surface temperature. The decrease in the Dead Sea water level is determined mainly by evaporation (Lensky et al., 2005, Al-Khlaifat, 2008, Shafir and Alpert, 2011). Therefore, measured long-term changes in Dead Sea water levels (Fig. 6a) reflect changes in Dead Sea evaporation. As shown in Fig. 6b, the estimated rate of water level changes from year to year reveals an accelerating decrease in the Dead Sea water level, in accordance with the obtained statistically significant linear fit (Fig. 6b and Table 1). This suggests a long-term increase in the Dead Sea evaporation, and this long-term increase is expected to be accompanied by a long-term decrease in sea surface temperature. However, despite the above-mentioned increase in Dead Sea water evaporation, MODIS shows statistically significant positive sea surface temperature trends in both daytime (0.06 ^{o}C year^{-1}) and nighttime (0.04 ^{o}C year^{-1}) (Table 1). This indicates the presence of steadily increasing sea surface warming which causes the observed positive SST trends and also compensates surface water cooling due to the increasing evaporation.

The above mentioned steadily increasing sea surface warming suggests some imbalance between incoming and outgoing surface heat flows. To describe the incoming and outgoing surface heat flows, we analyzed temperature differences between Dead Sea SST and land skin temperature, based on MODIS skin temperature measurements. Table 2 represents 17-year monthly means of sea surface temperature (SST) and land skin temperature (LST) in both winter (January) and summer (July). The land skin temperature was averaged over the following two land areas: 1) the land area adjacent to the Dead Sea (between the red boxes and the Dead Sea coastline (Fig. 1)) (LST1), and 2) the land area covered by the red boxes (LST2). One can see that, in the daytime both in summer and in winter: SST < LST1 < LST2, indicating surface horizontal heat transfer from land to sea. The most strong daytime heat transfer from land to sea exists in summer, when the maximum temperature difference of approximately 9 ^{o}C is observed between LST1 and SST, compared to that of only 2 ^{o}C in winter (Table 2). By contrast to the daytime, in the nighttime: SST > LST1 > LST2, indicating heat transfer from sea to land. The most strong nighttime heat transfer from sea to land exists in winter, when the maximum temperature difference of approximately 5 ^{o}C is observed between SST and LST1, compared to that of only 1 ^{o}C in summer (Table 2). The aforementioned temperature differences between Dead Sea SST and land skin temperature in the vicinity of the Dead Sea is

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evidence of the presence of two opposing surface heat flows: from land to sea in the daytime and from sea to land in the nighttime.

Furthermore, as mentioned in the Introduction, during the period from 1972 to 2013, the Dead Sea water area shrank on average at the rate of ~2.9 km^2 $year^{-1}$ (El-Hallaq and Habboub, 2014). Therefore, the surface heat flow from land to sea (which is proportional to the perimeter of the Dead Sea) heated the steadily shrinking Dead Sea water area. As the reduction of the Dead Sea water area is relatively higher than that of the Dead Sea perimeter (e.g., in the case of a circle: its perimeter is proportional to the radius, while its area is proportional to the square of the radius), this leads to some additional surface heating of Dead Sea water every year. This additional heating of Dead Sea surface water (as a result of Dead Sea shrinking) is leading to an increase in water evaporation, consequently, to some additional decrease in Dead Sea water levels, eventually to subsequent shrinking of the Dead Sea water area. Therefore, there is a positive feedback loop between the shrinking of the Dead Sea and the positive SST trends. This positive feedback loop contributes to the observed statistically significant accelerating rate of the decrease in Dead Sea water levels during the period under consideration (Fig. 6b and Table 1).

4 Conclusions

In the present study, long-term trends in Dead Sea surface temperature (SST) were analyzed using MODIS satellite data of skin surface temperature during the 17-year period of records (2000 – 2016). MODIS data showed positive trends of 0.06 ^{o}C $year^{-1}$ in the daytime and 0.04 ^{o}C $year^{-1}$ in the nighttime. These positive SST trends were observed in the absence of positive trends in surface solar radiation measured by the Dead Sea buoy pyranometer. We demonstrate that the observed increase in the Dead Sea SST over the study period cannot be related to increasing surface solar radiation. Neither long-term changes in water mixing in the uppermost layer of the Dead Sea under strong winds, nor long-term changes in evaporation could explain the observed SST trends. We consider that the steadily shrinking Dead Sea area leads to surface heating of Dead Sea water year on year: this contributes to the observed Dead Sea SST trends. It is worth mentioning that there is a positive feedback loop between the shrinking of the Dead Sea and positive SST trends, leading to the accelerating decrease in Dead Sea water levels during the period under consideration.

Note that there are two opposite processes, based on available measurements: on the one hand, the measured accelerating rate of Dead Sea water levels suggests a long-term increase in Dead Sea evaporation which is expected to be accompanied by a long-term decrease in sea surface temperature. On the other hand, the above-mentioned positive feedback loop leads to the observed shrinking of the Dead Sea area followed by sea surface warming every year. The total result of these two opposite processes is the statistically significant positive sea surface temperature trends in both daytime (0.06 ^{o}C $year^{-1}$) and nighttime (0.04 ^{o}C $year^{-1}$) during the period under investigation, observed by the MODIS instrument. Therefore, the steadily shrinking Dead Sea followed by sea surface warming not only compensates surface water cooling due to the increasing evaporation but even causes the observed positive SST trends.

Our results shed light on continuing danger to this unique site and its possible disappearance. Moreover, it is worth mentioning that the shrinking at alarming rates was detected for many of the world's saline lakes (Wurtsbaugh et al., 2017). Therefore, our approach can be appropriate for analyzing similar processes in those shrinking lakes.

Data availability and acknowledgements

Thanks are due to the MODIS teams (PI Name: Zhengming Wan) that produced the LST data. The Collection-6 of the MODIS MOD11C3 Level 3 LST data product DOI: 10.5067/MODIS/MOD11C1.006 was retrieved from the online Data Pool, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod11c1_v006#tools

The following data are included in the file with supplementary material uploaded separately: (1) measurements of Dead Sea water levels; (2) monthly data of pyranometer measurements of surface solar radiation from a hydrometeorological buoy, anchored in the Dead Sea; and (3) monthly data of near-surface wind speed measurements from a hydrometeorological buoy, anchored in the Dead Sea. Credit for the buoy data is given to the Israel Oceanographic and Limnological Research. Credit for the data of Dead Sea water levels is given to Israel Hydrological Service.

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Table 1. The slope (α) of the obtained linear fit of deseasonalized monthly anomalies of surface temperature over sea (SST) and land (LST) in the daytime (day) and nighttime (night); daily average and daily maximum surface solar radiation (SR_{DAVE} and SR_{DMAX}); and daily average near surface wind speed (WS). In addition, the slope (α) of the long-term trend in the rate of Dead Sea level changes from year to year (RateDSL, Fig. 6b) is presented. The decision based on the Shapiro-Wilk normality test for residuals (S-W test) and the significance level (p) is also displayed. If the p value was too high as compared with the 0.05 significance level, the obtained linear fit was considered as statistically insignificant.

Parameter	Period	α	S–W Test	P
SST_{day} (°C)	2000 – 2016	0.06 (°C year^{-1})	Normal	0.001
SST_{night} (°C)	2000 – 2016	0.04 (°C year^{-1})	Normal	0.006
LST_{day} (°C)	2000 – 2016	0.00 (°C year^{-1})	Normal	Not significant
LST_{night} (°C)	2000 – 2016	0.04 (°C year^{-1})	Normal	0.007
SR_{DAVE} (W m^{-2})	2005 – 2013	-0.80 (W m^{-2} year^{-1})	Normal	0.020
SR_{DMAX} (W m^{-2})	2005 – 2013	1.20 (W m^{-2} year^{-1})	Normal	Not significant
WS (m s^{-1})	2005 – 2014	0.00 (m s^{-1} year^{-1})	Normal	Not significant
RateDSL (m year^{-1})	1992 - 2016	-0.02 (m year^{-2})	Normal	0.001

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Table 2. Long-term (17 year) monthly means of sea surface temperature (SST) and land skin temperature (LST) together with their standard deviation (SD) in winter (January) and summer (July). The land skin temperature was averaged over the following two land areas: 1) the land area adjacent to the Dead Sea (between the red boxes and the Dead Sea coastline (Fig. 1)) (LST1), and 2) the land area covered by the red boxes (LST2).

Month	SST ± SD (^{o}C)	LST1 ± SD (^{o}C)	LST2 ± SD (^{o}C)
	Daytime		
January	20.4 ± 1.0	22.3 ± 0.3	22.7 ± 1.0
July	33.1 ± 0.5	41.9 ± 0.8	45.9 ± 0.9
	Nighttime		
January	18.4 ± 1.4	13.6 ± 0.4	10.9 ± 1.0
July	31.8 ± 0.5	30.5 ± 0.6	28.8 ± 1.0

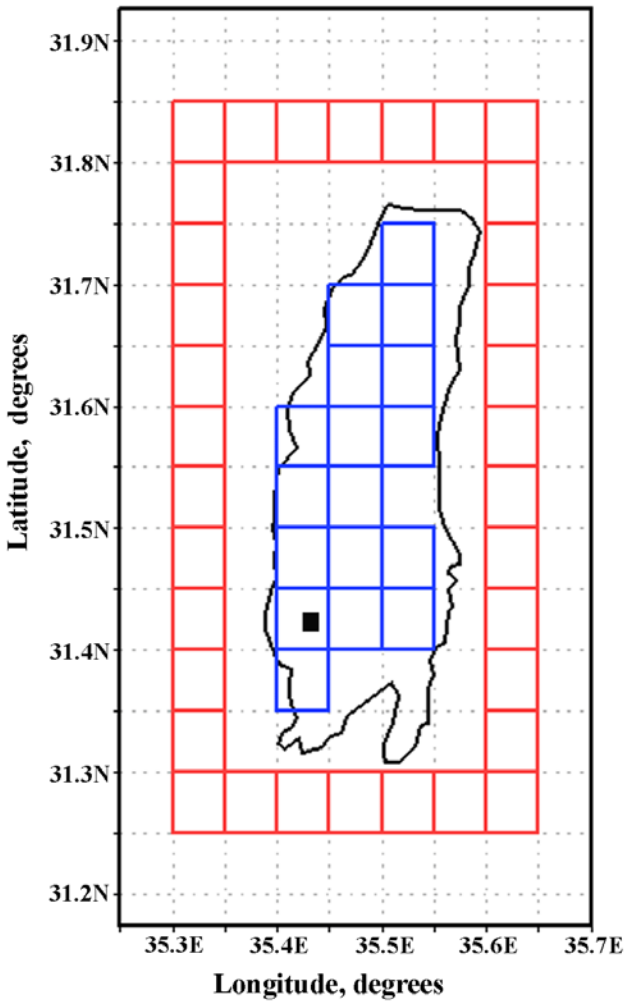

Figure 1: Map of the region under study. The 17 blue boxes show pixels covering the Dead Sea surface. The 34 red boxes show pixels which cover the land area in the vicinity of the Dead Sea. The black square shows the location of the Dead Sea hydrometeorological buoy (31.42°N, 35.44°E).

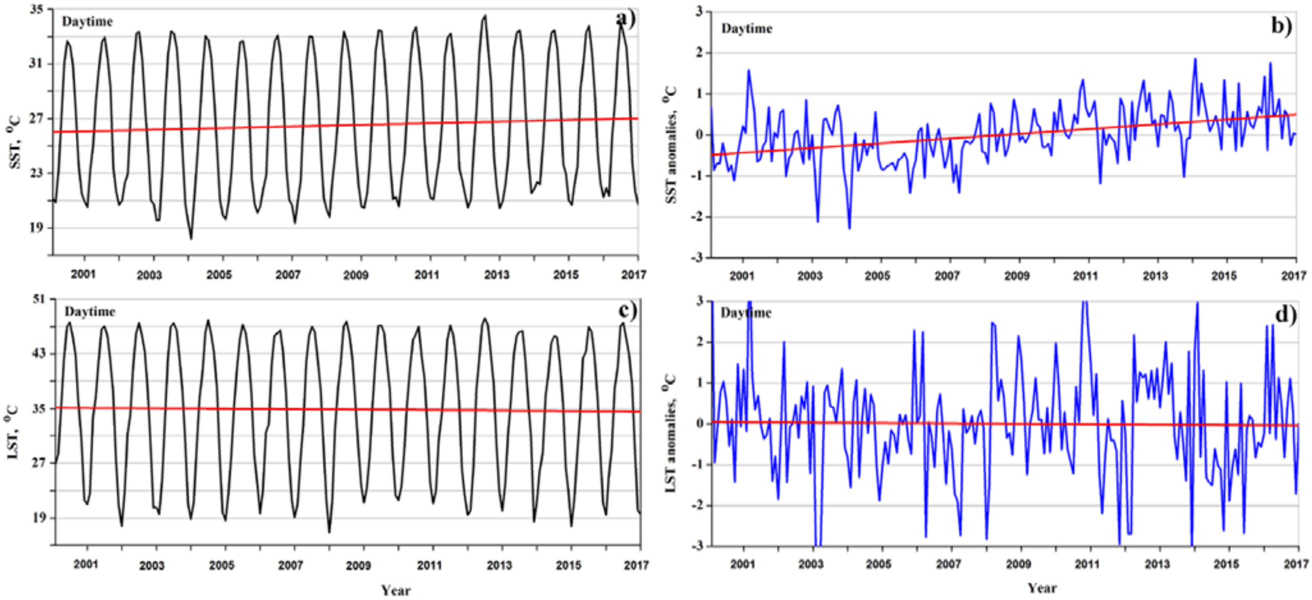

Figure 2: Daytime monthly variations of (a and b) Dead Sea surface temperature (SST) together with (c and d) land skin temperature (LST) over the land area in the vicinity of the Dead Sea, during the 17-year period under study. The left column represents original MOD11C3 Level 3 monthly data (averaged over the specified sea and land areas), while the right column represents their associated deseasonalized monthly anomalies. The red straight lines designate linear fits.

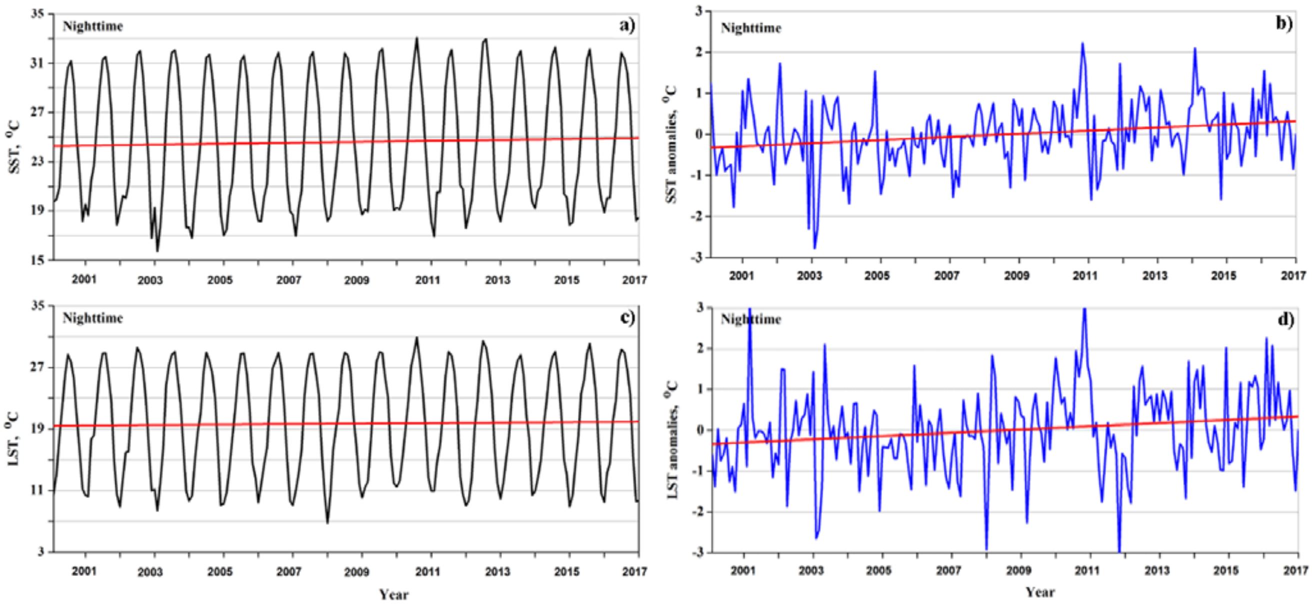

Figure 3: Nighttime monthly variations of (a and b) Dead Sea surface temperature (SST) together with (c and d) land skin temperature (LST) over the land area in the vicinity of the Dead Sea, during the 17-year period under study. The designations are the same as in Fig. 2.

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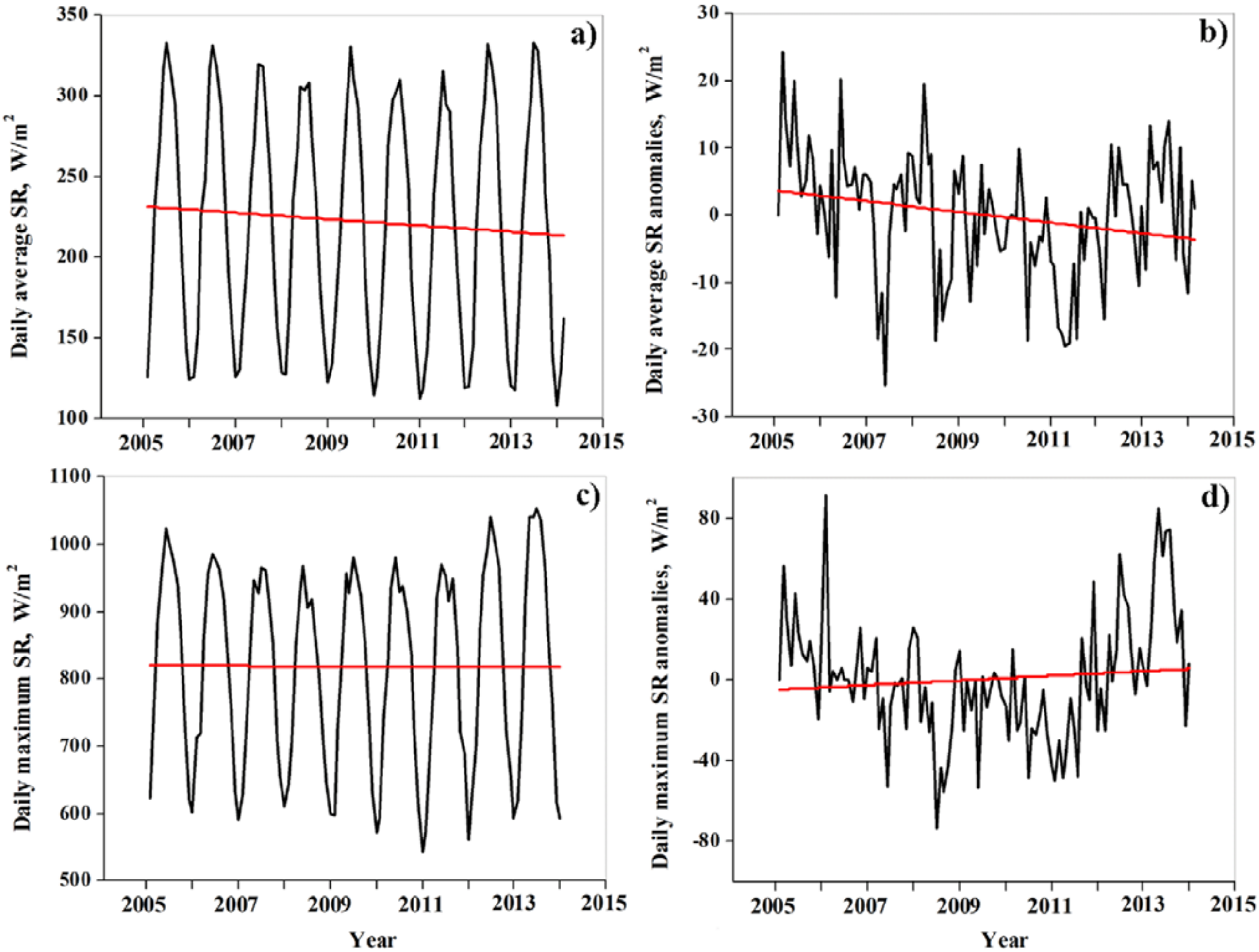

Figure 4: Monthly variations of (a and b) daily average surface solar radiation (SR); and (c and d) daily maximum surface solar radiation, based on pyranometer measurements at the hydrometeorological buoy anchored in the Dead Sea. The left column represents original monthly data, while the right column represents their associated deseasonalized monthly anomalies. The red straight lines designate linear fits.

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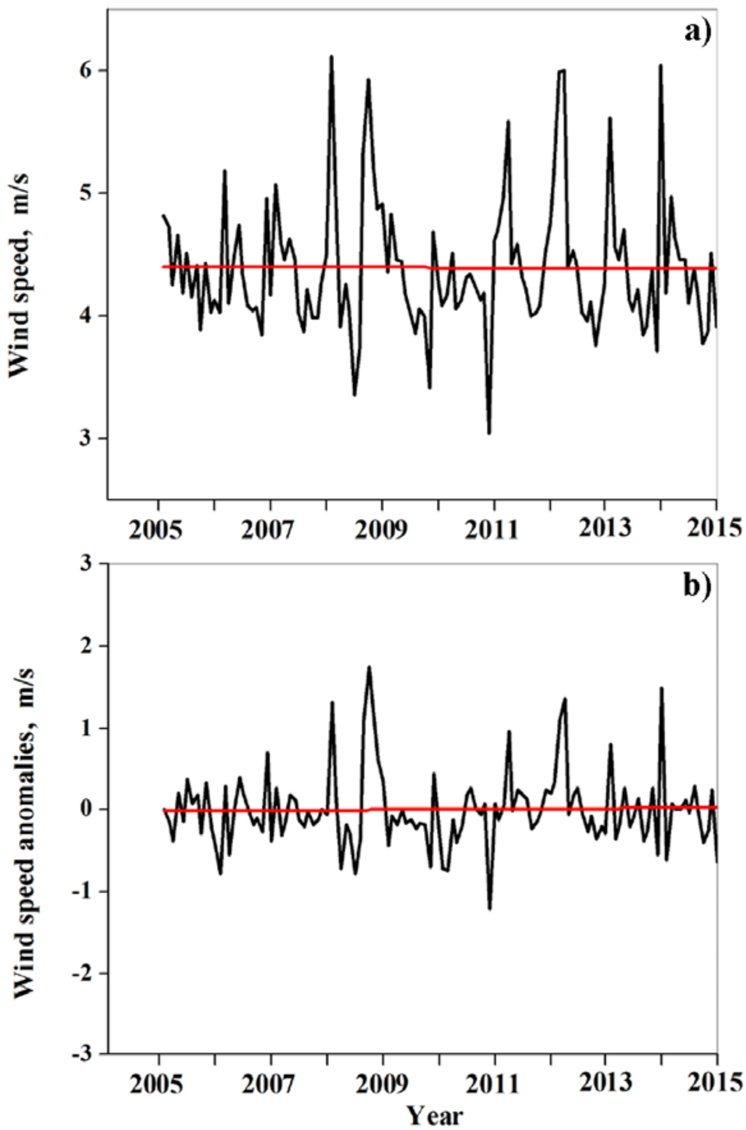

Figure 5: Monthly variations of daily average near-surface wind speed based on wind measurements at the hydrometeorological buoy anchored in the Dead Sea: a - represents original monthly data, while b - represents their associated deseasonalized monthly anomalies. The red straight lines designate linear fits.

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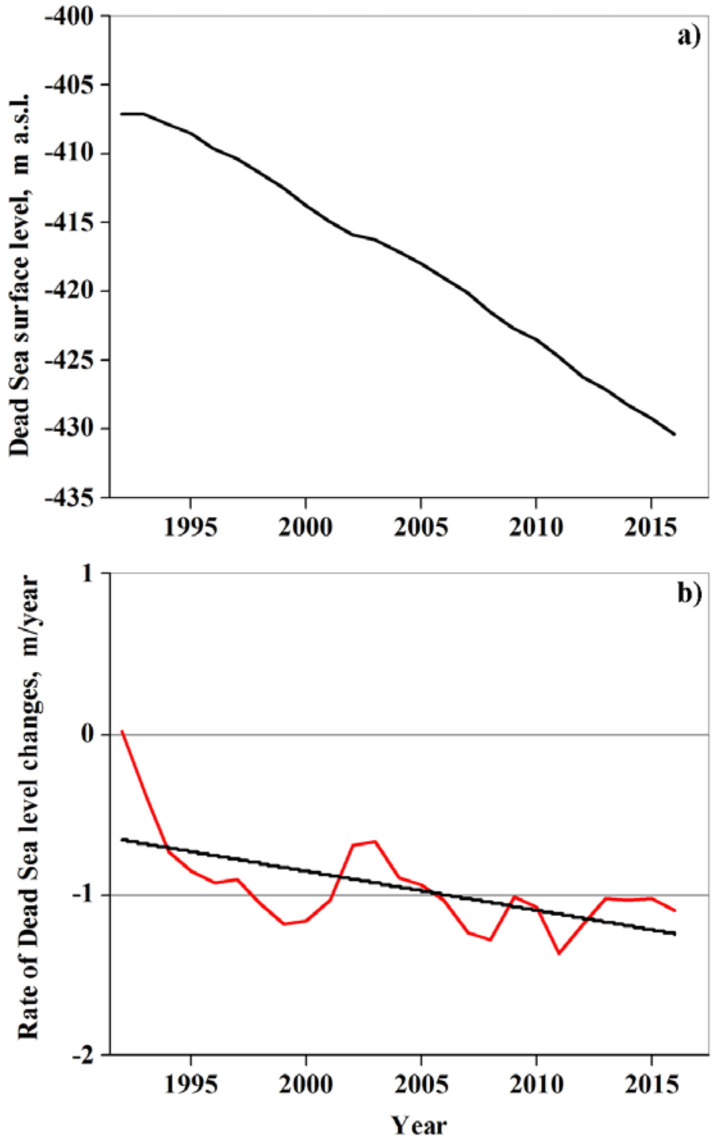

Figure 6: a - yearly data of the Dead Sea levels (based on available measurements from 1992 until the present); b - the rate of Dead Sea level changes from year to year. The black straight line designates the linear fit.