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The spatial and temporal behavior of brightness temperature in Tel-Aviv and its application to air temperature monitoring

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Abstract

This study applies remote sensing technology to assess and examine the spatial and temporal Brightness Temperature (BT) profile in the city of Tel-Aviv, Israel over the last 30 years using Landsat imagery. The location of warmest and coldest zones are constant over the studied period. Distinct diurnal and temporal BT behavior divide the city into four different segments. As an example of future application, we applied mixed regression models with daily random slopes to correlate Landsat BT data with monitored air temperature (T_{air}) measurements using 14 images for 1989–2014. Our preliminary results show a good model performance with $R^2 = 0.81$.

Furthermore, based on the model's results, we analyzed the spatial profile of T_{air} within the study domain for representative days.

Keywords

Land surface temperature (LST); Brightness Temperature (BT); Air Temperature (T_{air}); urban heat island (UHI); thermal profile; Landsat; urban planning

1. Introduction

High-rise buildings, dense constructions zones, industry and commercial centers, miscellaneous anthropogenic activities, opaque surfaces such as asphalt and concrete have each been associated with the city becoming warmer than its rural surrounding. This phenomenon is termed the Urban Heat Island (UHI) (Voogt & Oke, 2003). The UHI affects the comfort of city dwellers and was found to correlate with air pollution, heat stress, different environmental nuisances (Ben-Dor & Saaroni, 1997; Saaroni et al., 2000) and can exacerbate heat related mortality and morbidity (Luber & McGeehin, 2008; Smargiassi, et al., 2009; Zhang et al., 2015)

Thermal infrared (TIR) remote sensing techniques have been widely used to study urban climate. Radiance, converted to Brightness Temperature (BT), is a key parameter measured by the sensor. BT is widely used to characterize landscape characteristics, properties and

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processes, including UHI, and surface energy fluxes (Voogt & Oke, 2003). In a UHI study of Tel-Aviv, Israel, Saaroni et al. (2000) concluded that parks, open spaces and other vegetated areas appear relatively colder compared to other urban components. Rotem-Mindali et al., (2015) estimated the thermal effect of vegetation on Land Surface Temperature (LST) in four different urban areas in Tel-Aviv: residential areas with high vs low vegetation cover, industrial areas and parks. They found that industrial areas had the highest LST correlating with the lowest ratio of vegetation to free space area (1%), while 'green' areas displayed the lowest LST.

Notably, studies have suggested that effects of a given BT temperature on mortality vary spatially and temporally across the city (Laaidi, et al., 2012; Lee, et al., 2014). White-Newsome et al., (2013) used satellite-derived BT and percent of impervious surface to better understand spatial variation in heat exposures over long and short time frames. The authors concluded that accurate estimates of heat-related morbidity and mortality require knowledge concerning the location of areas with high vulnerability to heat in cities (White-Newsome, et al., 2013). Accordingly, understanding spatial and temporal variability in BT could serve as a useful parameter to assess areas of high vulnerability to heat in cities and potentially provide more accurate heat exposure estimates in future studies (Luber & McGeehin, 2008; Brauer & Hystad, 2014).

While satellite-derived BT allows analyses and qualitative/quantitative description of thermal patterns, there is a need to distinguish between BT and air temperature (Tair) due to differences in the two measured and the nature of the data acquisition of both parameters (Arnfield, 2003; Voogt & Oke, 2003). From the epidemiological point of view, it is of high importance to have information about the spatial variability of Tair in the city, rather than thermal patterns. Recent studies by Schwarz et al., 2012; Kloog et al., 2012; 2014 and Chen et al. (2012) show that ground-based air temperature measurements and surface temperature estimated from thermal sensors can be positively and significantly correlated. For example, a mixed effects model approach was applied by Kloog et al, 2013 to MODIS BT to assess Tair pattern (mean out-of-sample $R^2 = 0.946$), whereas Feyisa et al., 2014 used the same statistical approach to Landsat BT values to assess the impact of different vegetation types on observed Tair ($R^2=0.85$).

To the best of our knowledge, no systematic research has been conducted to survey changes in BT over the last 30 years on a macro-scale level in Tel-Aviv, with focus on identifying the location of warm vs cold BT zones. We asked the following questions: 1) What is the temporal pattern of cold/warm zones over the last 30 years? 2) Where are the areas of the highest/lowest diurnal and temporal changes in BT located? To this end, we analyzed BT data at the macro-scale level provided by Landsat imagery with 30 meters resampled resolution. Finally, to examine the utility of these BT data for deriving Tair data, we developed mixed regression models with daily random slopes to correlate Landsat BT data with monitored air temperature measurements using 14 images for 1989–2014.

2. Study area

The selected area for this study, shown in Figure 1, is the municipality boundaries of the city of Tel-Aviv. Tel-Aviv is located at the eastern shoreline of the Mediterranean Sea in the center of Israel, 32°N 34°E. The city has a subtropical climate (Saaroni et al., 2000) and covers an area of 51.8 km², with 14 km of coast line and 3–6 km width and has around 400,000 inhabitants. The city is considered the central city of Israel and is home to core financial and cultural activities. Like every other main city, Tel-Aviv has a complex urban surface including different types of buildings and facilities, transportation, industrial and commercial centers, bodies of water, parks etc.

3. Methods

For this study, we obtained selected satellite images from the mid-80s until the last few years (2013–2014) (www.glovis.usgs.gov). The exact times and dates of the imagery used for this study and selected metrological conditions can be found in the Table 1. The times (GMT) the images were taken and the spacecraft ID were retrieved from the metadata files from each image.

3.1 Meteorological data

The metrological conditions (found in table 1) were retrieved from Beit-Dagan station using the Israel Meteorological Service (IMS) at- <http://www.ims.gov.il>. The metrological data refer to the nearest time the image was taken, 09:00 (GMT) for daytime images and 21:00 (GMT) for nighttime image. In addition, the air temperature (T_{air}) data used for the mixed models were based on a meteorological network consisted of 9 stations constructed during 1989–1993, the project initiated by Tel-Aviv University (Bitan, A., personal communication), and existing stations of the IMS and other stations such as the meteorological mast of the Israel Electricity company at Hakfar Hayarok (The Green Village) located at the outskirts of Tel-Aviv (<http://www.svivaqnm.net/>). The T_{air} measurements during satellite overpass (11:30) were used. There were between 4 and 12 daily monitors operating across the study area during the study period.

3.2 Brightness Temperature (BT)

Brightness temperatures (BT) were acquired using the thermal bands (TIR) of the images that detect and record the emitted energy from the surface at 10.40–12.50μm wavelengths. We used band 6 for Images obtained from Landsat 4,5,7 and band 10 from Landsat 8. The TM (Landsat 4,5) and ETM+ (Landsat 7) sensors acquires data at 120 and 60 m thermal band spatial resolution respectively whereas the Thermal Infrared Sensor (TIRS) of Landsat 8 collects data at 100 meters. TM, ETM+ and TIRS are resampled to match the visible through middle infrared channels multispectral bands.

All images were radiometric calibrated and interpreted in order to represent values in BT Celsius degrees. The calibrations were according to the USGS website (USGS, 2014). To convert Digital Number (DN) values to radiance we used:

$$L_{\lambda} = M_L Q_{cal} + A_L \quad (1)$$

Where L_{λ} = TOA spectral radiance (Watts/(m² * srad * μ m)); M_L = Band-specific multiplicative rescaling factor from the metadata; A_L = Band-specific additive rescaling factor from the metadata; Q_{cal} = Quantized and calibrated standard product pixel values (DN). To convert from radiance to BT (in Kelvin) we used the following equation:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_{\lambda}} + 1\right)} \quad (2)$$

where: T = At-satellite brightness temperature (K), L_{λ} = TOA spectral radiance (Watts/(m² * srad * μ m)), K_1 = Band-specific thermal conversion constant from the metadata, K_2 = Band-specific thermal conversion constant from the metadata.

Finally, BT was converted from Kelvin to Celsius degrees. Of note, the BT is not necessarily the kinetic (the “true”) temperature of the object of interest, but rather the temperature that derives from the amount of energy emitted by the object. The relation between the two temperatures is related by

$$BT = \varepsilon^{0.25} T_k \quad (3)$$

Thus, the emissivity (ε) determines how close the BT is to the “true” temperature of the object. Since this study focuses on the urban environment, we can rely on BT due to the fact that most objects and surfaces like asphalt, vegetation, concrete and soil have a high emissivity values that are close to 1 (Sabins, 1997). Therefore the BT is very close to the kinetic temperature of objects and surfaces found in the city domain.

3.3 Data pre-processing and analyses

In order to create images indicating the BT values of the municipality area of Tel-Aviv, we used a polygon that represents the municipality boundaries of the city. To that end, all pixels value located outside of the mentioned boundaries were masked and received “no data” value. In addition, we applied the same mask for a few clouds that were inside the study area.

First, we analyzed the spatial distribution and temporal variability of BT over the course of 30 years. To that end we compared warm and cold season images from the mid-80s and recent times. In order to identify the spatial location of surfaces with highest and lowest BT, we applied a threshold whereby the warmest and coldest areas were defined as above 1 Standard Deviation (STD) and below -1 STD of the BT respectively, and mapped these areas accordingly. Next, we studied the temporal change in area coverage of the warmest and coldest areas over the course of 30 years. Only the data from the summer months of July–August were analyzed (16 images: 1984–2014). We reasoned that since the weather in Israel is relatively stable in these months as compared to in winter months (Bitan & Rubin, 1991), the intra-urban effects on BT are likely to be more marked.

Second, we evaluated the highest/lowest difference in BT on two scales: 1) diurnal and 2) temporal (i.e., over the two time frames taken from the last 30 years). To study the diurnal scale variability, day and night images from the warm season were selected and a subtraction image (day minus night) was generated. We employed a scatter plot chart to highlight areas of high/low BT difference. In this way, we could observe and analyze areas that were pronounced in terms of high/low BT difference during daytime and/or nighttime in relation to one another. A similar analysis, image subtraction and a scatter plot chart, was conducted to investigate the change in urban BT over the range of 30 years. For this purpose, to restrict and sharpen the defined sizes of warm and cold areas (as well as highest/lowest differences), we narrowed their definition to the 3rd and 1st quartiles of the temperature, respectively.

Third, to study the differences in BT on a temporal scale, a comparison between various parts of the city was made. Specifically, we captured the difference between two locations i and k , by dividing the difference in BT values between both for the same days by the sum of their corresponding BTs as follows:

$$NBTD = (BT_{i,j} - BT_{k,j}) / (BT_{i,j} + BT_{k,j}) \quad (4)$$

where, j is a date of observation (e.g., each point represents calculated normalized difference on a given day). Negative values of NBTD correspond to days when location k is warmer than i , values close to zero correspond to days when BT values at locations i and k are similar, whereas high values indicate days when location i is warmer. In this study we compared: 1) Ayalon Highway and the old central dense built-up area (“Old North”); 2) Ayalon Highway and park Hayarkon; 3) “Old North” and park Hayarkon; 4) “Old North” and the new neighborhoods at North Tel-Aviv (“New North”). We created polygons around the region of interests (ROI) of all studied areas. Then, we obtained BT values on a temporal scale for these regions. Road and neighborhood data were obtained from the Israel Survey Bureau mapping service (MAPI).

Finally, to demonstrate the powerful application of BT data for future climate quality monitoring, we investigated the associations between air temperatures (Tair) measured at meteorological stations Tair and satellite-derived BT measurements. Toward this end, we used BT data corresponding to clear-sky observations and Tair measurements conducted at the available meteorological sites. Because these relationships between Tair and BT vary daily (Kloog et al., 2012), mixed-effects models were used to allow for the regression intercepts and slopes to vary daily. A basic assumption is that the relationship between BT and Tair varies daily because it depends on time-varying parameters such as relative humidity, wind speed and direction, urban geometry, and surface reflectance (and other parameters).

We used the following mixed-effects model with random intercepts and slopes. For each day we estimate a separate slope in the relationship between Tair and BT that captures its temporal variability. Specifically we fitted the model:

$$\begin{aligned} Tair_{ij} &= (\alpha + u_j) + (\beta_1 + v_j) BT_{ij} + \varepsilon_{ij} \\ (u_j, v_j) &\sim \left[\begin{pmatrix} 0 & 0 \end{pmatrix}, \Sigma \right] \end{aligned} \quad (5)$$

Where: $Tair_{ij}$ is the measured $Tair$ at a spatial site i on a day j ; α and u_j are the fixed and random (site specific) intercepts, respectively, BT_{ij} is the BT value in the grid cell corresponding to site i on a day j ; β_1 and v_j are the fixed and random slopes, respectively. Σ is an unstructured variance-covariance matrix for the random effects and ε_{ij} is the error term at site i on a day j .

4. Results

4.1. The location of “warm” and “cold” zones

Figure 2a shows the spatial distribution pattern of BT in Tel-Aviv during the last 30 years, with warm areas colored in red (above 1 STD of BT) and cold areas colored in blue (Below -1 STD of BT). It can be seen that from the mid-80s until present day the overall spatial pattern of BT in Tel-Aviv is fairly constant. Notably, the older central part of Tel-Aviv exhibits lower BT compared with the much warmer industrial and commercial zones, or bare soils and highways located in the south-east part of the city. Fig 2b is a “generic” map of the BT pattern of Tel-Aviv (dark pixel are low BT, bright pixels are high BT) derived from the temporal findings in Fig 2a. This derivation supports the validity of our data analysis, in that the “warm” and “cold” zones are observed for the most part at all the different time points on the temporal scale.

Figure 3 shows the temporal change in percent area coverage of the “warm” and “cold” zones (i.e., above +1 STD and below -1 STD, respectively) over the course of 30 years. As can be seen, the early 80’s symbolized higher area coverage of “cold” zones, but this trend reversed in the 90’s. Notably, over the last few years the observed difference in area coverage between “warm” and “cold” zones has decreased.

4.2 Highest/lowest diurnal and temporal variability of BT

After establishing that the BT distribution model of Tel-Aviv is constant over the last 30 years, we explored the diurnal and temporal variability of BT. We asked the following question: What are the highest/lowest diurnal differences for each pixel with respect to BT and where these areas are located? A scatter plot chart comparing BT for day and night is an effective way to explore this question. Random scatter suggests no correlation of BT results between two time frames and indicates that changes occurred, whereas the opposite is implied by a linear scatter plot. In Figure 4 (upper panels), we divided the scatter plot into 4 segments in order to classify different diurnal patterns of BT and identify surfaces that exhibit this change. These chart segments were then highlighted on a subtraction image to reveal their spatial distribution and location. Here we classify warm and cold surfaces as mentioned in section 3.3 (i.e., 3rd quartile as warm and 1st quartile as cold).

Segment number I (delineated by a blue square) represents areas that are warm at night but relatively cold during the day time (i.e., under 35.42°C during the day time and above 24.14°C at night time). These areas contain water bodies, such as the sea shore, the Yarkon

river, ponds or are residential neighborhoods with vegetated areas. The latter finding is compatible with other studies that have reported the cooling effect of water and trees over urban areas (Chen et al., 2014; Shashua-Bar & Hoffman, 2000; Potchter et al., 2006).

Segment number II (delineated by a red square) shows areas that are hot during both the daytime and nighttime (i.e., above 37.46 °C during the daytime and above 24.14 °C at nighttime). These areas centered on the south part of Tel-Aviv, which contains mainly asphalt platforms, industry and commercial areas. Segment number III (delineated by a yellow rectangle) represents areas that are cold during both daytime and nighttime (i.e., under 35.42°C during the daytime and under 23.52°C at nighttime). These areas are mostly large vegetated areas with no urban elements inside, which accords with earlier studies showing the effect of parks on temperature (Cohen et al., 2014). Segment number IV (delineated by green square) shows areas that are warm during the daytime but relatively cold at nighttime (i.e., above 37.46 °C at daytime and under 23.52 °C at nighttime). These areas are surfaces and other urban components with high SVF, e.g., surfaces that are exposed to direct radiation during the day and radiative cooling at night. An example of a surface with these properties is bare soil, the thermal behavior of which enables rapid heating during the day and rapid cooling during the night due to the ground radiative characteristics (Sabins, 1997). Another example is granulate-paved surfaces, which stand out as one of the coldest areas at nighttime, and one of the warmest during the day, such as the surfaces located in Rabin square and the square in front of the Tel-Aviv Art Museum. In line with previous studies conducted in Tel-Aviv (Ben-Dor & Saaroni, 1997), the paved granulate surface in Rabin square surface was found to be one of the warmest urban objects and one of the most polluted (Cohen et al., 2014). Furthermore, a histogram of diurnal BT values (see right panel of Figure 4) illustrates the relatively high range of BT variability, up to 19°C among different urban surfaces, with the mean value of 13°C. Segments I and IV exhibited the highest diurnal variability in BT.

Having investigated the diurnal differences in BT, we asked the next question: What are the temporal differences per pixel with respect to BT? We employed the same approach, image subtraction and a scatter plot chart followed by chart segmentation and mapping (lower panels of Figure 4). Segment I (highlighted by the blue color) represents areas that were warm on August 14, 1987 but cold on August 5, 2013 and mostly represents changes where bare soil (warm) was turned into an urban area. Segment II (highlighted by the red color) represents areas that were warm on both images, August 1987 and 2013, for the most part bare ground, asphalt platforms, industrial and commercial areas. For example, the Ayalon Freeway, which has a heavy traffic load, and HaMasger street, with various factories, workshops, garages and automotive industry vehicle importers' offices, were warm at both time points. Segment III (highlighted by yellow color) shows areas and surfaces that were relatively cold at both time points, or displayed only a slight increase in BT in 2013 and comprises parks, the old city center, and vegetated urban neighborhoods. This segment also shows areas that changed from bare soil to newly constructed buildings. Finally, Segment IV (green color) shows areas cold in 1987 but warm in 2013, and mostly represent the change in BT due to vegetation turned into bare ground. A histogram of temporal BT values (panel on right) highlights that the temporal change is as high as 9 °C with mean value of 2.3°C. As for diurnal BT, Segments 1 and 4 are associated with the highest temporal change in BT.

4.3 Temporal variability between different parts of the city

We examined if there are temporal changes in BT by calculating NBTD between different parts of the city (Figure 5). First, we assessed the relative difference in BT on a temporal scale by calculating NBTD between warm and cold zones. As can be seen, there is a relatively stable pattern with only a slight decrease in NBTD. Furthermore, the difference between the Ayalon Highway and the “Old North” is positive, with a slight decreasing trend. Ayalon is the busiest road in the city with high traffic density that has increased over the years; the “Old-North” is a residential and leisure-oriented destination bordered by the expansive and green HaYarkon Park, an area that changed little over time. Therefore, we assume that the slight decrease in NBTD might be explained by anthropogenic activities. However, independent information about energy consumption, population density and other parameters at each location at the different time points would help to corroborate this premise. Similarly, Namir drive is warmer than HaYarkon Park, and on a temporal scale the difference between these zones is quite stable. Another interesting example is the NBTD between “Old North” and “New North” neighborhoods. “New North”, as opposed to “Old North”, exhibited the highest variability in BT and was found to be generally warmer until 2003 than its counterpart. This area is one of the most diverse areas in Tel-Aviv, comprising newly built-up neighborhoods, open spaces, sport facilities and highways. Surprisingly, more recently, the difference between old and new North neighborhoods has blurred, and both exhibit similar values.

4.4 Future application: air temperature monitoring

Estimates of T_{air} for each grid cell were obtained for 14 days selected during the period of 1984–2014. The fixed effects of the BT intercept and slope were statistically significant: $\alpha = 15.7$ ($P < 0.001$) and $\beta_1 = 0.39$ ($p < 0.01$), respectively. The random slopes showed important variations from day to day, ranging from -0.13 below the fixed slope of 0.39 to 0.42 above it. Note that these results support the findings mentioned above, that because the parameters influencing the relationship between T_{air} and BT vary from day to day within a given domain, it is necessary to adjust for this daily variability. Figure 6 shows a relatively high R^2 value, 0.81 ($P < 0.001$) for a model fit.

What governs spatial variability in T_{air} ? To address this question, we considered two days generated by our simple model: August 27, 1989, and August 8, 2014 (Figure 7). Although the general T_{air} pattern is quite similar, for example industrial zones, major roads and highways exhibit higher T_{air} compared to the old center area during the day, it can be seen that T_{air} differs by date and location. To examine in greater detail this variability in T_{air} across the city, we analyzed the spatial and horizontal T_{air} variability across “Old North” Tel-Aviv (Panel 3, Figure 7). This analysis revealed a marked difference in T_{air} behavior when one passes from the seashore inland and towards the Tel-Aviv suburbs. “Old North” is a residential and leisure-oriented destination bordered by the expansive and green HaYarkon Park. During daytime the T_{air} profile steeply increases towards the east part of the city reaching its maximum in the Tel-Aviv suburb cities and industrial zones, known for their intensive anthropogenic activity and high population density. This offshore increasing trend can be attributed mainly to a sea breeze effect, which is blocked by the buildings and anthropogenic activity that is higher in the industrial area of the Tel-Aviv suburbs.

Currently, high-rise buildings act as a barrier along large areas of the coast and intersections consist mainly of narrow streets. Ground monitoring experiments conducted across different parts of Tel-Aviv during 1989–1993 using nine meteorological sites found differences of 2–2.1 °C between seashore sites and industrial zone. The results of our simple model show similar trends in Tair. These results are also supported by ground IMS Tair measurements conducted in adjacent sites. Furthermore, our results are in accord with findings reported in Zhou et al. (2014) and Zhang et al. (2011) showing similar trends in Houston and Detroit.

Our findings notwithstanding, in order to derive fully the practical applications of Tair maps the following data must be incorporated into the model: 1) a greater number of days, and 2) more environmental variables (e.g., wind direction and speed, relative humidity, land use parameters, traffic density, etc.).

4.4 Discussion and conclusions

This study utilized satellite imagery retrieved from Landsat 4, 5, 7, and 8 in order to examine the BT characteristics on a spatial and temporal scale of the city of Tel-Aviv, Israel. Based on our results, the city can be divided into four different segments according to distinct BT behavior. We studied the surface properties of each area. Distinct warm versus cold BT zones over the last 30 years were identified that are constant in space. Although the percent coverage of warm zones is greater, this difference has slightly decreased over the last few years.

Our study indicates that the spatial and diurnal variation of satellite-derived BT is closely associated with surface properties and environmental conditions, whereas temporal variability is closely related to changes in land cover and land use. During the daytime, the most dominant surface elements contributing heat to the city are bare soils, streets, industrial & commercial areas (e.g., artificial pavements) and sport facility (turfs) exposed to solar radiation. This is because there is no evaporative cooling effect over these surfaces (Zhao et al., 2014; Kjelgren & Montague, 1997). In particular, football pitches with only synthetic grass were found to be one of the hottest spots during daytime but not at nighttime (Yaghoobian & Kleissl, 2010), whereas tennis courts (hard courts) were found to have the second highest mean BT both during the daytime and at nighttime. However, interpretation of our findings must take into account the limiting factors of thermal satellite remote sensing using Landsat imagery, which include a requirement for clear skies and a low temporal resolution.

Additionally, our preliminary results demonstrate how BT can be used to predict daily Tair. For example, we show that the Tair difference between the colder “Old-North” neighborhood and the warm industrial zones located next to the Ha-Shalom interchange, Ha-Masger street and main central bus station range between 0.7–1.8°C. In terms of BT, the difference can be as high as 10°C. This knowledge could be employed in various studies, such as health effect studies, urban climate and urban planning studies etc. To further investigate the strengths and limitations of a mixed effect model approach for modeling Tair, we are planning a comprehensive multi-year study based on the full set of Landsat measurements.

The predictive accuracy of the mixed effect model approach presented here can be further improved by incorporating additional parameters such as land use and meteorological measurements (such as wind speed and relative humidity). However, it should be noted that for this type of model a large amount of daily Tair stations is required, which are not always available in other areas.

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Figure 1.
Study area.

Figure 2.
Spatial distribution of Land surface temperature (BT) over the last 30 years in Tel-Aviv with warm areas colored in red (above 1 STD of BT) and cold areas colored in blue (Below -1 STD of BT).

Figure 3.
The temporal change in area coverage of the warmest and coldest areas over the course of 30 years;

Figure 4.

Upper: Diurnal variability in BT. (a) A subtraction image, day minus night. Blue (segment 1) represents areas that were cold during daytime and warm during nighttime. Red (segment 2) represents areas that were warm both during daytime and nighttime. Yellow (segment 3) represents areas that were cold during both daytime and nighttime. Green (segment 4) represents areas that were warm at daytime and relatively cold at nighttime. (b) The same data as represented in (a) but converted into a scatter plot form where the X-axis is the day BT and Y-axis is the night. (c) Histogram of the subtraction image.

Lower: Temporal scale variability in BT. (a) A subtraction image, most recent day minus historic day. Blue (segment 1) represents areas that were warm on August 5, 1987 but cold on August 5, 2013. Red (segment 2) represents areas that were warm in both 1987 and 2013. Yellow (segment 3) represents areas that were relatively cold areas and surfaces on both days. Green (segment 4) represents areas that were cold on 1987 but warm in 2013. (b) The same data as represented in (a) but converted into a scatter plot form where the X-axis is the day in 2013 and Y-axis is the day in 1987. (c) Histogram of the subtraction image.

Figure 5.
The temporal change in BT expressed by NBTD between representative areas.

Figure 6.
A scatter plot of the air temperature–surface temperature relationship after the daily calibration model was run based on 14 Landsat images.

Figure 7.
Panels A–B: Sequence of maps showing patterns of T air. Panels A and B are T air patterns on August 27, 1989 and August 8, 2014, respectively; Panel C: A cross-sections across “Old North” and Tel-Aviv suburbs area.

Table 1

Times, Dates and Metrological conditions of the imagery obtained for this study.

Daytime	Date	Time (GMT)	Spacecraft ID	Air temp (°C)	Wind (m/s)
Summer	05-Aug-84	07:40:32	LANDSAT 5	29	6
	06-Sep-84	07:41:10	LANDSAT 5	28.7	4.5
	21-Jun-85	07:41:10	LANDSAT 5	25.5	4.5
	11-Aug-86	07:32:53	LANDSAT 5	29.7	3
	14-Aug-87	07:37:07	LANDSAT 5	32	5
	27-Aug-89	07:44:34	LANDSAT 4	30.4	3
	03-Aug-92	07:19:38	LANDSAT 4	31.5	0.5
	14-Aug-99	08:10:09	LANDSAT 7	31.6	3.5
	26-Aug-03	07:48:16	LANDSAT 5	30.4	2.5
	17-Aug-06	08:06:56	LANDSAT 7	32.3	3.5
	06-Aug-08	08:06:29	LANDSAT 7	30.6	5
	24-Aug-11	08:04:29	LANDSAT 7	31	3.5
	04-Jul-13	08:13:05	LANDSAT 8	30.5	4
	05-Aug-13	08:13:06	LANDSAT 8	31.3	3.5
Winter	06-Sep-13	08:13:07	LANDSAT 8	31.3	3
	8-Aug-14	08:11:08	LANDSAT 8	31.4	3
	18-Jan-87	07:30:53	LANDSAT 5	25.2	0
	30-Dec-88	07:43:10	LANDSAT 4	15	1
	16-Feb-89	07:43:55	LANDSAT 4	16.8	5
	30-Jan-09	07:56:34	LANDSAT 5	17.8	6
	27-Dec-13	08:12:32	LANDSAT 8	18.7	1.5
	13-Feb-14	08:11:57	LANDSAT 8	24.8	2
	16-Jul-13	19:38:09	LANDSAT 8	24.9	2
Nighttime					