ANALYSIS OF LAND SURFACE Temperature Change for Northeastern North America Using MODIS Thermal Data, 2001 to 2011

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ABSTRACT

Many types of empirical research indicate that the globe's climate has been changing over the past century, and in particular, the world is getting warmer. The earth is not warming uniformly, with some places cooling and other places warming. There is a strong heterogeneity to the world's warming, with particular warming occurring at high latitudes. New England and Eastern Canada are experiencing a changing climate which is consistent to global patterns. There are currently a number of methods used to measure our changing climate from in situ air temperature measurements, satellite-based snow cover and surface temperature measurements, to recording physical and biological phenomenon such as first ice-out days and first date of sap flow. In this study we measured the land surface temperature of northeastern North America using the Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared bands on NASA's Terra satellite (MOD11C3). We analyzed changing surface temperature for daytime (10:30 AM) and nighttime (10:30 PM) from 2001 to 2011 on seasonal to interannual time scales. We found that at the annual time scale and each season (except summer), the study area warmed both at night and day. There was a strong correlation between the North Atlantic Oscillation's (NAO) negative phase and a warming of Northeast North America with 2010 having the warmest land surface temperatures. Throughout the time period most of the warming occurred at higher latitudes. *Keywords: climate change, remote sensing, northeastern North America, land surface temperature*

Introduction

From empirical evidence it is becoming clear that the world is warming (IPCC 2007). Not only have *in situ* and satellite-based air temperature measurements detected a warming world, but the oceans have undergone a warming (Domingues et al. 2008) and much of the cryosphere (areas of frozen water) is experiencing a melting of its ice and snow cover (Screen and Simmonds 2010). In response to this global warming, the climate is changing in many places, with hotter summers and winters to decreased snow cover. One of the results of the changing climate is that the flora and fauna on the earth, from the arctic to the tropics, are rapidly changing (Hughes 2000; McCarty 2001; Parmesan and Yohe 2003). Change is occurring to the phenology and physiology of organisms, the distribution and extinction of species, along with the structure and dynamics of ecosystems (Hughes 2000; Wuethrich 2000; McCarty 2001; Walther et al. 2002). The spatial distribution of climate change and global warming has been uneven, with some regions experiencing extensive change and others areas experiences few changes. Globally, surface air temperature has increased during the 20th century and continues to do so in the first decade of the 21st century, with disproportionate increases taking place in most northern temperate regions (Houghton et al. 2001; Hansen et al. 2006).

New England and eastern Canada have experienced a warming trend consistent with global patterns (Keim et al. 2003). Reflecting the warmer surface air temperatures are earlier dates of spring lake ice-out (Hodgkins, James, and Huntington 2002) and river ice-out (Dudley and Hodgkins 2002), as well as earlier snowmelt-driven spring runoff (Hodgkins, Dudley, and Huntington 2003) and fewer snow-covered days in winter (Burakowski et al. 2008). There has also been a decrease in the ratio of snow to total precipitation (Huntington et al. 2004) and decreases in river ice thickness (Huntington, Hodgkins, and Dudley 2003).

Northeastern North America has also experienced phenological changes. Early spring warming has caused earlier blooming of lilacs (Schwartz and Reiter 2000), as well as altering bird migration (Dunn and Winkler 1999), and anadromous fish migration (Huntington, Hodgkins, and Dudley 2003). The growing season in New England has increased over the past 200 years (Baron and Smith 1996; Cooter and Le Duc 1995).

This paper presents an application of the Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared bands for analyzing changes in surface temperature for Northeast North America from 2001 to 2011. Our study is the first, to our knowledge, to use the MODIS thermal data to document the surface temperature of northeastern North America on seasonal to interannual time scales. We chose to use MODIS data as these are the first satellite-derived data that provides high quality and calibrated temperature products (globally) which are extensively preprocessed and ready for use (Wan et al. 2004, 2002).

The MODIS thermal bands capture land surface skin temperatures (*T*skin), which are different from air temperatures (*T*air), as measured by an in situ instrument usually 1.5 to 2 m above the ground (Jin and Dickinson 2010; Shreve 2010). Remote sensing of *T*skin by sensors aboard satellites is the radiometric temperature derived from the inverse of Planck's function (Jin and Dickinson 2010). Jin and Dickinson (2010) show that *T*skin is a different physical parameter from *T*air, and *T*skin varies from *T*air. Surface temperatures (*T*skin) are determined by and responded to land surface-atmosphere interactions (Jin 2004; Jin and Dickinson 2002). *T*air and *T*skin especially vary depending on surface conditions (land cover) and cloud cover (Sun and Mahrt 1995). The sparser the vegetation cover the greater the temperature flux for *T*skin (Sun and Mahrt 1995). It is still uncertain in the scientific community how *T*skin will be used in climate studies, but it is believed that these data could be very beneficial for future climate studies (Shreve 2010). Errors in satellite-derived temperatures can come from a variety of sources such as instrument noise and drift, sun glint, residual cloud contamination, atmospheric attenuation, and various surface emissivity effects.

If there are differences between the data types and if we already have a long-term set of *T*air data, why do we need *T*skin data? One reason for the usefulness of *T*skin data is that *T*skin observations provide more coverage than *T*air. *T*air observations are not uniformly distributed over the globe and some places in the world have very limited *T*air stations and data, such as parts of northeastern North America. The high spatial resolution of satellite data allows us to analyze fine details over the globe. The *T*skin data also provides a different way to understand Earth's temperature. Jin and Dickinson (2010) found that despite the differences between *T*skin and *T*air, the major patterns of *T*air are consistent with those of *T*skin, although details differ.

Our study area includes the Canadian provinces of New Brunswick, Newfoundland & Labrador, Nova Scotia, Prince Edward Island, and Quebec, along with the American states of Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont (Figure 1).

Figure 1. Study area includes the Canadian provinces of New Brunswick, Newfoundland & Labrador, Nova Scotia, Prince Edward Island, and Quebec, along with the American states of Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

Data

Site Description

The surface temperature of northeastern North America was examined from 2001 to 2011 using 11 years of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the NASA Earth Observing System (EOS) Terra platform. The data used are the *MODIS/Terra Land Surface Temperature/ Emissivity Monthly L3 Global 0.05 Des V005,* CMG product (Short name: MOD11C3). Both day (10:30 AM) and night (10:30 PM) images were downloaded. Data were downloaded at the global scale from the National Aeronautics and Space Administration (NASA) Land Processes Distributed Active Archive Center (Wan 2008).

The MODIS sensor provides high radiometric sensitivity (12 bit) in 36 different spectral bands ranging in wavelength from 0.4 µm to 14.4 µm. The MODIS temperature product that we used is from the Terra satellite and is based on a daily 1 km spatial resolution of land surface temperature with high accuracy of 1° K for materials with known emissivities (Wan et al. 2002, 2004; Wan 2008). The MOD11C3 data are composited at a 0.05° latitude/longitude grid. The *Tskin* data are only retrieved on clear days and nights. Details of the MOD11C3 product (version 5) skin temperature process and validation can be found in Wan (2008, 2006) and Wan and Li (2008). This study utilizes the MODIS/Terra (PM and AM satellite) MOD11C3 product to study surface temperature change in Northeast North America (Figure 1).

Methodology

Data Preparation

MOD11C3 data (day and night) were downloaded from NASA's Land Processes Distributed Active Archive Center at the global scale and imported into the *Idrisi* image processing software (Eastman 2009). The *MOD11C3* data were in monthly maximum value composites (MVC). The MVC is created on a pixel-by-pixel bases where each pixel's *Tskin* value is the highest value during the monthly time period being composited (Holben 1986). The quality control data for each month were examined one by one before using the temperature data. There were no extensive errors found in northeastern North America and the total error was less than 1 percent for each month. In addition to analyzing NASA's quality control data, we ran a principle component analysis (PCA) to examine the data again and we found some night images in 2007 with noise greater than 5% which affected the quality of both seasonal and annual images. Therefore, we decided to remove all the night images for the year 2007.

Using the *Idrisi* software we further processed the data into seasonal and annual composites. We created seasons by averaging 3 month periods: Spring (March, April, May); Summer (June, July, August); Fall (September, October, November); and Winter (December, January, February - January and February are from the next calendar year). The winter of 2011 would include December 2011 plus January 2012 and February 2012. For annual averages we added all 12 months of the calendar year and then divided by 12. Therefore the annual averages do not include the same months used in the winter season. We did not process the 2007 *MOD11C3* night data as noted above.

We processed the seasonal and annual average images at the global scale. Once the images were produced, we used a raster mask image to window out northeastern North America. The windowed-out data were then transformed from Kelvin to Celsius with the following equation: [(MPVK x 0.02) – 273] = MPVC, where MPVK = the MODIS Pixel Value in Kelvin and MPVC = MODIS Pixel Value in Celsius. The data were then reprojected from the MODIS Sinusoidal projection into a latitude – longitude projection in the Idrisi image processing software.

For our research we undertook two major analyses: 1) Anomaly and Mean Time Series Analysis of all pixels of the study area to determine how the entire area in Northeast North America changed in temperature throughout the time period, and 2) Simple Differencing (Univariate Differencing) of all pixels to determine which pixels were increasing and which were decreasing in surface temperature in Northeast North America during the time period.

Anomaly Analysis

For the anomaly analysis, we created 11-year average images for each season and for the annual averages. To calculate the 11-year average images we used the equation: [2001-2011AAday = (MPVC2001 + MPVC2002+ … + MPVC2011) / 11] where AA = Annual Average, using the image calculator in *Idrisi*. We ran this equation for each season and for the annual averages for the day images. Because the 2007 night images were found to have noise (> 5%), the night eleven-year average images (seasonal and annual) were calculated as: 2001-2011AAnight = (MPVC2001+ MPVC2002+… +MPVC2006 + MPVC2008 +…+ MPVC2011) / 10. Then 2001-2011AA was subtracted by each year (annual averages and annual seasonal averages), for example: 2001AAA = 2001annual average – 2001-2011AA., where AAA = Annual Average Anomaly.

After finishing 11 years annual average and seasonal anomalies, we ran a Time Series Analysis (TSA) with these anomalies for the entire study area for the annual averages and each season (Spring, Summer, Fall, Winter) for each time period (day and night) to find the surface temperature change pattern during the time period. We also ran a TSA for the mean values of the annual averages and seasonal data.

Univariate Differencing

To determine change over the course of 11 years (2001 to 2011), a univariate differencing, or simple differencing, methodology was undertaken. Simple differencing is a basic method of expressing the difference between two dates which involves two spatially registered images of the same area taken at different times where one image is subtracted from the other. Mathematically:

$$Dx^k_{ij} = x^k_{ij}(t_2) - x^k_{ij}(t_1)$$

where x^k_{ij} = pixel value for band k, and i and j are line and pixel numbers in the image, t_1 = first date and t_2 = second date (Singh 1989). Simple differencing is a widely used change detection technique and has been used in a great variety of environments and with a wide assortment of satellite data (Singh 1989; Jensen 1996).

Because the annual average surface temperatures for northeastern North America have considerable inter-annual variation, we created a number of multiple year averages for our univariate differencing. The end points of our data set were averaged (in order to minimize the inter-annual variation) where: MPVC2001-02 = [(MPVC2001 + MPVC2002) / 2], and MPVC2010-11 = [(MPVC2010 + MPVC2011) / 2]. Using this method we created 2-year, 3-year and 4-year averages (MPVC2010-11, MPVC2009-10-11, MPVC2008-09-10-11, MPVC2001-02, MPVC2001-02-03, MPVC2001-02-03-04). Because the North Atlantic Oscillation in 2001 and 2010 had a strong influence on warm temperatures we also created a 4-year period without 2001 and 2010 (MPVC2002-03-04, MPVC2008-09-11). To determine changes in temperature over the time period we differenced the various end-point averages, for example: MPVC2010-11 - MPVC2001-02 = MPVC1011minus0102. Temperature change was evaluated in this manner for the annual data, both day and night at the 2-year, 3-year, 4-year and 4-year minus 2001 and 2010 levels. Results of the univariate differencing were then value sliced by temperature into 5 categories: 1) decrease > 20 C, 2) decrease from 10 C to 20 C, 3) slight change from decreasing 10 C to increasing 10 C, 4) increasing from 10 C to 20 C, and 5) increasing greater than 20 C.

Results and Discussion

Anomaly and Mean Analysis

The average annual surface temperature for the entire study area (Figure 1) was 1.230 C for the daytime (ranging from 0.110 C to 3.150 C) and -5.890 C for the nighttime (ranging from -7.340 C to -3.760 C). For both the day and night data sets there was an overall increase in surface temperature as expressed in the R2 of the linear regression line of the annual average data over the course of the time period (2001 – 2011). Surface temperature increased more in the night than in the day (day R^2 = 0.056 and night R^2 = 0.1913) (Figure 2). The day and night data showed a similar pattern of change with peak warming occurring in 2001, 2006 and 2010. These years are also the three distinct years of a negative phase of the North Atlantic Oscillation during the same time period of 2001 to 2011 (Figure 3) (Hurrell 2012). A negative phase brings about mild temperatures in Greenland and northern Canada (Hurrell et al. 2003), and with much of the study area at high latitudes there is a clear correlation with the negative phase of the North Atlantic Oscillation. The negative NAO index phase shows a weak subtropical high and a weak Icelandic low and the reduced pressure gradient produces fewer and weaker winter storms. Although the US east coast experiences more cold air outbreaks, Greenland and northern Canada have milder winter temperatures (Ghatak, Gong, and Frei 2010).

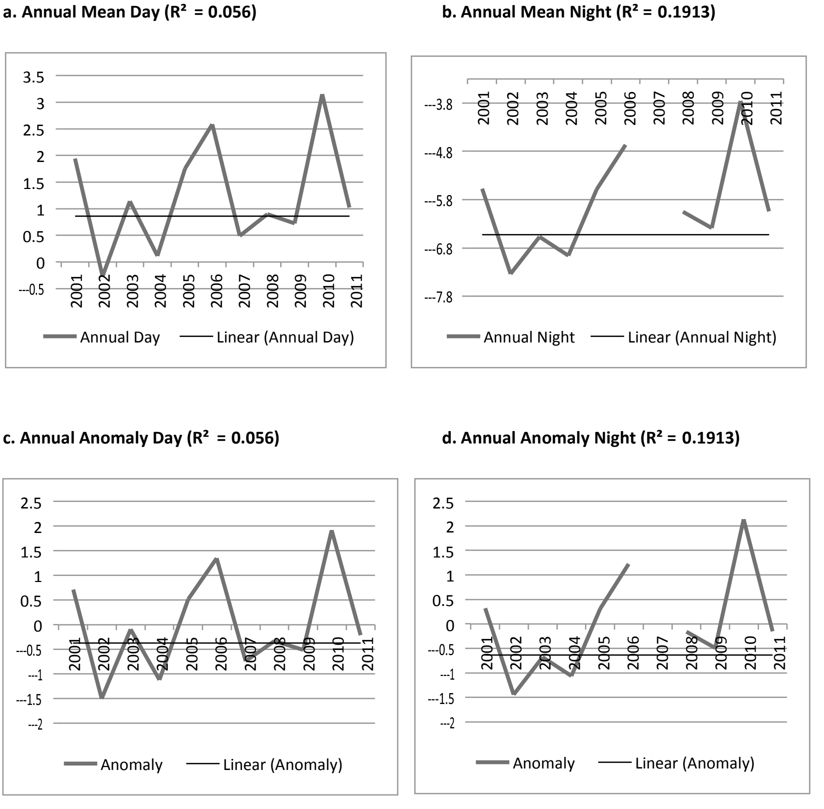


Figure 2. Annual Average Mean and Anomaly Analysis.

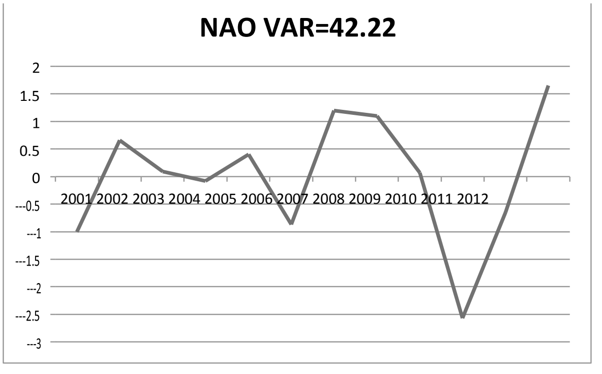
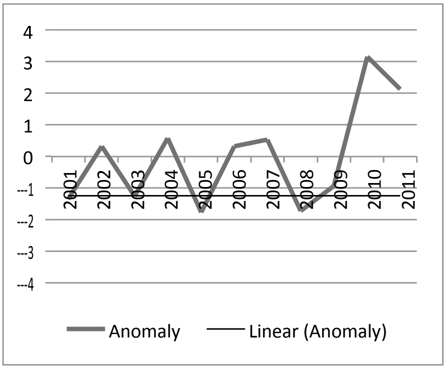


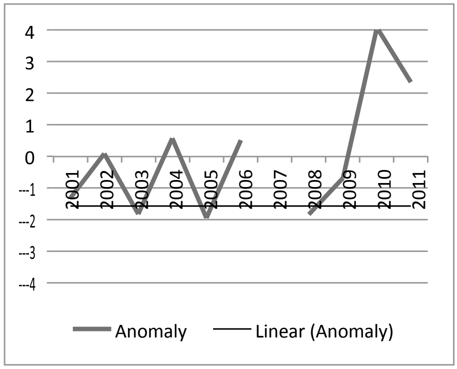
Figure 3. North Atlantic Oscillation for latitude: 42.22.

Concerning seasonal variation over the time period (Figure 4), all seasons showed an increase in temperature throughout the time period except for summer day (R2 = -0.034). In the winter, spring, and summer seasons there was a greater increase in temperature at night than in the day, with only the fall season showing a greater warming during the daytime. The greatest change occurred in the fall and winter seasons. Spring was the only season to show a strong correlation with the NAO negative phase, which was so prominent with the annual average anomaly analysis. The spring also had the greatest inter-annual variation due to the strong influence of the warming temperature in 2001, 2006 and 2010, during both day and night. The winter season, however, appears to have been strongly influenced by the 2010 NAO event. This coincided with an exceptionally negative phase of the NAO. Seager et al. (2010) suggests it was caused by a freak combination of an 'El Niño' event and the rare occurrence of an extremely negative NAO.

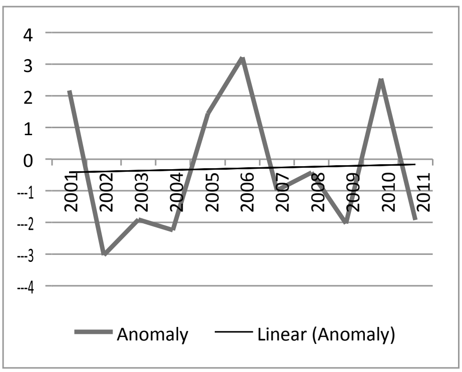
a. Winter Day ($R^2 = 0.2638$)



b. Winter Night ($R^2 = 0.3272$)



c. Spring Day ($R^2 = 0.0013$)



d. Spring Night ($R^2 = 0.0219$)

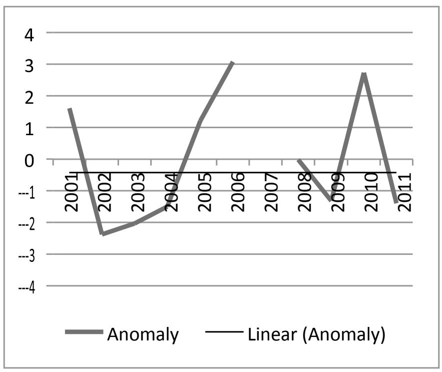
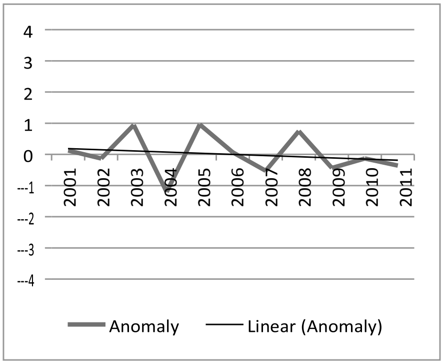
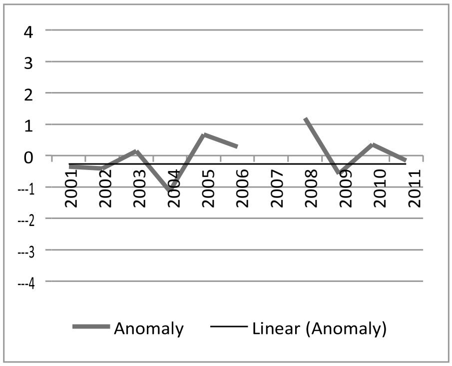


Figure 4. Seasonal Average Anomaly Analysis in Degrees Celsius (continued on next page).

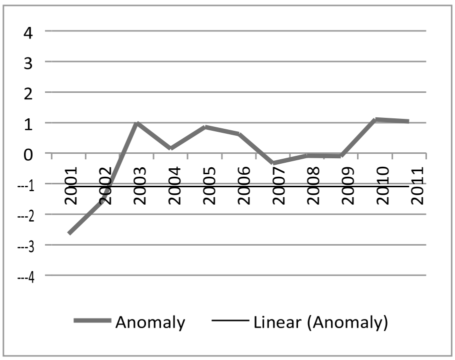
e. Summer Day (R^2 = -0.034)



f. Summer Night (R^2 = 0.0765)



g. Fall Day (R^2 = 0.3767)



h. Fall Night (R^2 = 0.1659)

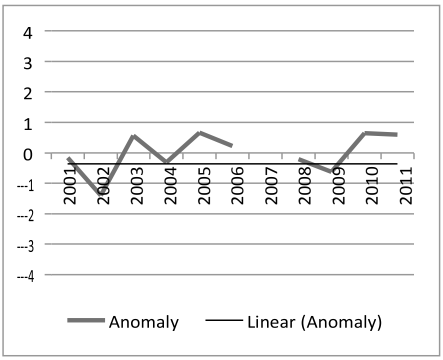


Figure 4 (continued). Seasonal Average Anomaly Analysis in Degrees Celsius

Univariate Differencing Analysis

Through the univariate differencing analysis the region showed extensive warming occurring through the time period (Table 1, Figures 5 and 6). As noted in the methods section above, because of the extensive inter-annual variation, we averaged the end points into 2-year averages (2001+2002 and 2010+2011), 3-year averages (2001+2002+2003 and 2009+2010+2011), and 4-year averages (2001+2002+2003+2004 and 2008+2009+2010+2011). Also because of the strong influence of the NAO's negative phase on years 2001, 2006 and 2010, we created a 4-year average minus 2001 at the beginning and 2010 at the end (2002+2003+2004 and 2008+2009+2011). The univariate differencing for all of these time periods showed extensive areas warming with very few pixels (<1% of study area) cooling (Table 1, Figures 5 and 6).

For every time period there was more warming at night than during the day (Table 1), with the most warming occurring with the 2-year averages. In the 2-year average univariate differencing 79% of the study area warmed by at least 1^0 C during the night and 69% warmed during the day. The least amount of warming occurred at the 4-year average, especially when 2001 and 2010 were removed from the data. However, even these long term averages showed 57% of pixels warming at night (33% when 2001 and 2010 are removed) and 25% during the day (14% when 2001 and 2010 are removed). Almost all of the warming has occurred in Canada with nearly all of New York and New England showing no change (between -1^0 C and $+ 1^0$ C) at all. The warming of higher latitudes is consistent with the current pattern of global warming (IPCC 2007).

Conclusion

The results of analyzing the Earth's land surface temperature (*Tskin*) for northeastern North America shows patterns of change which are consistent with global warming patterns emerging throughout the world (Keim et al. 2003). Not all areas throughout the world are warming. Globally, high latitude regions tend to be warming more than lower latitudinal regions and this pattern emerged from the MODIS land surface temperature data analyzed here.

For the annual average temperature of the entire study area, the temporal pattern of change which emerged was one with warming temperatures both in the day and night, with greater warming at night. The temporal pattern of change also

a. Day

Temperature Change	2 years Pixels Percent	3 years Pixels Percent	4 years Pixels Percent	4 years (no 2001, 2010) Pixels Percent
>-2 ^{0}C	44 (<1%)	91 (<1%)	93 (<1%)	54 (<1%)
-2 to -1^{0}C	324 (<1%)	9 (<1%)	0 (0%)	5 (<1%)
-1 to 1^{0}C	37519 (31%)	91254 (74%)	92094 (75%)	106395 (86%)
1 to 2^{0}C	69635 (56%)	31075 (25%)	30033 (24%)	15966 (13%)
> 2^{0}C	15633 (13%)	726 (1%)	935 (1%)	580 (1%)
Total	123155 (100%)	123155 (100%)	123155 (100%)	123155 (100%)

Table 1. Surface Temperature Change Analysis (2001 to 2011) (continued on next page).

b. Night Temperature Change	2 years Pixels Percent	3 years Pixels Percent	4 years Pixels Percent	4 years (no 2001, 2010) Pixels Percent
>-2 ^{0}C	3 (<1%)	18 (<1%)	21 (<1%)	18 (<1%)
-2 to -1^{0}C	115 (<1%)	37 (<1%)	4 (<1%)	4 (<1%)
-1 to 1^{0}C	25888 (21%)	45607 (37%)	53401 (43%)	81577 (66%)
1 to 2^{0}C	60789 (49%)	75552 (61%)	68254 (56%)	40901 (33%)
> 2^{0}C	36360 (30%)	1941 (2%)	1475 (1%)	500 (<1%)
Total	123155 (100%)	123155 (100%)	123155 (100%)	123155 (100%)

Table 1 (continued). Surface Temperature Change Analysis (2001 to 2011).

showed extensive inter-annual variation with a strong correlation to NAO's negative phase years of 2001, 2006 and 2010. Seasonally the region showed the greatest warming occurring in the fall and winter, both during the day and during the night. The summer day analysis was the only season to show a cooling effect, though it was very slight (R^2 = -0.034). The spring season was the season with the greatest inter-annual variation and the only season to show a strong correlation with NAO's negative phases which were prominently seen in the annual average temporal analysis.

Determining which regions in the study area were warming and cooling through a univariate differencing analysis showed that there was almost no areas cooling, and most of the warming was happening at higher latitudes. There was extensive warming occurring with more than half of the land area warming greater than 10 C at night for all analysis (except when years 2001 and 2010 were removed, then one-third of the land area warmed), and more than a quarter of the land area warming greater than 10 C at night for all analysis (except when years 2001 and 2010 were removed, then 14% of the land area warmed).

Eleven years of data is a short time period to record long-term climate changes. In northeastern North America weather patterns vary considerably from year to year, so long-term data sets are needed to compensate for the annual fluctuations of weather. However, with eleven years of land surface temperature data, patterns of long-term change are beginning to emerge which can be compared with other data sets such as air temperature, phenological changes, and physical changes such as lake ice melt. The main patterns to emerge from this research are that extensive areas of high latitudes are warming more than areas of low latitudes, which has been discovered in many parts of the world. Warming is happening more broadly and faster at night and seasonally, the fall and winter are warming faster than the other seasons. In addition, the negative phase of the North Atlantic Oscillation appears to have a broad warming of much of northeastern North America, both during the day and at night. Climate models are predicting continued climatic changes for the northeast (Hayhoe et al. 2007) and the MODIS land surface temperature data can help verify these predicted changes in the future.

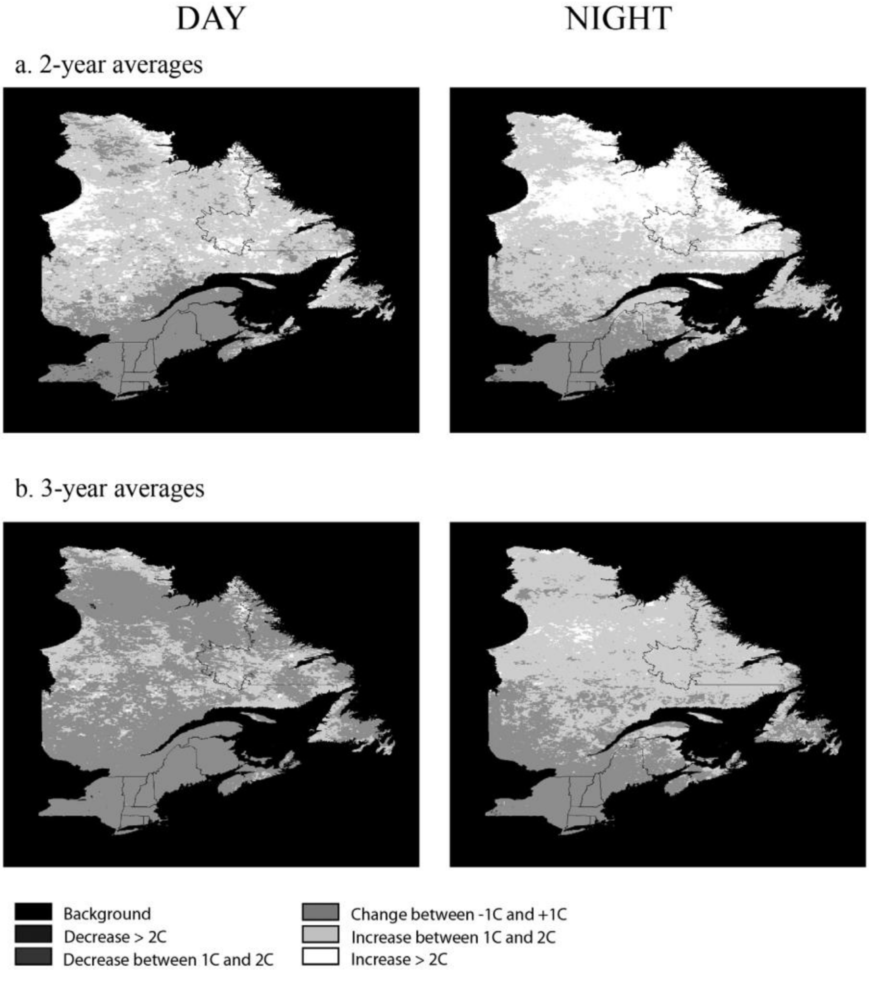


Figure 5. Regions of changing temperature for 2-year and 3-year averages. The daytime and nighttime results of univariate differencing for 2-year (2010 & 2011 minus 2001 & 2002) and 3-year (2009 & 2010 & 2011 minus 2001 & 2002 & 2003) composites.

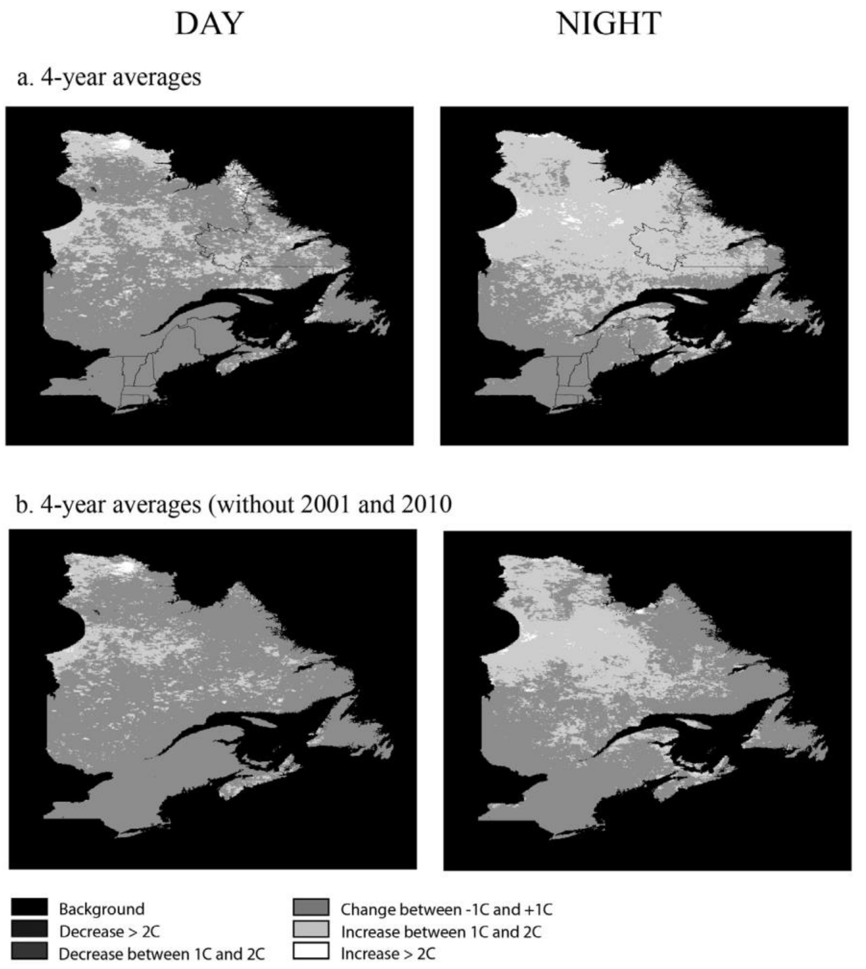


Figure 6. Regions of changing temperature for 4-year and 4-year (minus strong NOA negative phases) averages. The daytime and nighttime results of univariate differencing for 4-year (2008 & 2009 & 2010 & 2011 minus 2001 & 2002 & 2003 & 2004) and 4-year (minus strong NOA negative phases – 2001 and 2010 averages – 2008 & 2009 & 2011 minus 2002 & 2003 & 2004) composites.

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Acknowledgements

The authors would like to thank the National Aeronautics and Space Administration (NASA) Land Processes Distributed Active Archive Center for the MODIS data and the Digital Geography Lab (DGL) for the use of their computers and software. We also thank the anonymous reviewers for their helpful comments. NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (2011). Updated regularly. Last accessed 01 January 2012. We also thank the anonymous reviewers for their helpful comments.

References

Baron, W. R., and D. C. Smith. 1996. Growing season parameter reconstructions for New England using killing frost records, 1697–1947. *Maine Agriculture and Forestry Experiment Station Bulletin* 846. Orono, ME: Institute for Quaternary Studies, University of Maine at Orono. 76 pp.

Burakowski E. A, C. P. Wake, B. Braswell, and D. P. Brown. 2008. Trends in Wintertime Climate in the Northeast United States, 1965-2005. *Journal of Geophysical Research* 113: D20114, doi:10.1029/2008JD009870.

Cooter, E. J., and S. LeDuc. 1995. Recent frost date trends in the northeastern U.S. *International Journal of Climatology* 15: 65–75.

Domingues, C. M., J. A. Church, N. J. White, P. J.Gleckler, S. E. Wijffels, P. M. Barker, R. Jeff, and J. R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453: 1090-1093.

Dudley, R. W., and G. A. Hodgkins. 2002. Trends in streamflow, river ice, and snowpack for coastal river basins in Maine during the 20th century. *U.S. Geological Survey, Water-Resources Investigations Report.* no. 02-4245, 26 pp.

Dunn, P. O., and D. W. Winkler. 1999. Climate change has affected breeding date of tree swallows throughout North America. *Proceedings of the Royal Society London* B266, no. 1437: 2487–2490.

Eastman, J.R., 2009. IDRISI Taiga. [computer software]. Worcester, MA: Clark University.

Ghatak, D., G. Gong, and A. Frei. 2010. North American Temperature, Snowfall, and Snow-Depth Response to Winter Climate Modes. *J. Climate* 23: 2320–2332.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade. 2006. Global temperature change. *PNAS* 103, no. 39: 14288-14293.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. F. Luo, M. D. Schwartz, E. W. Sheffield, B. Anderson, J. Bradbury, A. Degaetano, T. J. Tro, and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. *Climate Dynamics* 28: 381-407.

Hodgkins, G. A., I. C. James, and T. G. Huntington. 2002. Historical changes in lake ice-out dates as indicators of climate change in New England. *International Journal of Climatology* 22: 1819–1827.

Hodgkins, G. A., R. W. Dudley, and T. G. Huntington. 2003. Changes in the timing of high river flows in New England over the 20th century. *Journal of Hydrology* 278: 244–252.

Holben, B. N. 1986. Characteristics of maximum-value composite images from temporal AVHRR data. *International Journal of Remote Sensing* 7: 1417-1434.

Houghton, J. T., Y. Ding, D. C. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, eds. 2001. *Climate Change 2001*: The Scientific Basis. Cambridge, U.K.: Cambridge University Press. 944 pp.

Hughes, L. 2000. Biological consequences of global warming: is the signal already apparent? *Trends in Ecology and Evolution* 15: 56–61.

Huntington, T. G., G. A. Hodgkins, and R. W. Dudley. 2003. Historical trend in river ice thickness and coherence in hydroclimatological trends in Maine. Climatic Change 61: 217–236.

Huntington, T. G., G. A. Hodgkins, B. D. Keim, and R. W. Dudley. 2004: Changes in the Proportion of Precipitation Occurring as Snow in New England (1949–2000). *J. Climate* 17: 2626–2636.

Hurrell, J. and National Center for Atmospheric Research (NCAR) Staff (eds.) 2012 (posted originally on 06 Nov 2011) "The Climate Data Guide: Hurrell North Atlantic Oscillation (NOA) index (station-based)." Retrieved from https://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based) (last accessed 20 January 2012).

Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck. 2003. "An overview of the North Atlantic Oscillation" in Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck (eds.) The North Atlantic Oscillation (Washington, DC: American Geophysical Union).

IPCC (The Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis*. eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. Cambridge, U.K.: Cambridge University Press.

Jensen, J.R. 1996. I*ntroductory Digital Image Processing, a remote sensing perspective*. Upper Saddle River, NJ: Prentice Hall.

Jin, M., and R. E. Dickinson. 2002. New Observational Evidence for Global Warming from Satellite Data. *Geophysical Research Letters,* 29, no.10: 1029/2001GL013833.

Jin, M. and R. E. Dickinson. 2010. Land surface skin temperature climatology:
benefitting from the strengths of satellite observations. *Environmental Research Letters* 5: doi:10.1088/1748-9326/5/4/044004.

Jin, M. 2004. Analyzing Skin Temperature variations from long-term AVHRR. *Bulletin of the American Meteorological Society* 85, no. 4: 587-600.

Keim, B. D., A. Wilson, C. Wake, and T. G. Huntington. 2003. Are there spurious temperature trends in the United States Climate Division Database? *Geophysical Research Letters* 30, no. 1404: doi:10.1029/2002GL016295.

McCarty, J.P. 2001. Ecological consequences of recent climate change. *Conservation Biology* 15: 320–331.

Parmesan, C. and G. A. Yohe. 2003. Globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421: 37–42.

Schwartz, M. D. and B. E. Reiter. 2000. Changes in North American spring. *International Journal of Climatology* 20, no. 8: 929–932.

Screen, J. A. and I. Simmonds. 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature* 464:1334–1337.

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik. 2010. Northern hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. Lamont-Doherty Earth Observatory, Columbia University. http://www.ldeo.columbia.edu/res/div/ocp/drought/snow.shtml (last accessed December 2010).

Shreve, C. 2010. PERSPECTIVE Working towards a community-wide understanding of satellite skin temperature observations. *Environmental Research Letters* 5, 041002 doi:10.1088/1748-9326/5/4/041002.

Singh, A. 1989. Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing* 10: 989-1003.

Sun J. and L. Mahrt. 1995. Determination of Surface Fluxes from the Surface Radiative Temperature. *Atmospheric Science* 52, no. 8: 1096–106.

Walther, G. R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J.C. Beebee, J. M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature* 416: 389–395.

Wan, Z., Y. Zhang, Q. Zhang, and Z. L. Li. 2002. Validation of the land-surface temperature products retrieved from Terra Mode rate Resolution Imaging Spectroradiometer data. *Remote Sensing of Environment* 83:163-180.

Wan, Z., Y. Zhang, Q. Zhang, and Z. L. Li. 2004. Quality assessment and validation of the MODIS global land surface temperature. *International Journal of Remote Sensing* 25: 261-274.

Wan, Z. 2006. MODIS land surface temperature products user's guide. Institute for Computational Earth System Science, University of California, Santa Barbara, CA. http://www.icess.ucsb.edu/modis/LstUsrGuide/usrguide.html (Last accessed 20 January 2012).

Wan, Z. 2008. New refinements and validation of the MODIS land-surface temperature/emissivity products. *Remote Sensing of Environment* 112: 59−74.

Wan, Z. and Z-L. LI. 2008. Raidance-based validation of the V5 MODIS land-surface temperature product. *International Journal of Remote Sensing* 29: 5373-5395.

Wuethrich, B. 2000. How climate change alters rhythms of the wild. *Science* 287: 793–795.