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Integrated remote sensing and wavelet analyses for screening short-term teleconnection patterns in northeast America

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SUMMARY

Global sea surface temperature (SST) anomalies have an inherent effect on vegetation dynamics and precipitation processes throughout the continental United States (U.S.). SST variations have been correlated with precipitation patterns via ocean–atmospheric interactions known as climate teleconnections. Prior research has demonstrated that understanding excitation mechanisms of the teleconnection patterns can be instrumental for climate prediction across a wide region at sub-continental scales, yet these studies tend to have large uncertainties in estimates by assuming linearity when examining teleconnection signals. The co-existence of non-stationary and nonlinear signals embedded in SST anomalies makes the identification of the teleconnection patterns difficult at the local scale. This study explores the short-term (10-year) frequencies (i.e., interannual and seasonal) embedded in the non-stationary teleconnection signals between SST at the North Atlantic and North Pacific oceans and the responses of terrestrial greenness and precipitation along multiple pristine sites in northeast U.S., including (1) White Mountain National Forest – Pemigewasset Wilderness, (2) Green Mountain National Forest – Lye Brook Wilderness, and (3) Adirondack State Park – Siamese Ponds Wilderness. Each site was selected to avoid anthropogenic influences that may otherwise mask climate teleconnection signals. Lagged pixel-wise linear teleconnection analysis based on remote sensing satellite images across anomalous global SST datasets found significant correlation regions between SST and these terrestrial sites. With the aid of wavelet analyses including continuous wavelet transform, cross-wavelet analysis, and wavelet coherency analysis, nonlinear and non-stationary signals exhibit salient covariations at biennial and triennial frequencies between terrestrial responses and SST anomalies across oceanic regions in agreement with the El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) signals. Multiple regression analysis of the combined ocean indices explained up to 50% of the greenness and 42% of the precipitation in the study sites. These identified short-term signals in association with some hydrometeorological forcing processes of circumglobal teleconnection can improve the understanding and projection of the climate change impacts at local scales and harness the interannual periodicity information for future precipitation and greenness projections.

1. Introduction

Climate change and variability estimates from the Intergovernmental Panel on Climate Change (IPCC) in 2007 forecast an increase in North American temperature and precipitation during the 21st century (Meehl and Stocker, 2007). In general, global vegetation density, or greenness, is highly correlated with temperature and precipitation (Los et al., 2001), which is susceptible to future climate variability. Yet it is still unclear how the teleconnection signal propagation could affect local precipitation patterns and subsequent ecosystem response in terms of vegetation greenness across different locales of North America. These IPCC forecasts trigger a renewed interest to study the response of precipitation patterns and terrestrial ecosystem in association with some hydrometeorological forcing processes of circumglobal teleconnection in the context of climate change. Such circumglobal teleconnection in atmospheric science refers to climate anomalies being related to each other at large distances (typically thousands of kilometers).

Global vegetation density, or greenness, is highly correlated with temperature and precipitation (Los et al., 2001) and will be subject to future climate variability. New tools in remote sensing and spatial statistical analysis now permit deepened investigation of the mechanistic links between changing teleconnection patterns and their residual effect or memory on local terrestrial environments (Hodson et al., 2010; Keener et al., 2010; Mestas-Nunez and Trimble, 2001; Raible et al., 2004). These mechanistic links can then provide a basis to estimate future impact on local

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precipitation and greenness in association with teleconnection patterns through various hydrometeorological forcing processes (Cai et al., 2008; Keener et al., 2010).

Strong oceanic, hydrometeorological, and ecological phenomena are physically linked across the globe by atmospheric circulation through some excitation mechanisms (Buerman et al., 2003; Franzke and Woollings, 2010; Hubeny et al., 2011; Johnstone, 2011; Joseph and Nigam, 2005; Sutton and Hodson, 2005). Climate teleconnections are often categorized in known oceanic–atmospheric circulation patterns, such as the El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and the Pacific North American Pattern (PNA). These climatic patterns can be linked with time-series observations based on a multivariate array of oceanic (e.g., sea surface temperature, SST), and atmospheric (e.g., sea level pressure, SLP) variables. Teleconnection signals can be found between univariate oceanic variables (e.g., SST), and inland terrestrial temperature, precipitation or greenness (Huber and Fensholt, 2011). In traditional teleconnection identification, a linear correlation is often assumed between anomalous SST and SLP across the Pacific Ocean (Montroy, 1997) for projections of many local and regional terrestrial responses, including the number and location of wildfires (Dixon et al., 2008), groundwater recharge rates (Holman et al., 2011), streamflow levels, and nutrient loading (Keener et al., 2010).

Of particular interest in teleconnection research is the exploration of specific periodicity of these climate signals over which multiple terrestrial phenomena can be linked with each other. Long-term multidecadal teleconnections have been observed and modeled over North America (Franzke and Woollings, 2010; Hodson et al., 2010; Mestas-Nunez and Trimble, 2001; Sutton and Hodson, 2007). These studies demonstrated low-frequency covariability in periods of 80 years between Atlantic and Pacific SST-related climate indices and the variability of temperature and precipitation in North America. Higher-frequency teleconnections ranging from days to biennial and triennial periods also have been observed (Athanasiadis and Ambaum, 2008). Johnstone (2011) documented more than 30 global quasi-biennial (25–26 months) temperature and precipitation oscillations that were discovered during the past 40 years, with six existing cases over the United States (U.S.), yet the study sites involved with coupled natural forcing and anthropogenic disturbance made the teleconnection signals unidentifiable.

The aim of this study was to examine the low- or high-frequency teleconnection signal signals in association with hydrometeorological patterns between the Northern Atlantic and Pacific oceans simultaneously at the pristine terrestrial forest regions of northeastern U.S., with minimal anthropogenic disturbance in the study period. In the context of high temporal resolution for hydroclimatic applications, the high-frequency teleconnections are defined here as correlation signals at the intraannual scale, whereas the low-frequency scale is for the interannual scales. In specific, the study was designed to investigate climate teleconnections at the local level in Northern America based on short-term (10 year) climate teleconnection signals in the precipitation and greenness over three pristine forested sites to gain a statistical insight of relevance region wide. The short-term time scale was chosen based on the availability of EVI greenness data at high spatial resolution scales. Middle and long-term studies can be performed in this region, although at a lower spatial resolution in the future. Such coarseness of data would preclude the study of small wilderness areas, however, causing the wilderness areas to broaden, introducing anthropogenic disturbance (i.e., bias in wavelet analysis) into the data record given the current site screening process.

Integrated remote sensing and wavelet analysis were employed to detect distinct interannual (2–3 years) signals of enhanced variability suggestive of these aforementioned teleconnection patterns into the region of northeast U.S. The teleconnection signal propagation was investigated by using statistical methods, including a pixel-wise correlation between precipitation, greenness, and SST, as well as spectral analyses of the time series data using wavelet analysis for each independent site. This research helps confirm how low-frequency transients through the teleconnections affect terrestrial vegetation cover and precipitation patterns at the three predetermined pristine forested sites including (1) White Mountain National Forest – Pemigewasset Wilderness, (2) Green Mountain National Forest – Lye Brook Wilderness, and (3) Adirondack State Park – Siamese Ponds Wilderness.

2. Northeastern U.S. teleconnection patterns

Observations during the past 1000 years indicate the strong role that the Pacific and Atlantic oceans play in the New England area (Hubeny et al., 2011). The correlation signals between the PNA, ENSO, and the New England climate are still predominant in the precipitation and temperature response for the region today. Precipitation amounts over the past century have increased by 10–15% and are expected to increase up to 34% during the next century (Beckage et al., 2008; Tang and Beckage, 2010). This increased precipitation has been influenced by positive cycles of PNA, characterized by above-average temperatures in western Canada and the U.S. and below-average temperatures across the south-central and southeastern U.S. (National Weather Service Climate Prediction Center, 2012).

ENSO, a coupled ocean-atmospheric system, has a strong influence over the global climate system, including the New England area. The Southern Oscillation Index (SOI) is a standardized index based on the observed sea level pressure differences between Tahiti and Darwin, Australia, which is one measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific (i.e., the state of the Southern Oscillation) during El Niño and La Niña episodes (National Climate Data Center, 2012). The negative phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin. Prolonged periods of negative (positive) SOI values coincide with abnormally warm (cold) ocean waters across the eastern tropical Pacific typical of El Niño (La Niña) episodes (National Climate Data Center, 2012). Linking with a difference in tropical Pacific sea level pressure between Tahiti and Darwin, ENSO has a general oscillation period of 2–7 years (National Weather Service Climate Prediction Center, 2012). The warm El Nino phase influences climate across the eastern U.S. by shifting the jet stream southward, bringing cold winter weather, whereas the cold La Nina cycle shifts the jet stream poleward, bringing warmer and milder winter weather to the same region (Greene, 2012). Pacific–Atlantic communication may also exist along the equator, with the tropical Pacific modulating the Hadley cell across Central and South America. Along this teleconnection, Atlantic SST and wind patterns are influenced by ENSO, with ENSO-derived Atlantic SST variations lagging the Pacific patterns by 4–5 months (Enfield and Mayer, 1997) based on various interannual time scales. Thus, New England climate associated with Atlantic-based variability may originate in the Pacific.

Atlantic patterns have a clear effect on the New England climate, particularly temperature. The NAO is the dominant pattern of climate variability in the northern Atlantic and is sometimes considered the Atlantic component of the northern hemispheric annular mode, the AO. NAO is simply the SLP difference between the Icelandic Low and the Azores High (Marshall et al., 2001). Other primary modes of variability in the northern Atlantic include the Tropical Atlantic Variability (TAV), consisting of the fluctuations in tropical Atlantic SST and trade winds along the Intertropical Convergence Zone (ITCZ), and the Atlantic Meridional Overturning