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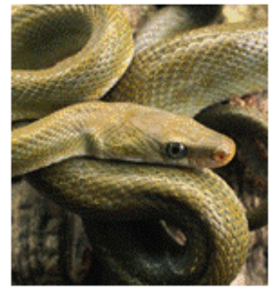

Phenology as a bio-indicator of climate change impacts on people and ecosystems: towards an integrated national assessment approach

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Phenology as a bio-indicator of climate change impacts on people and ecosystems: towards an integrated national assessment approach

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This report complies with the US Geological Survey Fundamental Science Practice Standards. It has undergone peer and policy review and approval.

1. Executive Summary

The 2013 National Climate Assessment (NCA) process calls for the identification of national indicators of climate change as a mechanism for communicating the effects of change on people and ecosystems. Additionally, indicators provide a vehicle for establishing consistent methods of evaluation of impacts of climate change for future Assessments. This technical report helps develop one indicator approaches for the NCA across geographic regions and sectors.

Phenology, the study of the timing seasonal life cycle events in plants and animals (e.g., timing of leaf-out, blooming, hibernation, migration), is a well-recognized indicator of climate variability and change. Phenology has been called a “globally coherent fingerprint of climate change impacts” on plants and animals [1-3]. Many phenology-linked indicators have broad application across economic sectors and geography. Depending on the application, phenology can indicate species’ sensitivity to change in both climate and ecological processes. Phenological information combined with climate data can be combined to construct integrative indicators of climate change impacts.

This technical input demonstrates two complementary approaches for using phenology as a bioclimatic indicator of ecological change. These approaches can be used together in integrated national climate assessments. As a first step toward a comprehensive synthesis and meta-analysis (see below), we conducted a review of the recent phenology literature to document regional variation in species’ response to changes in climate and the environment. We report this peer-reviewed information in a series of short, self-contained regional syntheses that will be periodically updated and used as communication pieces by the USA National Phenology Network. We then introduce a new bioclimatic model for evaluating regional to continental trends in the timing of the onset of spring. This work is presented as a newly submitted manuscript that is currently in the peer-review process.

Changes in regional phenology across the United States

To document observed changes in regional phenology, we compiled phenology studies that met a pre-determined set of criteria. In total, we reviewed 175 studies and selected 64 studies that covered a variety of taxonomic groups, spanned a range of scales, and that analyzed the relationship between phenological observations and climatic variables. We organized this information into eight geographic regions delineated by the NCA: Alaska and the Arctic, Great Plains, Hawaii and the Pacific Islands, Midwest, Northeast, Northwest, Southeast, and Southwest.

The most published reports of recent long-term phenological patterns occurred in the Southwest region (24 publications). In contrast, the Hawaii and the Pacific Islands region had the fewest published studies (2 publications). Bird and plant taxonomic groups were well represented in the reviewed studies. In contrast, there was a paucity of phenological information for mammals, insects, reptiles, and amphibians. We also found a growing body of research focused on examining trophic mismatch, a phenomenon that can result from differential phenological responses to climate or other cues. Though few studies documented the specific consequences of asynchronous species interactions, most predicted population declines, local extirpations, and the emergence of novel biotic interactions. Overall, most studies documented an advance in timing of springtime phenological events across species in response to climate warming. In contrast, organisms in the southeastern U.S. typically showed great variability in onset of spring events. This may be the result of a recently described southeastern “warming hole”, a region of climate where warming is happening at a slower rate than elsewhere in the U.S. [4].

This compilation of regional syntheses is the first step toward a more comprehensive, forthcoming manuscript detailing phenological change in the U.S. Subsequently, this manuscript will be the foundation for a quantitative meta-analysis using datasets derived from this qualitative review. Results of the future meta-analysis will eventually be used to validate the bioclimatic models described below.

National bioclimatic indicators of climate change

To demonstrate the use of phenology as an effective and robust bioclimatic indicator, we describe a suite of metrics that can be used to determine the timing of leaf emergence and flowering derived from a calibrated and long-established observation network of genetically identical lilac and honeysuckle plants from across the U.S. Known as the Spring Indices [5], these phenology models have been successfully applied to evaluate variations and trends in the onset of spring across the Northern Hemisphere's temperate regions. However, these models have been limited by producing output in locations where two of the plants' growing requirements are met: chilling and growing-degree-hour.

To overcome this limitation, we present analyses using a new, extended form of the Spring Indices (SI-x) that can be mapped from polar to subtropical latitudes by ignoring chilling requirements while still retaining the utility and accuracy of the original SI. For the continental U.S., SI-x measurements from 1900-2010 capture regional variability in the onset of spring around 1958, with an abrupt and sustained delay of 4-8 days in parts of the southeastern U.S. and southern Great Plains, and an advance of 4-8 days in parts of the northern Great Plains and the western U.S. These patterns are likely the result of natural ocean-climate variability acting in concert with warming associated with human-linked greenhouse gas accumulation. Overall, these results show promise for future development of regional to continental spring onset forecast models for use in a variety of the nation's economic sectors (e.g., natural resource management, agriculture, tourism, public health, etc.).

In sum, our approaches demonstrate the utility of phenology as a bioclimatic indicator of change. For example, our regional literature review highlights the existence of broad directional shifts in phenology, in addition to regional variability in species' response to climatic changes. Output from the SI-x analyses showed consistency with these observed regional patterns, particularly in areas with delays in spring onset. In future work, we will perform analyses to examine these relationships more closely. Furthermore, we argue that the SI-x can be used to indicate ecological, hydrological and socioeconomic phenomena, in addition to its use for exploring connections between atmospheric drivers and seasonal timing. Ultimately, these findings have far-reaching consequences for physical, biological, and human systems that include changes in water quality and quantity, the frequency and size of ecological disturbances, the duration of growing seasons for agriculture, and the quality and availability of wildlife habitat in the United States and elsewhere.

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2. About the USA National Phenology Network

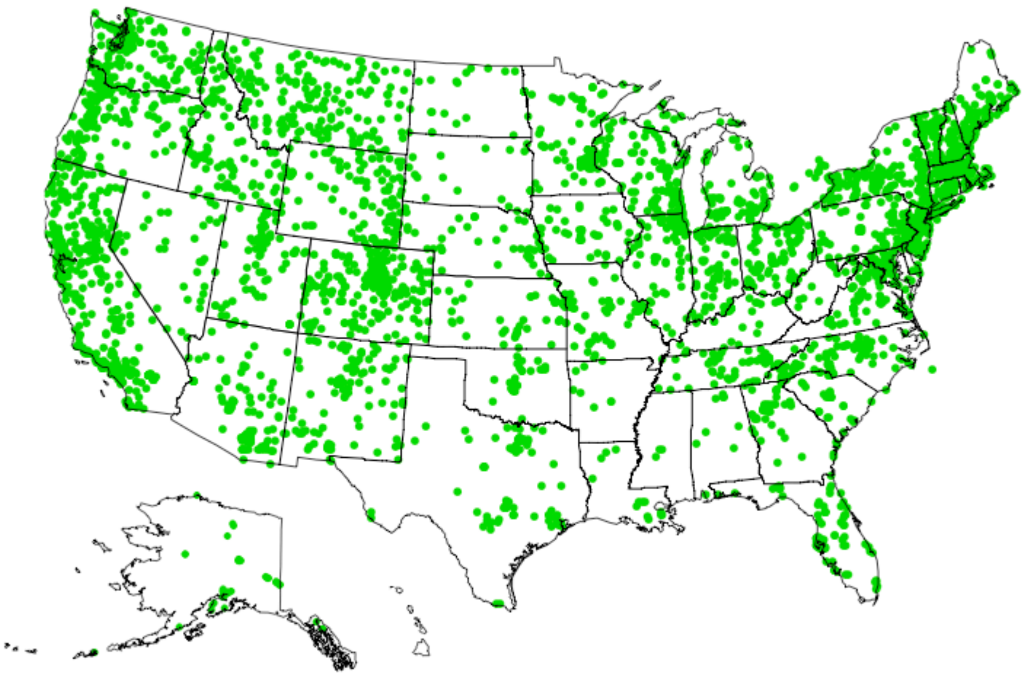
The USA-National Phenology Network (USA-NPN, **http://www.usanpn.org**), established in 2007, is a national science and monitoring network that organizes and facilitates the collection and integration of phenological observations across space and time. The Network is a partnership-driven program with leadership by the US Geological Survey and with funding from the National Science Foundation, US Geological Survey, and several other organizations. Partners include individual scientists, resource managers, educators, and policy-makers, in addition to governmental and non-governmental organizations, Native American tribes, specialized networks, and academic institutions.

The primary goals of the Network are to (1) understand how plants, animals, and landscapes respond to environmental variation and climate change, (2) develop tools and techniques to facilitate decision making and, ultimately, climate change adaptation by humans and natural systems, and (3) use experiential learning to engage and educate the US public by involving them in the process of place-based science in the natural world. The Network meets these goals through the development of information management systems, creation of partnerships, facilitation of research, development of decision-support systems, and promotion and implementation of education and outreach activities.

An essential activity of the Network is the collection and organization of contemporary phenology data for plant and animal species across the nation. Since 2007, the Network has focused on the development of a national biological observation program with scientifically rigorous monitoring protocols for over 500 plant and animal species. USA-NPN partnered with NatureServe and The Wildlife Society to develop and vet criteria for selection and prioritization of the initial species list, including known or presumed sensitivity to climate change.

Standardized phenology monitoring protocols, documentation, and an on-line user interface for data entry, visualization and download are now available as part of the USA-NPN program *Nature's Notebook* (Figure 1). Data from the program can be used to develop new indicators of onset of spring, validate remote imagery, model the probability of western wildfires, predict the onset of allergy seasons, plan management of invasive species, inform adaptive management, and establish baselines for ecosystem restoration. In addition, the national monitoring framework provided by the Network is being adopted by a variety of organizations (e.g., NPS, USFWS, NEON) as a fully operational platform for mission-based programs or projects related to science, resource management, information technology, and education/outreach activities.

Figure 1. The USA National Phenology Network has developed a multi-taxa phenology monitoring program, Nature's Notebook, which has ~4,000 registrants at ~5,000 sites (green dots on figure) tracking ~16,000 organisms across the nation as of January 2012. These sites include those maintained by members of the public (as individuals or organizations including nature preserves, schools and clubs, and neighborhood associations), as well as governmental and non-governmental organizations focused on natural resource management.



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This series of informational sheets summarizes changes in phenology for the eight regions of the U.S. defined by the NCA. A peer-reviewed manuscript based on this series is forthcoming, providing a more detailed summary (Young, Enquist, and Weltzin 2012, in preparation for the journal *Ecosphere*).

National bioclimatic indicators of climate change

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National bioclimatic indicators of climate change

In review, *International Journal of Climate*

5. Observed Regional Changes in Phenology across the United States

Introduction

For centuries, phenological events—such as flowering, migration, and breeding— have signaled the onset of spring and thus are universally understood as nature's response to climate. Documented changes in these events are well recognized as a "globally coherent fingerprint of climate change impacts" on plants and animals [1, 2, 3]. Climate-induced changes in phenology have been linked to shifts in the timing of allergy seasons and cultural festivals, increases in wildfire activity and pest outbreaks, shifts in species distributions, declines in the abundance of native species, spread of invasive species, changes in agricultural yield, and changes in carbon cycling in natural ecological systems [4].

Approach

Regional to continental climate is a critical driver of phenological variation of organisms across scales from individuals to landscapes [2, 3]. To document observed changes in regional phenology across the United States, we compiled phenology studies that met the following criteria:

(1) Appeared in the peer-reviewed literature between 2001-2012;
(2) Provided analyses of long-term (at least 10 years) phenology data sets [5];
(3) Included concurrent analyses or other consideration of climatic variables;
(4) Focused on non-marine, field-based, population-level observations of individual organisms;
(5) Focused on land surface phenology captured by remote instrumentation, such as satellite sensors, carbon flux towers, and landscape cameras.

We recognize that caution needs to be taken when using remote sensing data to infer organismal phenology [6]. However, this approach is important for interpreting regional to continental scale patterns and processes. Further exploration of how to link field observations with remote sensing data is an emerging research direction that will be critical for developing ecological forecast models [7].

In total, we reviewed 175 studies. From these, we selected 64 studies that spanned taxonomic groups, a range of scales, and examined the relationship between phenological observations and climatic variables. We subsequently organized this information into eight geographic regions specifically delineated by the National Climate Assessment: Alaska and the Arctic, Great Plains, Hawaii and the Pacific Islands, Midwest, Northeast, Northwest, Southeast, and Southwest (Figure 2).

This compilation of self-contained regional syntheses is the first step toward a more comprehensive, forthcoming manuscript detailing phenological change in the U.S. Subsequently, this manuscript will be the foundation for a quantitative meta-analysis using datasets derived from our qualitative review. As a final step, results of the meta-analysis will be used for validation of the bioclimatic models described in Section 6 of this report.

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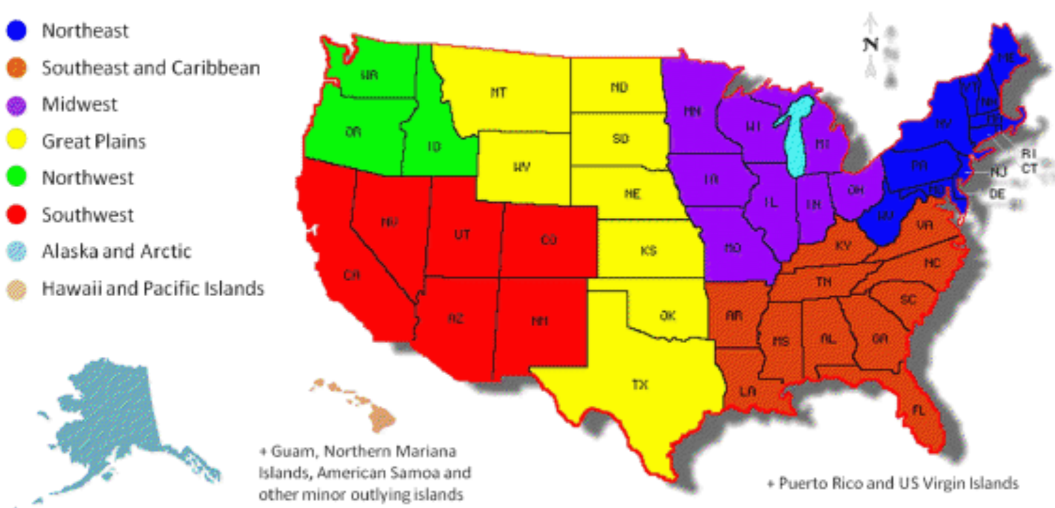
Figure 2. The eight regions of the United States as defined by the NCA.



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5.1 Alaska/Arctic Region

Alaska

Alaska's diverse terrain consists of high mountains, meadows, tundra, boreal and rainforests, and coastal zones. The climate is mostly subarctic, with smaller areas of arctic and marine west coastal climates. Relative to other regions of the United States, Alaska and the Arctic have experienced twice the rate of warming over the past century, with mean annual summer temperatures increasing 1.9°C (3.4°F) and mean annual winter temperatures increasing 3.5°C (6.3°F), compared with 0.8 – 2.0°C in other regions [1, 2]. Temperatures are expected to rise another 1.9 – 3.9°C (3.5 – 7.0°F) in the next half century. Longer summers with drier conditions have already occurred, resulting in an increase of drought and wildfires [1, 2].

Observed Changes in Phenology in Alaska and the Arctic

- *Timing of snowmelt affects phenology of plant species*
    - Researchers used remotely sensed data to show that plants are greening-up earlier and exhibiting higher productivity with advanced spring thaws [3]. In the short-term earlier green-up and longer growing seasons may benefit the studied species by providing a longer window for photosynthesis and resource acquisition. However, it is unclear how this increased period of growth will interact with increasingly dry conditions in Alaska [3]. A recent evaluation suggested that while green-up is occurring earlier in the Eurasian Arctic, it may not be occurring earlier in the Alaskan Arctic [4]. These inconsistencies suggest that additional research will be required to discern long-term changes in timing of green-up in this region.
    - Two species of mountain-avens (*Dryas spp.*) exhibited earlier flowering with earlier snowmelt. Plants that grew in regions where snowmelt occurred later than other regions were more sensitive to changes in snowmelt than those that grew in areas where snow melted earlier. The relationship between flowering and snowmelt was non-linear, suggesting that other environmental factors such as pre-flowering environmental conditions are also important [5].
- *Ecological mismatches result from changing bird migration patterns*
    - Researchers found population declines in migratory birds in the Nearctic are likely caused by a climate-induced ecological mismatch. This mismatch occurs when temperatures at wintering grounds change more slowly than at spring breeding grounds. A late departure from winter grounds can result and birds subsequently arrive after food resources have peaked at breeding grounds [6].
- *Fry of pink salmon migrate earlier*
    - In a 34-year study of an Alaskan creek, fry of pink salmon (*Oncorhynchus gorbuscha*) emigrated increasingly earlier over time. Higher water temperatures and earlier migration of adults may have contributed to this change. The study also suggested that earlier migration of pink salmon could result in fish arriving too early to take advantage of optimal foraging conditions [7].
- *Trumpeter swans expand range due to longer breeding season*
    - Trumpeter swans (*Cygnus buccinator*) in Alaska have responded positively to longer breeding seasons by occupying new northern habitats. In addition to the longer breeding season, habitats that were previously inhospitable to this species have become available as a result of an extended ice-free period. This range

expansion, however, may result in competition with the tundra swan (*C. columbianus*) for breeding areas [8].

Case Study: Trophic mismatches in large herbivores

US FWS, DIVISION OF PUBLIC AFFAIRS, WO3772-023, taken by Dean Wiggins

Researchers examined the relationship between plant phenology and caribou (*Rangifer tarandus*) calving and found that the calving season has become unsynchronized with the phenology of forage plants.e An advancement of two weeks in the onset of the plant growing season resulted in a fourfold decline in calf production, most likely as a result of caribou missing peak foraging opportunities. In addition, the research found an 80% difference in spatial variability of plant phenology between the coldest and warmest years, with warmer years having less variability in plant phenology. In this case, less spatial variability in phenology resulted from a shorter growing season. In turn, this reduced spatial variation in new growth, reduced forage quality as the caribou moved across the landscape. Caribou not arriving at peak forage times had a greater negative impact on calf production calving than the reduced spatial variability of forage. This study highlights that as animals move across the landscape, trophic mismatches in phenology are not just restricted to plants or the availability of resources at a certain time, but also their availability in space. These factors can negatively affect the persistence of species populations [9, 10].

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5.2 Great Plains Region

North Dakota, South Dakota, Montana, Wyoming, Nebraska, Kansas, Oklahoma, and Texas

The Great Plains region is dominated by warm and cool season grasslands, with deciduous tree cover in the far eastern reaches. Much of this region is used for farming and ranching [1, 2]. Climate in the Great Plains varies across its large geographical expanse, and includes semi-arid steppe in the west, humid continental climate with cool summers in the north, humid continental with warm summers in the east, and subtropical patterns in the south (Texas). The Prairie Pothole region in the northern part of the Great Plains is critical for the production and migration of waterfowl [1, 2]. Mean annual temperatures have increased over the past century, especially in the winter and in the northern states, and since the 1970s has increased 0.83°C (1.5°F). Future temperatures are expected to increase, especially in the summer months in the central and southern areas of this region, and rainfall is projected to increase more in the north than in the south [1, 2].

Observed Changes in Phenology in the Great Plains

- *Human allergy seasons longer*
  - From Texas to Saskatchewan, the length of pollen season for ragweed (*Ambrosia* spp.), a common human allergen, has increased from 1995-2009 by as much as 16 days in certain areas, with longer allergy seasons in the north. Researchers attributed this to regional warming that delayed the onset of first frost in autumn, effectively increasing the number of frost-free days 3].
- *Changes in duration of stay in migratory birds*
  - Data collected in Texas between 1978 and 2005 showed a trend of later arrival, earlier departure, and shorter duration of stay for three species of winter-resident coastal birds. Summer residents showed greater variability in directional trends of arrival, departure, and duration of stay. These changes in phenology were not correlated with warming summer and winter temperatures. However, climate change impacts on the birds elsewhere along their migratory route may be contributing to these observed differences [4].
- *Snowmelt changes timing of egg laying*
  - Between 1961-2002 in the mountains of Wyoming, egg-laying by American Pipits (*Anthus rubescens*) advanced by 5 days, and mean clutch size increased by 0.2 eggs; reproductive phenology was positively correlated with snowmelt, which occurred approximately 7 days earlier over this same time-period [5].
- *Agricultural crops advance in bloom time*
  - Data from six locations throughout the Great Plains showed that winter wheat is blooming 6 – 10 days earlier now than 70 years ago. Spring temperatures increased over this same period [6].

Case Study: Flowering Phenology Shifts in the Northern Great Plains Over a 100-Year Period

Researchers examined first flowering dates (FFD) for 178 species of plants from 1910-1961 and 2007-2010 in North Dakota. They found up to 41% of plants flowered unusually earlier or later in 2007-2010 compared to the 1910-1961 period. FFD and temperature were tightly correlated, with greater deviations in warmer years of flowering date, compared to dates in the early

Violet woodsorrel (*Oxalis violacea*), © Copyright Steve Baskauf/www.discoverlife.org part of the century, indicating that increases in temperatures were a likely mechanism for the observed shift in FFD. The species that showed a change in FFD were projected to show a continued response with increasing temperatures. Between the first temperature period and the last temperature period of the study, temperatures increased 1.7°C (3.0°F) and the average growing season duration increased from 132 days to 154 days. However, phenology of > 50% of all flowering species examined did not change. The reasons for this are unclear, but it appears that phenology of these species was not predominated by temperature and precipitation, and that other cues may be important to their phenology [7].

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5.3 Hawaii and Pacific Islands Region

Hawaii, Guam, Northern Mariana Islands, American Samoa, and other minor outlying islands

The Hawaiian and Pacific Islands contain both tropical moist and tropical dry rainforests. Islands, because of their isolation, are especially vulnerable to ecosystem changes, particularly since these systems have many endemic species [1, 2]. The Hawaiian Islands have been affected by invasive species and substantial native species loss. Changes in sea level, increasing ocean temperatures, and extreme weather events such as typhoons, also can greatly affect these systems [1, 2]. In the Pacific, air and sea temperatures are expected to increase in the next century and there is a projected increase in heavy rainfall events [1, 2]. Elevation and temperature can also interact, with intra-island temperatures projected to increase more at higher elevations than at lower elevations [3]. High elevation habitats are often refugia for endemic species on these islands. These species are likely to be affected by ongoing changes in climate in these regions [3].

Observed Changes in Phenology in Hawaii and the Pacific Islands

- *Collecting phenological data – first steps*
    - In a study that began to detail protocols for collection of phenological data on Maui, plots were established across both an elevation and east-west gradient. Researchers found an east to west gradient of differences in vegetation composition that were sensitive to moisture [4]. Vegetation composition and weather data in these plots, will be monitored so that changes in phenology and what drives these changes can be observed.
    - There is a scarcity of long-term phenological data and how it relates to climate for Hawaii and the Pacific Islands. While there is research on phenology in other tropical regions, the biogeography of Hawaii and the Pacific Islands is different from continental tropical regions, and caution should be taken in extrapolating results. The research that has been done (see case study below) indicates that the timing and amount of precipitation influence phenology in this tropical system more than temperature. In addition, elevation, and its interaction with precipitation, are also important influences on phenology of species.

Case Study: Responses of Hawaiian Forests to Drought


'Ohi'a lehua (*Metrosideros polymorpha*)
Hawaii Experimental Tropical Forest

Researchers examined the responses of Hawaiian rainforests and dry forests to both seasonal and El Niño responses to drought. They examined NDVI (Normalized Difference Vegetation Index) and cloud cover using satellite data for 2000-2009. During dry years, vegetation of the dry forests responded with 'brown-down', while rainforests 'greened up.' In these dry years, there was less cloud cover in the rainforests, which resulted in NDVI exhibiting increased greenness in rainforests due to increased light availability. Thus, leaf phenology of dry forests was more closely linked to precipitation while phenology in rainforests was more related to light availability. This study illustrates that in the tropics, phenology is often linked more to moisture availability than temperature and that different ecosystems may respond very differently to changing precipitation patterns. With projected changes in precipitation patterns in this region, changes in tropical forest phenology are likely [5].

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5.4 Midwest Region

Michigan, Ohio, Indiana, Illinois, Wisconsin, Minnesota, Iowa, and Missouri

The Midwestern U.S. has great expanses of both agricultural and forest lands with fragments of once extensive prairie ecosystems [1, 2]. Climate of this region is described as humid continental, characterized by warm summers, with regions in the far northern parts experiencing cooler summers. The Great Lakes are part of this region and influence climate patterns by generating lake effect snow and moderating temperatures thereby protecting against frost. The lakes also having a cooling effect on the surrounding area, which can delay leaf out compared to inland areas. In the past century, there has been an increase in mean annual temperatures coupled with an increase in duration of the growing season [1, 2]. Precipitation events in the form of heavy summer downpours also are twice as frequent relative to earlier in the 20th century. In the next century, water levels of the Great Lakes are expected to drop between 0.25 – 0.4 m (0.8 – 1.3 ft.) [3].

Observed Changes in Phenology in the Midwest

- *Early spring species blooming even earlier*
  - A 27-year dataset from Ohio showed that earlier flowering species, such as crocus (*Crocus* spp.) and snowdrop (*Galanthus nivalis*), exhibited greater sensitivity to warming temperatures by blooming earlier in the spring than species that typically bloom later in the season [4].
  - By examining a combined first bloom date for 53 plant species observed from 1962-1998 in Wisconsin, researchers determined that first bloom dates advanced at different rates depending on the attributes of the geophysical region within the state [5].
- *Walleye spawning earlier*
  - In Minnesota, the sport fish species walleye (*Sander vitreus*) advanced its spawning date by 0.5 – 1 day in conjunction with every 1 day earlier ice-out, which also advanced concurrently over the study period [6].
- *Short-distance migrants arriving earlier*
  - A 22-year study of bird strikes in Chicago found that arrival of short-distance migrants is more negatively correlated with spring temperatures (i.e., birds arrived earlier in warmer years) than autumn temperatures [7]. Long-distance migrants – consistent with other studies – did not change their arrival times as often as short-distance migrants.
  - In Minnesota over a 40 year span, of 44 species of birds monitored, 36% showed significantly earlier arrival dates. Increasing winter temperatures correlated negatively with the earlier arrival of the birds, particularly for short-distance migrants [8].

Case Study: Ecological Mismatch for Wood Warblers and Their Food Sources

Under current climate change predictions, birds migrating between southern Illinois and northern Minnesota may have up to 20 days less to make the trip due to later spring arrival in southern Illinois and earlier spring arrival in Minnesota. Two long-term data sets from Minnesota (40 years) and Illinois (100 years) showed that out of the eight warbler species examined, six warbler species in Illinois and seven in Minnesota did not show an earlier date of migration. Only one species, the yellow-rumped warbler (*Dendroica coronata*, pictured), shifted its

Yellow-rumped Warbler (*Dendroica coronata*), © Larry Thompson/www.discoverlife.org phenology at both locations. There is concern that if the remaining bird species do not adjust their migration times to earlier spring they may miss optimal conditions for foraging in their breeding grounds. The authors suggest that such an ecological mismatch could result in declines in population size [9].

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5.5 Northeast Region

Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, Pennsylvania, West Virginia, New Jersey, Delaware, Maryland, and the District of Columbia

The Northeast is characterized by high forest cover, extensive shorelines and mountainous terrain, and high human population density [1, 2]. Most of the region's climate is classified as humid continental, although southernmost portions of the region are more subtropical. Mean temperatures in this region are expected to increase 1.4 – 2.2°C (2.5 to 4°F) in winter and 0.8 – 1.9°C (1.5 to 3.5°F) in summer over the next several decades, which will increase the number of days over 32°C (90°F), extend the duration of the growing season, and increase the number of large rainfall events [1, 2]. Changes such as these could affect iconic Northeastern species such as the sugar maple (*Acer saccharum*), the migration of songbirds in the spring and fall, and the timing of the Washington DC Cherry Blossom Festival [9, 10].

Observed Changes in Phenology in the Northeast

- *Birds, bees, and frogs active earlier in the spring*
  - Native bees have appeared in spring an average of 10 days earlier over the last 130 years (1880-2010). Most of this advance occurred in the last 40 years, paralleling trends in warming over this same period. Bee pollinated plants also showed a trend of earlier blooming, helping preserve synchrony in timing between the observed plant species and their insect pollinators [3].
  - Four of six frog species called 10-13 days earlier in springtime than they did in the early 20th century, coincident with an increase in mean maximum daily temperatures [4].
  - On average, birds are now arriving earlier in the spring; however, there is substantial interspecific variation: some species are arriving earlier, others are arriving later, and still others have not shown changes in arrival time [5-7]. Compared to the early 1900s, short-distance migrants are now arriving 12 days earlier in the spring while long distance migrants are arriving only 4 days earlier [5]. Other studies corroborate earlier arrival of short-distance migrants relative to long distance migrants, and raise the concern that long-distance migrants may experience trophic mismatch with food sources whose phenology is now earlier in possible response to increases in temperature [8].
- *Many plant species bloom earlier*
  - Cherry tree cultivars in Washington DC now bloom an average of 7 days earlier relative to the 1970s [9]. By mid-century, peak bloom dates of cultivated cherries are projected to advance 5 to 13 days and, by the end of the century, 10 to 29 days [10].
  - On average, invasive plant species tracked warming climates more closely than native species, blooming an average of 11 days earlier now than in the mid-1800s [11]. Population sizes of plants that do not track changes in temperature are more likely to decline as temperatures warm [12].
  - Using 30 years of data, researchers generated projections of sugar maple production, and timing of tapping. Results showed a decrease in the number of optimal sapflow days, and earlier sapflow by the mid-21st century. In some cases, this change may be offset by changing sapflow tapping windows, however, little can be done if duration of sapflow becomes shorter [13].
- *Changes in landscape phenology related to several factors*
  - Elevation and proximity to urban environments influence spring 'green up' and autumn 'brown down' in some mid-Atlantic forests. Delays in autumns affect growing season length more than earlier springs [14].

Case study: Flowers Bloom Earlier Today than in Thoreau's Time

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Henry David Thoreau, followed by other citizens of Concord, MA, made observations of first flowering date for many plant species starting in 1852. Researchers compared these unique data to their own observations made from 2004-2006. Flowering species on average bloomed 7 days earlier in 2004-2006 than in Thoreau's time. Some species, such as highbush blueberry (*Vaccinium corymbosum*; pictured) and wood sorrel (*Oxalis stricta,* formerly, *O. europaea*), flowered as much as 21 and 32 days earlier, respectively. When climate patterns over the same period were examined, mean temperature in January emerged as the variable most closely related to flowering. Colder January temperatures resulted in later flowering times. Thus, with increasing winter temperatures, many species flowered earlier [15].

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5.6 Northwest Region

Washington, Oregon, and Idaho

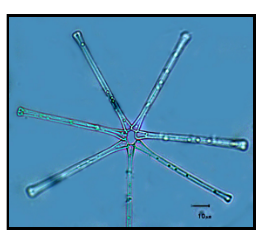
The Pacific Northwest is characterized by the Cascade Mountains dividing temperate rainforest along the Pacific coast from more arid rangeland in the western part of the region. The climate of the northwestern U.S. has great diversity, ranging from marine west coast climate, to high alpine regions, to semi-arid steppe [1, 2]. Human population in this region has doubled since 1970 with three-quarters of the people living west of the Cascade Mountains. Mean annual temperatures have gone up 0.8°C (1.5°F) in the past century and are predicted to go up another 1.6-5.6°C (3.0-10.0°F) in the next century [1, 2]. The Northwest is also highly dependent on snowpack and subsequent snowmelt for regional water consumption. Higher temperatures in the cool season have resulted in more precipitation falling as rain, contributing to earlier snowmelt [1, 2]. There has already been a 25% decline in snowpack in the Northwest in the past 40-70 years [3].

Observed Changes in Phenology in the Northwest

- *Salmon migrating earlier in Columbia River*
  - Migration of sockeye salmon (*Oncorhynchus nerka*) in the Columbia River is 10.3 days earlier than in the 1940s. This change was attributed to warmer waters, with a rise of 2.6°C (4.7°F) since 1949. Salmon survival during upstream migration decreased as a function of increasing water temperatures [4].
- *Flowers blooming earlier over the last 38 years*
  - Time of first bloom for lilac and honeysuckle showed a trend of earlier flowering (average advances of 7.5 days for lilac and 10 for honeysuckle) over an almost 40 year period. Earlier blooming was especially strong from 1970 to 1994. In this same region, mean annual temperatures increased 1-3°C (1.8-5.4°F) during the same period [5].
- *Temperature influences arrival of birds to breeding sites*
  - In a 12 year study of Northern Flickers (*Colaptes auratus*), birds arrived earlier at breeding sites when temperatures along the migration route rose. Temperatures at the breeding site correlated positively with initiation of egg laying. Nonetheless, the authors suggested that the relationship between egg laying and overall climatic trends needs additional investigation [6].
- *Temperature and snow accumulation impact breeding of amphibians*
  - Western toads (*Anaxyrus boreas*, formerly, *Bufo boreas*) in the Cascade Mountains of Oregon appear to be breeding earlier [7]. Although there is a negative relationship between mean March and April air temperatures and onset of breeding, Western toads bred earlier in years with less snow accumulation [8].

Case Study: Predator-Prey Mismatch in Lake Washington

Spring water temperatures in Lake Washington increased an average of 1.4°C (2.5°F) from 1962-2002, and water stratification occurred 21 days earlier at the end of this period. Algal blooms (left picture) in the lake paralleled this trend, advancing 27 days from the onset of the study. One of the predators of the algae



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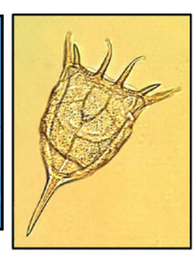

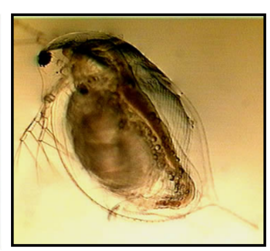

Haney, J.F. et al. "An-image-based Key to the Zooplankton of the Northeast, USA" version 4.0 released 2010. UNH Center for Freshwater Biology.

(*Keratella*, middle picture) closely tracked the change in algal bloom time. However, *Daphnia* (rightmost picture) did not follow this trend and became increasingly offset from the timing of the algal bloom. The population of *Daphnia* in Lake Washington has declined dramatically during this period, suggesting a mismatch between this species and the algae that serves as its primary food source. This study illustrates the potential for cascading effects in an ecosystem when changes in phenology occur in some species but not in others [9].

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5.7 Southeast Region

Virginia, Kentucky, Tennessee, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Arkansas, Puerto Rico, and U.S. Virgin Islands

Landcover of the Southeast is varied and is characterized by productive forests, mountains, and extensive wetlands and shorelines [1, 2]. Climate is humid and subtropical, with the tip of Florida classified as tropical with wet and dry seasons. The large wetlands in the Southeast are especially vulnerable to predicted shifts in water levels, which could impact critical regions such as the Everglades. This region is also susceptible to hurricanes; these storms are expected to increase in intensity with increased ocean water warming [3]. Since 1970, the annual mean temperature of the region has increased by nearly 1.1°C (2.0°F), with most of this warming in the winter [1, 2]. Over the past century, the region has experienced significant growth in urban areas, increased evaporation and cloudiness from increased temperatures, and a general cooling trend until 1980 when temperatures began to increase. The last hard freeze dates have become significantly later from 1901-present on the order of more than 1 day/decade [4]. The so-called "warming hole" (a gap where warming is happening at a slower rate than elsewhere in the U.S.) in the Southeast is the subject of much interest, most recently linked to internal Pacific decadal variability [5].

Observed Changes in Phenology in the Southeast

- *Delays in plant leafing and flowering*
  - In contrast to many parts of the U.S., plants of the Southeast on average are experiencing, and likely will continue to experience, delays in leafing and flowering. Specifically, the study suggests that a lack of sufficient chilling days with increasing temperatures may result in a delay in spring budburst for plants that require this chilling period [6].
  - Herbarium specimens collected in Florida from 1819-2008 showed a delay in blooming (with a range of 4-19 days later than the beginning of the dataset) for both native and non-native species. This delay was correlated to within-year variability in minimum temperatures, suggesting that the physiology of the examined species may be connected to changes in minimum temperatures [7].
- *Timing of bird migrations in flux*
  - According to 40 years of data from the Northeastern U.S. and Louisiana on long-distance migrating birds, the interval between capture dates in Louisiana and the Northeast was less in warm years and longer in cold years illustrating birds' capacity to adjust their migration times to changing temperatures [8].
- *Loggerhead turtles nesting in terrestrial sites*
  - The median date of egg laying for loggerhead turtles (*Caretta caretta*) shifted 12 days earlier over a 15 year period at the most populated nesting beach in the western hemisphere. Sea surface temperatures increased during this same period and were correlated with this median date [9].
- *Plants of economic importance are vulnerable to increased frequency of 'false springs'*
  - The pattern of an early spring followed by a hard freeze (a 'false spring') has occurred more frequently in the past 100 years [4, 10]. Agricultural crops and other plants will be more vulnerable to frost damage due to hard late spring freezes following 'false springs.'
  - Invasive plant species sustained significantly less damage to early leaf growth than native counterparts in false spring scenarios [11].
  - Damage to plants during frosts following more frequent false springs has both economic (i.e., damaged apple and peach crops) and ecological ramifications. Cascading effects can also result – such as higher primary production in streams as a consequence of increased light at the water surface from canopy damage sustained during the late frost. Increased

primary production led to an increase in the snail population and higher rates of nitrate uptake by autotrophs [12].

Case Study: Salamander Arrives to Breed 76 Days Later Than 30 Years Ago

Over a 30 year time span (1978-2008) in South Carolina, researchers observed that two species of autumn-breeding amphibians arrived at breeding sites increasingly later, while two winter-breeding species arrived increasingly earlier. The autumn-breeding dwarf salamander (*Eurycea quadridigitata*, pictured) arrived as much as 76 days later. Rates of change overall ranged from 5.9 – 37.2 days/decade, and are some of the fastest rates of phenological change observed to date. Increasing overnight temperatures during the breeding season and amount of cumulative rainfall were correlated with the changes in arrival times. The authors noted that alterations in breeding phenology can affect the outcome of competitive interactions and predator-prey dynamics [13].

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5.8 Southwest Region

California, Nevada, Utah, Colorado, Arizona, and New Mexico

The western and southwestern regions of the U.S. consist of a variety of biomes, ranging from deserts and coastal areas to mountains and forested regions [1, 2]. Climate also varies widely, ranging from Mediterranean and semi-arid steppe, to mid-latitude desert and alpine. This region is considered a biodiversity "hot spot" in terms of the number of endemic species [3]. Temperatures in the Southwest have increased more than other regions in the continental U.S. [1, 2]. Drought is also an important component of the climatic landscape of the Southwest. Major droughts, including those described as 'mega-droughts,' can persist for long durations and are expected to become more severe in the future [4]. The human population in this region has nearly quadrupled since 1950, increasing competition for already over-allocated water resources [1, 2].

Observed Changes in Phenology in the Southwest

- *Spring flight of butterflies advances by nearly one month*
  - In California's Central Valley, 70% of 23 butterfly species displayed a trend towards earlier spring flights over the past 31 years, with one species advancing nearly one month. Higher maximum temperatures in winter and drier winters were correlated with the earlier appearance of these butterflies [5].
- *Earlier snowmelt in the Rocky Mountains influences timing of blooming*
  - For certain subalpine wildflowers in the Rocky Mountains in Colorado earlier snowmelt was linked to earlier blooming. Subsequently, earlier blooming led to greater susceptibility to late-season frost damage in aspen sunflower (*Helianthella quinquenervis*) [6].
  - Glacier lily (*Erythronium grandiflorum*), bloomed earlier (3.2 days/decade) over a 30 year period in Colorado. The study linked earlier snowmelt and greater summer precipitation in the previous year to earlier blooming [7].
  - Winter and spring dust deposition from deserts on alpine snow promotes snowmelt, similar to the effects of warming temperatures. In contrast to conditions in which warming accelerates snowmelt and flowering time, however, some alpine wildflowers respond to dust deposition by delaying the onset of spring growth and flowering [8]. The authors suggested that this will affect ecological processes and interactions across the alpine landscape, including competition for pollinators [8]. A separate study indicated that warmer, drier conditions linked to changes in climate will likely increase desert dust deposition on alpine snow [9].
- *Yellow-bellied marmots emerge earlier from hibernation*
  - Yellow-bellied marmots (*Marmota flaviventris*) observed over 33 years (1976-2008) in Colorado emerged earlier from hibernation, and gave birth earlier in the season. This change gave marmots more time to grow before the end of the season. As a result, marmots tended to have larger body sizes at the beginning of hibernation than two decades ago. Larger body size is associated with lower mortality rates and higher population sizes. The authors conclude that an increase in the length of the growing season associated with climate change may have strong effects on the individual health and population size of these small mammals [10].
- *Shifts in the arrival times of long-distance migrant birds documented*
  - In northern California, 13 of 21 species of Nearctic-Neotropical birds showed a change in arrival time, with eight species arriving earlier, two later, and three with a mixed response at different sites. This study linked shifts in arrival to changes in temperature and natural variability in climate [11].

- *Hotter and drier conditions affect desert plants*
    - At a field site in the Sonoran Desert, mean annual precipitation decreased while mean annual temperatures increased during the growing season over a 25-year period. However, a study of desert annuals found that the timing of germination actually occurred under colder conditions due to delays in the occurrence of winter rains, which now peak in December rather than October. This shift in the timing of rainfall led to an increase in abundance of cold-adapted plant species in that they were able to successfully germinate in cool conditions [12].
    - Researchers created a phenological model using information on the physiological requirements of desert shrubs coupled with temperature and precipitation data to estimate advancement in flowering over a 110-year period. To test the validity of the predicted 20-41 day advancement, researchers extracted blooming time information from herbarium records collected during this same time period, ultimately confirming predictions of the models. In particular, a greater proportion of plants bloomed in March instead of May during the last 10 years of the study when compared with the first 10 years [13].
- *Type of vegetation is important for evaluating phenology on a landscape scale*
    - Analyses of remotely sensed data from the Great Basin Desert indicated that phenological changes vary according to vegetation type (e.g., grasses, sagebrush). Vegetation was sensitive to inter-annual changes in climate and, while there was no long-term trend, the changes in phenology of the vegetation types in response to moisture (especially in very wet or dry years) suggested that vegetation would be sensitive to climatic changes on a long-term scale. The researchers stated that additional data beyond the 10 years they examined would be necessary to evaluate long-term trends in phenology [14].

Case Study: Changes in Plant Communities in the Sky Islands Region of the Southwest

Photograph by Theresa Crimmins

Researchers examined a 20-year dataset in southeastern Arizona across a 1200 m elevation gradient to determine whether local plant communities have changed over time [15]. Out of 363 plant species, 93 (25.6%) showed a significant shift upward in the lowest elevation at which they flowered. Furthermore, there was an expansion in flowering range of some species into higher elevations, a pattern consistent with expectations under increased summer warming. In a related study, researchers found that only 10% of the total species exhibited a trend toward earlier spring blooming. The drivers of bloom time were diverse, with a general trend of plants at lower elevations showing a delay of spring flowering when insufficient chilling or moisture occurred the previous autumn and those plants at higher elevations blooming earlier with warmer spring temperatures. With future warmer and drier conditions, plants at lower elevations are expected to experience delayed flowering if the timing or amount of rain is altered, or if it is too warm for plants to experience sufficient chilling, whereas plants at higher elevations are expected to advance blooming with increased temperatures [16]. In contrast, additional research found that onset of flowering in summer is strongly linked to the amount and timing of July 'monsoon' rains across elevations and plant life forms [17]. As a result, with projected future drying in the Southwest, species across elevations are predicted to flower later in summer due to decreased soil moisture conditions resulting from increased summer temperatures.

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6. National Bioclimatic Indicators of Climate Change

6.1 The Spring Indices

Local to regional climatology is a critical driver of phenological variation of organisms across scales from individuals to landscapes [1, 2]. Because plants respond to the cumulative effects of daily weather over an extended period, their development stages are effective integrators of climate data. One specific measure, first appearance of spring foliage, is particularly important because it often shows the strongest response to temperature change, and is crucial for accurate assessment of processes related to start and duration of the growing season [3].

Schwartz et al. [4] developed a suite of modeled and derived measures (produced from daily maximum-minimum temperatures) linking plant development (based on historical data from leafing and flowering of lilac and honeysuckle) with basic climatic drivers to provide a reliable and spatially extensive method for monitoring general impacts of global warming on the start of the growing season. These spring indices (SI) models can be generated at any location that has daily maximum–minimum temperature time series, so they can be produced and evaluated over broad geographic areas. In addition, the model output is spatially and temporally consistent because SI circumvents issues associated with differential response among species, as well as variations in methodology or human observers.

Application of the SI models to temperate regions of the Northern Hemisphere indicated an advance of early spring warmth (SI first leaf date, -1.2 days/decade), late spring warmth (SI first bloom date, -1.0 days/decade), and last spring freeze date (-1.5 days/decade), from 1955 to 2002, and demonstrated spatial differences in relative timing of the onset of spring and last spring freeze dates (Figure 3) [4]. SI models also revealed recent (1959-1993) regional variations in the timing of spring's onset across the continental USA, with dates moving earlier at a faster rate in the Northeast and Northwest than in other areas [5].

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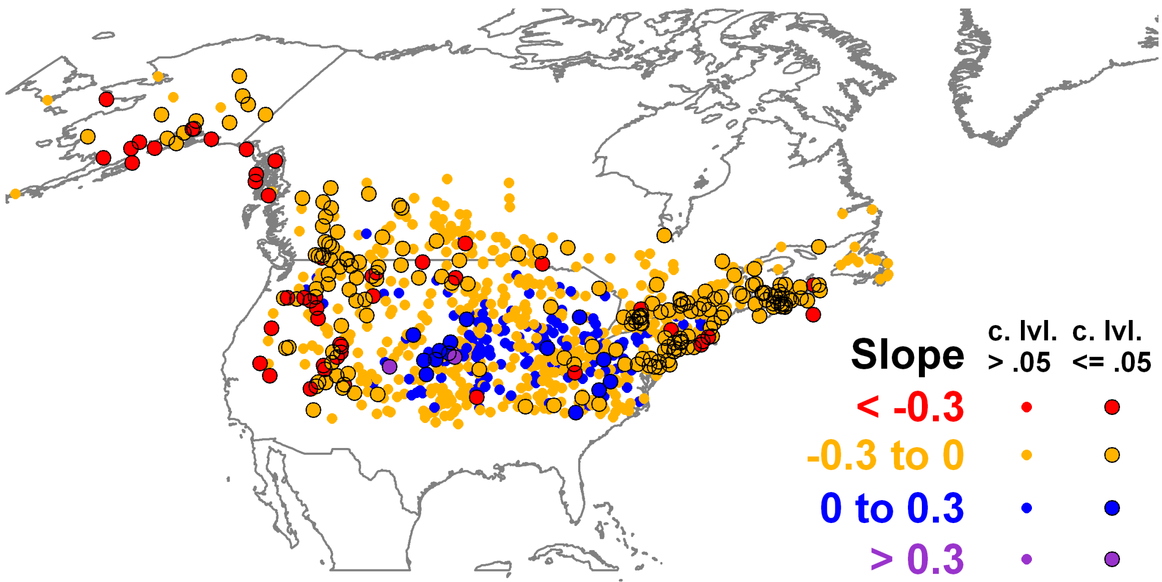
Figure 3. Spring indices (SI) first bloom date 1961–2000 trend by station in North America. Trend values are in days per year and colors show categories. Stations with trends significant at the p<0.05 level are shown with larger symbols outlined in black (previously unpublished figure from analyses/results reported in Schwartz et al. [4].



6.2 The Extended Spring Indices

Spring Onset Variations and Trends in the Continental USA: Past and Regional Assessment Using Temperature-Based Indices

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Abstract

Phenological data are simple yet sensitive indicators of the impacts of climate change on ecosystems, but observations have not been made routinely or extensively enough to evaluate spatial and temporal patterns across most continents, including North America. As an alternative, many studies use easily calculated and weather-based algorithms linked to a specific phenological response, for example the seasonal accumulation of growing degree-hours that triggers the onset of leaf out/flowering in many plants. The Spring Indices (SI, Schwartz et al. 2006) are one set of phenological models that have been successfully applied to evaluate variations and trends in the onset of spring across the Northern Hemisphere's temperate regions. To date, SI have been limited by only producing output in locations where the plants' SI were designed to simulate grow successfully, principally where both the plants' chilling and growing-degree-hour requirements are met. In this paper, we consider an extended form of the Spring Indices (abbreviated SI-x) that can be mapped from polar to subtropical latitudes by ignoring chilling requirements while still retaining the utility and accuracy of the original SI (now abbreviated SI-o). For the continental USA, SI-x variations from 1900-2010 show an abrupt and sustained delay in spring onset of about 4-8 days around 1958 in parts of the Southeast and southern Great Plains, and a comparable advance of 4-8 days in parts of the northern Great Plains and the West. These conspicuous regional patterns are associated with the Pacific North American (PNA) pattern, defined by anomalously high geo-potential heights over the Northwest and anomalously low ones in the Southeast. The SI-x are promising metrics for tracking regional variations and trends in spring's onset, relating them to relevant ecological, hydrological and socioeconomic phenomena, and exploring connections between atmospheric drivers and seasonal timing, both in the past and elsewhere in the world.

Introduction

Phenology is the study of plant and animal life cycle events in relation to environmental drivers (especially weather and climate), and phenological data are simple, yet sensitive indicators of the impacts of climate change on ecosystems (IPCC 2007). Phenological measurements are made routinely and extensively in Europe (van Vliet et al. 2003), new national networks were established recently in the USA (Betancourt et al. 2005) and Australia (ClimateWatch 2012), and pleas are being made for developing networks in India and other continents (Kushwaga and Singh 2008). Considerable challenges remain, however, in using phenological data to assess the environmental impacts of climate variability and change across most regions (Schwartz et al. 2006). Chief among these are the lack of: 1) historical and contemporary phenological data in general; 2) long-term and replicated measurements of different populations across the range of the target species; 3) coordination and standardization among existing national phenological networks in terms of species and protocols; and 4) worldwide phenological data sharing agreements.

Given these limitations, many researchers have used available phenological data to first develop biologically-relevant algorithms for simulating "spring's onset", typically driven by daily surface maximum-minimum air temperatures. Once tested and calibrated, such models extend the possible spatial coverage and temporal range of phenological assessments of environmental change, given the greater availability of meteorological data, both currently and in the past. Now it would be fair at this point to ask "Why use phenological models instead of just using the meteorological data alone for such assessments?" In order to answer this question, one must consider that, when measuring environmental change, there are various levels of precision related to the type of measure used, the length of time addressed, and the degree of spatial aggregation. Let us consider changes in the start of the growing season for plants. Average monthly (or seasonal) temperatures can give a general idea of the expected change at a specific station and of the overall average change over a region. However, monthly values will not be as responsive as a model designed to produce a precise output related to a specific phenological response, for example the initiation of leafing and flowering. Also, if the phenological event ranges over a broad geographic area or can be triggered by a brief period of extreme temperatures, this may be poorly represented in general measures like average monthly or seasonal temperature.

One set of phenological models that have been successfully applied to assess the impact of environmental change on the onset of the spring season across temperate regions around the Northern Hemisphere are the Spring Indices (SI, Schwartz et al. 2006; Ault et al. 2011; McCabe et al. 2011). This suite of measures includes several sub-models and associated measures, all of which can be calculated using daily maximum-minimum surface (shelter-height) temperatures and station latitude. SI process weather data into a form comparable to the spring growth of plants that are not water limited and are responsive to temperature increases (Schwartz et al. 2006).

SI were initially designed to simulate the growth of specific plants. As such, earlier versions of SI do not produce output in locations where these plants do not grow successfully, most specifically in areas where warm winter weather provides inadequate chilling (Schwartz et al. 2006). Here, we explore development of an extended form of the Spring Indices (abbreviated SI-x) that retains the utility and accuracy of the original SI (now abbreviated SI-o) while allowing mapping into the subtropics. This permits assessment of spring onset variations and trends in the Southeastern USA, particularly in reference to this region constituting a "warming hole," where the secular trend during the past century has been towards later hard freezes (Marino et al. 2011) and generally cooler springs and summers (Robinson et al. 2002; Pan et al. 2004; Kunkel et al. 2006; Wang et al. 2009; Meehl et al., in review).

Data and Methodology

The meteorological stations used in this study came from the over 22,000 observation sites that record standard surface-level (1.5 m above the surface) daily maximum-minimum across the continental (lower-48) United States. The data were obtained from the National Climatic Data Center (NCDC) archives, covering the period of record for these stations through 2010. The final 716 station locations selected for inclusion in the analyses were those that had sufficient data to produce valid Spring Indices (SI) model output for at least twenty-five of thirty years over the 1981-2010 (30-year) period.

The methodology for producing the extended SI (SI-x) model output (SI first leaf date and SI first bloom date) are the same as described in McCabe et al. (2011) for the original SI models (SI-o) with the following exception. For SI-x first leaf calculation, no chilling hours are accumulated, rather energy accumulation starts for all stations from the same fixed day, January 1st, each year. For the selected stations, SI-x first leaf and first bloom model dates were first calculated for the station period of record. Next, from these yearly values, 30-year averages ("normals") were calculated for the 1981-2010 period, and these normals were subsequently used to turn the yearly SI-x output into departures-from-normal. These departures were used for all subsequent analyses.

In addition, given the well-documented performance of SI-o, SI-x output was compared to SI-o station output at all available stations where both model sets would produce output. The comparisons included Pearson's correlation, mean bias, and mean absolute differences. Lastly, for stations where cloned lilac (*Syringa chinensis* 'Red Rothomagensis' data—the main type of plants used in the original development of SI) were also available, these data were used to compare SI-o model and SI-x model accuracy.

The SI-x station departures from normal were accumulated, examined, and plotted over the 1900-2010 period. This initial examination suggested that the time series was different in the Southeastern United

States (SEUS), than the rest of the continental USA (REST). Further, it appeared that the decade from 1951-1960 was a pivotal period when broad changes appeared to be taking place in the previous trends. To further explore these changes: 1) the temporal trends were accumulated in two regions, the SEUS (defined as the area south of 37°N latitude and west of 103°W longitude) and REST; and 2) changes in SI-x output values were compared by station between the 1951-1960 and 2001-2010 periods, for all stations that had at least eight years of valid output in both periods.

To assess the role of large-scale circulation anomalies on the timing of spring in the SEUS time series, we correlated it with January and February 300mb heights from the National Center for Environmental Prediction's (NCEP) reanalysis data (Kalnay et al. 1996). These 300mb fields were computed using a numerical model of climate constrained by observational data from 1950 through 2010, and hence provide insight into the dynamical mechanisms responsible for interannual variability in SI-x.

Results

Table 1 shows the results of the comparison of SI-x and SI-o output. Both the first leaf and first bloom models are highly correlated, and the mean bias and mean absolute differences are around 2 days or smaller, with the first bloom models values closer to one day. The comparison of SI-x and SI-o model performance when compared to cloned lilac data are very similar, in terms of both bias and absolute errors. The error differences are 0.25 days or less, well within the 1-day resolution of model predictions.

The temporal trends in SI-x first leaf date are considerably different between the SEUS and REST for the first half of the 20th century (1900-1950), but begin to converge in the late-1950s (Fig. 1). By the 1980s the two regions seem to have come into phase. The spatial coherence across the SEUS is considerable, and well shown by the station comparison between the 1951-1960 and 2001-2010 periods (Fig. 2).

Correlations between SEUS and 300mb heights for January and February are shown in Figure 3. Although correlations are stronger during January (Fig. 3a), the sign and geographic pattern of the correlation fields are very similar for both months. Regions of negative correlation (early SEUS spring with high 300mb heights) occur over the subtropical Pacific and southeastern US, whereas negative correlations occur over northern North America. The pattern during both months is highly reminiscent of the Pacific North American (PNA) stationary wave pattern in mid-tropospheric flow (Wallace and Gutzler 1981). Leathers and Palecki (1992) attributed a sharp increase in the PNA index to the dramatic decline in geo-potential heights over SEUS in the late 1950's, which accounts for winter/spring cooling and earlier onset in SEUS.

Discussion

Schwartz et al. (2006) and Parmesan (2007) have documented that SI spring onset and phenological trends for comparable species (shrubs) are both moving earlier at rates of approximately 1.1 to 1.2 days/decade on average at the hemispheric scale. With respect to this hemispheric average, trends in the western USA are anomalously negative, while trends in the southeastern USA are anomalously positive. Biological evidence for the dramatic advance in SI-SEUS around the late 1950's includes delayed seasonal flowering in many Florida plants, inferred from herbarium specimens (Von Holle et al. 2010).

Previous studies have implicated large-scale atmospheric circulation patterns in driving interannual variability and trends in the western USA (Ault et al. 2011; McCabe et al. 2011). In particular, Ault et al. (2011) argued that the atmospheric trends towards an enhanced ridge over western North America, with troughs over the subtropical Pacific and southeastern US, were linked to a greater number of warm days earlier in the year and hence earlier spring. This pattern, which resembles the positive phase of the PNA, would also be expected to generate a greater number of outbreaks of cold air in the southeastern USA and consequently delays the onset of spring in that region (Marino et al. 2011). The positive trend in the SEUS time series and the correlation map in Figure 3 both support this explanation. Hence, the anomalous (and opposing) trend in the western USA and southeastern USA are counterbalanced and linked by the same large-scale mechanism.

The geographic pattern of southeastern USA stations where spring has been arriving later is consistent with the well-documented "warming hole" in the southwestern USA (Robinson et al. 2002; Pan et al. 2004; Kunkel et al. 2006; Wang et al. 2009; Meehl et al., in review). Recently, Meehl et al. (in review) have attributed this warming hole to decadal variability in the Pacific Ocean, which induces atmospheric changes favoring a trough-ridge-trough (positive PNA) structure that brings a greater number of cold outbreaks of air to the southwestern USA. Using a coupled global climate model (GCM), the study further documents that the pattern of Pacific decadal variability responsible for the warming hole in North America may be internally generated, and therefore not directly linked to climate change (Meehl et al., in review). Because the warming hole also evidently impacts seasonality, as shown here, projections of future phenological change should take into account both the forced and natural sources of variability.

Future studies could use the new SI-x product to further explore the patterns of variations and trends and natural low-frequency variability of spring's onset in other parts of the world or over other time domains. For example, the springtime cooling trend in southwest China has been attributed to the teleconnection between the winter North Atlantic Oscillation (NAO) and surface air temperature over the lee side of the Tibetan Plateau (Li et al. 2005).

We emphasize that the calculation of SI-x only require daily maximum-minimum temperatures as input, and so they could be calculated from daily reanalysis data and GCM output to develop a more refined dynamical explanation for the sources of spring onset variability on interannual to centennial timescales. Such efforts would provide insight into the sources of spring onset predictability, which in turn could be of critical importance to agricultural and natural resource managers alike.

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Table 1: Comparison of Original Spring Indices (SI-o) to Extended Spring Indices (SI-x) and both to lilac phenological data

Pearson's correlation	*SI-x first leaf date*	*SI-x first bloom date*
SI-o first leaf date	**0.975**	
SI-o first bloom date		**0.995**

Mean Difference (days)	*Bias difference*	*Absolute difference*
SI-x first leaf date	**-1.4**	**2.5**
SI-x first bloom date	**-0.7**	**1.1**

n of cases = 71,926

Mean Error to Lilac (days)	Bias Error	Absolute Error	Error Difference
SI-x first leaf date	**-2.47**	**6.57**	**0.14**
SI-o first leaf date	**-1.78**	**6.43**	
SI-x first bloom date	**-3.66**	**5.46**	**0.25**
SI-o first bloom date	**-3.15**	**5.22**	

n of cases = 830

Figure 1: Smoothed (9-point moving average normal curve) SI-x First Leaf Date Departures from 1981-2010 normals in the SEUS compared to rest of the continental USA, 1904-2006.

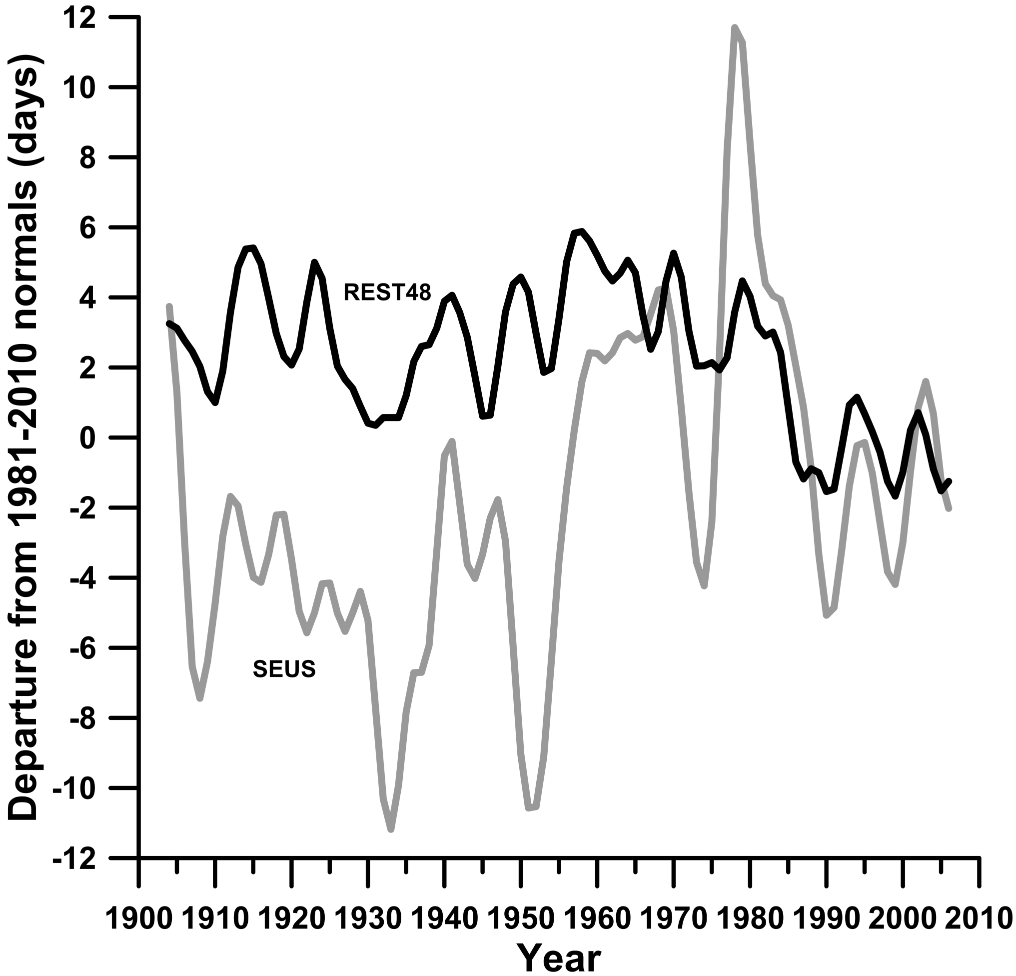


Figure 2: Change in average SI-x first leaf date by station (in days) between 1951-1960 and 2001-2010.

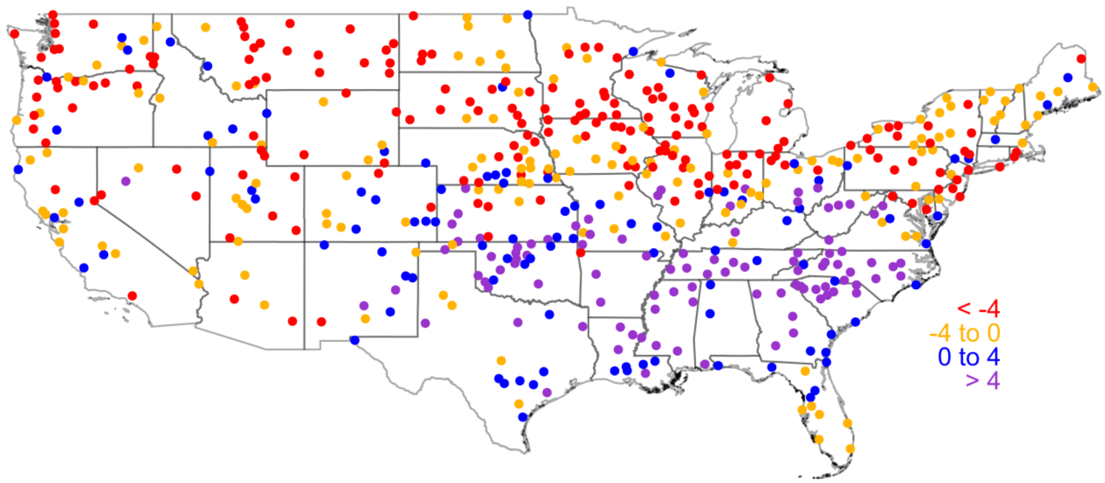
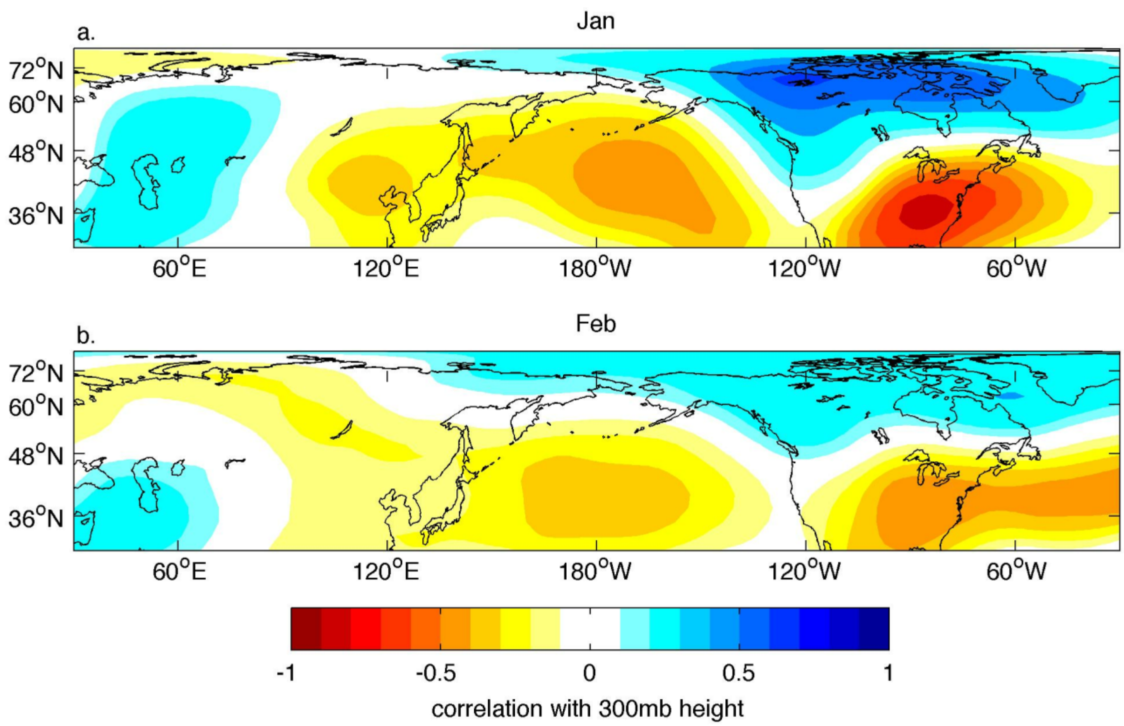


Figure 3: Correlation between the SEUS time series and 300hPa heights during the preceding January and February.



7. Appendix 1

USGCRP National Climate Assessment 2013 Technical Contribution
Expression of Interest
23 September 2011

Sponsoring organization:
The USA-National Phenology Network (http://www.usanpn.org) is a large-scale network of repeated and integrated plant and animal phenological observations, linked with other relevant biological and physical data sources, and the tools to analyze these data at local to national scales. The network consists of many partners including federal, state and local agencies, universities, colleges and schools, non-governmental organizations, and individual volunteers. The primary goal of the USA-NPN is to enhance climate change mitigation and adaptation strategies by building and sustaining a coordinated, national effort to observe, understand and predict variations and trends in the seasonal timing of natural and managed ecosystems and their societal consequences.

Primary Point of Contact:
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Type of Technical Input:
Mapped assessments of variability and recent trends in a suite of national indicators of seasonal timing, supported by a literature review on the national, regional, and sectoral consequences of shifts in seasonal timing.

NCA Assessment Capacities and Topic of Interest:
Support for developing indicator systems

Work Statement:
The NCA aims "*to incorporate advances in the understanding of climate science into larger social, ecological, and policy systems, and with this provide integrated analyses of impacts and vulnerability.*" To this end, we will contribute an advanced suite of spatially and temporally explicit bioclimatic indices to facilitate assessment and communication of the effects of climatic change on seasonal timing of natural and managed systems. We will specifically quantify the timing of leaf emergence and flowering derived from a calibrated and long-established observation network of genetically identical lilac and honeysuckle plants. For centuries, these phenological events have signaled the onset of spring and thus are universally understood as nature's response to climate. Unusual springtime warming since ~1980, attributed to both greenhouse gas buildup and natural variability, is having far-reaching consequences throughout physical, biological, and human systems in the U.S., including changes in water quality and quantity, the frequency and size of ecological disturbances, and the quality and availability of wildlife habitat.

Inputs:

The team aims to provide:

- A standardized set of metrics depicting the onset of spring across the U.S.
- A baseline set of metrics from which anomalies can be detected through time.
- The foundations of a forecasting tool to facilitate natural resource management, agricultural planning, recreation, education and outreach, and policy-making.
- A technical report detailing the methodology of data collection and analysis including graphics and appropriate metadata.

Spatial and temporal scales:

All 50 United States; annually from 1900 through present.

Scope and specific range of issues:

Our contribution will address how climate affects people and ecosystems in multiple ways. We will briefly touch on the direct influences of climate (e.g., temperature and precipitation variability and the availability of water) and the indirect influences (e.g., abundance and distribution of species, the function of ecological processes, and the occurrence of disturbance regimes). In particular, we will emphasize and demonstrate that the *timing* of these climate-mediated phenomena is critical for the provisioning of key ecological services that benefit society, such as water quality, air quality, pollination, food production, forest products, carbon sequestration, and recreation.

Core Team Members:

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