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# Diagnosis and Attribution of Recent Changes in Vegetation Productivity and the Regional Water Balance for the Pan-Arctic Basin and Alaska

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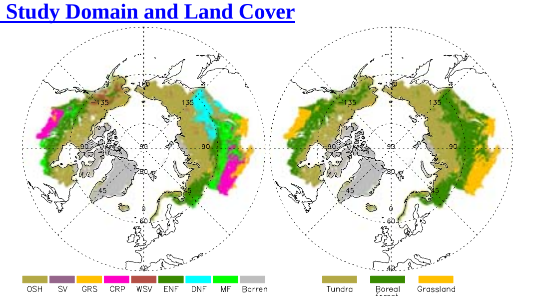
## Abstract

We applied a satellite based production efficiency model (PEM) using an integrated AVHRR and MODIS FPAR/LAI time series with a regionally corrected NCEP/NCAR reanalysis surface meteorology and NASA/GEWEX solar radiation inputs to assess annual terrestrial net primary productivity (NPP) for the pan-Arctic basin and Alaska from 1983 to 2005. We also developed a satellite based evapotranspiration (ET) algorithm using GIMMS NDVI with the above meteorology inputs to estimate ET over the region. We then applied these data with in situ measurements and global precipitation records (GPCC, GPCP) to analyze changes in the regional water balance (P-ET) and the effects of natural climate oscillations (AO and PDO) on vegetation productivity and water balance patterns and anomalies.

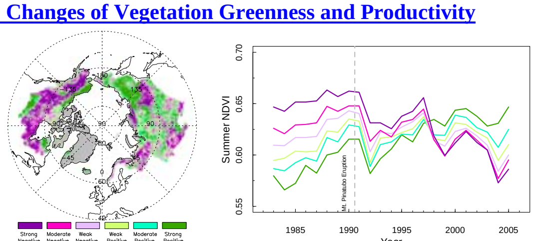
Warming in the Boreal-Arctic region is significantly reducing the low temperature constraints on NPP by 0.43% per year (P<0.001), whereas a positive trend in vegetation moisture constraints of 0.49% per year (P=0.04) are offsetting potential benefits of a longer growing season and contributing to recent drought related disturbances in NPP. Generally positive trends in ET, precipitation and available river discharge measurements imply that the pan-Arctic terrestrial water cycle is intensifying. Increasing water deficits occurred in some boreal and temperate grasslands, consistent with regional drought records and recent satellite observations of vegetation productivity decreases. Mean annual NPP showed a positive growth trend of 0.34% per year (P=0.002) from 1983 to 2005 but with recent, large NPP declines from regional drought. The AO and PDO influence NPP by regulating the low temperature and moisture constraints to photosynthesis. Relatively strong, negative PDO phases from 1998-2002 coincided with prolonged regional drought and recent widespread water deficit and NPP declines in boreal and temperate grassland regions.

## 1. Study Domain and Land Cover

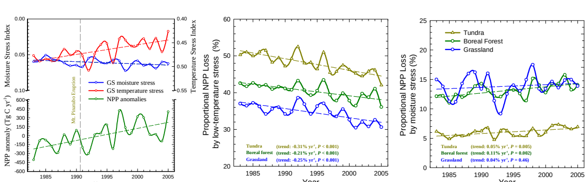



The study domain encompasses the pan-Arctic basin and Alaska (**left**). The MODIS-IGBP land cover map (**left**) defines 8 vegetation classes, including open shrubland (OSH), grassland (GRS), cropland (CRP), savanna (SV), woody savanna (WSV), evergreen needleleaf forest (ENF), deciduous needleleaf forest (DNF), and mixed evergreen & deciduous forest (MF). To study climate change effects on major biomes within the domain, we aggregated the land cover into three major regional vegetation types: tundra, boreal forest and grassland (**right**).

## 2. Changes of Vegetation Greenness and Productivity



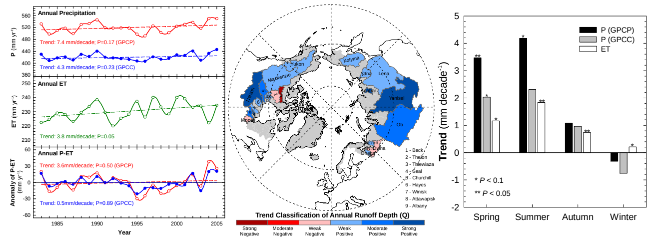

Summer NDVI shows moderate to strong browning trends from 1983 to 2005 in many boreal forest and grassland regions located in central Alaska, western, central and eastern Canada, northwestern and southwestern Eurasia, and eastern Siberia, while other areas show generally greening trends (**left**). For all six trend categories, the spatial average NDVI time series show generally positive trends from 1983 to 1990; large declines in 1991 and 1992 caused by temporary global cooling following the Mount Pinatubo eruption; a renewed upward trend from 1992 to 1997. After 2000, the NDVI trend categories are predominantly declining.



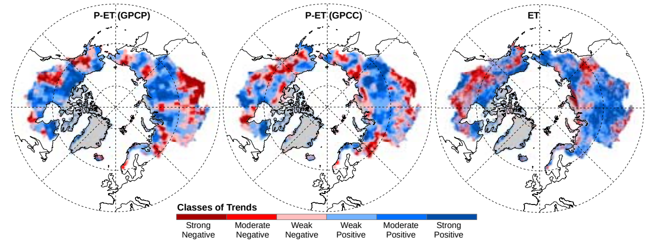

Warming in the Boreal-Arctic region is significantly reducing the low-temperature constraints on NPP by 0.43% per year (P<0.001), whereas a positive trend in vegetation moisture constraints of 0.49% per year (P=0.04) are offsetting potential benefits of a longer growing season and contributing to recent drought related disturbances in NPP (**left**)[1]. As a result, regional mean annual NPP showed a positive growth trend of 0.34% per year (P=0.002) from 1983 to 2005 but with recent, large NPP declines from regional drought (left)[1].

The low-temperature constraint induced NPP losses are significantly decreasing over the 23-year period for all three biomes, which benefits tundra the most and less so for boreal forests and grasslands (**middle**) [1]. However, the moisture constraint induced NPP losses show significant positive trends for tundra and boreal forest biomes and an insignificant positive trend for the grassland biome, implying that increasing moisture constraints are partially counteracting the potential benefits of warmer temperatures (**right**) [1]. The magnitudes of proportional NPP losses due to moisture constraints are much larger for the grassland (~13%) and boreal forest (~12%) biomes than for tundra (~5%). Periodic dry conditions from 1989-1991, 1998-1999 and 2001-2003 (**left and right**) coincided with large NPP declines for the pan-Arctic region (**left**). Dry conditions in 2001-2003 are also consistent with post-2000 vegetation browning and productivity declines.

## 3. Pan-Arctic Water Balance Changes

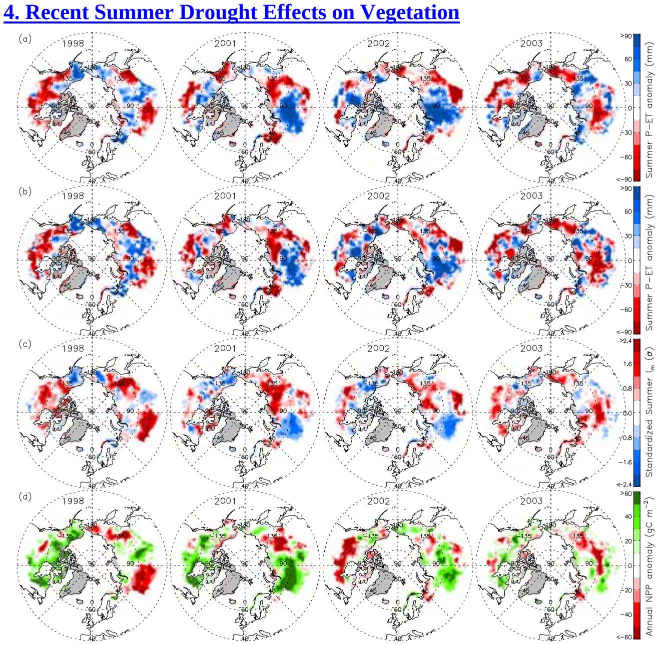



The pan-Arctic region shows small positive P trends and a significant positive ET trend (**left**). Annual P-ET shows an insignificant wetting trend indicated by both GPCP and GPCC P results. Measured annual runoff depths (Q) from regional basin gauges show positive trends for 18 out of 22 major sub-basins (94.3% of total basin area) (**middle**). Positive trends in ET, P and Q imply that the regional water cycle is intensifying for the 23-yr period. Both P and ET show significant seasonal trends for the domain (**right**). ET shows significant positive trends for all four seasons with larger trends in spring and summer. P shows larger positive trends than ET in spring, summer and autumn but a small negative trend in winter, indicating that the region is becoming wetter during the growing season but drier in winter.



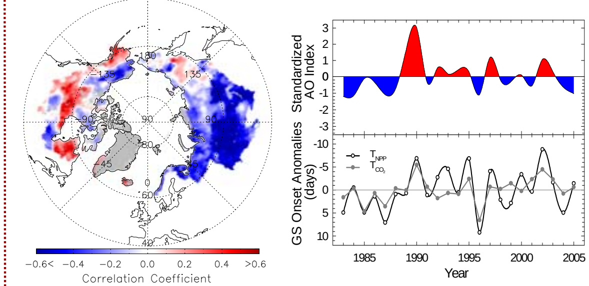

There is considerable spatial variability in water balance trends for the domain. The P-ET results show similar spatial patterns with respect to GPCP and GPCC P sources. Approximately 72% and 62% of areas with negative P-ET trends occur in boreal forests and grasslands, respectively. The ET results show generally positive trends for 68% of the domain. Approximately 62% of areas with moderate to strong negative ET trends occur over boreal forest, especially boreal regions of North America, while other areas show generally positive ET trends.

## 4. Recent Summer Drought Effects on Vegetation

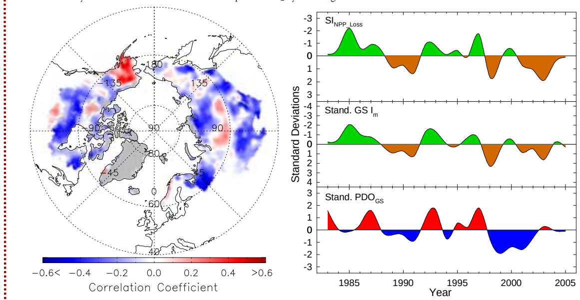



Standardized summer vegetation moisture stress index ($I_m$) and summer P-ET anomalies indicate that years 1989-1991, 1995, 1998, 2001 and 2003 had the driest summers (**red color**) over the 23-year period (**left**). Summer P-ET (**top (a) and (b)**) and $I_m$ (**top (c)**) anomalies also show similar spatial patterns and widespread dry conditions for years 1998, 2001, 2002 and 2003, especially for boreal forest and grassland biomes. Areas impacted by droughts also coincide with anomalous decreases in satellite-derived annual vegetation productivity (**top (d)**).

## 5. Teleconnections between Climate Oscillation and Vegetation Productivity

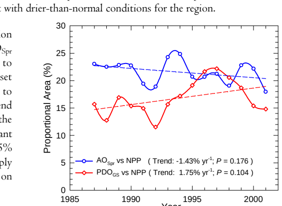



The timing (day of year) of GS onset was estimated by the seasonal onset of terrestrial NPP ($T_{NPP}$) from the daily PEM NPP series, and the timing of the spring drawdown of atmospheric $CO_2$ concentrations ($T_{CO2}$) from NOAA GMD arctic and sub-arctic monitoring stations (**right**). The correlation between spring AO index ($AO_{Spr}$) and $T_{NPP}$ is predominantly negative for Eurasia, but positive for Central and Northeastern Canada (**left**). This is because a positive $AO_{Spr}$ reflects stronger-than-normal pressure patterns and westerly winds across the North Atlantic Ocean in the 40-60$^{O}$N latitude belt; warmer-than-normal conditions and earlier growing season onset over Eurasia, and colder-than-normal conditions and later growing season onset over the eastern Canadian Arctic. The pan-Arctic average $T_{NPP}$ was negatively correlated with $AO_{Spr}$ ($r$=-0.653; $P$=0.001). Positive $AO_{Spr}$ phases (red) coincided with generally earlier growing season onset, while negative $AO_{Spr}$ phases (blue) are concurrent with later growing season onset. The relatively strong correlation ($r$=0.78; $P$<0.001) between $T_{CO2}$ and $T_{NPP}$ indicates that northern terrestrial ecosystems dominate the seasonal atmospheric $CO_2$ cycle at high northern latitudes.




The GS PDO index ($PDO_{GS}$) and GS $I_m$ relationship is predominantly negative in most of the region indicating a reduced moisture (VPD) constraint to NPP under positive $PDO_{GS}$ conditions (**left**). $SI_{NPP\_Loss}$ is the standardized value of the proportional difference between annual NPP calculations without (potential) and with (actual) moisture stress. Negative (green) and positive (brown) values denote less-than-normal and larger-than-normal NPP losses, respectively. The $PDO_{GS}$ index was correlated to regional standardized GS $I_m$ ($r$=-0.471; $P$=0.02) and $SI_{NPP\_Loss}$ ($r$=-0.485; $P$=0.02, indicating that North Pacific SST patterns during the growing season impact atmospheric moisture inputs to the pan-Arctic land mass, especially for boreal forest and grassland biomes. Positive phases of the $PDO_{GS}$ correspond to wetter-than-normal conditions, while negative $PDO_{GS}$ phases are concurrent with drier-than-normal conditions for the region.

Time series of the proportional areas (%) of the region showing significant correlations between annual NPP and $AO_{Spr}$ shows a negative trend (1.43% $yr^{-1}$; $P$=0.176) from 1983 to 2005, indicating that the $AO_{Spr}$ influenced timing of GS onset became less important to NPP as low-temperature constraints to photosynthesis relaxed under a significant warming trend (0.5°C/decade; $P$=0.002 ) for the period. Coincidently, the proportional area of drought prone regions showing significant correlations between $PDO_{GS}$ and annual NPP increased by 1.75% per year ($P$=0.10), indicating that the $PDO_{GS}$ influenced supply of plant-available moisture became an increasing constraint on annual productivity with regional warming.




## Conclusions

- Warming is significantly relaxing the low-temperature constraints to NPP across the Pan-Arctic domain, whereas positive trends in moisture constraints are offsetting potential benefits of warming;
- The pan-Arctic terrestrial water cycle shows an intensification over the 23-year period indicated by generally positive trends in P, ET and measured runoff for most of the sub-basins examined;
- Increasing water deficits occurred in some boreal and temperate grasslands, consistent with regional drought records and recent satellite observations of vegetation productivity decreases;
- Mean annual NPP showed a positive growth trend of 0.34% per year (P=0.002) over the 23-year period but with recent, large NPP declines from regional drought;
- The AO and PDO influence NPP by regulating low temperature and moisture constraints to photosynthesis. Relatively strong, negative PDO phases from 1998-2002 coincided with recent prolonged regional drought and water deficit and NPP declines in boreal and temperate grassland regions.

### Acknowledgements

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