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Satellite based analysis of recent changes in ET and the terrestrial water balance over Canada and Alaska: Implications for vegetation productivity and the northern carbon cycle

Ke Zhang[1,2], John S. Kimball[1,2], E. H. Hogg[3], Kyle C. McDonald[4], and Walter C. Oechel[5]

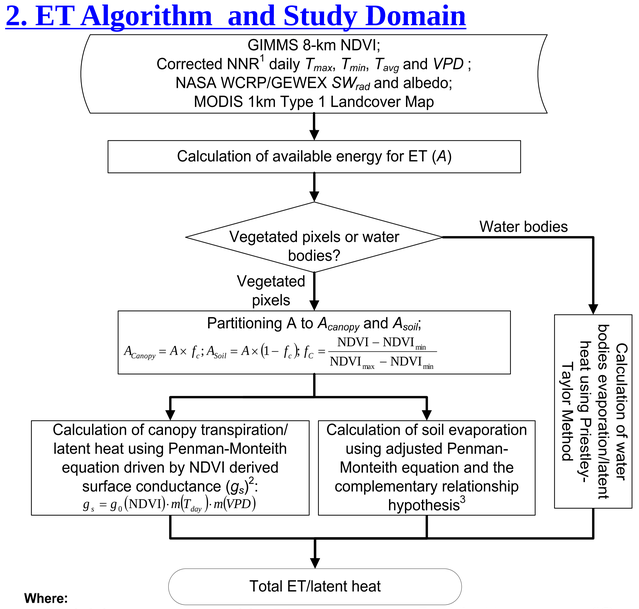
[1]Flathead Lake Biological Station, University of Montana; [2]Numerical Terradynamic Simulation Group, University of Montana; [3]Northern Forestry Centre, Natural Resources Canada; [4]Jet Propulsion Laboratory, California Institute of Technology; [5]Global Change Research Group, San Diego State University.

Email: zhang@ntsg.umt.edu Web Site: www.ntsg.umt.edu

1. Abstract

We applied a satellite remote sensing based evapotranspiration (ET) algorithm using AVHRR GIMMS NDVI, regionally corrected NCEP/NCAR reanalysis surface meteorology and NASA/GEWEX solar radiation inputs to assess spatial patterns and temporal trends in ET over Canada and Alaska from 1983 to 2005. We then analyzed associated changes in the regional water balance (P-ET), where precipitation (P) was defined from GPCP and GPCC monthly precipitation. We also assessed linkages between the regional water balance and vegetation net primary production (NPP) derived using a satellite remote sensing based production efficiency model. The satellite based ET results agree well (RMSE=8.3 mm month^{-2}, R^2=0.89) with *in situ* measurements from northern grassland, boreal forest and tundra flux towers. The ET results showed positive trends over 57% of the region, mainly in tundra regions, and corresponded with regional warming, vegetation greening and increasing NPP. 61% of the boreal forest and northern grassland regions show negative ET trends, while 68% of the tundra regions displayed positive ET trends. Approximately 45-60% of the study region exhibited a below-average water balance during the summer (June to August) from 2002 to 2003 indicated by the GPCP and GPCC sources, of which 20-36% showed anomalies that were more than one standard deviation below 23-year average conditions. These recent large annual water deficits in boreal regions agree well with regional drought records and explain recent anomalous declines in satellite-derived NPP and stand-level measurements. Our results also show that the regional water balance is changing in complex ways in response to global warming, with direct feedbacks to regional vegetation productivity, composition and distribution.

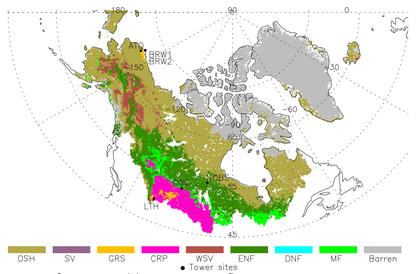
2. ET Algorithm and Study Domain



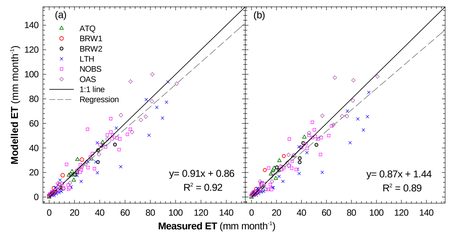
Where:

VPD : daylight average vapor pressure deficit (Pa);
SW_{rad} : incoming shortwave solar radiation (Wm^{-2});
A : available energy for ET (Wm^{-2});
A_{canopy} : available energy for canopy transpiration (Wm^{-2});
A_{soil} : available energy for soil evaporation (Wm^{-2});
g_0 : biome - specific potential surface conductance (m s^{-1});
NDVI : normalized difference vegetation index;
T_{min} : daily minimum temperature (°C);
T_{max} : daily maximum temperature (°C);
T_{avg} : daily average temperature (°C);
T_{day} : daylight average temperature (°C);
$m(T_{day})$: temperature stress factor;
$m(VPD)$: water/moisture stress factor;
g_s : actual surface conductance (m s^{-1});
$NDVI_{min}$ and $NDVI_{max}$ are set as seasonally and geographically invariant constants 0.05 and 0.95;

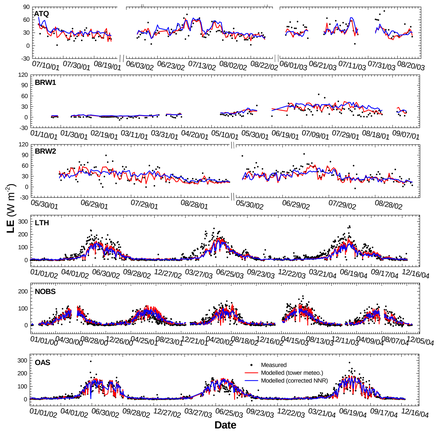
The study area encompasses the North American portion of the pan-Arctic basin and Alaska (**right**). The MODIS-IGBP land cover map classifies regional vegetation into 8 classes, including open shrubland (OSH), savanna (SV), grassland (GRS), cropland (CRP), woody savanna (WSV), evergreen needleleaf (ENF), deciduous needleleaf (DNF), and mixed (MF) forests. The ET model was calibrated and verified using measurements from six eddy covariance flux tower sites representing dominant vegetation classes, including the Barrow one (BRW1) and two (BRW2), Atqasuk (ATQ), Northern Old Black Spruce (NOBS), Lethbridge (LTH) and Old Aspen (OAS) sites (**right**).



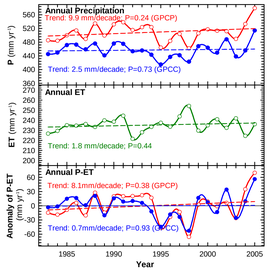
3. Model vs. Tower based ET

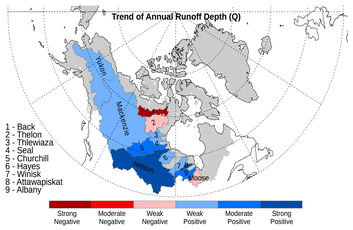


Two sets of modeled daily latent heat (LE) fluxes, derived using *in situ* meteorological measurements and coarse resolution reanalysis inputs, show favorable agreement with the observations and capture observed LE seasonality (**right**). On the monthly basis, both sets of modeled ET agree well (RMSE=7.4-8.3mm month^{-1}; R^2=0.89-0.92; **above**) with observed tower fluxes.



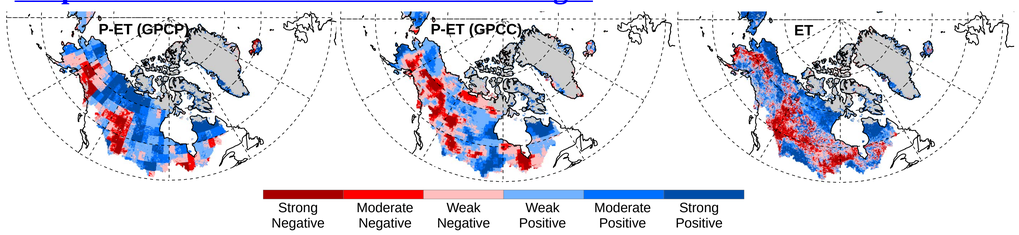
4. Annual Water Balance Changes





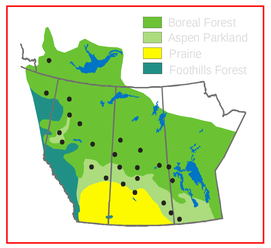
The domain shows small positive P trends and a slightly increasing ET trend (**left**). Annual P-ET shows insignificant positive trends indicated by both GPCP and GPCC P results. Measured annual runoff depths (Q) from regional basin gauges show positive trends for 10 out of 13 major sub-basins (90.2% of total basin area) (**right**). Positive trends in ET, P and Q imply that the regional water cycle is intensifying over the 23-yr period.

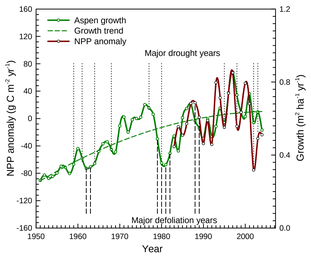
5. Spatial Patterns of Water Balance Changes



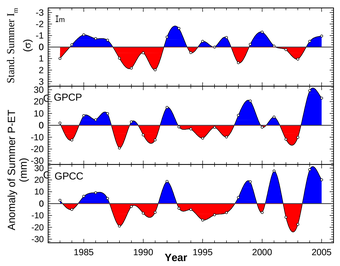
There is considerable spatial variability in water balance trends for the domain. The P-ET results show similar spatial patterns with respect to GPCP and GPCC P sources. Approximately 71% and 57% of areas with negative P-ET trends occur in boreal forests and grasslands indicated by GPCP and GPCC sources, respectively. The ET results show positive trends for 57% of the domain. Approximately 62% of areas with moderate to strong negative ET trends occur over boreal forest and temperate grassland areas.

6. Recent Summer Drought Effects on Vegetation

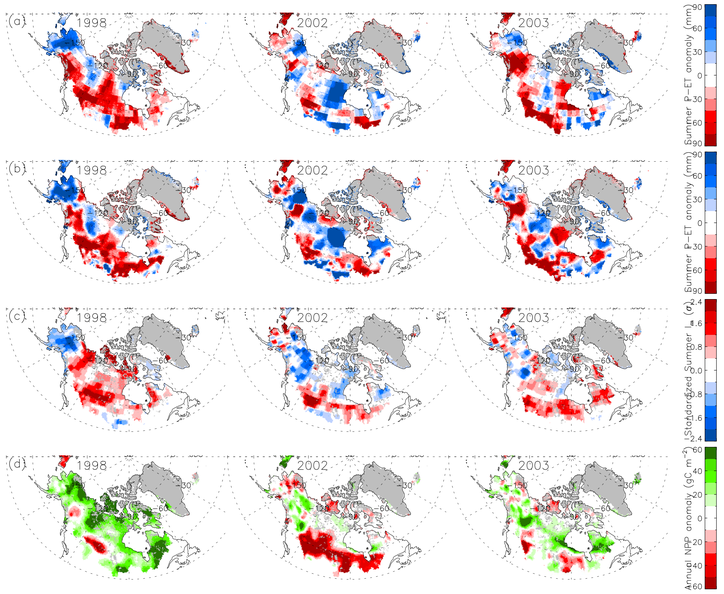




Stand inventory measurements at 72 CIPHA[4] (Climate Impacts on Productivity and Health of Aspen) sites (**left**) show a general pattern of vegetation growth, decline and recovery in response to periodic drought and insect defoliations across west-central Canada. The years 1995, 1998, 2002 and 2003 are documented drought years for the region. Satellite-derived NPP anomalies are highly correlated with the stand-level observations (r=0.61; P=0.002) and capture the negative impacts of recent droughts.



Standardized summer vegetation moisture stress index (I_m) and summer P-ET anomalies indicate that years 1988-1991, 1995, 1998, and 2002-2003 had the driest summers (**red color**) over the 23-year period (**left**). Summer P-ET (**below (a) and (b)**) and I_m (**c**) anomalies also show similar spatial patterns and widespread dry conditions for years 1998, 2002 and 2003, especially for boreal forest and grassland biomes. Drought impacted areas also coincide with anomalous decreases in satellite-derived annual NPP (**d**).



7. Conclusions

- Satellite-derived LE/ET results agree well with tower observed fluxes within regionally dominant biomes;
- The terrestrial water cycle over Canada and Alaska shows a slight intensification over the 23-year period indicated by generally positive trends in P, ET and measured annual runoff for most of the sub-basins examined;
- Regional patterns of wetting and drying are spatially complex with some boreal forest and grassland regions showing moderate to strong drying trends over the 23-year period, with recent (post-2000) summer droughts coinciding with anomalous decreases in satellite-detected annual vegetation productivity and stand-level measurements.
- Results indicate strong water/energy/carbon cycle coupling; a changing water balance is impacting regional NPP and C sequestration by altering plant-available moisture supply, while vegetation influences water and energy cycles through strong canopy controls to LE/ET.

Selected References

1. Zhang, K., et al. (2008), Satellite based analysis of northern ET trends and associated changes in the regional water balance from 1983-2005, *J. Hydrol.,* submitted.
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4. Hogg, E.H., et al. (2005), Factors affecting interannual variation in growth of western Canadian aspen forests during 1951-200, Can. J. For. Res., *35*, 610-622.

Acknowledgements

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