Summary of the IPY Greening of the Arctic Project

Skip Walker
Institute of Arctic Biology and Department of Biology and Wildlife
University of Alaska Fairbanks

Talk given at Institute of Arctic Biology Seminar, April 6, 2012
What are the causes of the greening observed in Arctic tundra regions during the period of satellite-based observations?
Principal GOA collaborators

• **Co-PIs:** D.A. Walker\textsuperscript{1}, U.S. Bhatt\textsuperscript{1}, H.E. Epstein\textsuperscript{2}, B.C. Forbes\textsuperscript{3}, M.O. Leibman\textsuperscript{4}, V.E. Romanovsky\textsuperscript{1}

• **Major contributors:** P. Bieniek\textsuperscript{1}, J. Comiso\textsuperscript{6}, D. Drozdov\textsuperscript{4}, K. Ermokina\textsuperscript{4}, G.V. Frost\textsuperscript{2}, G.J. Jia\textsuperscript{5}, O. Khitun\textsuperscript{9}, A. Khomutov\textsuperscript{4}, G. Kofinas\textsuperscript{1}, T. Kumpula\textsuperscript{7}, G. Matyshak\textsuperscript{8}, N. Metschtyb\textsuperscript{3}, N. Moskalenko\textsuperscript{4}, P. Orekov\textsuperscript{4}, J. Pinzon\textsuperscript{6}, M.K. Raynolds\textsuperscript{1}, F. Stammler\textsuperscript{3}, C.J. Tucker\textsuperscript{6}, N. Ukrain'tseva\textsuperscript{4}, Q. Yu\textsuperscript{2}

• \textsuperscript{1}University of Alaska Fairbanks, \textsuperscript{2}University of Virginia, \textsuperscript{3}Arctic Centre, Rovaniemi, Finland, \textsuperscript{4}Earth Cryosphere Institute, Tyumen, Russia, \textsuperscript{5}Institute of Atmospheric Physics, Beijing, China, \textsuperscript{6}NASA-Goddard, Beltsville, MD, \textsuperscript{7}University of Eastern Finland, Joensuu, Finland, \textsuperscript{8}Lomonosov Moscow State University, Russia, \textsuperscript{9}Komarov Botanical Institute, St. Petersburg, Russia

• Funding mainly from NSF (4 projects), NASA (2 projects), Russian Academy of Science and Finnish Government.
Overview of talk

• Hierarchical spatial and temporal analysis of Arctic greening
  – Quick overview of NDVI and early findings.
  – Update on spatial and temporal PanArctic sea ice, land temperature, and NDVI change emphasizing a recent change in these patterns possibly related to humidification of the Arctic.
  – Regional observations along Arctic transects in North America and Eurasia that help explain the PanArctic changes.
  – Two studies in Russia and at Toolik using Landsat and very high resolution satellite data to help understand the details of change.


Gray area corresponds to AVHRR NDVI record in top graph.
Tundra NDVI trend first noticed in time series of peak NDVI for northern Alaska (1981-2001)

- 17 ± 6% increase in peak regional NDVI (red line) from 1981-2001.
- Changes also appeared to correspond to yearly fluctuations in temperature.

Rationale for the IPY project: Are these same magnitude of trends occurring on a PanArctic scale and what are the drivers?

Time series of peak NDVI anomalies in the tundra and boreal forest (1981-2005)

Green: increasing NDVI
Red: decreasing NDVI
White: no trend

- Most of the positive changes are in tundra areas, particularly in North America.
- Forest areas are showing an overall decline in NDVI.
- But focus was not in the Arctic and could not examine change in the High Arctic because of problems with the original GIMMS data set.

Bunn et al. 2007. EOS. Northern high latitude ecosystems respond to climate change. 88: 333-335.
The pigment in plant leaves, chlorophyll, strongly absorbs visible light (from 0.4 to 0.7 µm) for use in photosynthesis.

NDVI refresher

Absorption spectra for different plant pigments and photosynthetic response

The pigment in plant leaves, chlorophyll, strongly absorbs visible light (from 0.4 to 0.7 µm) for use in photosynthesis.
Reflectance spectra for vegetation

On the other hand, the cell structure of the leaves strongly reflects near-infrared light (from 0.7 to 1.1 μm).

The difference in the reflectance in the NIR and visible regions, is a good proxy for the photosynthetic capacity of the vegetation.

Normalized Difference Vegetation Index: \( \text{NDVI} = \frac{(\text{NIR} - \text{VIS})}{(\text{NIR} + \text{VIS})} \)

Dividing by the sum normalizes the index to help account for shadow and slope angle effects.

MaxNDVI and TI-NDVI

- NDVI is measured twice daily for every spot on Earth using AVHRR and other sensors.
- Cloud cover may prevent getting good daily NDVI values, so the maximum values during biweekly collections of data are used to trace the seasonal trends in NDVI.
- Peak NDVI (also referred to here as MaxNDVI) is the highest value of NDVI reached in the summer and represents maximum greenness.
- Time-integrated NDVI (TI-NDVI) is the annual sum of bi-weekly NDVI values, a better index of total productivity.
Change in multi-year sea ice

White areas are areas of multi-year ice in 1980 and 2009.

Rigor and Wallace 2004, updated to 2009
Models indicate that periods of rapid sea-ice loss are accompanied by strong land warming and permafrost degradation.

Linkage between climate, sea-ice shrinkage and vegetation.

**Main PanArctic hypothesis:**

Periods of reduced sea ice should correspond to periods of warmer land temperatures and this should in turn correspond to periods of more rapid greening.
Greening is highly variable across the Arctic and within landscapes.
Webs of social and ecological factors that influence vegetation productivity and NDVI.

NDVI: Integrator of vegetation change
Main Landscape-level hypothesis:

Disturbance is the primary driver of NDVI change within landscapes.
Circumpolar patterns of change of sea-ice, land temperature and NDVI change in the Arctic detected with AVHRR satellite sensors

Examining the correspondence between the different patterns

Updated to 2011 for BAMS 2011 *State of the Climate*
Analysis by sea basin Approach

- Division of the Arctic into sea basins and associated land areas based on Russian Arctic Atlas.
- Developed time series of coastal May-Sep sea-ice concentration (100-km coastal zone), summer land temperatures for the full tundra region (summer warmth index), and NDVI based on 1982-2011 AVHRR satellite data.
- Examined trends and correlations between factors for each sea.
Percentage change of coastal open water and summer land temperatures

**Most noticeable:**

- Positive changes in open water across the Arctic.
- Greatest open water changes are in the E. Kara Sea.
- Greatest percentage warming changes are in the Baffin Bay, Davis St., Greenland Sea areas.
- Cooling in the E. Kara region despite very large increases in open coastal water (More fog? More snow? Shorter growing season?)

Updated from Bhatt et al. 2010, *Earth Interactions.*
In general, areas of enhanced NDVI patterns are corresponding to areas of warmer land temperatures.

- Strong greening in the Beaufort, Canada, Greenland and Laptev (all areas of strong warming).
- Weak trend in the Barents / Kara region (area of cooling).
Trends in NDVI

- General upward trend of NDVI in N. America and Eurasia.
- Much higher NDVI in Eurasia due to relative amount of land in the more productive Low Arctic.
Recent changes in NDVI trends

Diverging patterns after about 2001:

- Eurasia: flat MaxNDVI and declining TI-NDVI.
- North America: strongly increasing NDVI, flat TI-NDVI.
Diverging patterns of NDVI change in the Beaufort and Kara sea areas

**Beaufort**: 24% overall increase but trend flat since 2004.
**Kara**: 4% overall increase, essentially flat since 1990.


- **Beaufort**: 26% increase
- **Kara**: +4% increase
PanArctic findings

• Largest negative changes in sea-ice (positive changes in open-water) are in the regions of 1) the Kara/N. Barents seas, 2) the East Siberia/Chukchi/Beaufort seas, and 3) the Baffin Bay/Davis Straight/Foxe Basin/Hudson Bay. There are a few areas of positive sea-ice change (e.g. E. Bering Sea).

• Largest positive land-temperature changes are in the Greenland Sea/ Baffin Bay area. Cooling in the Y-K delta, parts of central northern Canada, and much of NW Siberia.

• Strongest positive NDVI changes are in Alaska and Beaufort Sea area. Some weak negative trends in NW Siberia.

• Why the strong contrast of NDVI change of the Beaufort and Kara sea areas?
The Arctic tundra zone is a maritime biome

- 177,000 km of coastline
  - 1/5 of global total.
  - for a biome that comprises less than 5% of the Earth’s land surface.

- But it is not all equally maritime because the ocean is covered by varying amounts of ice during the winter and summer.

- Which promotes relatively continental climates in areas with long periods of winter and summer sea ice.
Arctic vegetation patterns are strongly linked to differences in sea ice

Yurtsev’s (1994) floristic division of the Arctic:
• Divides the Arctic into 6 floristic provinces and 22 subprovinces.
• Separates oceanic and continental areas of the Arctic.

Yurtsev, B.A. 1994, *Journal of Vegetation Science*
Yurtsev’s oceanic and continental regions within the Arctic

- **Gray areas:** continental Arctic areas with an Arctic climate, cold winters, long periods of summer sea ice, permafrost, and an Arctic flora.
- **Blue areas:** Treeless areas, mainly outside the true Arctic, with warm winters, no permafrost (except in mountains), and an oceanic boreal flora.
- **Green areas:** Intermediate Arctic tundra but with strong oceanic influence, long periods of ice-free ocean in fall and winter.

Yurtsev, 1994, *Journal of Vegetation Science*
The transitional areas with mixed oceanic and continental influences are currently the areas where some of the greatest ocean and land changes are occurring.

1. N. Bering seas/ Chukchi
2. Foxe Basin/Baffin Bay
3. N. Barents/Kara seas

Yurtsev 1994, Journal of Vegetation Science
Seasonal trends in open water

Large fall increases in open water:
- Beaufort / Chuckchi
- N. Barents / Kara
- Baffin Bay / Hudson Bay / Foxe Basin

Bieniek, Bhatt, et al., in progress
Changes in open water

Oct-Nov
Dec-Feb
Mar-Apr

Open Water Magnitude of Change (pct.)

No midwinter or early spring trend in the Beaufort. Ocean frozen.

Snow trends based on CFSR reanalysis. Bieniek, Bhatt, et al., in progress
Changes in open water

Oct-Nov

Dec-Feb

Mar-Apr

Open Water Magnitude of Change (pct.)

Large winter and spring increases in open water mostly on Atlantic side:
- Davis Strait / Labrador Sea
- N. Barents
- Greenland Sea

Some decrease in open water in the Bering.

Snow trends based on CFSR reanalysis.

Bieniek, Bhatt, et al., in progress
Changes in snow water equivalent

Fall:
Decreases:
• Beaufort / Chukchi / Bering
Increases:
• Barents / Kara / Laptev

Snow water equivalent data are from CFSR reanalysis trends.

Bieniek, Bhatt, et al., in progress
Mid winter:
Decreases:
• Beaufort / Chukchi / Bering
• Ungava Peninsula / S. Baffin I.

Increases:
• Barents / Kara / Laptev
• N. Canada W. of Hudson Bay

Bieniek, Bhatt, et al., in progress
Changes in snow water equivalent

**Oct-Nov**

**Dec-Feb**

**Mar-Apr**

Open Water Magnitude of Change (pct.)

Snow Water Equivalent Magnitude of Change (mm)

Spring: Increases in SWE in most areas of the Arctic.

Snow trends based on CFSR reanalysis.

Bieniek, Bhatt, et al., in progress
Recent reports on Arctic snow increases

Toolik Lake snow-free date trend suggests later snow melt

First day of snow-free ground at Imnavait Creek, AK

However, MODIS record for last 10 years shows a generally earlier snow free date across most of Arctic Alaska.
An earlier analog of massive maritime change in the Arctic:

Dale Guthrie’s mesic tundra “buckle” in Beringia during the era of the mammoth steppe followed by the opening of the Bering Strait.

Fig. 8. Mammalogists have puzzled over the several Pleistocene species whose distribution approaches the Bering Strait then apparently ends. This pattern is not typical of most of northern species in the Pleistocene. There does appear to have been some kind of barrier in that region, but has received little speculation as to its nature. It is probable that this filter was related to the more mesic buckle.
Leading to warming and humidification of the Arctic
Correlations of Mar-Apr SWE with Climate Indices

- Patterns in snow are driven by large-scale climate phenomena. Correlations exist but it is very complex.
- Uma and Peter are now trying to find the mechanism (e.g. changes in weather patterns).
- They are first focusing on Alaska with local weather experts first.

Bieniek, Bhatt, et al. in prep.
What do the changes in NDVI mean at the ground level in terms of biomass change?

**Bioclimate subzones**

A (Cushion forb subzone)
- MJT: 1-3 °C
- Shrubs: none

B (Dryas subzone)
- MJT: 3-5 °C
- Shrubs: prostrate dwarf (< 5 cm)

C (Cassiope subzone)
- MJT: 5-7 °C
- Shrubs: hemi-prostrate dwarf (< 15 cm)

D (Betula subzone)
- MJT: 7-9 °C
- Shrubs: erect dwarf (< 40 cm)

E (Alnus subzone)
- MJT: 9-12 °C
- Shrubs: low (40-200 cm)

Two transects through all 5 Arctic bioclimate subzones

CAVM Team 2003
Linking spatial and temporal trends of NDVI observed on satellite images to ground observations.

- Climate
- Vegetation
- Soils
- Permafrost
- Spectral properties
The North America Arctic Transect (NAAT)

Biocomplexity of Arctic Patterned Ground Ecosystems Project (NSF)
2002-2006

The Eurasia Arctic Transect (EAT)

Adaptation to rapid land-use and climate changes on the Yamal Peninsula, Russia: Remote sensing and models for analyzing cumulative effects (NASA) 2007-2011

Integrated field studies at zonal study sites along both transects

Hayes Island, Russia
Photo: D.A. Walker
Zonal vegetation along both transects

**Eurasia Transect**
- A - Hayes Island
- B - Ostrov Belyy
- C - Kharasavey
- D - Vaskiny Dachi
- E - Laborovaya

**North America transect**
- A - Isachsen
- B - Mould Bay
- C - Green Cabin
- D - Sagwon MNT
- E - Happy Valley
Climate and soil at key zonal sites in each subzone along the NAAT and EAT

<table>
<thead>
<tr>
<th>Arctic Bioclimate subzone (Walker 2005)</th>
<th>Transect: location</th>
<th>Latitude Longitude</th>
<th>SWI (°C mo)</th>
<th>Precipitation (mm)</th>
<th>Soil texture pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Air (SWIa)</td>
<td>Surface (SWIb)</td>
<td>Total</td>
</tr>
<tr>
<td>A</td>
<td>NAAT: Isachsen</td>
<td>78.7° N 103.6° W</td>
<td>3</td>
<td>6.8</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>EAT: Krenkel</td>
<td>80.6° N 57.9° E</td>
<td>1</td>
<td>1.9</td>
<td>282</td>
</tr>
<tr>
<td>B</td>
<td>NAAT: Mould Bay</td>
<td>76.2° N 119.3° W</td>
<td>4.6</td>
<td>6.5</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>EAT: Ostrov Belyy</td>
<td>73.3° N 70.1° E</td>
<td>11.5</td>
<td>11.5</td>
<td>234</td>
</tr>
<tr>
<td>C</td>
<td>NAAT: Green Cabin</td>
<td>73.2° N 119.6° W</td>
<td>16.6</td>
<td>22.7</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>EAT: Kharasavey</td>
<td>71.2° N 67.0° E</td>
<td>15.5</td>
<td>28.7</td>
<td>298</td>
</tr>
<tr>
<td>D</td>
<td>NAAT: Franklin Bluffs</td>
<td>69.7° N 148.7° W</td>
<td>24.2</td>
<td>32.7</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>EAT: Vaskiny Dachi</td>
<td>70.3° N 68.90° E</td>
<td>na</td>
<td>29.6</td>
<td>277</td>
</tr>
<tr>
<td>E</td>
<td>NAAT: Happy Valley</td>
<td>69.147° N 148.8° W</td>
<td>29.5</td>
<td>36.2</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td>EAT: Laborovaya</td>
<td>67.7° N 68.0° E</td>
<td>na</td>
<td>36.4</td>
<td>664</td>
</tr>
</tbody>
</table>

Walker et al. ERL 2012
Comparison of a mainly continental transect (NAAT) and a more maritime transect (EAT)

**NAAT:**
Beaufort / Canadian Archipelago, a relatively continental area

**EAT:**
N. Barents / Kara, a relatively maritime area

Continental Subzone A, Isachsen, Ellef Ringnes, I., NAAT

Oceanic Subzone A, Krenkel, Franz Josef Land, EAT

Photos D.A. Walker
• More forbs & evergreen shrubs (mostly *Dryas integrifolia*) along the NAAT, due mostly to higher soil pH of the NAAT.

• More mosses and biomass in subzones B, C, D of the EAT (moister climate, older landscapes of EAT particularly in subzones B and C).

Walker et al. ERL 2012
Leaf Area Index vs. Biomass: EAT and NAAT

- An equivalent amount of biomass has higher LAI values along the NAAT than along the EAT and the difference increases at higher biomass values.

- Reflects the different structure of the vegetation along the two transects. Higher proportion of the total biomass is woody along the NAAT (more wood, taller plants) vs. reindeer-foraged and mossy vegetation along the EAT.
Comparison of EAT and NAAT
1-km AVHRR NDVI & biomass, vs. summer warmth index

- Biomass values are landscape-level averages for zonal landscapes.
- EAT is greener and has more biomass at equivalent summer warmth.
- Possibly a function of more maritime conditions along the EAT.

Walker et al. ERL 2012
Strong correlation between NDVI and aboveground biomass

- Despite differences in vegetation structure, glacial history, pH, grazing regimes, phenology, etc., there is a very similar relationship between AVHRR NDVI and biomass along both transects.
- Gives us moderate confidence that it is possible to construct Arctic biomass map based on the NDVI.

Rate of change in zonal biomass 1982-2010 (kg m$^{-2}$ y$^{-1}$)

Plot-based evidence for change in biomass?

- Numerous groups are measuring NDVI and biomass, but integrated long-term, panArctic monitoring using consistent standardized protocols are lacking.

New information on long-term changes:
- BTF synthesis (Callaghan and Tweedie 2011),
- ITEX synthesis (Elmendorf et al. in 2012)
- ERL special shrub issue (Epstein et al. 2012)
Other factors influencing the NDVI:
Landslides and cryogenic erosion

- Large effect on patterns of greenness in many areas.
- Need temporal series of high-resolution satellite images and/or photos in landslide areas to assess the rate of change.

Strong greening on landslide slopes cover extensive areas of the Yamal.

Low-willow shrublands develop on landslides during 200-yr succession, greatly changing biomass and NDVI.

Biomass

- Before landslides
- After landslides

Key:
A – stable areas
B – shear surface
C – landslide body

- 1 – young landslide
- 2 – old landslide
- 3 – very old landslide

Other factors influencing the NDVI:
The Nenets people and their 300,000 reindeer

Photo: D.A. Walker.
Effects of landscape-scale disturbances on panArctic NDVI patterns are presently unknown, but new high-resolution satellite data show great promise for studying the effects.

Cryogenic erosion and greening patterns on the Yamal are clearly discernable on new GeoEye scene (0.41 m resolution).
Analysis of greening trend and alder growth near treeline in Polar Urals

Quickbird image with Landsat-trend pixels overlaid.

Grid points with new alder cover since 1968.
Alder establishment on patterned ground features

**Organic thickness**

Alders exploit circle microsites that lack organic mat and competing vegetation.

**Mineral thickness**

>90% of alders concentrated on <50% of available sites

Alder density maps showing alders and circle-centers in recent expansion areas. Squares are 1x1 m.

X = circle center

Alder density (shrubs m⁻²)

- 20 alders
- 0 alders
Analysis of greening trends at Toolik Lake using Landsat data (30 m pixels)

Significant greening mainly on disturbed sites and younger geological surfaces.

Glacial Geology (based on Hamilton 2003)

M.K. Raynolds.
CRSS Conf. 2012
Take Home Points

• A general greening of Arctic tundra vegetation occurred from 1982-2011.
• The trends are stronger in N. America than in Eurasia.
• Since about 2001, the trends in North America and Eurasia have diverged.
• Remote sensing and reanalysis products indicate that the trend of more open water is focused in several areas (three largest highlighted here).
• The effects of more open water appear to be stronger in the relatively continental areas of the Arctic.
• Ground-based information from two Arctic transects help to interpret the remotely-sensed information in maritime versus more continental areas of the Arctic.
• Analysis of NDVI trends with respect to ground based studies revealed:
  – Patterned ground plays key role in alder shrub establishment in the Polar Urals (Frost et al. 2012).
  – Landscape age plays key role in greening trends at Toolik Lake (Raynolds et al. 2012).
Effects of industrial development and reindeer grazing

Courtesy of Pam Miller.

Prudhoe Bay oil field.
History of infrastructure expansion on the Yamal

• Bovanenkovo transportation and pipeline networks and the main area impacted by gas-field activities as of 2011.

• Routes of five Nenets reindeer-herder brigades (yellow dotted lines).

Landsat image of Bovanenkovo gas field.

Courtesy of Timo Kumpula.
History of infrastructure expansion, Bovanenkovo gas field, Yamal (1988-2011)

- **(Left) The stages of visibly affected area expansion** encompassing off-road tracks, roads, quarries and residential or other buildings. The last three years has been a period of rapid infrastructure expansion, including railroad and pipeline building.

- **(Right) Growth of permanent infrastructure development including roads, pipelines, quarries and residential or other buildings.** Since the mid-1990’s new infrastructure advanced slowly. Most of the expansion since 1998 has occurred between 2009-2011 (red lines + light gray and tan areas).

- A similar mapping analysis is underway for the Prudhoe Bay oil field 1968-2011, building on the NRC (2003) report.
Effects of industrial expansion on greening patterns

**Kekh**, the first area affected at Bovanenkovo in 1988.

a. Large zone of exposed mineral soils (marine clay) denuded of vegetation by heavy off-road vehicle traffic and construction activities. The black polygon circumscribes the extent of disturbance.

b. VHR Quickbird-2 shows the extent of revegetation after 14 years of natural regeneration.

c. Much of the bare ground has been totally revegetated by 2011. But, a significant amount of new permanent infrastructure has been built since 2004.

Courtesy of Timo Kumpula.
Nenets perception of changes

Nenets brigade crossing the Se-yakha river in the center of Bovanenkovo gas field on 5 July 2011. (Photo by Timo Kumpula).

Participant observation in winter pastures on the south side of Ob Bay:
left Dr. Nina Meshtyb and right Nenets reindeer herding brigadier Nyadma Khudi from Yarsalinskii sovkhoz brigade 4. Photo from Nina Meshtyb archive.
Modeling the effects of climate change and reindeer grazing

Effects of climate change, soil texture, and grazing on plant-functional-type and total-aboveground tundra biomass (Yu et al. 2011)

NMS ordination showing relative effects of climate change and grazing scenarios on tundra plant-functional-type and total biomass in the five bioclimatic subzones and two dominant soil types on the Yamal. Biplots (cluster of vectors in the centers of the plots) show relative direction and strength of (a) original latitudinal gradient and treatment factors (climate change, grazing, and soil organic nitrogen [SON, as a function of soil texture]. Axis 2 is strongly correlated with the latitudinal summer temperature gradient (~12 °C MJT) (42% of total variance), Axis 1 is strongly correlated with the grazing gradient (13% of total variance); (b) trends in relative biomass of plant functional types; and (c) trends in absolute biomass of plant functional types. (d) Total biomass for each simulation scenario; each point represents one model simulation; color indicates different grazing intensities, size of dot is relative total biomass. Grazing is parameterized with two components: frequency of each grazing event and percent biomass removal. For example, (0.1, 25%) indicates the grazers will graze the same area every ten years and each time a maximum of 25% biomass will be removed. Percent biomass removal matters more than frequency of visit: (0.1, 50%) is of greater grazing intensity than (0.5, 25%) through this analysis. Side plots show trend in biomass along each axis. The biomass trend is strongest along the latitudinal gradient. (Modified from Yu et al. 2011).