What Drives Change in the Climate System?

\[ \Delta \text{Earth’s Heat Balance} = \text{Warming} - \text{Cooling} \]

**Warming:**
- Greenhouse gases
- Absorbing aerosols

**Greenhouse Gases**
- Carbon dioxide \( \text{CO}_2 \)
- Methane \( \text{CH}_4 \)
- Water Vapor \( \text{H}_2\text{O} \)
- Nitrous Oxide \( \text{N}_2\text{O} \)
- Chloroflorocarbons CFC’s
- Ozone \( \text{O}_3 \)

**Absorbing Aerosols**
- Smoke
- Soot

**Cooling:**
- Reflective aerosols
- Natural carbon sequestration

**Reflective Aerosols**
- Impact on cloud formation
- Dust
- Volcanic aerosols \( \text{SO}_2 \)

**Natural carbon sequestration**
- Forests/Soils
- Air-sea CO2 equilibrium
- Ocean Biota
The Global Carbon Cycle

About half the CO₂ released by humans is absorbed by oceans and land.

Will this continue?

*PgC = Peta (10^{15}) grams of carbon

Humans

Ocean

Land

Atmosphere

+ 3/yr

7 PgC*/yr

~ 90

~ 92

~ 122

~120

2 to oceans

2 to land

~ 90

~ 120
Current Uncertainties

Current source and sink strengths are uncertain.

Prediction of future climate forcing is therefore uncertain as well.

Current Uncertainties

- Fossil Fuels to Atmosphere: 5.5 ± 0.3
- Land use change: 1.6 ± 0.8
- Ocean uptake: 2.0 ± 0.6
- Unidentified sink: 1.8 ± 1.5

Current strengths are uncertain, and prediction of future climate forcing is therefore uncertain as well.

Peta (10^15) grams of carbon/year

Atmospheric storage = human input + biosphere uptake
Is The High Latitude (> 40°N) Northern Hemisphere The Missing Sink?

20 million km²

50gCm²y⁻¹  ≈ 10^{15} gmC y⁻¹
Uncertain Futures

As CO₂ emissions have increased, the land and oceans have absorbed more and more carbon.

Projections of future CO₂ levels depend on our knowledge of the biosphere and how it interacts with climate.

Given identical human emissions, different models project dramatically different futures.

Which is correct? How can we know?
USGCRP Science Questions

- What has happened to the CO₂ that has already been emitted by human activities?

- How do land management and land use, terrestrial ecosystems and ocean dynamics, and other factors affect carbon sources and sinks over time?

- What will be the future atmospheric CO₂ concentration resulting from environmental changes, human actions and past and future emissions?
Development and Validation

Developing, testing models and measurements

Satellite Biospheric Data
- Vegetation Photosynthesis
- Ocean Photosynthesis
- Meteorology
- Temperature
- Cloudiness

Satellite CO₂

Compare & Compute

Accuracy

Predicted CO₂

QuickTime™ and a decompressor are needed to see this picture.

Model Surface Carbon Flux, Winds Data Assimilation

Field Campaigns
- Validate Remote Sensing
- With Ground observations
- With Aircraft CO₂ Budgets
- Develop Remote Sensing Methods
- Develop Process Models
- Validate Models
- Calibrate Sensors

QuickTime™ and a GIF decompressor are needed to see this picture.
Carbon Analysis Framework

Synthesized Biosphere Data Series

- Land Use, Land Cover Change
- Biophysical Parameters
- Meteorology
- Snow, Ice
- Soil Moisture
- Soil Type and Carbon

Fossil Fuel, Land Use Other Scenarios

Process Models

Data Assimilation

Projections

Future atmospheric CO₂ concentration due to environmental changes, human actions and past and future emissions.

Assessments

Effects of land management and land use, on terrestrial ecosystems and ocean dynamics, and carbon sources and sinks over time.
Critical Gaps

- **MISSING:**
  - Global time series of CO₂ atmosphere-surface exchange.

- **MISSING:**
  - Ecosystem carbon storage due to biomass and its change.
  - Carbon consequences of disturbance.

- **MISSING:**
  - Measurements of critical biochemicals mediating global ocean surface layer uptake and export of carbon.
  - Models of air-sea CO₂ exchange.

- **SOLUTION:**
  - Design and launch satellite to measure column and profile CO₂.
  - Develop and use data assimilation techniques to generate surface flux fields.

- **SOLUTION:**
  - Design and launch satellite to measure biomass and its change.
  - Process on-orbit satellite data to map disturbance and recovery.

- **SOLUTION:**
  - Develop satellite sensor to measure organic and inorganic compounds and models to compute carbon uptake.
  - Develop exchange process models.

**Supported by Field Campaigns, Calibration/Validation Efforts, Model Development and Data Assimilation Research to Fully Utilize Satellite Observations.**
Surface Energy Budget

Net Radiation Absorbed =
Net Short Wave \( \{ Sw \cdot (1 - \alpha) \} \) + Net Long Wave \( \{ Lw \cdot Lw' \} \)

Remote Sensing Inputs

Atmospheric Aerosols and Clouds, Surface Albedo \( \rightarrow \) Net Short Wave \( \{ Sw \cdot (1 - \rho) \} \)
Atmospheric Water Vapor, Temperature Profiles, Cover Type \( \varepsilon \) \( \rightarrow \) Net Long Wave \( \{ Lw \cdot Lw' \} \)

Surface Heat and Mass Budget

Net Radiation Absorbed = \( R_n = \)
Latent Heat (LE) + Sensible Heat (H) + Ground Heat Flux (G)

Remote Sensing Inputs

\( \text{Fpar, Cover Type (C3 or C4), LAI} \rightarrow \) Latent Heat (LE)
\( \text{Canopy Temperature, Air Temperature, Roughness Length,} \rightarrow \) Sensible Heat (H)
\( \text{Snow Cover, Soil Moisture Content and State} \rightarrow \) Ground Heat Flux (G)

Remote Sensing Parameters for Carbon, Water and Energy Cycling

Surface Carbon Budget

Net Ecosystem Exchange = NEE = Gross Primary Production (GPP) - Autotrophic Respiration (\( R_a \)) - Heterotrophic Respiration (\( R_h \))

Remote Sensing Inputs

\( \text{GPP, Gross Primary Production (GPP)} \rightarrow \) Autotrophic Respiration (\( R_a \))
\( \text{Biomass, Cover Type, Temperature,} \rightarrow \) Autotrophic Respiration (\( R_a \))
\( \text{Soil Moisture, Soil Temperature, Snow Cover} \rightarrow \) Heterotrophic Respiration (\( R_h \))

Missing Land Surface Parameters

Biomass and biomass change
Disturbance
Land Use, Land Cover Change
Science Activity Roadmap

- New Satellite Formulation/Implementation
- CO₂, Aerosols, Ocean Carbon, Biomass
- N. American Carbon Program
- Future
- U.S. Coastal Campaigns, S. Ocean
- Calibration/Validation
- Remote Sensing Techniques Development
- Process, Coupled and Inverse Model Development
- Satellite Data Assimilation
- Land cover & biomass change, fire, CO₂, ocean carbon, meteorology etc.
- Data Synthesis
- Regional and Global Analyses
- Answers, Assessments, Projections, Consequences

Current/Planned Space Assets: Landsat, SeaWiFS, Terra, Aqua, SeaWinds, VCL, Aura, NPP...

USGCRP Science Questions & Goals
Research & Observation Requirements
Mission Simulation Experiments

The Global Boreal Ecosystem

Global Boreal Ecosystem
ISLSCP-1

20 million km²

50 gC m⁻² y⁻¹ \( \equiv \) \( \times 10^{15} \) gC y⁻¹

40° & 60° Latitudes

- **Coniferous Forest**
- **Mixed Forest**
- **Tundra**
- **C3 & C4 Grasslands**
- **Shrubs & Bare Ground**
- **Boreal Deciduous Forest**
- **Ice**
- **Agriculture**

ANNUAL CARBON BUDGET AT SOBS IN BOREAS DURING 1996
JARVIS et al.

grams m⁻² yr⁻¹
Four Years of NEE at the BOREAS Northern OBS Site

GPP Increase with early spring, cool summers, late fall

Respiration decrease with late spring, cool summers, early fall.

Respiration loss increases with soil temperature increase.

GPP decreases with dry hot summer conditions.
Changes in Fire Frequency Alters Surface Carbon Uptake

Needed:
Area of disturbance
Age of disturbance
Prefire Vegetation
Postfire Land cover
Recovery Rate
North American Carbon Sink

Pacala et al. (’01) most recent land based inventories -- Coterminous US 0.3 to 0.58 pg/yr

<table>
<thead>
<tr>
<th>Category</th>
<th>Low pg/yr</th>
<th>High pg/yr</th>
<th>Land Area m ha</th>
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</thead>
<tbody>
<tr>
<td>Forests</td>
<td>0.11</td>
<td>0.15</td>
<td>247-247</td>
</tr>
<tr>
<td>Organics</td>
<td>0.03</td>
<td>0.15</td>
<td>247-247</td>
</tr>
<tr>
<td>Cropland soils</td>
<td>0</td>
<td>0.04</td>
<td>185-183</td>
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<tr>
<td>Woody Encroachment</td>
<td>0.12</td>
<td>0.13</td>
<td>334-336</td>
</tr>
<tr>
<td>Wood Products</td>
<td>0.03</td>
<td>0.07</td>
<td></td>
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<tr>
<td>Reservoirs</td>
<td>0.01</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Commercial export imbalance</td>
<td>0.04</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Riverine transport</td>
<td>0.03</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Apparent Sink (wo woody enc)</td>
<td>0.25</td>
<td>0.58</td>
<td>766</td>
</tr>
<tr>
<td>Apparent Sink (w woody enc)</td>
<td>0.37</td>
<td>0.71</td>
<td>766</td>
</tr>
<tr>
<td>Sink excluding export imbalance</td>
<td>0.3</td>
<td>0.58</td>
<td>766</td>
</tr>
</tbody>
</table>
USGCRP Science Goals

1. Quantify North American carbon sources and sinks and the processes controlling their dynamics.
2. Quantify the ocean carbon sink and the processes controlling its dynamics.
3. Quantify the global distribution of carbon sources and sinks and their temporal dynamics, and report the "state of the global carbon cycle" annually.
4. Evaluate the impact of land use change and land and marine resource management practices on carbon sources and sinks.
5. Project future atmospheric CO₂ concentrations and changes in terrestrial and marine carbon sinks.
6. Provide the scientific underpinning, and evaluations from specific test cases, for management of carbon in the environment.
NORTH AMERICAN CARBON PROGRAM
NASA ROLE AND PARTICIPATION

OBJECTIVES

- Demonstrate, develop OBS./modeling approach
  CO₂ OBS - IN SITU, AIRCRAFT, AIRS
  TOP-DOWN, INVERSE MODELING
  BOUNDARY LAYER BUDGET
  BOTTOM-UP MODELING

- Develop, demonstrate instruments/algorithms
  CO₂ - ACTIVE/PASSIVE
  BIOMASS - RADAR/LIDAR/HYPERSONPECTRAL
  LAND COVER (ALGORITHMS) - LANDSAT
  OCEAN CARBON

- Provide forcings, boundary conditions
  & state changes from satellites

- Data synthesis / distribution

- Cal-Val infrastructure for satellites

SCALING STRATEGY

1/4 degree
Grid Cell

Pixel Level
Plant Level

Coastal ocean sites

Miss River

Open ocean surveys

Flux towers

Bering Sea

North American Carbon Program
Flux Tower SCALING STRATEGY

G. Maine

Atlantic Bight

Bering Sea

Miss River

A/C 2X/DAY EACH 2-3 DAYS

PBL

Up-looking spectrometers

EC

FLASKS

Mid-Atlantic Bight

Arm Cart

Arm

ARM

Wood Encroachment

Pacific NW
Land Cover at 1 km Confuses Carbon Cycling Rates

30 m

1 km

Land Cover

Biomass Density
BOREAS WINTER TIME ALBEDO DATA IMPROVES ECMWF NORTHERN HEMISPHERE WEATHER FORECASTS

March-April 1997 850 hPa T day 5 error
-4°C to -3°C  -3°C to -2°C  -2°C to -1°C  1°C to 2°C

March-April 1996 850 hPa T day 5 error
-7°C to -6°C  -6°C to -5°C  -5°C to -4°C  -4°C to -3°C  -3°C to -2°C
-2°C to -1°C  1°C to 2°C  2°C to 3°C  3°C to 4°C  4°C to 5°C

Reduction in the mean 850 mb cold temperature in 5-day forecasts at the European Center for Medium Range Forecasting between 1996 and 1997 (March thru April average) achieved by substituting BOREAS-measured winter-time albedos for ECMWF estimated surface albedos.
Daily Maximum Air Temperature Interpolated From Met Stations

NSCAT-Based Freeze/Thaw State
Land activities

1. Solicit a 2003 continental NA 30 m land cover, land cover change and disturbance map (1980’s to 2003) to support the NACP.
   Carbon cycle specific but closely related to Millennium Assessment effort
   Utilizes the 1970/80, the 1990 and the 2000,2001 Landsat data sets from USGS and the Earth Satellite Corporation.

2. Solicit a 2004 global 30 m land cover, land cover change and disturbance map based on USGS, Earth Satellite Corporation Landsat data sets.

3. Initiate in 2003 R&D activities to develop automated procedures to refresh the global 30 meter product beginning in 2006.
   A. Global each 4 years 2 year refresh for regional "hot spots"
   B. N America in 2006
   C. Global in 2008

4. Initiate in 2003 the development of data analysis and data fusion approaches for using VCL, GLAS, ALOS together with TM land cover, ground-based forest inventory information to
   A. Produce biomass change information in 2005 to support NACP analyses.
   B. Produce GLOBAL biomass change information post 2005 in support of NCCI.
**Vegetation Canopy Lidar**

- **Description:** A satellite mission that provides the first globally consistent estimates of terrestrial biomass via forest canopy measurement.

- **Key Technologies:** 1064 nm lasers operating at 242 pulses per second with 15mJ per pulse.

- **Instrument:** A multi-beam laser altimeter, with 25m resolution and 1m vegetation height accuracy.

- **Orbit:** 390-410 km at 67° inclination

- **Space Access:** Taurus-class launch vehicle or shared Delta II class

- **Mission Option:** complete mission originally selected under ESSP

- **Launch Date:** FY 2005

- **Mission Life:** 2 Years
5. Initiate in 2003 preformulation of advanced high-density biomass mission to launch in post 2005 time frame.
   A. Develop mission requirements studies to define observational requirements
   B. Conduct 2003 NA flights with ac instruments define space-based observational approach

6. Initiate in 2003 a data synthesis activity in support of carbon, water and energy modeling to support both the NACP and the NCCI global analyses.

7. Initiate in 2003 a land component to the coupled modeling and data assimilation effort, focused on carbon consequences of land use change including disturbance.

8. Design and implement land data processing, management and synthesis requirements and approach.
Biomass from Space

Hyperspectral Concept

Imaging Lidar Concept

P-band SAR with Profiling Lidar Concept
Land Activities (continued)

5. Initiate in 2003 preformulation of advanced high-density biomass mission to launch in post 2005 time frame.
   A. Develop mission requirements studies to define observational requirements
   B. Conduct 2003 NA flights with ac instruments define space-based observational approach

6. Initiate in 2003 a data synthesis activity in support of carbon, water and energy modeling to support both the NACP and the NCCI global analyses.

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8. Design and implement land data processing, management and synthesis requirements and approach.
NASA Carbon Cycle Land Products

1. CARBON SPECIFIC continental NA 30 m land cover, land cover change and disturbance map in 2003 to support the NACP utilizes the 1970/80, the 1990 and the 2000,2001 TM orthorectified, georegistered products to be produced by Earth satellite corp.

2. 2004 global 30 m land cover, land cover change and disturbance map.

   A. More automated processing
   B. Global each 4 years 2 year refresh for regional "hot spots"
   C. N America in 2006, global in 2008

4. Develop data analysis and data fusion approaches for using VCL, GLAS, ALOS together with TM land cover, ground-based forest inventory information to
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6. Data synthesis activity in support carbon, water and energy modeling to
   support both the NACP and the NCCI global analyses.

7. Coupled modeling and data assimilation effort, focused on carbon
   consequences of land use change including disturbance.
EXPECTED RESULTS

- Characterize the most likely response of land and ocean CO₂ sources and sinks to climate change.
- Provide quantitative understanding of processes that control variability of atmospheric CO₂ sources and sinks.
- Reduce uncertainties in predictions of future levels of atmospheric CO₂ for specific emission scenarios.
- Establish a sound scientific underpinning for management of carbon in the environment (e.g., reforestation, marine management, sequestration).
- Provide the scientific basis to assess (quantify) the economic and societal impact of various carbon sequestration options.