Carbon cycle reanalysis: Progress and *many* challenges in tracking carbon through land, ocean and atmosphere

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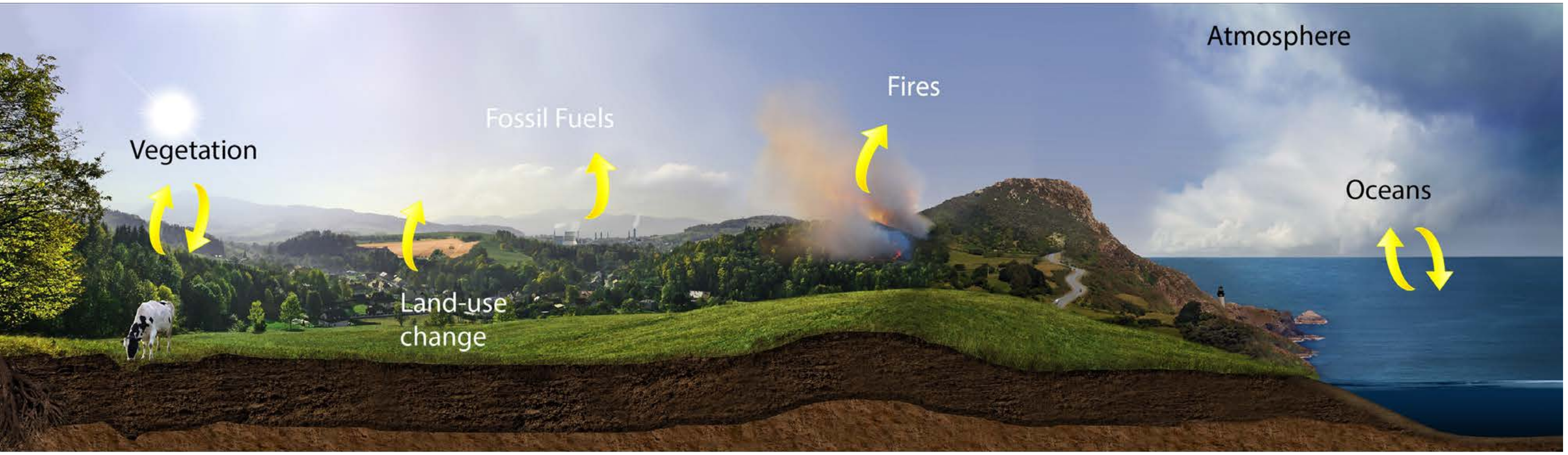
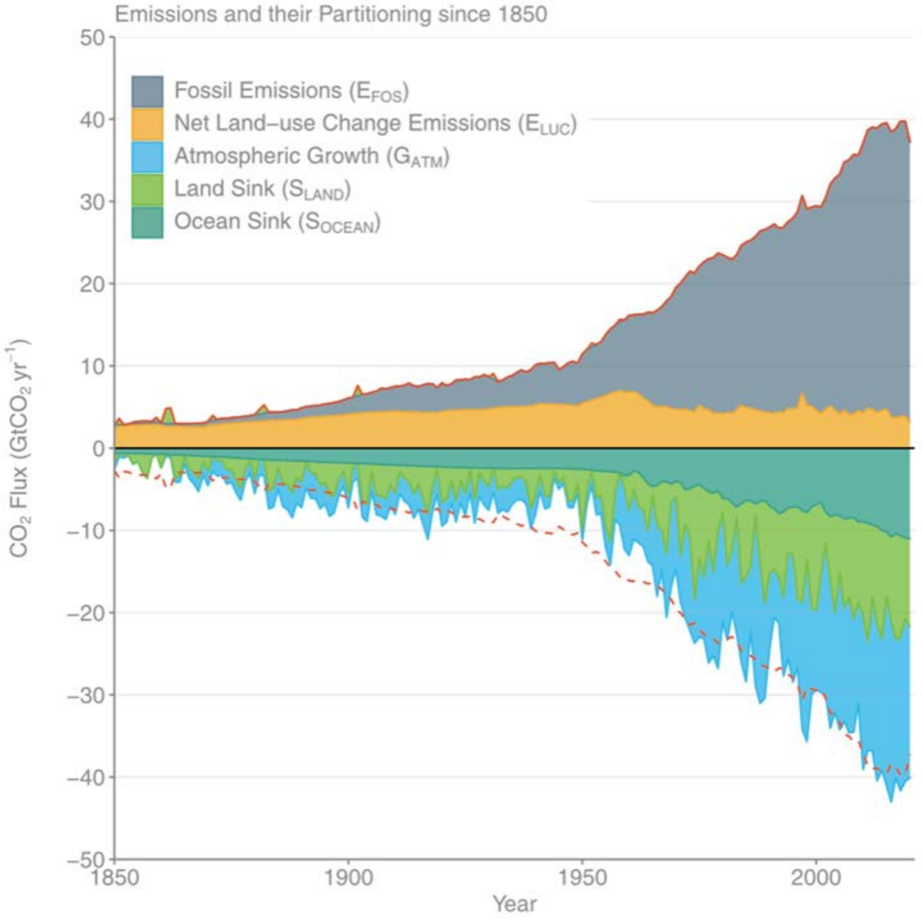
Motivation: Why we should care about carbon cycle reanalysis



Credit: NASA/Jenny Mottar and Abhishek Chatterjee



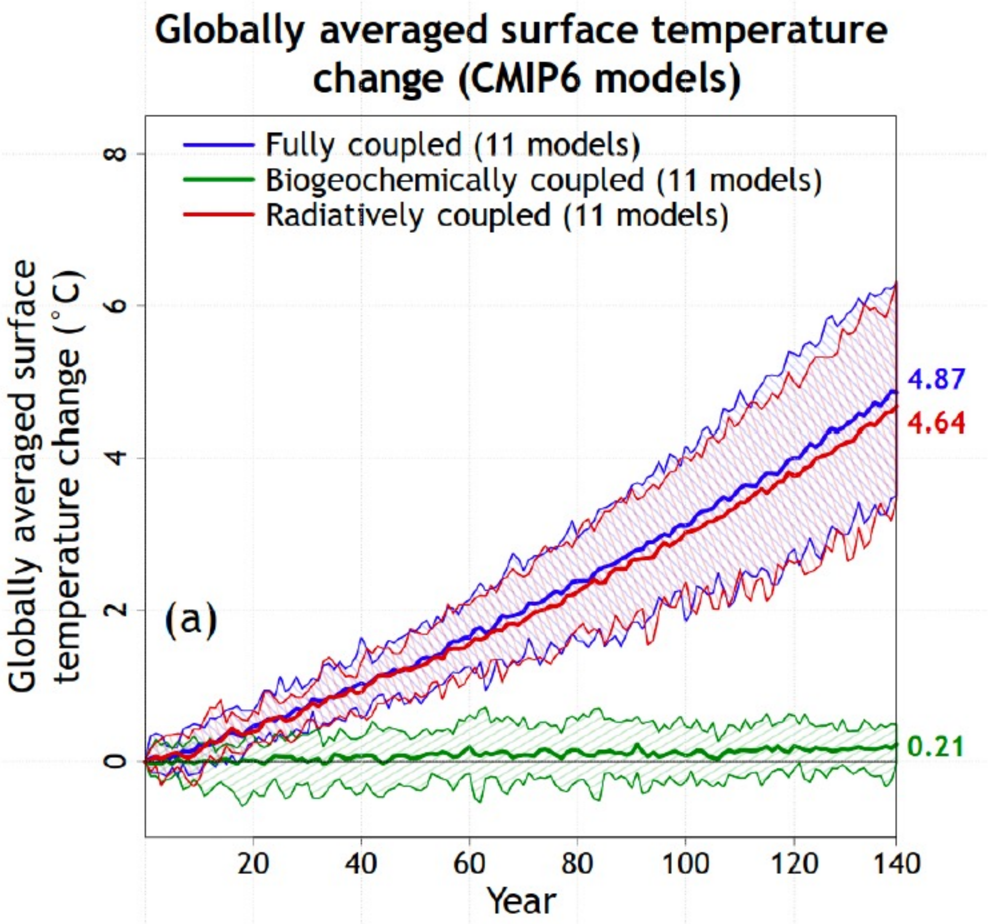
The carbon cycle controls the atmospheric abundance of the main driver of climate change, atmospheric carbon dioxide (CO_2). Approximately 50% of emitted CO_2 remains in the atmosphere with the other 50% absorbed by land and ocean carbon sinks.

Source: Friedlingstein et al., 2021

Motivation: Why we should care about carbon cycle reanalysis

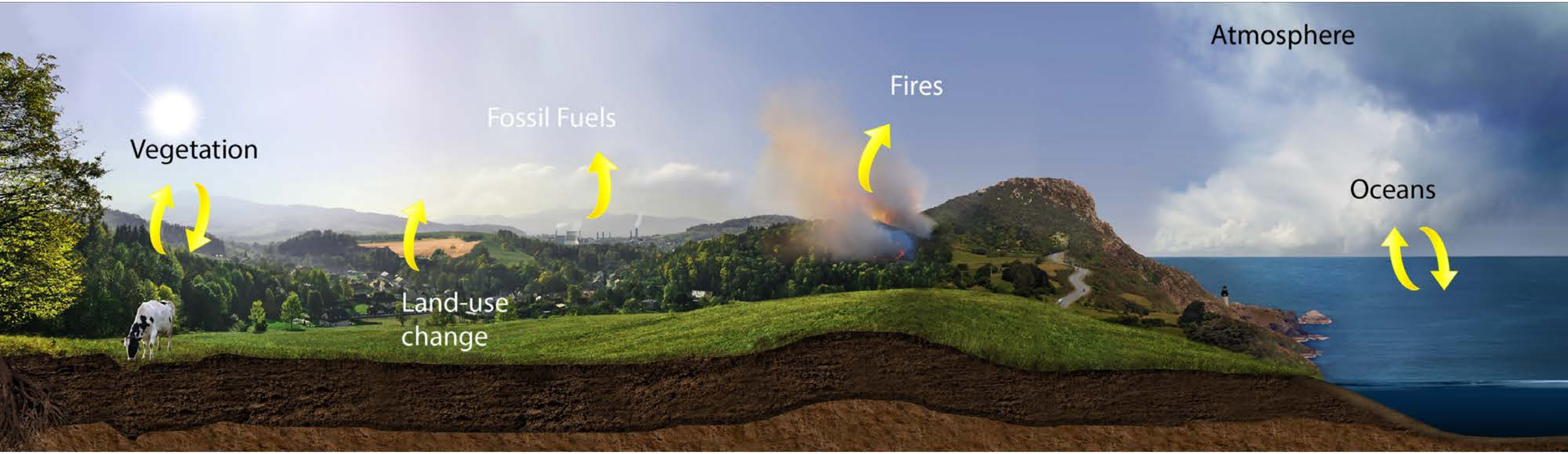
Monitoring land and ocean carbon uptake is critical for setting reliable emissions targets. Better understanding of the carbon cycle is also critically needed to reduce uncertainty in climate projections.

Reanalysis of carbon cycle processes provides an understanding of the baseline conditions needed to support these and many other applications.



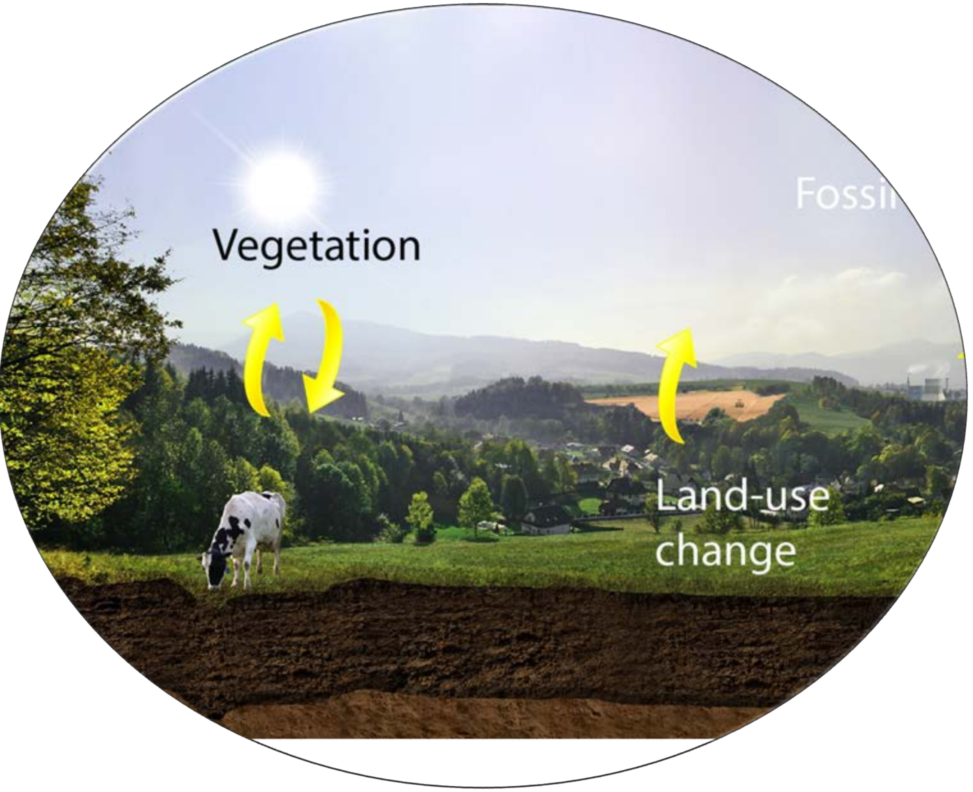
Source: Arora et al., 2020

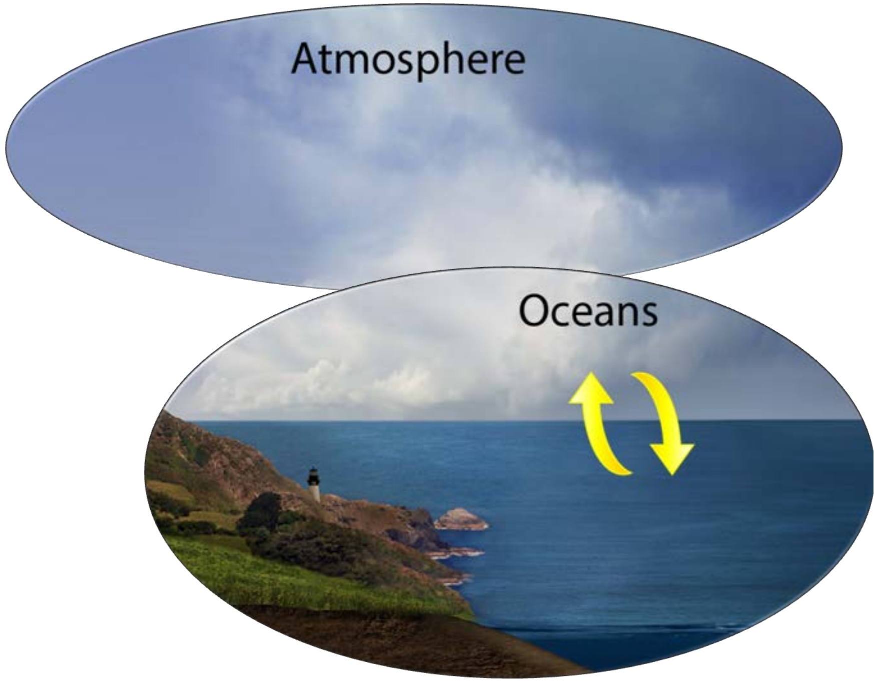
Current status of carbon cycle reanalysis



Credit: NASA/Jenny Mottar and Abhishek Chatterjee

Current status of carbon cycle reanalysis



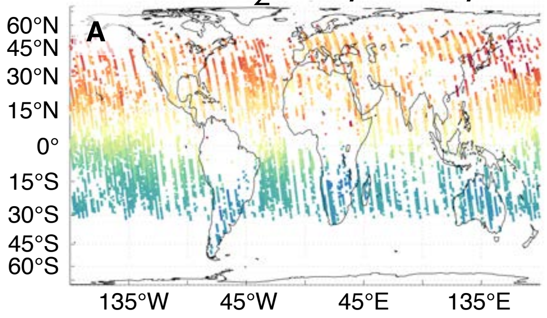


Atmospheric carbon: Highlights

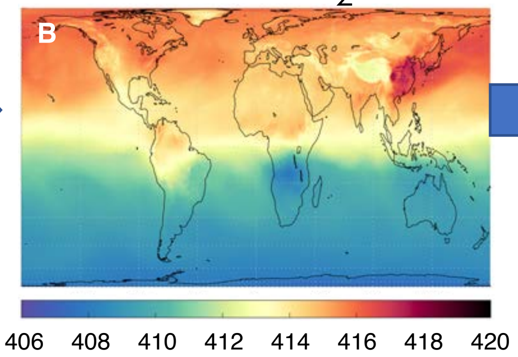
Ability to track global CO_2 concentrations and detect changes with relatively low latency (~2 months) using assimilated OCO-2 retrievals and GEOS Constituent Data Assimilation System (CoDAS)

Product	Platforms	Description	Record
In situ CO_2	Surface sites, aircraft	High quality, limited coverage concentration data	1950s-present
XCO_2	GOSAT, OCO-2/3	Dry-air column averaged mole fraction of CO_2 from (NIR)	2009-present

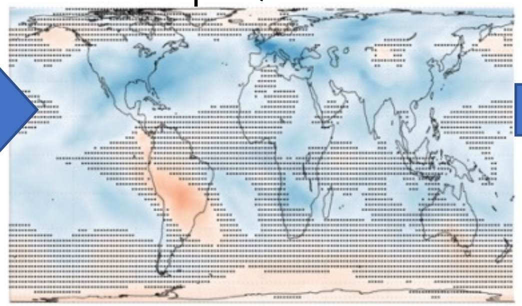
16 days of cloud-screened OCO-2 XCO_2 – 4/1-16/2020



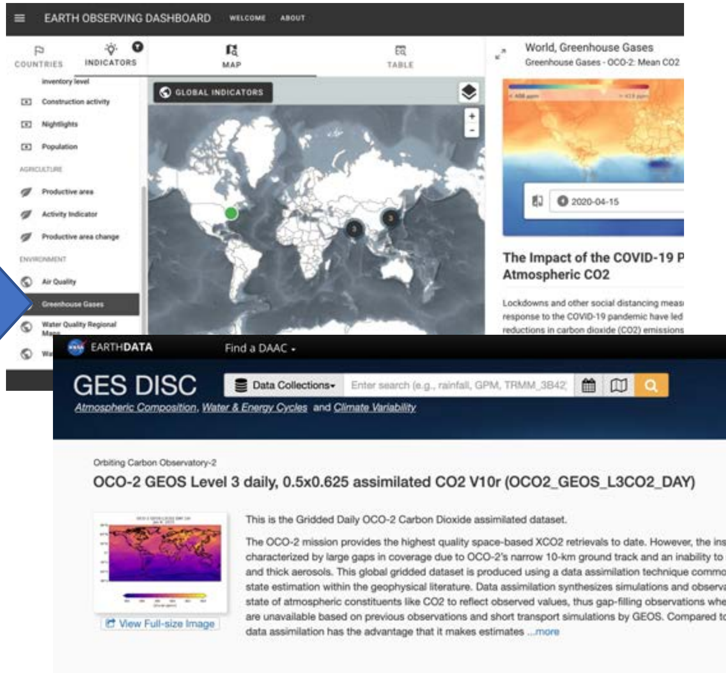
16-day average L3 XCO_2



XCO_2 Anomaly April, 2020



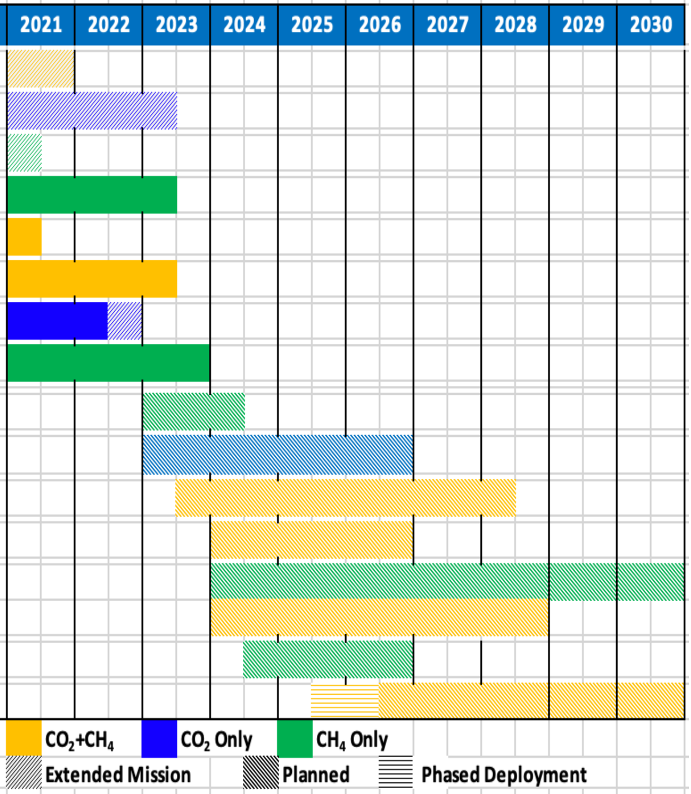
Interactive dashboards, OCO L3



Source: Weir et al., 2021

Atmospheric carbon: Challenges/Opportunities

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●	
OCO-2	NASA/USA	●		●	
GHGSat-D - Claire	GHGSat/Canada		●		●
Sentinel 5P TROPOMI	ESA/Europe		●	●	
GaoFen-5 GMI	CHEOS/China	●	●	●	
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●	
OCO-3	NASA/USA	●			
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada		●		●
MethaneSAT	EDF/USA		●		●
MicroCarb	CNES/France	●		●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	●	●	●	●
GeoCarb	NASA/USA	●	●	●	
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
MERLIN	DLR/Germany-CNES/France		●	●	
CO2M	EC Copernicus/Europe	●	●	●	



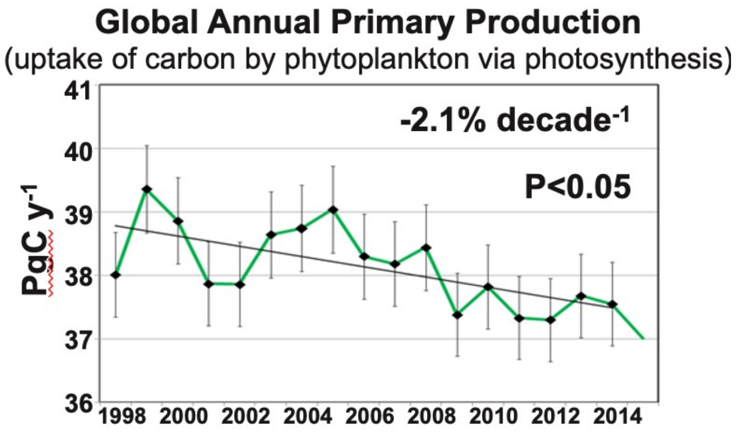
[1]Carbon Mapper is a public/private partnership between California and Carbon Mapper LLC.

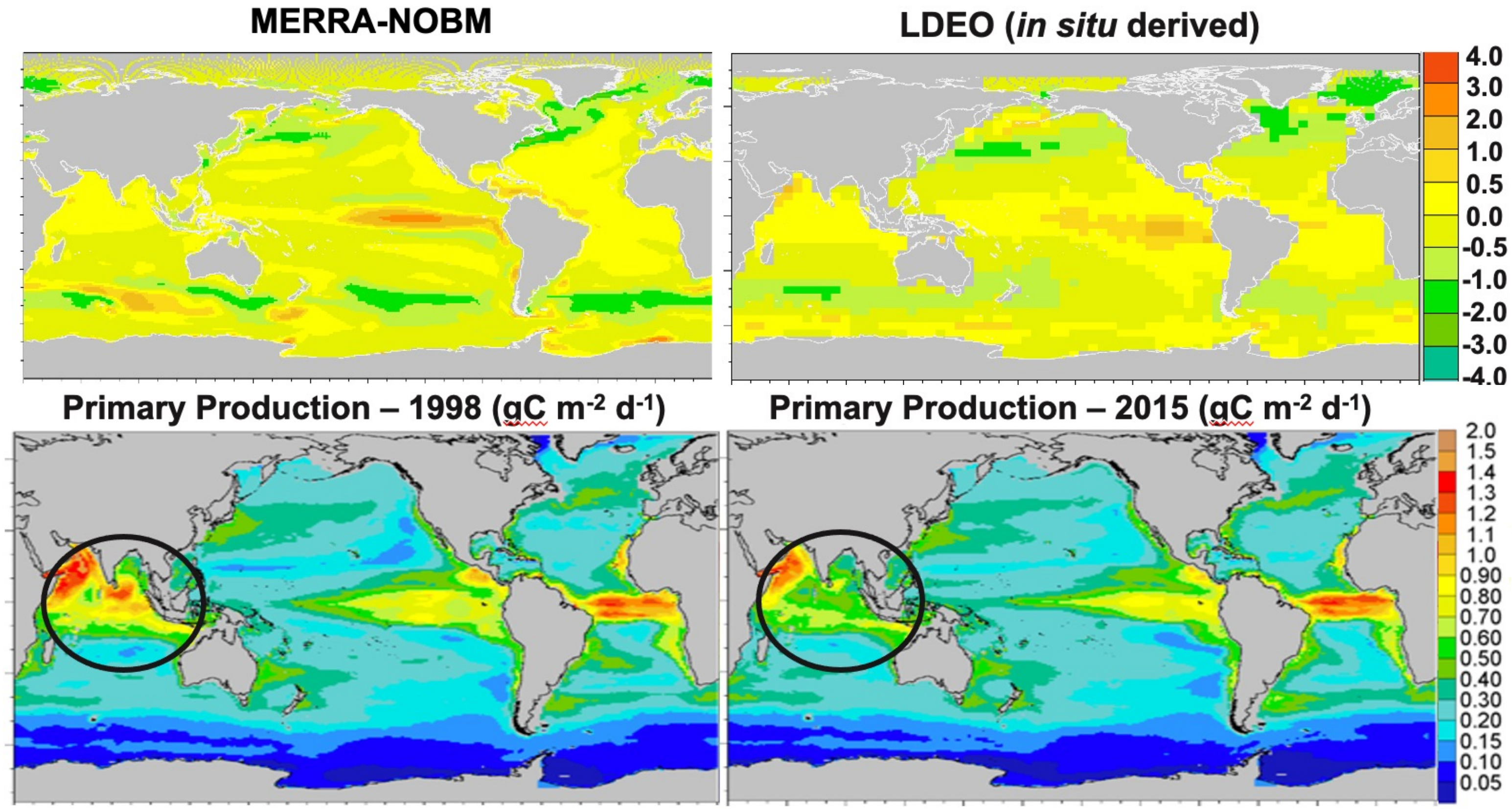
Source: Adapted from Crisp et al., 2019

- **(Left)** Transition from data-limited to data-rich regime brings challenges of data volumes, intercalibration
- Lack of radiance assimilation capability introduces delays (currently 1-2m+ for OCO) and errors from retrieval process
- State estimation methods can only infer concentration and/or net flux, not information about land, ocean flux processes
- Limited spatial coverage before GOSAT launch in 2009 (worse for CH_4) – challenging to reconcile pre- and post- satellite eras
- Lack of vertical information in total column measurements means that errors in model transport can have substantial impact

Oceanic carbon: Highlights

When combined with an OGCM and ocean-atmosphere radiative transfer model, the NASA Ocean Biogeochemical Model (NOBM) is able to use satellite ocean color data to realistically estimate global air-sea CO_2 flux (**top panels**) and provide insights on the drivers of multi-decadal changes in global primary production (**bottom panels**).

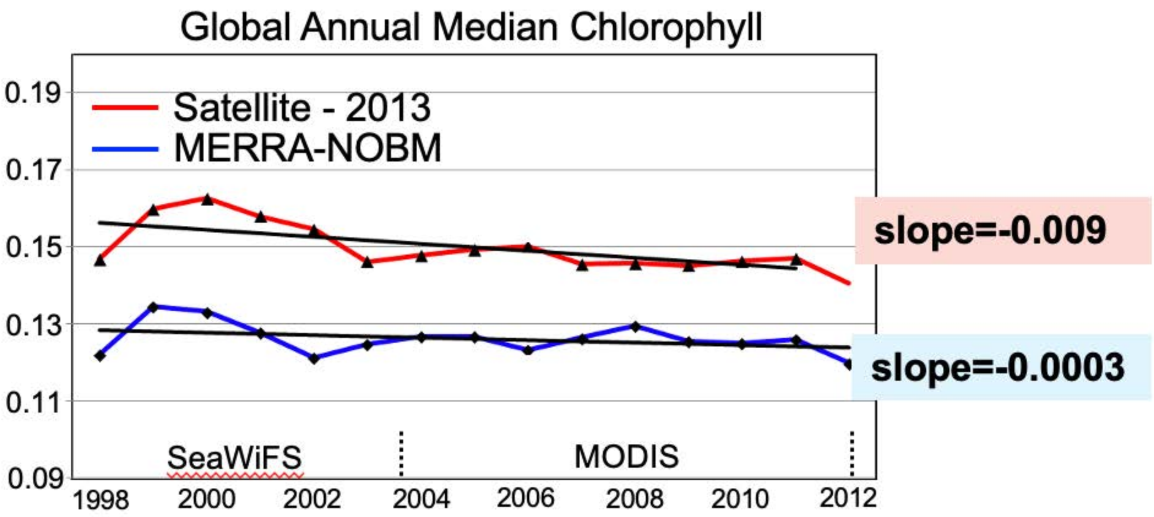


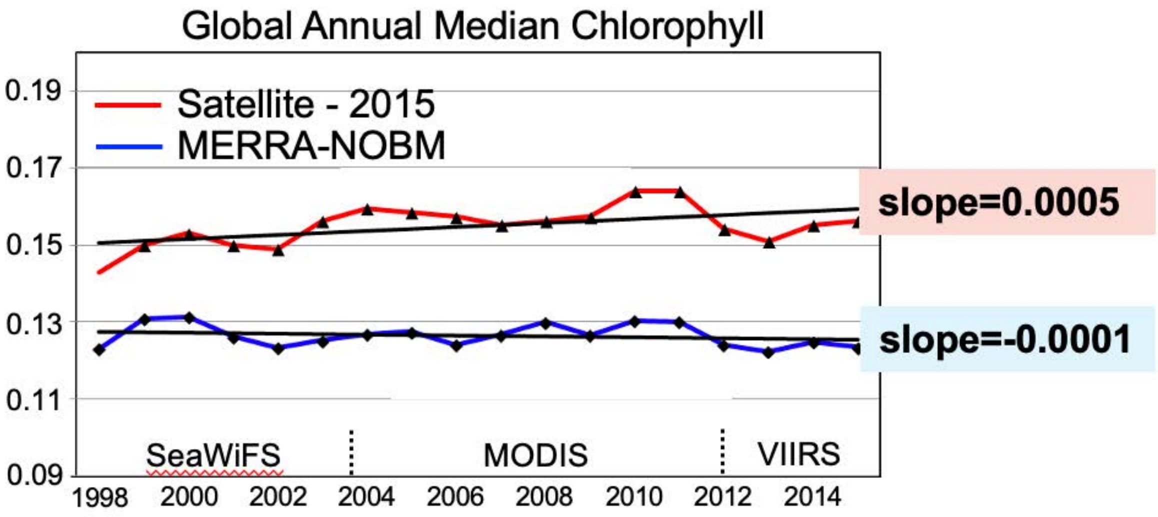


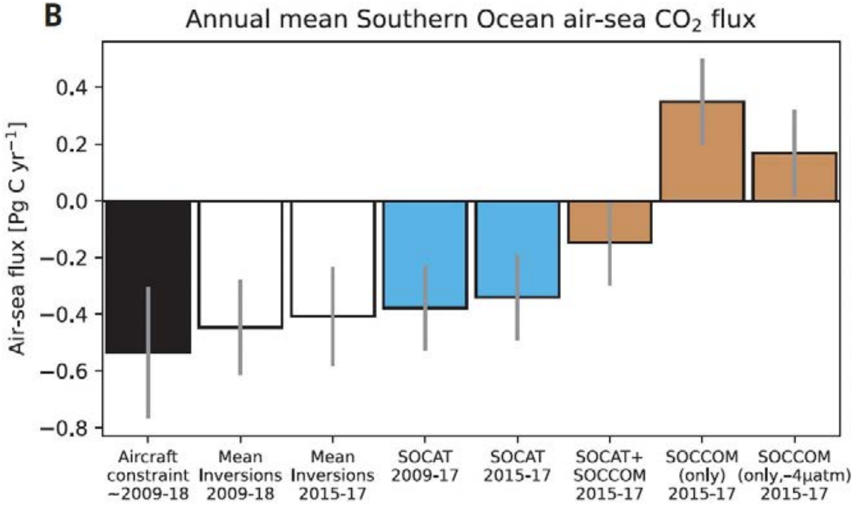
Top: Gregg et al., 2014
Bottom: Gregg and Rousseaux, 2019

Oceanic carbon: Challenges and opportunities

- **(Right)** Ocean color intercalibration is very challenging, makes analyzing long time series difficult
- Large uncertainty on export of carbon from surface to deep oceans – improved process understanding and representation urgently needed
- Riverine transport of carbon, impact in coastal ecosystems remains limited by model resolution in most regions
- Sparse observations in Southern Ocean leads to disagreement on magnitude of air-sea flux (**bottom**)





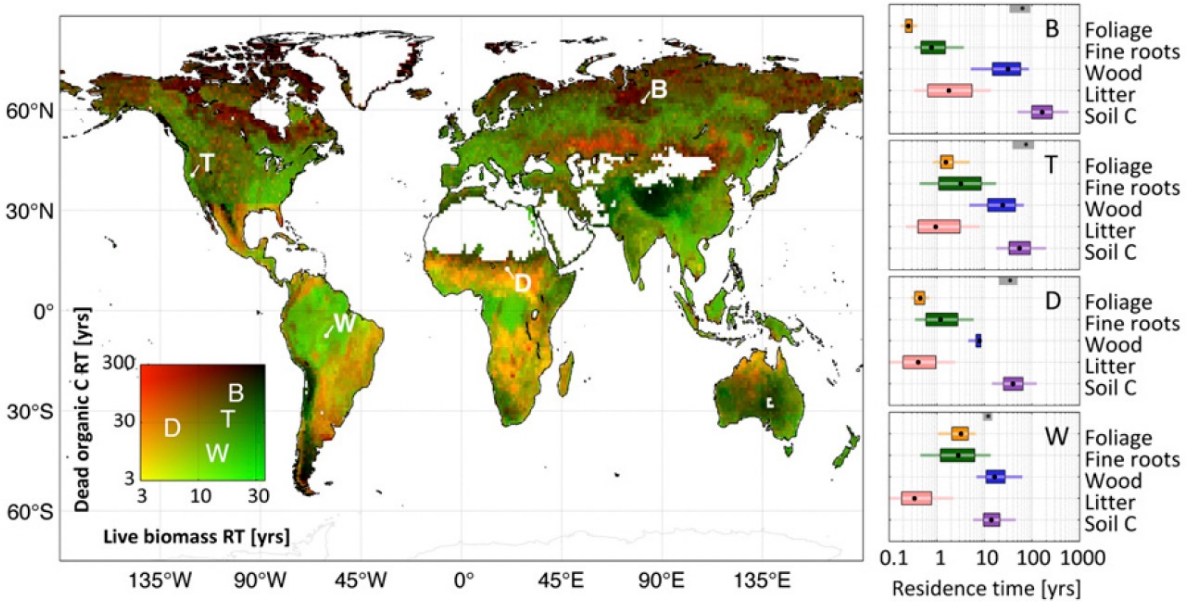


Right: Gregg et al., 2017
Bottom: Long et al., 2021

Terrestrial carbon: Highlights

Product	Platform/Inst.	Description	Record
NDVI, EVI, LAI	AVHRR, MODIS, VIIRS	Vegetation greennees	1981-present
SIF	GOME-1/2, GOSAT, OCO, S5P	Photosynthesis retrieved from solar Fraunhofer lines	1995-present
Biomass	IceSat, GEDI, IceSat-2	Lidar measurements of structure	2003-present
VOD	SSM/I, TMI, AMSR-E/2	Plant water content	1987-present

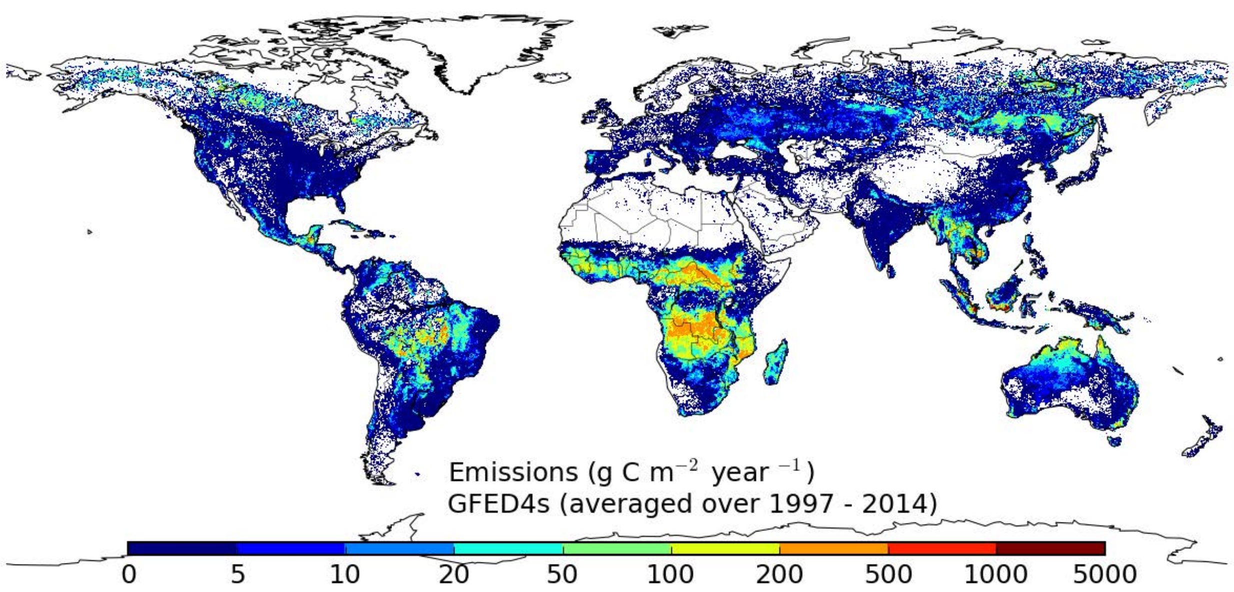
JPL's CARDAMOM framework combines a simple diagnostic model with multiple vegetation observations to estimate global carbon flux and cycling. The example shows the derived estimates of carbon residence time. While making advances in ability to integrate multiple observations, CARDAMOM is not connected to a land surface or coupled modeling/DA framework.

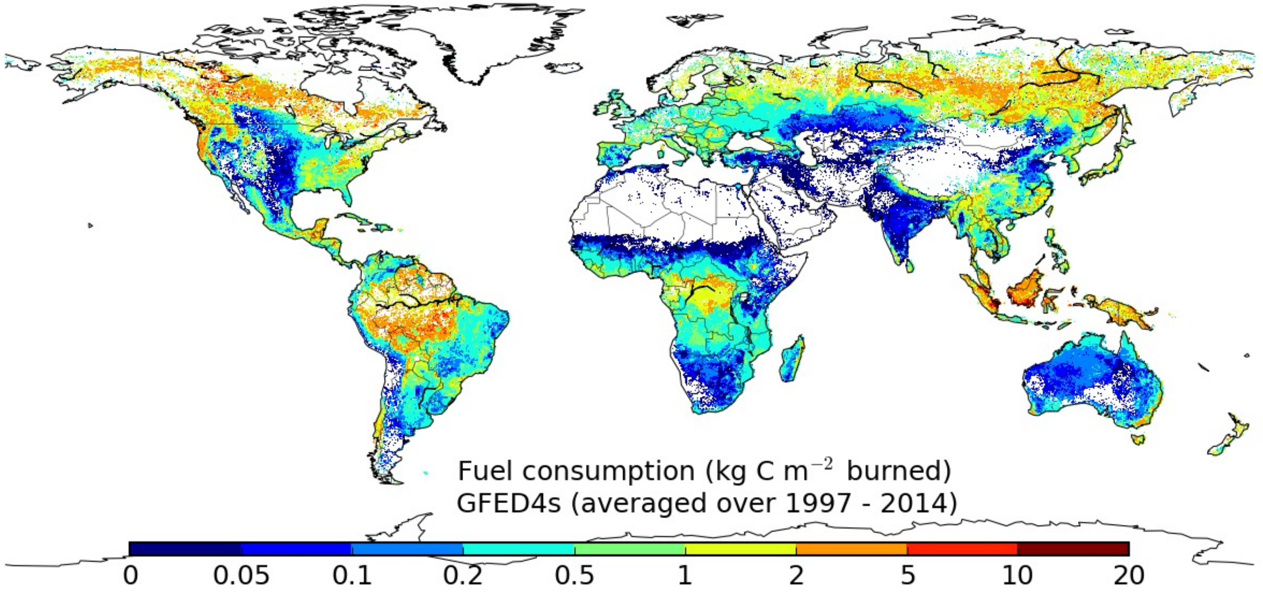


Terrestrial carbon: Fire

The Global Fire Emissions Database (GFED) combines diagnostic vegetation model and fire models to estimate biomass burning emissions and fuel consumption. Representation of fire models in most vegetation models remains crude and GFED data are often used as input.

Product	Platform/Inst.	Description	Record
FRP	MODIS, VIIRS	Fire radiative power/intensity	2001-present
Burned area	MODIS, VIIRS	Burned area (derived from differencing successive images)	2001-present

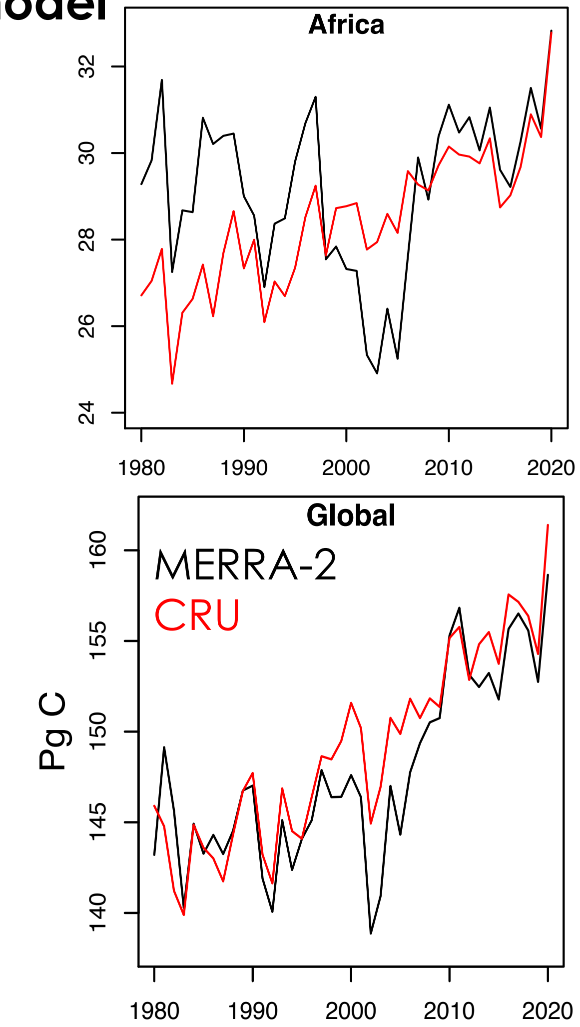




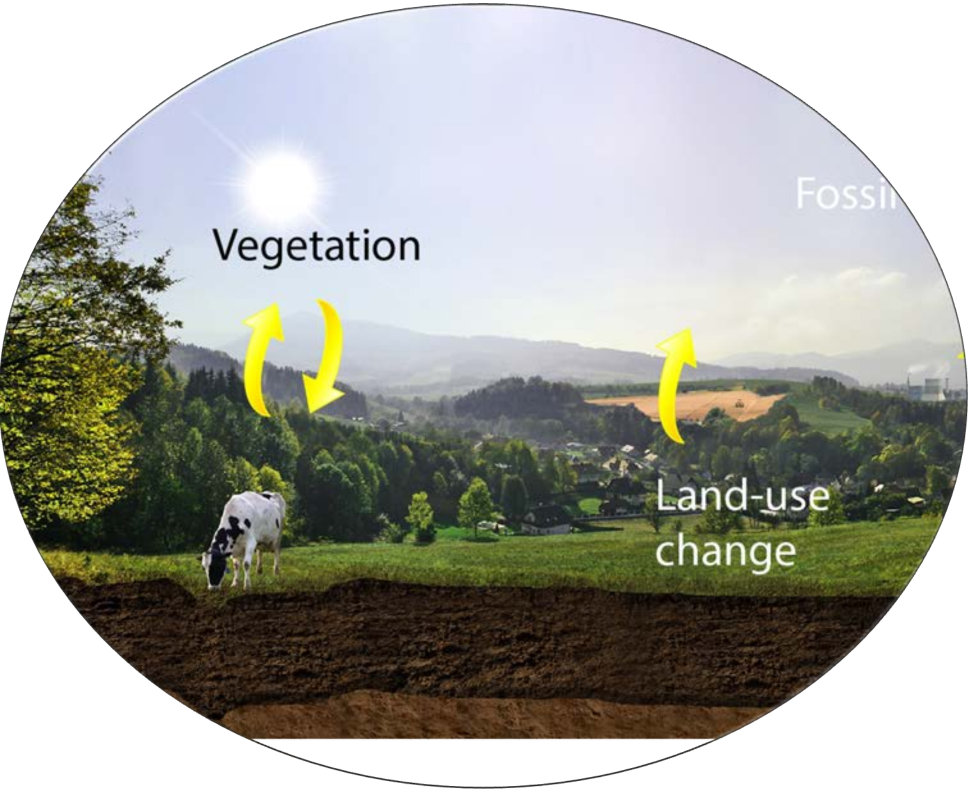
Terrestrial carbon: Challenges and opportunities

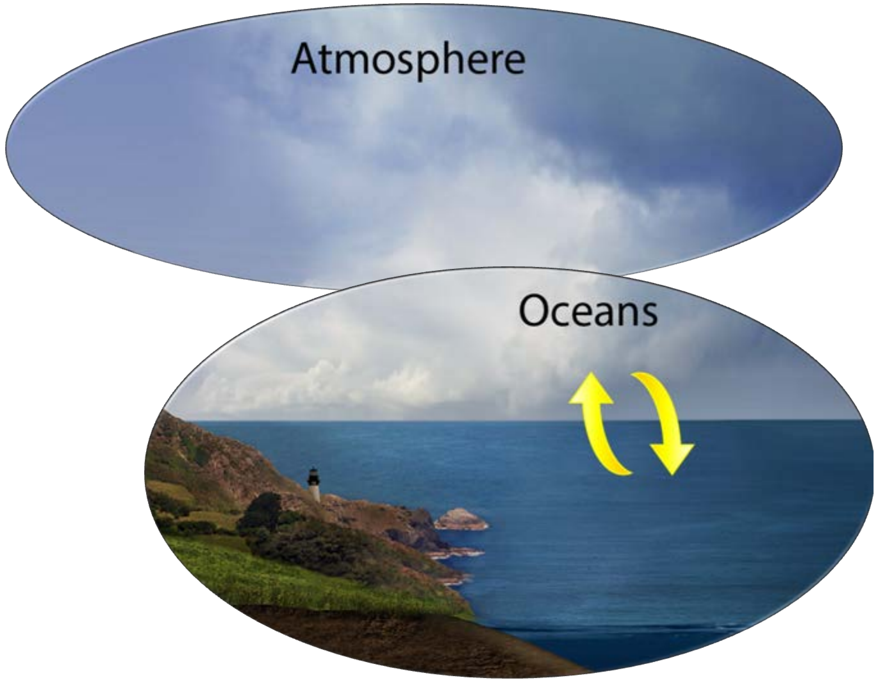
- Vegetations models can be very sensitive to 'jumps' in meteorological forcing associated with observing system changes (**right**).
- Scale mismatch between observations, model grid cell complications parameter estimation and data assimilation - and makes models hard to validate, especially in tropical ecosystems.
- Complexity of canopy radiative transfer means most DA must be done with derived data products whose estimation carries additional uncertainty.
- Highly simplified veg. models struggle to represent long term changes in vegetation composition and to address important applications (e.g. biodiversity, ecosystem services) while expensive individual models are most suitable for small scales where initial data is well known. Hybrid approaches in development, but relatively low maturity.
- Univariate assimilation often leads to getting one quantity right and another wrong. Matching the full suite of observations and land-atmosphere exchange may mean a complex mix of initialization, calibration, and state DA.

Annual Gross Primary Production, LPJ model



Key future challenge – laying out a framework for more complete, coupled representation of carbon cycle





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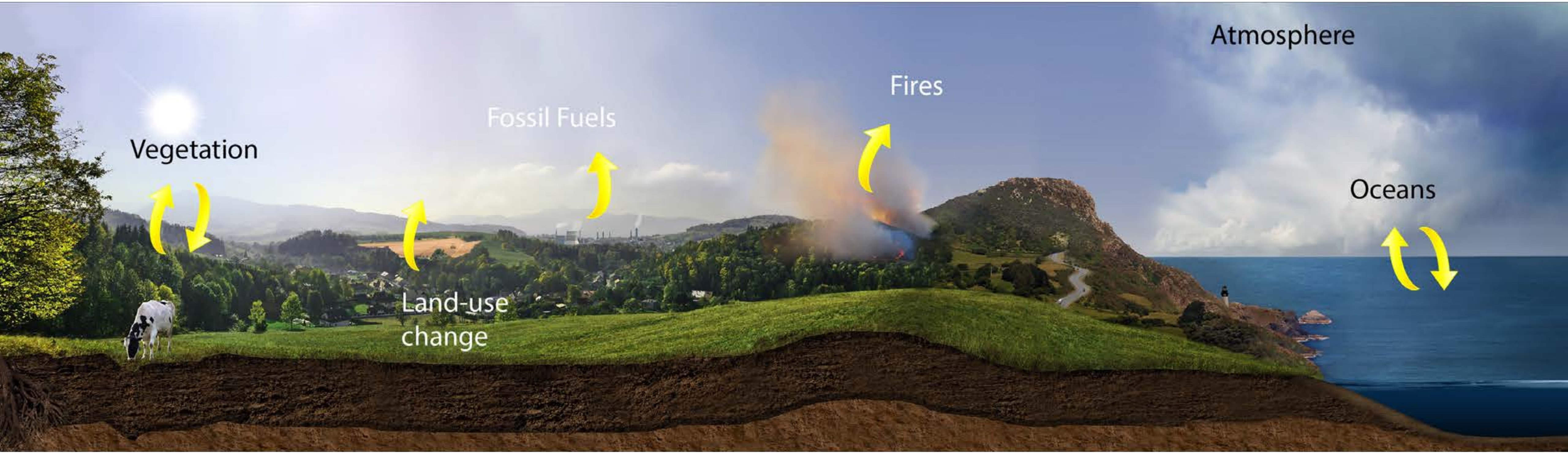

Credit: NASA/Jenny Mottar and Abhishek Chatterjee

Toward Workshop Goals

1. Most significant advances to date:
•Quasi-operational assimilation of atmospheric CO_2
•Capability to assimilate current generation ocean color

2. Most significant barriers:
•Reliance on retrieved products
•Poor understanding, representation of lateral land-ocean fluxes
•Maturity of vegetation models

3.Collaborations:
•Strong collaboration across NASA centers and laboratories with subject matter expertise
•NASA-NOAA, JCSDA collaboration on ocean color DA

4. Critical requirements:
•Ability to assimilate multiple vegetation observations to characterize carbon stocks and fluxes
•Ability to tie atmospheric observations to process level understanding of land, ocean flux
•Strategy for coupling between components
•Ability to reproduce observed trends and interannual variability