The Problem

The concentrations of CO_2 and CH_4 in the atmosphere are higher than they have been in the past 25 million years. Current levels of CO_2 have increased nearly 40% from pre-industrial levels of ~280 ppm to more than 386 ppm in 2009, to levels not seen in at least the last 800 thousand years (Fig 1). CO2 has risen at about 2 ppm per year over the past decade and this rate has been barely impacted by the current economic slowdown. Current levels of CH_4 of over 1800 ppb are two-and-a-half times the pre-industrial value of 700 ppb. After a decade of stability, CH_4 has begun rising again in recent years.

The primary causes of observed increases in greenhouse gases are fossil fuel combustion and modifications of global vegetation through deforestation, land use and agricultural management. The amount of CO_2 released each year through fossil fuel burning alone continues to increase exponentially and, in 2008, was 8.2 billion tons of carbon (One billion tons = one petagram = 10^15g)[1] . An estimated 0.5-2.5 Pg C per year was emitted from deforestation and land-use change during the same interval. Emissions rose sharply between 2000 and 2008, with emerging economies contributing the largest share of global emissions, and coal being the single largest fuel emission source.

Only 46% of these CO_2 emissions accumulate in the atmosphere; the rest are absorbed by sinks in oceanic and terrestrial ecosystems. These natural sinks offer a 50% discount on the increasing greenhouse effect of CO_2. (Fig. 2) The ocean annually takes up some 2.2 Pg C and soils and vegetation 2.7 Pg. The future global magnitude of these sinks is uncertain, as are their patterns in time and space. As the ocean takes up CO2, it becomes more acidic, RW[impacting entire ecosystems in ways that are likely to be ecologically and economically unsound.] "impacting calcifying organism and changing ecosystems"

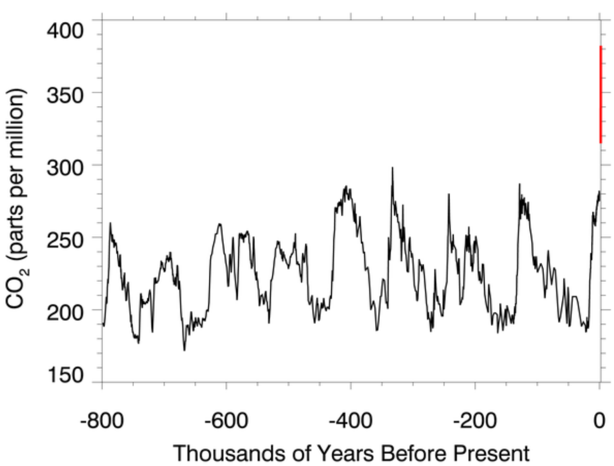

Fig 1. Vostok/Dome C combined CO2 record (black) and MLO (red)

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1. Throughout this report amounts of carbon, whether static reservoir sizes or dynamic fluxes, will be counted in terms of carbon only. I.e. we will not count the mass of the oxygens in CO2 as is sometimes done in the non-scientific literature.

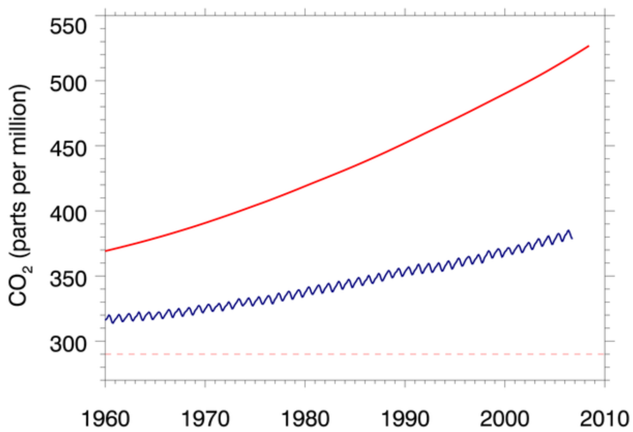


Fig 2. MLO monthly mean CO2 (blue), CO2 without any sinks (red solid) and pre-industrial CO2 (red dash)

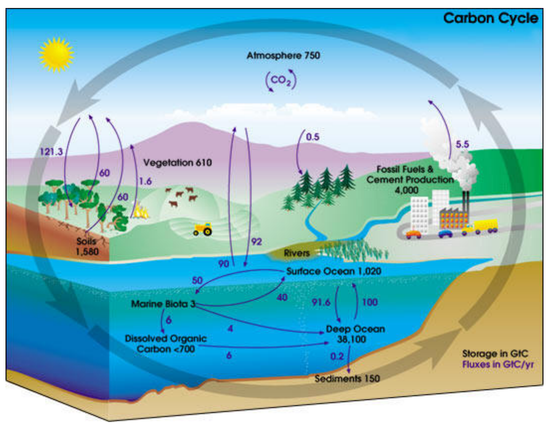


Fig 3.[This last image is a place holder. We should probably make our own that includes:
a) up to date numbers, especially for ff
b) highlights permafrost and tropical biomass C as a separate reservoirs
c) highlight NOAA measurement programs
d) Simplified reservoir exchanges.

Natural CO_2 sink strengths vary with weather and climate. The largest global climate perturbations such as El Niño and volcanic eruptions exert a strong impact onRW [the] "storage and" exchange of CO_2 among the ocean, atmosphere, and terrestrial systems (Fig 3). Regional climate spells such as the 2005 drought in the Amazon, or the 2002 and 2003 droughts in North America and Western Europe have caused carbon losses from terrestrial ecosystems, though the precise linkages between climate anomalies and carbon storage remain poorly known.

After being stable for nearly at decade, CH_4 showed signs of renewed growth starting near the beginning of 2007, although time will tell whether the increase is sustained. CH_4 emissions comprise man-made sources reflecting the use of fossil fuel, livestock production, and rice cultivation, as well as natural sources such as peatlands and fires. These sources are sensitive to socioeconomic drivers and to climate variations and their spatial distribution is poorly constrained. Methane also has a chemical cycle in the atmosphere,

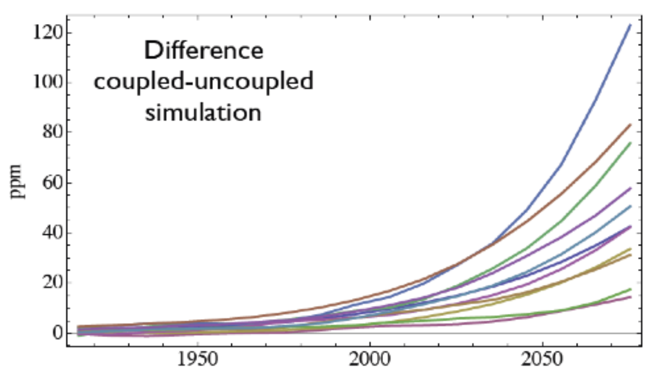
unlike CO_2. Hydroxyl radicals remove CH_4 from the atmosphere, a process that is also sensitive to climate change. Even a small change in CH_4 sources or in the chemical sink can tip the CH_4 budget out of balance.
[RW, note: CH4 is prominently mentioned in the problem but hardly discussed in rest of text]
[JBM: very good point. My inclination is to mention CH4 much less here.]

The Issues

(from J. Miller)
Understanding of Earth's carbon cycle is rapidly emerging as a critical part of the foundation required to build science-based policy all the way from the local to global scale. Here we identify three fundamental and equally important aspects of the carbon cycle that define NOAA's carbon cycle research program.

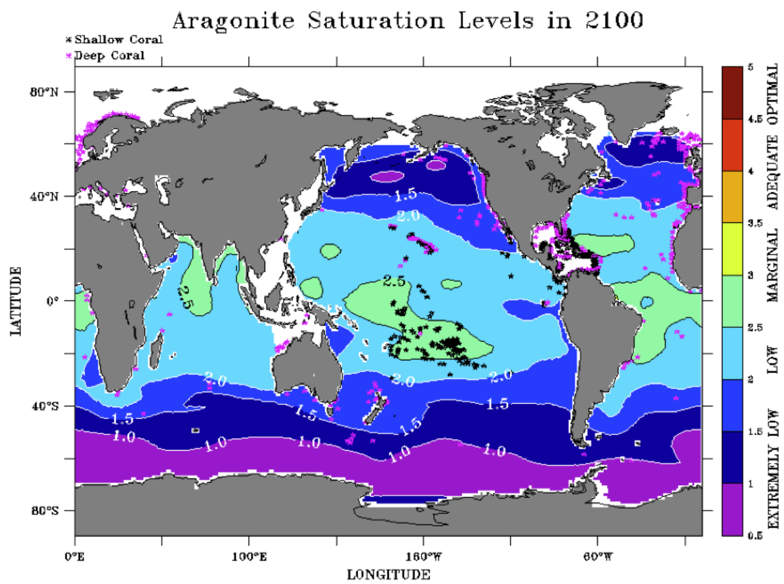
1) Carbon cycle as a *first*-order uncertainty in climate prediction.

The carbon-cycle and its two-way interactions (feedbacks) with the climate system are currently poorly understood and thus represent a first-order uncertainty in prediction of future climate. There is good reason to believe that increasing temperatures will greatly decrease the stability of the two the largest terrestrial carbon reservoirs: tropical ecosystems and high-latitude soils, which would further increase global warming in a positive feedback. Additionally, there is RW[significant]uncertainty of the oceans' response to increasing temperature and changing precipitation patterns vis a vis RW"changing circulation and transport patterns and" their ability to absorb atmospheric carbon dioxide. Sensitivity tests with couple climate-carbon models suggest that carbon cycle uncertainty translates into a global mean temperature uncertainty of up to 2 degress Celsius (about 4 degress Farenheit), a sensitivity on par with prediction uncertainty arising from cloud effects (and other water vapor feedbacks?).



2) Increases of atmospheric CO_2 as the cause of ocean acidification.

The fact that oceanic calcium carbonate, including marine animal shells and coral reefs, is susceptible to dissolution RW "and reduced growth" by increasing ocean acidity RW"and corresponding decrease in carbonate ions" is well known. What has recently emerged is that even at current atmospheric CO2 levels of about 385 parts per million (ppm), the invasion of atmospheric CO2 into the surface ocean, and concomitant decrease in ocean pH, has already resulted in decreased RW "rate"[ability] of organisms to form CaCO3 shells. This evidence, combined with the increases in ocean acidity that will go along with increasing atmospheric CO2 in the coming decades, means that large parts of the oceanic food web are at risk. To a large degree, ocean acidity increases and their threat to marine ecology are independent of climate impacts of a high CO2 world.



Aragonite Saturation from Orr et al 2005

3) **There is an emerging need to observationally track anthropogenic and total carbon emissions.**

Emissions of CO2 from fossil fuel combustion have totaled about 350 billion metric tons of carbon since the onset of the industrial revolution and are currently averaging more than 8 billion tons per year. This represents a huge perturbation to the carbon cycle and is the primary source of our research interest. Nonetheless, we currently have few observational constraints on this critical carbon cycle component, instead relying on "bottom-up" inventories, which are often self-reported.

Over the last two decades of carbon cycle research, "bottom-up" estimates of fossil fuel combustion have represented the surface fluxes with the least uncertainty. But, in a future environment of carbon regulation nationally and internationally, there will be significant incentives to under-report emissions. For carbon cycle science research objectives, for example where partitioning of ecosystem and anthropogenic fluxes is required, the bottom-up inventories will cease to be accurate enough. Moreover, it will be critical to have independent verification of emission mitigation efforts, in order to assess the efficacy of various strategies.

[Fig.?]

Section II

II. Why NOAA?: NOAA's global and national leadership role in CC research and its relationship to C-cycle research efforts of NASA, DOE, NSF, etc. (Butler)

A. Global leader in measurements and analysis of both atmospheric CO_2 and CH_4 and (WMO/GAW, GCOS, GEOSS linkages, etc. – n.b. some of these and other intl associations need to be added for B and C.)

B. Global leader in oceanic carbon measurements and modeling.

C. Global leader in climate modeling (including the incorporation of interactive oceanic and terrestrial carbon cycles)

D. Research support for future operational level National Climate Service

(From Jim B)

Why NOAA?

RW note- It is worth stressing that NOAA is the only US gov. agency tasked to monitor the changing environment

[JBM: Global leadership roles in modeling and Climate Service issues -- part of B and, C, D still need to be mentioned]

The measurement of carbon dioxide in the atmosphere and oceans has been nourished by and flourished under NOAA for 40 years. It is a scientifically based, global effort requiring extreme precision and accuracy for measurements made at part-per-million levels. NOAA's expertise and leadership in providing long-term measurements and scientific understanding of carbon dioxide and other greenhouse gases in the ocean-atmosphere system is acknowledged by the scientific community throughout universities, federal agencies, and international organizations. Scientists conducting carbon-cycle science or climate research at all of these organizations have come to depend upon NOAA for providing consistent, accurate measurements in the ocean and atmosphere.

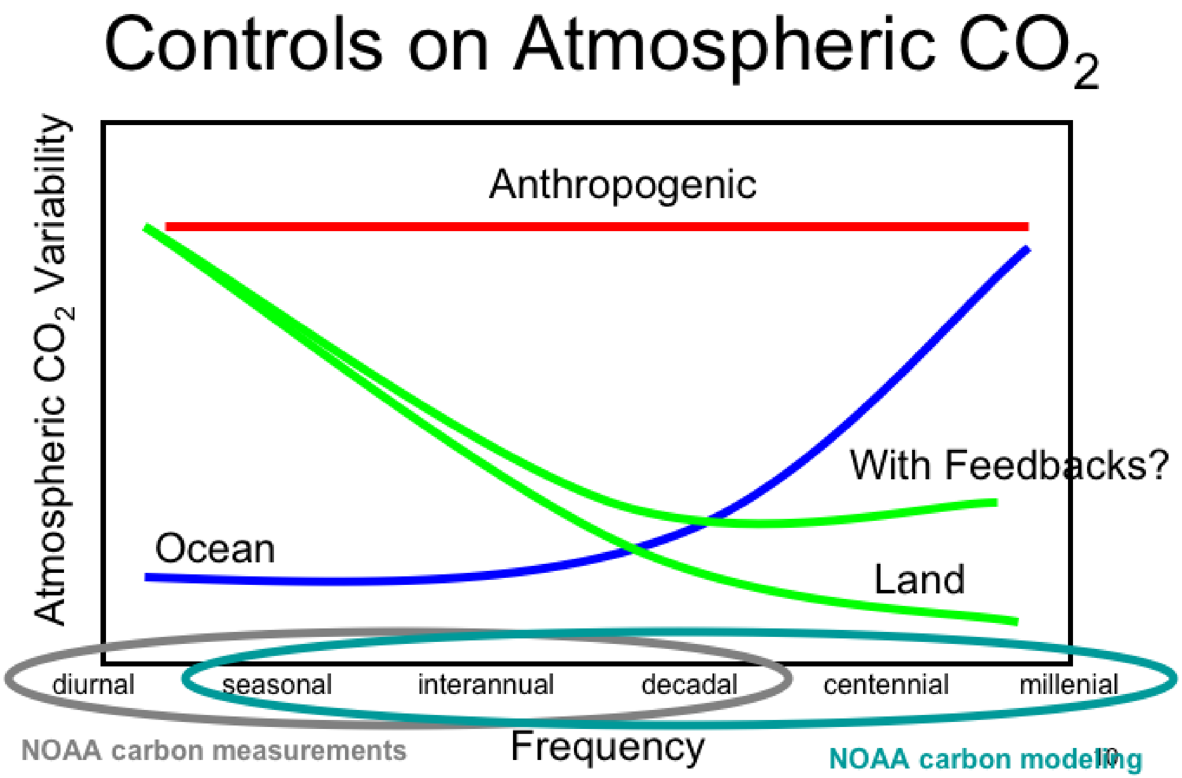
NOAA's atmospheric monitoring sites constitute over half of the global monitoring network for the major greenhouse gases and, along with NSF, NOAA provides half of the world's ocean measurements of carbon dioxide in both deep[and]. RW "NOAA and the Japanese National Institute of Environmental Science are the only agencies who are performing sustained observations surface water CO2 levels". NOAA scientists are leaders in understanding the processes that drive gas exchange between the ocean and atmosphere. They also are leaders in understanding ocean acidification and are major players in the international effort to monitor, understand, and assess the trends of carbon in the ocean and their impacts on ocean habitat and living resources.

WMO's Global Atmospheric Watch Programme (GAW), the international umbrella for greenhouse gas measurements, was established based upon a NOAA design. NOAA scientists have a long record in leading, promoting, and maintaining this network, providing leadership in the WMO Science Advisory Group on Greenhouse Gases, participating in *WMO biennial Experts' Meetings on CO2, GHGs, and Related Tracers* for 30 years, and producing reports and intellectual guidance to the world community. NOAA is the WMO Central Calibration Laboratory for CO2, CH4, and N2O, providing world calibration scales for these and other gases. NOAA scientists have co-authored numerous guidance documents for WMO/GAW, participate on the Commission for Atmospheric Sciences, which oversees WMO/GAW and World Weather Watch, and participate in GCOS through its Atmospheric and Ocean Observation Panels for Climate. NOAA provides leadership implementing GEOSS, including co-chairing the task for Carbon Observation and Analysis, and is active in the USGCRP Carbon Cycle Science Program with representatives on the Interagency Working Group and all three Scientific Steering Groups. NOAA's skill in maintaining QA and QC for a global network of measurements is unsurpassed.

The climate-change challenges facing society in the 21st century require an understanding of the global carbon-cycle, and of the impacts and feedbacks of past, present, and future emissions of carbon-cycle gases. NOAA's long-standing capabilities span a range of activities, including observations, analysis, modeling, prediction, and assessment. NOAA maintains the global observational networks and field programs on which society will increasingly depend for reliable information.

[JBM: Butler will insert figures showing a) the relationship of NOAA C research to that of other agencies and b) something similar in the international context.]

[JBM: No specific text yet related to this figure, but I think it highlights the breadth of NOAA C research]



Section III

III. What have we done; what are we doing; what gaps need filling?

Focus:
What gaps need to be filled (theoretical, experimental/measurement, other) in order to get the stage where I. A, B, and C can be addressed sufficiently to provide 'actionable information'? Also, what research on A, B, and C is overlapping – i.e. what efficiencies can be gained. I'm highlighting gaps here, but for the actual document, each sub-section should be prefaced by emphasizing current capabilities and past accomplishments.

Before we start with gaps, we have for decades been documenting carefully a number of important changes as they occur – this is an essential start for understanding, and also provides a baseline for what is yet to come. (However, we do not yet have good baselines for anthropogenic emissions and carbon release from the arctic and tropics, for example.)

A. Observational gaps in the ocean and atmosphere (A, P, Tans)

1. Current focus on N. Am. and environs (mainly atmos.) but huge gaps in tropics and S. Hemisphere. What is the right balance wrt: a) learning how to construct an observational system and b) making sure the global nature of the problem is sufficiently addressed.

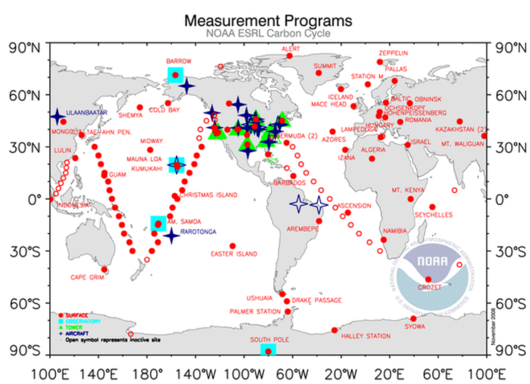
2. What new measurements (higher frequencies, higher accuracy/precision, different chemical species, new locations) would help goals A, B, and C above?

3. Mention gaps in satellite-based accuracy and precision.

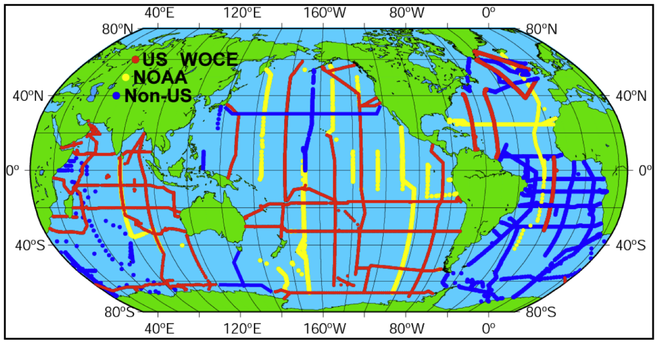
4. Eddy covariance?

Intro: JBM:

At its core, understanding climate and the carbon cycle is a global problem. This is reflected in the global reach of NOAA atmospheric and oceanic carbon observations as well as its diagnostic and predictive modeling efforts and its satellite programs. (Fig 3.x). For decades, NOAA has been carefully documenting changes in the atmospheric and oceanic carbon reservoirs. Data sets like the Mauna Loa CO2 time series and the integrated history of ocean carbon accumulation have proved to be the most important observational constraints in all carbon cycle research. However, many significant spatial and informational gaps remain unaddressed at present. Further, existing observations have not typically been explicitly geared towards answering our fundamental problems of climate feedbacks, ocean acidification and anthropogenic emissions. However, the global focus and in some cases, targeted nature, of these measurements has allowed for progress on these questions. And most importantly, the long history of measurements has created a baseline to which many future changes in the carbon cycle can be compared. Moving forward, the implementation of new measurement and modeling strategies needs to be targeted more explicitly to addressing our primary goals. In doing we so, we need to fill existing spatial gaps in our observing networks; create and fill out baselines for some aspects of the carbon cycle that have not been fully established; and integrate new measurements more closely with diagnostic and prognostic modeling efforts, in a two-way process.



NOAA ESRL Carbon Cycle operates 4 measurement programs. Semi-continuous measurements are made at 4 baseline observatories and from tall towers. Discrete surface and aircraft samples are measured in Boulder, CO. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, the stable isotopes of carbon dioxide and methane, and halocarbon and volatile organic compounds are measured. Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.



WOCE/JGOFS/OACES Global CO_2 Survey
~72,000 sample locations collected in the 1990s
DIC ± 2 μmol kg^{-1}
TA ± 4 μmol kg^{-1}
Sabine et al (2004)

A. Ocean and Atmosphere Gaps

JBM."Currently, significant spatial and temporal gaps exist in both the atmospheric and oceanic observation networks. Different oceanic and atmospheric carbon observing strategies are dictated by the time and space correlation scales of carbon content in and fluxes from each reservoir. The high spatial heterogeneity of terrestrial surface fluxes and of the atmosphere more generally requires a temporally and spatially denser sampling strategy than is required for ocean carbon observations. [true?] Conversely, repeat hydrography transects may be required only every 10-15 years in order to track long-term accumulation of carbon. For both oceanic and atmospheric carbon observations, NOAA measurements constitute large fractions of the global totals, but many other institutions contribute high quality measurements. As articulated in the [new GEO-carbon document] transparency and sharing of observations is critical, so that resources are not wasted duplicating measurements. NOAA labs have been global leaders in free and open access to measurements and plan to make even more up to date data available."

Ocean:Rik, this is great. I think it would be more powerful if framed in a more scientific context. i.e., what fundamental science questions remain tough to answer regarding oceanic carbon uptake in the future and ocean acidification? We need to develop justification in this section for what we propose to do research-wise in section 4. -John Miller 11/2/09 2:46 PM

RW"Ocean CO2 monitoring and research encompasses several synergistic objectives. The repeat hydrography program is focussed on the changes in ocean carbon inventory and processes controlling the changes while the surface CO2 program emphasizes the magnitude and control of the air-sea CO2 flux. The ocean acidification research and monitoring activities are focussed on forcing and impacts in US coastal and coral ecosystems. The repeat hydrography program has a series of ocean transects that will be repeated every 10-15 years. The key issue is to maintain the effort and streamline the activities with improved technology. In addition, a recommendation from the ocean observation community calls for higher temporal resolution monitoring at select chokepoints in the ocean (e.g. Drake passage, Kurishio current, and Florida/ Western Boundary current). Currently, only two surface ocean pCO2 time series sites exist: in Bermuda and Hawaii. The surface CO2 measurements that are performed on moorings and ships of opportunity (SOOP) with coverage in the North Atlantic, Equatorial Pacific, and North Pacific sufficient to meet the goal of constraining the [global?] fluxes to 0.2 Pg C yr-1 . Maintaining the coverage in these areas and improved timely central data dissemination are critical. The surface efforts need to be expanded to provide a global network to offer a firm constraint on the ocean's impact in sequesting carbon. Areas with lowest coverage are the South Pacific (> 20 S), the South Atlanitc (> 40 S) and Northen Indian Ocean (< 20 S). [what about far Southern Indian (> 30 S) and Austral summer bias?] Because of lack of ships in these regions alternative infrastructure (high latitude moorings, gliders, and floats) need to be explored. The framework for ocean aidfication monitoring and research is mandated by the Federal Ocean Acidification Research And Monitoring (**FORAM**) **Act** of 2009 and detailed in the NOAA national ocean acidfication plan, and the National Academy report on ocean acidification. The CO2 component will be focussed on bi annual transects on research cruises for comprehensive surface and water column investigations, coastal SOOP, and moorings to capture the temporal and spatial variability. Special focus will be on coral reefs that are believed to be critically impacted by ocean acidification "

Atmosphere:
JBM"

The existing global set of atmospheric CO_2 and CH_4 observations originated as a dominantly marine boundary layer-based network in the 1970s and 80s. In the 1990s, there was a substantial increase in measurements over continents and in the last 10 years, there have further increases in atmospheric carbon observations over the continents, especially in the form of tall tower (> 100 m) and light aircraft observations over Europe and North America. These recent continental increases reflect the emerging scientific consensus from the early 1990s that the terrestrial biosphere could be an important sink for atmospheric co2. The increased observation density in North America and Europe reflects a local funding bias as well as a methodological experiment to test what density of measurements is required to determine carbon fluxes from atmospheric measurements over politically relevant spatial scales.

However, the existing suite of airbone and surface platforms have substantial spatial gaps in Africa, South America and northern Eurasia, as well as over large reaches of the Southern Hemisphere Oceans, limiting our ability to apply carbon budgeting constraints to regions expected to be hot-spots of potential carbon-climate feedback processes. Our third carbon goal, tracking the addition of anthropogenic carbon to the atmospheric reservoir does not currently have a well-established baseline. Creating such a baseline, especially in the Northern Hemisphere near the American and Eurasian centers of emission is a critical need. Additionally, much of the current surface network is based on the collection of discrete air samples over ~5 minute periods on a weekly or less frequent basis, seriously limiting the temporal coverage. Substantial efforts are needed in: a) expanding the number of measurement sites in under-observed regions of the world and b) increasing the number of quasi-continuous in situ measurements at existing sites.

Instituting new sites over continents where the major gaps exist is very challenging. Unlike in the marine boundary layer (MBL) and above treeline, air sampling above vegetated continents requires the use of towers – at least reaching above canopy and preferably reaching into the daytime boundary layer – or aircraft, in order to avoid undue influence of local vegetation signals and obtain regionally ($\sim 10^5$ – 10^6 km^2) representative measurements. The absence of these obstacles is one of the fundamental attractions of satellite-borne remote sensing of trace gases, but the current accuracy and precision of remotely sensed CO_2 and CH_4 is at least an order of magnitude lower than in situ observations. In order to expand land-based CO_2 observations in under-sampled regions, partnerships between laboratories with long histories and emerging ones have proved very effective. For example, LSCE, France has partnered with [Indian lab] to establish measurement sites in Ladakh; and NOAA has partnered with Instituto de Pesquisas Energeticas e Nucleares in Brazil to establish measurement sites in coastal Brazil (GAW site Arembepe) as well as aircraft sites in Amazonia. Finally, there are many existing aircraft and tower sites (e.g. NOAA NACP sites; EU Chiotto and CarboEurope sites; and NIES/Japan Siberian sites) at which high quality measurements are being made, but the data is not readily available.

In addition to the spatial and temporal gaps, there are also substantial gaps in process understanding of spatial and temporal CO2 variations. supporting trace gas species beyond CO_2 (and sometimes CH_4), like O2/N2, the stable and radio (^{14}C) isotopomers of CO_2 and CH_4, and anthropogenic halo- and hydro-carbon species. Terrestrial exchange processes impact atmospheric O2/N2, $d^{13}CO_2$, and d18O of co2. In situ sensors for O2/N2 exist, although they are not commercially available; commercial instruments for $d^{13}CO_2$ are available, but not yet at the precision required for background monitoring.   Fossil fuel emissions have readily identifiable impacts on atmospheric $^{14}CO_2$ and and various halo- and hydro-carbon species.

B. Theoretical gaps: the link between obs and modeling/data assimilation.
[All need to contribute to this, probably after A and C are developed better. This is hard to deal with and we may not have all the expertise in house to solve these kinds of issues. This is where engagement with partners comes in including a large role for CPO to sponsor research to fill this need.]

1. (e.g., What controls terrestrial photosynthesis and respiration? What is the most accurate way of inverting atmospheric or oceanic obs to determine fluxes – v. high res mesoscale models nested in global ones?)

2. This is one area in which CPO has a big role to play: i.e. funding internal and external research projects that aim to fill these gaps.

C. Modeling/synthesis gaps (Jacobson, Stouffer, Dunne)

1. Computational gaps: (e.g. If we had really fast computers we could run model X at 0.25 x 0.25 degree globally. What would that get us?) This applies both to prediction and reanalysis. Also, more work is needed on uncertainty estimation. E.g., there is a need to employ ensembles of multiple models to produce more realistic uncertainty estimates.

[JBM: Diagnositc part still needs to be added]

JD -"Climate simulations have always been severely limited by the computational resources even on the largest computers, and the situation remains so today. Some of the first programs run on computers were climate and weather simulations where GFDL was an early player. Since those early days, the computing power has increased more than a million fold. One way we have used these increases is in increasing the number of grid locations in the model with each doubling of the resolution (i.e. 200 km spacing to 100 km spacing zonally and meridionally, 10 vertical levels to 20, time stepping from 2 hours to 1 hour) resulting in about a 16-fold increase in power needed. As computer power has increased, researchers have performed longer simulations. Instead of extending over several years, to several centuries. The complexity and comprehensiveness of the models has increased mover the years. They now include cloud and radiative processes, and detailed ocean, ecological and biogeochemical components. Finally the number of ensemble members we conduct has increased. Present day physical climate models use a grid spacing of about 200 km in the atmosphere with about 25 vertical level and 100 km in the ocean with about 50 vertical levels. This class model also includes components that close the carbon cycle with terrestrial and ocean ecological/biogeochemcical models and atmospheric cycling of CO2. These models simulate several centuries and with a typical ensemble size is 5.
Thus, there are at least four types of computational gaps that limit our ability to perform carbon cycle reanalysis and prediction: uncertainty in initial and boundary conditions, process-level comprehensiveness, resolution, and ability to run ensembles that adequately capture the uncertainties in the first three gaps. The types of uncertainties in initial conditions include observational gaps and biases as well as the challenge of adequately incorporating these types of observations into the model framework which includes a

necessarily simplified representation of the earth system. Add to this the uncertainty in projections of natural and human-induced forcings of boundary conditions. Process-level comprehensiveness is another important gap. While many of the physical, dynamic, numerical, ecological and biogeochemical processes involved in climate have been described independently and in great detail, the challenge of incorporating all of these processes into a comprehensive, internally consistent earth system model is a daunting task – one to which the 'state of the art' still includes critical biases such as the infamous 'double ITCZ', cloud-radiative biases and others. Resolution can solve some of these problems, but often adds new challenges as parameterizations that work well at one scale fail at other scales. Thus, high resolution models usually have degraded fidelity until they are undergone the same level of vetting as the coarser models. Finally, ensemble methods are critically important tools to address uncertainty in weather and climate initial condition uncertainty as well as parameterization uncertainty for adequate assessment of total reanalysis and predictive uncertainty. In addition, having a large number of ensemble members also helps us quantify the signal of a particularly forcing response embedded in overall climatic noise.

2. Link back to obs: What are the most efficient and effective ways to fill gaps? What observations are best suited to existing and anticipated modeling capabilities (for determining fluxes when thinking about inverse models and for validating mechanisms when thinking about prognostic models). à emphasize OSSEs.

Observations fill three main roles in global earth system modeling. The most direct is in the establishment of initial and boundary conditions of the earth system. The adequate filling of these roles requires data that are globally synoptic in scale. Less direct is the roles of parameterization through synthesis and theoretical development in which observations are assessed in the context of the state of the science to develop mathematical representations of the dominant controlling earth system processes. In between the first two is the role of model fidelity assessment and iterative improvement wherein model results are critically compared to observations to expose model weaknesses and the modeler is forced to re-evaluate assumptions and develop new theoretical approaches and new parameterizations to improve model performance.
In return models can provide important insight into the utility of observational approaches both directly through Observation System Simulation Experiments (OSSEs) and indirectly through identifying critical model uncertainties that could be addressed through the collection of new data. In an OSSE, models are sampled in the same way that observations are collected in order to quantitatively assess the ability of the given observational design to capture the underlying variability in the 'perfect' model. Thus the observational design can be critically assessed for their viability to achieve the desired result and potentially iteratively improved so as to make best use of available resources. As model uncertainties are exposed, they can identify critical spatial, temporal and comprehensiveness gaps for new observations to drive improvements in understanding of the earth system.
Specific examples of what observations could help improve paramterizations and help validate could be included. -John Miller 10/22/09 12:52 PM

D. Are we prepared to identify potentially rapid, large global carbon cycle changes? What measurements *and* modeling/analysis approaches are necessary?

1. Initiation of carbon release from Arctic permafrost. (Bruhwiler, Stouffer, Dunne)

Lori:
The Arctic has potentially vast stores of carbon that could be released to the atmosphere as a result of ongoing climate change. Recent estimates indicate that there may be 1400-1850 PgC in Arctic soils and permafrost (McGuire et al., 2009; Tarnocai et al., 2009). Some of

this carbon has been in place since the last ice age in regions that were once unglaciated steppe-tundra (Zimov et al., 2006). Another several hundred PgC may exist in marine permafrost and hydrates on continental shelves that were above sea level during the last glaciation (McGuire et al., 2009), and these may be in danger of destabilizing as the shallow Arctic Ocean waters warm. Arctic land temperatures have risen by 0.35^{o}C degrees per decade from 1970 to 2000 (Serreze and Francis 2006), and climate models predict further warming as well as increased precipitation in the future (IPCC AR5?). Understanding the future stability of Arctic carbon stores is of utmost importance considering the potentially large feedback from mobilization of carbon sequestered in soils and continental shelf sediments.

At present, the processes controlling the potential release of Arctic carbon are poorly understood, and parameters controlling Arctic carbon storage are poorly quantified. For example, the future evolution of Arctic hydrology needs to be understood, since wetter conditions could lead to expanded wetland coverage and more emissions of CH_4, which has a high global warming potential. On the other hand melting permafrost could lead instead to drainage of high-latitude wetlands, possibly resulting in enhanced CO_2 emission. Finally, climate change could lead to ecosystem changes that also alter the carbon, and moisture balances of the Arctic.

Our current Earth System models do not represent terrestrial soil, hydrological and cryological and biogeochemical processes any where near to the degree necessary to prognose with an adequate degree of certainty of timescales and amounts of CO2 and methane that may be released under climate warming. This effort will necessitate the coordination of observationalists, theoreticians and modelers both within NOAA and in the larger scientific community.

2. Changes in surface and deep ocean storage of C. (Sabine; not sure who wrote the modeling contribution to this section but thanks)

A significant impetus for recent ocean biogeochemical research has been to understand the ocean's role in the global carbon cycle and how it might be changing over time. To accomplish this, one must understand the rate at which the oceans absorb anthropogenic CO_2 from the atmosphere, referred to as C_{ant} uptake, as well as how and where that CO_2 is stored in the ocean interior, C_{ant} storage. Uptake is not necessarily the same as C_{ant} storage because ocean transport can move carbon that is removed from the atmosphere in one place and store that carbon in another place.

In the 1990s the WOCE/JGOFS global carbon survey inspired the development of several approaches for estimating anthropogenic carbon inventories in the ocean interior. Most approaches agree that the total global ocean inventory of C_{ant} was around 120 Pg C in the mid 1990s. This means that nearly half of the CO_2 released into the atmosphere from burning fossil fuels between 1800 and 1994 ended up in the ocean. Based on ocean uptake estimates, the global ocean inventory should be increasing by about 2.2 Pg C per year giving a total inventory of about 135 Pg C in the early 2000s. This rate of ocean carbon uptake, however, does not seem to be keeping pace with the CO_2 emissions growth rate. Repeat occupations of the WOCE/JGOFS survey lines consistently show increases in carbon inventories over the last decade with clear spatial patterns, but the first decadal re-survey will not be completed for a few more years and the interim estimates have not yet been synthesized enough to verify a slowdown in the carbon storage rate. Ocean interior observations, however, remain the best mechanism for verifying the changes in ocean C_{ant} inventory.

It is extremely difficult to predict how the many possible carbon cycle feedbacks will affect ocean carbon storage; modeling and proxy techniques are limited by our current understanding of the ocean carbon cycle. Up to this point, the assumption has been that ocean storage of C_{ant} has been controlled by purely physical and chemical processes directly responding to rising CO_2 concentrations in the atmosphere. We know that on long enough time scales the physical, biological and biogeochemical feedbacks will start altering the ocean's role as a sink for CO_2, but are we in a position to know when these changes occur or whether they will happen gradually or as an abrupt transition? It is critically important that we continue to improve our understanding of how C_{ant} is accumulating in the ocean on time scales relevant to human civilization (years to decades). Continued observations are necessary to monitor the changes and provide the basic science on the mechanisms controlling ocean carbon uptake and storage today and in the future.

Insofar as our current generation of earth system models represents ocean dynamics, we are capable of simulating changes in ocean storage of carbon remarkably well given our detailed understanding of carbon chemistry and our general understanding of the ocean's biogeochemical and ecological controls. The largest gaps in our ability to understand changes in deep ocean carbon storage are in our ability to dynamically represent the controls on atmospheric forcing of the ocean (primarily radiation-cloud interactions) and our ability to model the formation and evolution of interior ocean waters via surface and subsurface physics.

3. C fluxes from burning and respiration of tropical carbon stores. (Miller, Stouffer, Dunne)

The tropical terrestrial biosphere represents one of the largest reservoirs of carbon in contact with the atmosphere, up to xxx Pg C, and some models (Cox, 2000; others) have suggested that it is highly vulnerable to predicted increases in surface temperature. Additionally, historical, contemporary and future land use change, primarily in the form of deforestation, must be accounted for not only to close carbon budgets, but also because it influences the future trajectory of terrestrial carbon balance. The current terrestrial component of the Earth System Model (ESM) at GFDL includes detailed land use physics. Land use scenarios for historical and/or future periods are given to the model as input and the model predicts the amount of carbon in various carbon pools including the secondary regrowth of forests after harvesting. Measurements of carbon emitted from land use change are therefore critical to validating both the ESM and diagnostic models like CarbonTracker.

Because of the dominant role of convective transport in the tropics, the atmospheric signal of tropical terrestrial carbon flux is weak at remote surface observation sites. In order to better monitor changes in this part of the world, more observations are needed. The two most likely avenues for this are cooperation with partner labs as is being done with Brazil and India currently and the use of satellite remote sensing, although co2 and ch4 measurements from space are currently in their infancy. CH4 measurements by the SCHIAMACHY sensor aboard the ESA ENVISAT have shown tremendous promise in resolving tropical ch4 fluxes (Frankenburg, 200x; Meirink, 2007). Future measurements of CO2 and CH4 from OCO, GOSAT, and AIRS will also be very useful if they can be validated by well calibrated in situ observations from airborne and surface platforms. Additionally, existing remote sensing measurements of land use change, vegetation state (e.g NDVI), and fire must be maintained or expanded in order to better monitor tropical carbon stocks.

4. Rapid changes in oceanic CaCO3 brought on by acidification. (P, A)

There is currently a critical need to establish the scope of changes that ocean acidification will impinge on both the CaCO3 cycle and more broadly on ocean ecosystems in general. From what we have learned thus far, many species precipitate CaCO3 linearly with respect to CaCO3 super-saturation, but the broader ecological consequence of acidification remain elusive. The state of modeling has been to include acidification impacts only in terms of carbonate chemistry and the role of solubility on pelagic calcite and aragonite precipitation. There is still a great deal of observational, synthesis and theoretical work to be done to characterize both the short term physiological and long term evolutional impacts of acidification on ocean ecosystems.

5. Large changes/trends in anthropogenic fossil fuel emissions (that may or may not be reported accurately under Intl. treaty obligations). (Miller/Petron)

E. How does addressing the questions above satisfy existing NOAA, CarbonCycleSP and other goals? (Sabine)
also the GEO-carbon report (Miller/Butler)

For the last several years large-scale carbon cycle research in the U.S. has been coordinated through two national programs: the North American Carbon Program (NACP) and the Ocean Carbon and Climate Change (OCCC) program (Wofsy and Harris, 2002; Doney et al., 2004). NOAA carbon researchers have been closely involved in the development and implementation of both of these programs. The NOAA carbon plan presented here is consistent with and builds on the advancements made in both of these programs over the last five or more years.

The NACP and OCCC programs were developed to conduct the research outlined in the US Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999). However, under the auspices of the United States Carbon Cycle Science Program's Science Steering Group, a working group of 27 scientists was formed in 2008 to review the 1999 U.S. Carbon Cycle Science Plan and to develop an updated strategy for research on the global carbon cycle to be conducted by U.S. researchers for the period from 2010 to 2020. The plan is still under development, but should be completed by summer 2010.

In outlining a research agenda for the next decade the working group chose to preserve the hierarchal structure adopted in the 1999 Carbon Cycle Science Plan. That is, three overriding questions that guide the research agenda, seven goals that define the anticipated accomplishments, and the primary research elements that we believe will have to be pursued to achieve the stated goals. The research elements are the backbone of observations and analyses needed for all of the research science.

At the core of the U.S. Carbon Cycle Science Plan is the development of baseline data sets and monitoring systems for key carbon system variables and establishment of long-term records to detect change. The plan identifies the need for an optimally designed and integrated long-term monitoring system of essential atmospheric, oceanic, biologic, demographic, and socioeconomic data to establish baselines, evaluate change, understand processes, and monitor mitigation actions. These observations must be accompanied by a commitment to data management, rapid data access, and a core modeling effort to ingest and interpret these results. This integrated observing system will feed into the stated science questions and goals of the Science Plan. The NOAA Carbon Program outlined in this document is designed to provide that core set of observations and modeling needed to provide the backbone for the U.S. Carbon Cycle Science Plan.

As part of the Federal Ocean Acidification Research and Monitoring Act of 2009, the United States Joint Subcommittee on Ocean Science and Technology (JSOST) is tasked with coordinating federal activities on ocean acidification. JSOST will establish an interagency working group to develop the strategic research and monitoring plan to guide federal research on ocean acidification. Although the plan is not yet complete, NOAA researchers are actively involved in the development of the plan and are ensuring that the ocean acidification components of the NOAA Carbon Plan support the developing national ocean acidification research program.

Doney, S.C., R. Anderson, J. Bishop, K. Caldeira, C. Carlson, M.-E. Carr, R. Feely, M. Hood, C. Hopkinson, R. Jahnke, D. Karl, J. Kleypas, C. Lee, R. Letelier, C. McClain, C. Sabine, J. Sarmiento, B. Stephens, and R. Weller, 2004: *Ocean Carbon and Climate Change (OCCC): An Implementation Strategy for U. S. Ocean Carbon Cycle Science*, UCAR, Boulder, CO, 104pp.

Sarmiento, J.L. and S.C. Wofsy, *A U.S. Carbon Cycle Science Plan*, University Corporation for Atmospheric Research, Washington, D. C., 1999.

Wofsy, S.C. and R.C. Harris (2002) *The North American Carbon Program (NACP),* Report of the NACP Committee of the U.S. Carbon Cycle Science Program. Washington, DC: US Global Change Research Program. Available on-line http://www.esig.ucar.edu/nacp/

F. What measurements serve (or could be expanded to serve) dual purposes? (do later and in section 4).

1. E.g.

a) atmospheric CO_2 measurements can help determine last year's surface fluxes and also be used to help validate the carbon component of a prognostic climate model and satellite retrievals.

b) And (I imagine) oceanic pCO2 measurements can yield information related to both ocean acidification and surface and ocean interior carbon fluxes.

c) What additional measurements made at buoys or on research ships could help in the validation of prognostic ESM?

As Earth System Models are necessarily global in scope and designed for decadal and longer time-scales, the kinds of observations that can provide significant assessments of the fidelity of these models are also global and decadal (and longer) in scope. Satellite chlorophyll has been particularly useful in this regard, as have the creation of world ocean atlases of nutrients and the carbon system through NOAA's National Ocean Data Center and DOE's Carbon Dioxide Information Analysis Center. Most of the current state of these data sets is in terms of annual climatological averages with some variables represented in a monthly climatological cycle. Enhancing these datasets to include seasonal forcing at high latitude and inter-annual forcing in general through incorporation of additional observations and synthesis would be extremely valuable.

d) CO_2 and other tracers used as transport tracers. – link to validation of transport models. Also links to weather/meteo community (as other atmos obs might link to air pollution study).
e) Many measurements and analysis/modeling will have links to studies both within and outside of NOAA.

Section IV

IV. Research Plan

Focus:
How do we fill the gaps identified above in a systematic, scientifically defensible manner? ***The overriding priority in this section is that every proposed aspect of research plan should be clearly linked to a research objective (A,B, and/or C from I).***

A. Observations
[With regard to new approaches and technology it is not explicit below, but should be included in each sub-section based on III.A.2 above.]

4. Terrestrial Biosphere Observation (Myers)

a) Eddy covariance measurements in representative North American biomes

b) Coordination with GFDL land model development

A. Observations

1a. RW" The repeat hydrography program has a series of ocean transects that will be repeated every 10-15 years. The key issue is to maintain the effort, streamline the activities with improved technology, and adapt to recent findings. High quality CO2 and tracer measurements were first performed during the WOCE/WHP surveys in the 1990's that established a robust baseline of anthropogenic CO2, natural carbon, and transient tracers in the ocean. This campaign was followed by the CLIVAR/CO2 effort starting with cruises in 2004. The results so far have shown that the natural sub-decadal variability at mid-depths is significantly greater then expected necessitating new approaches to discernthe antrhopogenic CO2 component. The transient traces used during the earlier campaigns (CFC's and helium/tritium) need to be augmented and replaced by new tracers such a sulfur hexafluoride to quantify ventilation pathways in the upper ocean. Ocean pH has been added as a core measurement to better characterize the inorganic carbon system of the ocean. Closer interactions with modelers will be necessary to properly place the observations in a proper temporal and spatial framework.

The surface CO2 measurements that are performed on moorings and ships of opportunity (SOOP), with coverage in the North Atlantic, Equatorial Pacific, and North Pacific, are sufficient to meet the goal of constraining the fluxes to 0.2 Pg C yr-1 . Maintaining the coverage in these areas and improved timely central data dissemination are critical. While the NOAA program has put a emphasis on obtaining traceable high quality data that are tied to atmospheric CO2 standards from ESRL/GMD, other national and international groups have limited adherence to best practices protocols, and meta data and data sharing. Providing continued leadership and support to improve data quality and reporting by other groups remains an important priority. In addition, the surface efforts need to be expanded to provide a global network to offer a firm constraint on the ocean's impact in sequesting carbon. Areas with lowest coverage are the South Pacific (> 20 S), the South Atlantic (> 40 S) and Northen Indian Ocean (< 20 S). Because of lack of ships in these regions alternative infrastructure (high latitude moorings, gliders, and floats) need to be explored. The future observational network and needs is outlined in the community white paper from Ocean Obs-09 by Pedro Monteiro et al. ref . NOAA's focus will be on maintaining the North Atlantic, the North and Equatorial Pacific SOOP network with international partners, and expanding in the South Atlantic and south Pacific, while assisting in the Indian Ocean efforts, in particular with mooring deployed sensors. The air-sea CO2 flux observing system design calls for observations at 10- 30 degree latitude/longitude spacing at intervals 4 to 8 times a year depending on local spatial and temporal variability in surface water CO2 measurements.
The automated CO2 systems that measure surface water and air values are currently a interfaced with conductivity/salinity sensors. augmentation with nutrient and oxygen sensors is planned to improve the process level understanding of controls of surface water CO2 that can feed into models.

b. RW" A recommendation from the ocean observation community (OceanObs-09) calls for higher temporal resolution monitoring at select chokepoints in the ocean (e.g. Drake passage, Kurishio current, and Florida/ Western Boundary current). The ocean CO2 observational program has focussed on fluxes and decadal inventory changes but is currently not optimized to study transport. Changes in carbon transport in the ocean are a key diagnostic to impacts of natural and climate change on the ocean carbon cycle and rate of sequestering CO2. It also provides closure in the ocean reservoir between points of entry of CO2 in the ocean and storage of CO2. The sites selected for sustained yearly observation for carbon and transient tracers are those chokepoints whose currents will be measured on continuous basis and are detailed in the community white paper from Ocean Obs-09 by Garzoli et al. ref

c. RW" The ocean aidfication monitoring and research in NOAA is mandated by the Federal Ocean Acidification Research And Monitoring (**FORAM**) **Act** of 2009 and detailed in the NOAA national ocean acidfication plan, and the national academy report on ocean acidification. The CO2 component will be focussed on bi-annual coastal transects on research cruises for comprehensive surface and water column investigations; and coastal SOOP, and moorings to capture the temporal and spatial variability. The moorings, shipbased work and process studies are separated in three components. An open ocean component focussed on global trends of rising surface CO2 level and associated decline in carbonate ion. This effort will utilize and augment the SOOP and moorings used to constrain air-sea CO2 fluxes. The early warning system component is geared to practical applications in the near-shore environment, by providing timely information when waters with high CO2 could impact local fisheries, hatcheries, and coral reefs. The coral reef component is broken out as a seperate research component as these are the ecosystem that are likely to experience some of the greatest impacts with associated economic and ecological issues. These areas will be outfitted with moorings and a strong emphais will be placed on process studies to imrpove understanding of overall ecosystem dynamics and impacts. The global research and monitoring framework is provided in the community white paper from Ocean Obs-09 by Feely et al. ref

d. Hot spots?

A.2.a) JBM (for Pieter)
Increasing the number of terrestrially-based observations North America can be very difficult, given the logistical difficulties of operating in other countries, especially when the use of light aircraft and tall towers is required to avoid local vegetative influence on sampling. The continuation of partnerships with existing foreign trace gas labs and the creation of new partnerships represents a practical method to fill in many of the existing spatial gaps. Strong collaborations started in the last 15 years with Chinese and Brazilian labs continue to this day, and a new measurement and modeling collaboration with the Indian Meteorological Department has just begun. It is a priority to foster relationships with more laboratories in the tropics, especially in Africa and Southeast Asia. To address uncertainties surrounding the stability of Arctic carbon, long-term observations of atmospheric trace species such as CO_2, CH_4 and their stable and radio isotopes are needed at high frequency and spatial resolution. It will be especially important to commit to long-term monitoring soon so that baselines can be established. Observations capable of identifying trends in air-sea fluxes of greenhouse gases will also be essential to assessing the fate of marine permafrost.

Institution of atmospheric measurements aboard commercial ships should be easier than on land, and air samples from north-south ship routes in the Pacific have been collected by NOAA since the 1980s. There have been intermittent expansions to the Atlantic and South China Sea, and an existing route across the Drake Passage. Expansion and maintenance of these sampling efforts to the North Pacific, and North and South Atlantic would fill critical gaps in our atmospheric observation network.

Application of new multi-component gas analyzers (e.g. long-path absorption and ring-down and closed-path FTIR spectroscopy) can help in the network extension by providing reliable, stable, and continuous measurements of several gases at a multitude of sites. These instruments require less use of reference gases than the previous generation of sensors, reducing the complexity and cost of installation. Instruments like these also allow for easier deployment aboard commercial aircraft. Several programmes like the NIES JAL aircraft program, CARABIC, MOZAIC and their follow on project XXX, are all examples that can and should be expanded globally in the future. While only during landing and takeoff are these programs reasonably sensitive to surface fluxes of carbon, the high altitude (> 10 km asl) measurements provide information critical to large scale transport of CO_2 and CH_4 as well as remote sensing evaluation. One very promising new technology, especially useful in satellite evaluation is the AirCore (TM) developed at NOAA/ESRL, which is a very long sampling coil that has been shown to successfully capture vertical profiles from the surface to over 80,000 ft.

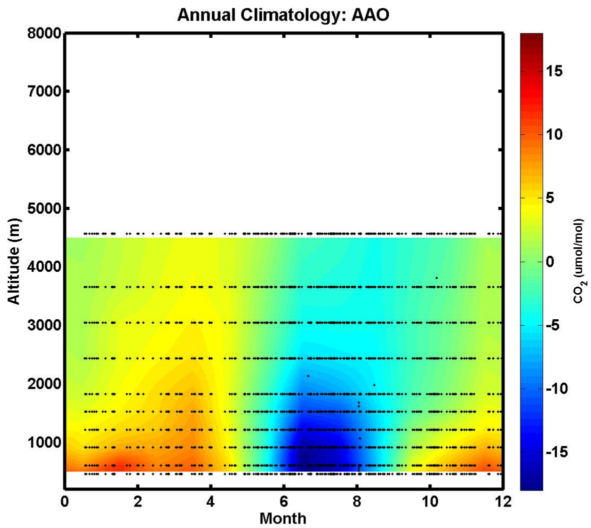
Measuring a wider array of atmospheric gases related to carbon sources and sinks will allow us to better understand the processes controlling atmospheric co2 concentrations. In the past 20 years the gases CO, CH4, N2O and SF6 have been added to CO2. For example, CO is sensitive to fuel and biomass burning and SF6 can be used as a tracer of atmospheric transport. d13C is sensitive to terrestrial biosphere carbon uptake (See Fig 4.x). In the past 5 years, new tracers including a suite of 40 (?) hydro- and halo-carbons and the radiocarbon content of co2 have begun. [Table of gases measured] These, alone and in combination, are offering an ability to directly measure fossil fuel co2 emissions. Expanding these anthropogenic measurements is underway, and needs to be a high priority moving into the future.

A.2.b) Colm:
Over the last 5 years the NOAA/ESRL Carbon Cycle Gas Aircraft Program has become an essential benchmark for analysis of long-lived trace gases over the North American continent using either models or satellite observations. In particular, forward and inverse analyses of CO_2, CH_4, SF_6 and carbonyl sulfide have been significantly improved with weekly to monthly aircraft profiles made at 16 sites throughout North America (i.e. Stephens et al. 2007; Yang et al., 2007; Peters et al. 2007; Montzka et al. 2007; Maddy et al. 2008; Xiong et al. 2008; Xiong et al. 2009; Campbell et al. 2008; Crevoisier et al. 2009; Sweeney et al. 2010; Gloor et al. 2010). Additionally, the aircraft program has dedicated significant resources to flying intensive aircraft missions directed at monitoring changes in greenhouse gases at small (<20km) scales. These flights (i.e. Martins et al., 2009; Mays et al., 2009; Karion et al. 2010) seek to bridge the scaling gap from bottom-up flux estimates for fossil fuel and the terrestrial biosphere to top-down estimates from mole fraction measurements made at towers and infrequent aircraft profiles. Despite the success of the aircraft network in providing an independent estimate of regional fluxes (Crevoisier et al. in review and Sweeney et al. 2010), there continues to be a need to increase the spatial and temporal resolution of the aircraft network. Specifically, the regional CO_2 flux estimates have been made using data from multiple years in order to make estimates of average annual fluxes. To make independent flux estimates for single individual years at sub-continental resolution it will be necessary to dramatically increase the frequency and spatial resolution of profiles throughout North America. Below we outline how the aircraft program should be scaled up to resolve inter-annual variability in fluxes at a regional level. This plan takes advantage of two new sampling techniques that will add to the temporal and spatial sampling resolution of CO_2 and CH_4 in particular but is also likely to include many more tracers in the future.
Aircraft Flask Network – There are currently 16 sites in North America that do profiles every 2-4 weeks. The basic network plan will increase the sampling frequency to weekly at every station and add 8 additional stations by 2012 and another 12 stations by 2015. These new

sites will focus on areas such as the northwestern U.S. and Canada, and the southwestern and southeastern U.S., which presently have very few observations. The flask sampling network is of significant value to the air quality and atmospheric community because in addition to CO_2, CO, CH_4, SF_6, N_2O and H_2 we also measure isotopes of CO_2 and CH_4 a variety of halocarbons and hydrocarbons, in total about 50 chemical species. As the only network of its kind to regularly sample these gases up to 8000 m in altitude throughout the year, it serves a tremendous resource for the atmospheric community. These additional gases serve as a tool for carbon cycle gas source attribution.

Commercial Aircraft Network – Over the past four years the Aircraft Project has dedicated tremendous resources towards identifying and testing in-situ analyzers capable of making continuous measurements of CO_2, CH_4 and H_2O to be deployed on commercial aircraft. Like ships of opportunity, commercial airlines offer a relatively low cost way to collect large amounts of data throughout the continental US and abroad. Assuming a typical aircraft serving the continental US takes off and lands 3-4 times a day for 350 days, we estimate an additional 2500 profiles of CO_2, CH_4 and H_2O per year per aircraft. Although transcontinental aircraft fly far less frequently, deploying instrumentation on flights to South America will serve as a very important constraint on the role that the tropics play in the land-atmospheric carbon cycle. By deploying 10 instruments on domestic aircraft by 2016 and 2 more to tropical South America we expect to increase the number of profiles to roughly 26,000 per year with commercial aircraft alone, a very large increase from the ~430 profiles that we currently collect each year.

AirCore/Radiosonde profiles – Using a technology originally conceived of by Pieter Tans (NOAA/ESRL) the Aircraft Project has recently been able to demonstrate the utility of deploying a long (~150m) tube open at one end and closed at the other. As the tube ascends in either an airplane or on balloon a fill gas of a known mole fraction flows out. As the tube descends, the original fill gas is sequentially replaced by ambient air with a decrease in altitude. Because the diffusion of gas in the tube increases as the square root of time and is typically about three meter a day, the profile of CO_2 and CH_4 is preserved. Lab and field studies (Karion et al., 2009) show that after 9 hours of storage a 150 meter AirCore has vertical resolution of 170 m at sea level and 400 m at 8000 meters altitude. While we have demonstrated that aircraft deployment of the AirCore is relatively simple, work is still underway to design a system to facilitate retrieval of the AirCore after deployment for immediate analysis. Because the AirCore is lightweight and has very minimal power needs for temperature and location data, it could be deployed on many different aircraft, as well as on balloons. We have targeted 2016 as a time to have 5 balloon launch sites with weekly profiles of CO_2 and CH_4 to altitudes as high as 30 km. The AirCore program would be essential to help improve estimates of CO_2 and CH_4, and potentially other gases, from radiances measured by satellites, and could also be deployed in areas where aircraft availability is limited.



A.2. c) (Arlyn)

- Approximately 30 surface sites in combination with aircraft and global network data are needed for flux extimation and source attribution for the continental US in order to provide accurate continental totals and some regional detail.
- All sites should be equipped with automated flask sampling equipment so that air samples can be collected at least once per day. Data for multiple-species including pollution tracers like CO and refrigerants, especially when combined with radiocarbon, will aid in CO2 flux partitioning. Carbonyl sulfide is a promising tracer for biogenic uptake, at least for plants with a C3 photosynthesis pathway. The flask sampling will also provide daily time series for all of the important GHGs.
- New technologies have recently made continuous measurements of N2O and CH4 practical for deployment throughout the network. (All it takes is $$$)
- Partner sites could provide additional details at state and local scales. A major challenge would be to ensure that partner networks are reporting well-calibrated and quality assured data. Quality assurance for partner networks should include routine on-going comparision with flask samples to be collected at the sites and analyzed by NOAA.
- In the near-term (2010-2015), it makes sense to leverage measurements from sites that have been established by university researchers e.g., for use in CarbonTracker. In order to ensure data comparability, installation of NOAA automated flask sampling equipment at these sites should be a high priority. Sites that are maintained by university researchers often do not have stable funding. University sites that are shown to have sufficiently high-value could be supported by NOAA and eventually equipped with the NOAA instrument suite for continuous GHG

monitoring.

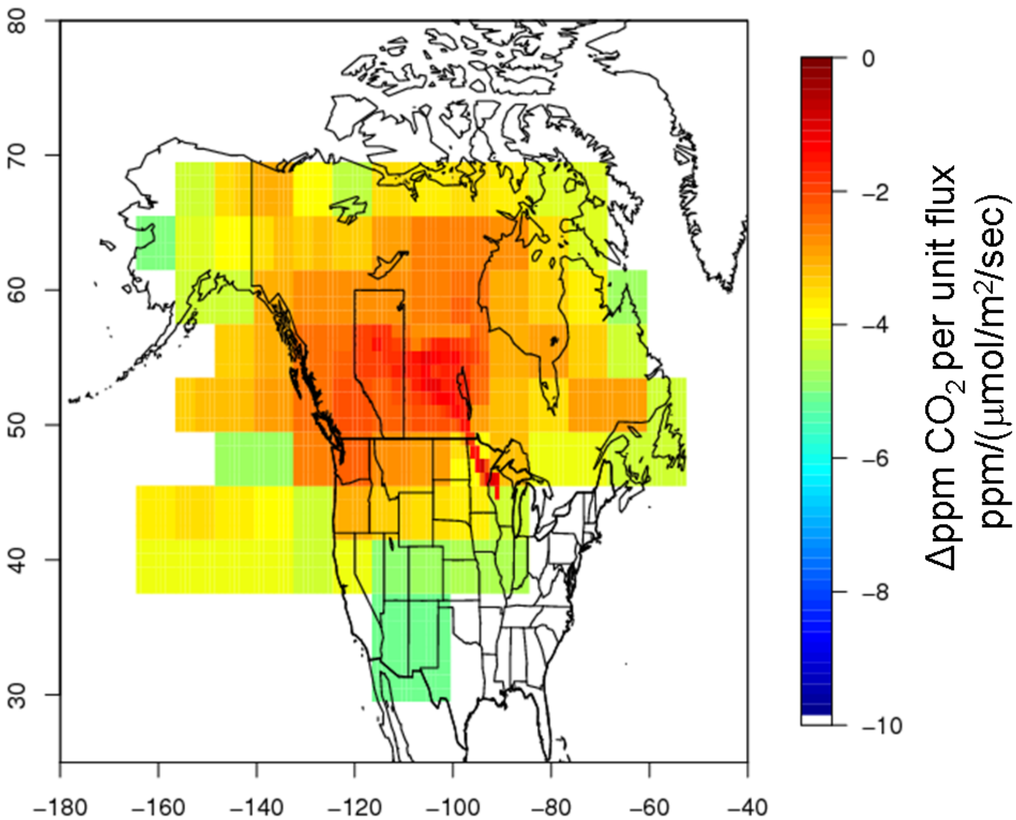


Image above: Example of a sampling footprint for a single mid-day measurement from a tall tower site (LEF, 14 LST 30 July 2008). The measured concentration is sensitve to CO2 fluxes hundreds of kilometers upwind.

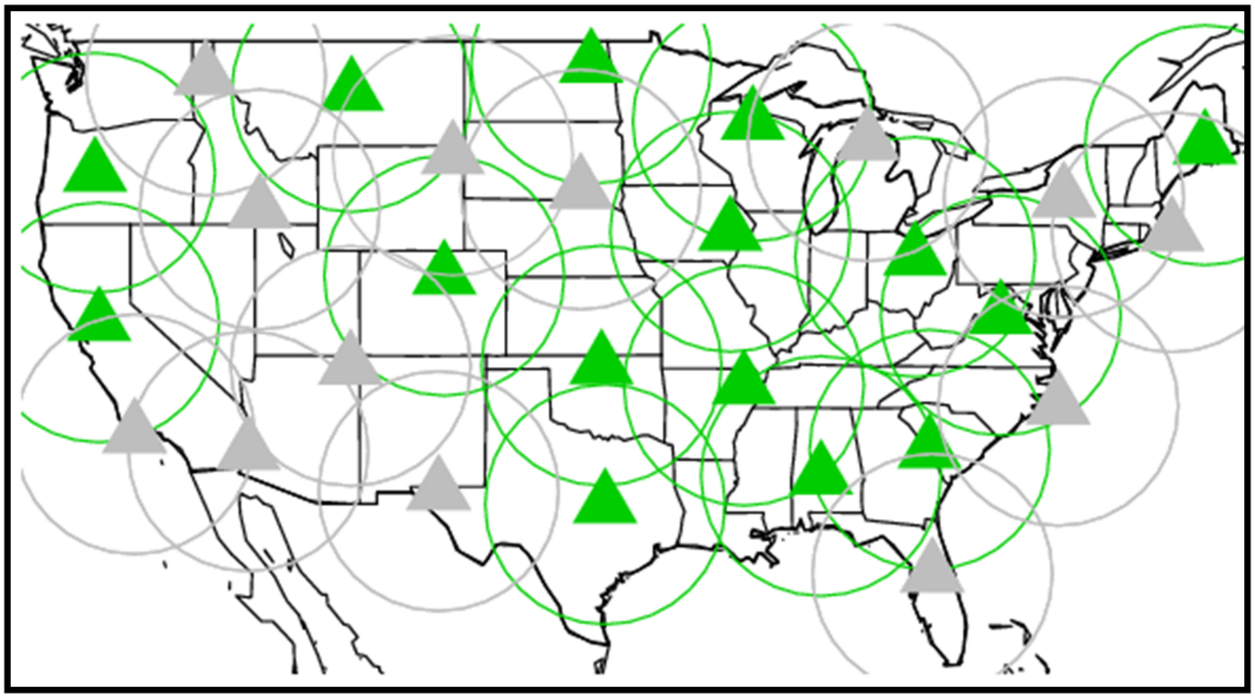


Image above: A hypothetical future tall tower and complex terrain sampling network that in combination with aircraft and global sampling would enable accurate flux estimation and source attribution at regional scales (10^5 - 10^6 km^2) for the continental US. The circles are meant to denote the approximate integrated footprint of each measurement location. Sites that are colored green are either existing or included in current NOAA plans. Grey symbols denote additional sites that would be needed to cover CONUS.

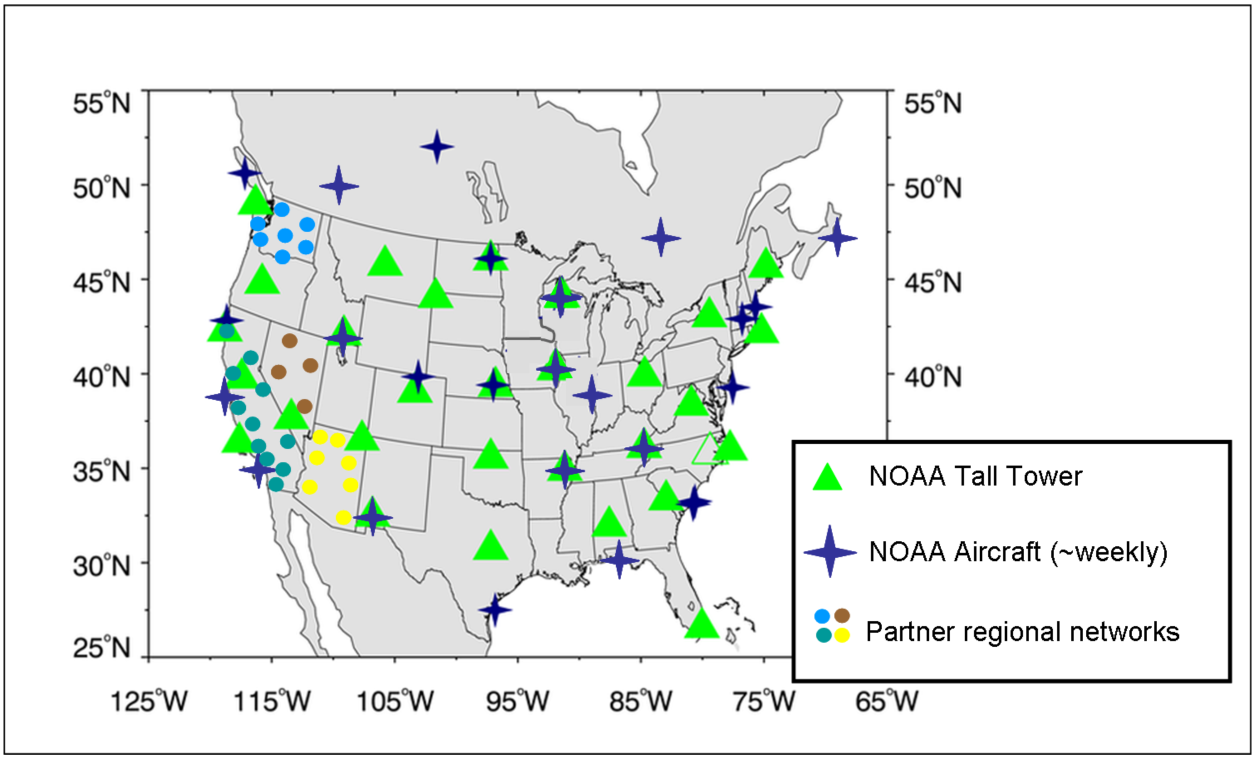


Image above: A hypothetical future North American network that shows the contribution of possible partner networks. The national scale 'core' network that would be maintained by NOAA would enable accurate flux estimation and partioning at the national and large regional scale. Partner networks would add information at state and local scales. A major challenge will be to ensure data comparability across individual partner networks. The core NOAA network will provide an integral constraint on the national budget and will provide enough regional detail to identify obvious biases in partner networks.

(Maybe above should have more A/C sites? e.g., over WKT, over 4 corners, over MT tower site, over OH tower site?--Arlyn) -- yes more AC sites

d) Focus on Arctic and tropics as regions of potential feedback.

3. Remote Sensing (Barnet)

a) Continued retrievals of CO_2 and CH_4 from AIRS

b) Retrievals of CO_2 and CH_4 from GOSAT (SCIMACHY, too?)

c) Ocean color, land cover (is this ‘in-house’?)

A.3.)(Barnet)

[JBM: GOES is used for fire detection and I allude to this in section III.]

A.3.a.)

The advantages of using satellites for the measurement of carbon are obvious. Satellites provide global, long-term coverage using instruments that are not subject to political boundaries. The difficulties in using satellites, however, are numerous. Making measurements from space with an accuracy of 0.5%, or better, are inherently difficult:

biases arise due to modeling of radiative transfer; unique solutions are difficult to achieve when multiple combinations of the values of geophysical variables can explain the measured radiance and when interference by clouds and aerosols occurs. Threading together multiple satellite records can lead to small inter-satellite biases and there are limitations imposed by spatial, vertical, and temporal sampling. In short, the present skill in the measurement of carbon from space is analogous to the measurement of meteorological parameters in the early 1970s [or ozone (O3) in the 1980s]. It took many years before spaceborne measurements had positive impact on numerical weather modeling and it will probably take many years before we can reliably employ satellite information in carbon cycle models.
Advances have been achieved by exploiting existing operational thermal sounder measurements from hyperspectral instruments such as NASA's Atmospheric InfraRed Sounder (AIRS), launched onboard the NASA Aqua satellite in 2002, and the European organization for exploitation of Meteorological Satellites (EUMETSAT) Infrared Atmospheric Sounding Interferometer (IASI), launched onboard MetOP-A satellite in 2006. These instruments have 1000s of high quality spectral "channels" between 2.3 and 15 microns that translate into a mid-tropospheric layer column average with a precision of 10%, 1.5% and 0.5% for CO, CH4, and CO2, respectively. Global retrievals from AIRS and IASI radiances have proven valuable to understand the distribution as well as the transport mechanisms of CO (McMillan et al. 2005 and Turquety et al., 2009), CH4 (Xiong et al., 2008 and Razavi et al., 2009) and CO2 (Engelen et al., 2004; Creviosier et al 2004, 2009; Chahine et al., 2005; Maddy et al., 2008; Strow et al. 2008). A major near-term challenge is to understand, in detail, the extent that these instruments can uniquely separate clouds, temperature, and CO2, which are all derived from the CO2 spectral bands, and to decide the best approach for exploiting these space assets. The choice of algorithms and a-priori information can radically affect the geophysical regimes sampled by these instruments, and the spatial and temporal scales as well as precision and accuracy of the potential products. Initial studies of the impact of these products in inversion models has not been positive (Chevallier et al. 2009, 2005) and indicates that there is much to learn about how to properly utilize the information measured by these satellites.
EUMETSAT has plans to launch a total of 3 IASI instruments and is currently working on the next generation of the IASI instrument. Measurements from these and similar instruments, as well as the planned Cross-Track Interferometric Sounder (CrIS) onboard NPP (launch no earlier than spring 2011), NPOESS C1 (Mar 2014) and C3 (2019)) should be available for the next 15+ years, thus having the potential for a 20-year self-consistent record of satellite thermal sounder-derived carbon trace gases along with information about temperature, moisture, ozone, clouds, surface changes and other trace gases. In the long-term, these measurements are invaluable because the top-of-atmosphere radiances themselves are a direct measure of climate change. The thermal infrared sounders along with co-located microwave sounders and visible imagers measure the complete state of the atmosphere, albeit at lower precision than *in-situ* measurements, and have the potential for understanding not only the atmospheric concentration of carbon, but also climate feedbacks, such as cloud, moisture, lapse-rate, and albedo.
A.3.b.)The short-wave infrared (SWIR) can also be used in reflected sunlight to measure the total column of CO2 and O2 to provide a surface weighted CO2 concentration. The reflected SWIR technique also has numerous challenges due to its higher sensitivity to reflected radiation from the surface, clouds, and aerosols. NASA's Orbiting Carbon Observatory (OCO) was designed to test this methodology, but unfortunately OCO failed to achieve orbit. A re-flight of a rebuilt OCO is currently being considered by NASA; however, it would not occur before 2012. NASA also has plans for an active SWIR mission called Active Sensing of CO2 Emissions over Nights, Days, and Seasons (ASCENDS); however, as a Phase-II decadal survey mission it would be launched no earlier than 2014.
The Japanese Aerospace Exploration Agency (JAXA) launched the Greenhouse gases Observing Satellite (GOSAT) in January of 2009 with a possibility of follow-on launches (GOSAT-II no earlier than 2014). This instrument has both SWIR and thermal sounding

capability. The stated goal of this mission is to demonstrate a 1% (4 ppmv) precision in monthly averaged total column CO_2. NOAA/NESDIS has near-term plans to inter-compare CO_2 and CH_4 derived from AIRS and IASI thermal IR measurements, GOSAT SWIR measurements, and profiles output from NOAA/ESRL/GMD's CarbonTracker assimilation system. This three-way inter-comparison should enable a better understanding of the strengths and weaknesses of satellite observations with varying vertical column sensitivities as compared to surface CO_2 and CH_4 driven models.

A.3.c.)Spaceborne observations of the terrestrial ecosystem are also critical for the understanding of the carbon exchange between land and atmosphere. Observations from the NOAA Advanced Very High Resolution Radiometer (AVHRR) instrument onboard TOVS and METOP satellites, NASA Moderate resolution Imaging Spectroradiometer (MODIS) instrument (onboard the Terra and Aqua satellites) as well as the European MSG SEVERI are useful for deriving parameters that characterize vegetation functioning, such as normalized difference vegetation index (NDVI), green vegetation fraction, leaf area index (LAI), net primary production (NPP), fraction of photosynthetically active radiation (fPAR). These sensors also allow for disturbance mapping, such as fire detection and burned area estimation. In the future, the R-series of the Geostationary Environmental Operational Satellite (GOES-R) and NPOESS Visible/IR Imaging Radiometer Suite (VIIRS) will also provide these products.

Terrestrial ecosystem disturbances, including biomass burning, can also be monitored by a number of current and future sensors. Capabilities exist for both active fire detection and characterization, and burned area mapping; these variables can be used for direct or indirect estimation of biomass burning emissions. Satellite data also can be used to estimate fire risk, thus providing predictive capability of potential leakage from terrestrial sequestration. Estimates of above ground biomass can be monitored now using moderate resolution (i.e. Landsat-class) optical instruments. Available sensors include the current Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the future Landsat Data Continuity Mission (LDCM), and NASA/HyspIRI missions as well and international assets. Above-ground biomass measurements can be done by active remote sensing from LIDAR and Radar observations. Missions include the current ICESAT-GLAS and the future decadal survey missions ICESAT-II and NASA/DESdnyl as well as ESA's current Radarsat-2 and upcoming GMES Sentinel-1 European Radar Observatory. NOAA/NESDIS intends to fully exploit these experimental missions to develop capacity for future enhanced products. Radar data are also useful for all-weather land cover mapping.

The operational commitment of hyperspectral sounding instruments and high spatial resolution imagers for weather applications translates to a low-cost, long-term asset for the carbon community. In the short-term we need to understand how to incorporate low-precision measurements of carbon into data assimilation systems. It seems plausible that thermal sounders can improve the knowledge in large-scale vertical and horizontal transport of greenhouse gases in the atmosphere. Given that all satellite sounder measurements (e.g., AIRS, IASI, GOSAT) represent a volume measurement (large spatial footprint and thick vertical column) there is much to learn about assimilating measurements with large "transport footprints" into models. Vertically, these soundings represent a mixture of air from different sources and coupled with inherent biases (in the soundings and model transport); thus, these measurements pose a distinct challenge for models.

What is needed is a complete carbon accounting system that includes changes in anthropogenic emissions, land use change, land disturbance, and changes in terrestrial and oceanic responses. The intelligent use of direct measurements provided by sounders and imagers should be able to provide useful constraints to the scientific understanding of carbon cycle and climate.

In the long-term it is not clear what the satellite role can be for high accuracy, small spatial scales that will be needed for emissions monitoring. The current cap-and-trade legislation under consideration will require monitoring on small regional scales (country, state, and county scales). Accommodation of emission offsets in cap-and-trade legislation may require monitoring of point sources, which as stated above is a challenge for the volume measurements, as well as diffuse sources from agriculture and afforestation projects that may be equally problematic for models driven by emission estimates from these sources.

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B. Modeling

1a. Atmosphere: CarbonTracker (Jacobson)

- **i)** Improvements in transport including incorporation of very high resolution (say 5 x 5 km) nested mesoscale models. Use of additional transport models including the ESRL FIM and GFDL AM2 models.
- **ii)** Increased use of observations, including nighttime and hourly resolution data (currently only 1 obs/site/day) and satellite data.
- **iii)** Use of multiple species, e.g. $CO_2 d^{13}C$ of CO_2, $^{14}CO_2$, CO, COS, and halo/hydro-carbons in order to solve for processes.
- **iv)** Estimation of bio-geo-physical parameters from observations.

1b. RW" The ocean SOOP and mooring CO2 network will ultimately provide near real-time coverage of surface water CO2 levels at a course resolution. Means for spatial and temporal interpolation and a means to convert surface CO2 levels to fluxes will be critical to obtain a high resolution air-sea CO2 flux fields. Moreover, improved mechanistic understanding will aid model development. A promising approach, to complement the inverse modeling efforts such as performed in Carbontracker for land,. are the empirical air-sea CO2 flux maps in which surface water CO2 levels are related to SST at the highest resolution practical. CO2 and SST show a strong co-variance over the ocean with spatially and seasonally distinct trends. Current efforts obtain the pCO2sw and SST trends from the climatology of Takahashi et al. (2009) and for the 1600+ pixels derive trends for each pixel with an average correlation coefficient of over 0.8. These correlations are then used to determine interannual variability in air-sea CO2 fluxes from 25-year SST and wind records. Since the air-sea CO2 flux is the product of the gas transfer velocity, mostly parameterized with wind, and air-water CO2 difference, improved knowledge of the factors impacting the gas transfer velocity are necessary. The three successful gas exchange studies funded by NOAA and other agencies have provided key insights in the gas transfer process and aided in decreasing the uncertainty in the gas transfer-wind speed parameterizations. The studies have also been a treasure trove of understanding the controls of CO2 levels in the surface ocean and the interaction between organic carbon and nutrient cycles.

The air-sea CO2 flux maps have been validated using a ocean biogeochemical model showing that the approach is robust albeit underestimating the interannual variability by about 25 %. The immediate application is to utilize the maps as priors in inverse modeling effort. The approach should be applied to the near real-time data coming from SOOP and moorings, and incorporate other diagnostic input parameters such as mixed layer depth that can now be obtained from the profiling float program for much of the world's ocean.

2. Prognostic: GFDL Earth System Model (Stouffer, Dunne)

a) Our research plans for the next several years will focus on producing the integrations needed in support of CMIP5 and IPCC AR5 to assess carbon-climate feedbacks in the earth system. We will also be making runs to investigate various scientific questions which will arise from those runs and elsewhere. These studies include a suite of investigations of the earth system:

i) Land use impacts on the global carbon budget
ii) Impacts of increasing CO_2on ecosystems
iii) Oceanic heat and carbon uptake
iv) Carbon cycle feedbacks
v) Climate – Living Marine Resource interactions
vi) Paleo-climate simulations with a focus on the holocene and last glacial maximum

b) Over the next several years, using the analysis of the integrations outlined above, we will also be improving our models. These improvements include:
i) Closing additional biogeochemical cycles (e.g N, P, CH_4, Fe)
[JBM: Can carbon stable isotopes d13C and d18O be added to this list?}
ii) Enhancing representation of biodiversity
iii) Improving existing components such as dust, sea salt, fire, land use
iv) Migrate to the next generation climate model (CM3)-based ESM
v) Investigation of high resolution simulations
vi) Assessment of the role and representation of coastal processes
vii) Simulation of seasonal-decadal scale variability analysis/prediction