Abstract

The high latitude regions of both hemispheres have experienced significant climate change over the past several decades, which is strongly linked to secular trends in the Northern and Southern Hemisphere annular modes (NAM and SAM, respectively). Both annular modes have marked climate impacts at the ocean and land surfaces, and hence have likely had a substantial impact on the global carbon cycle. Inverse modeling of atmospheric CO_2 shows that the time-mean carbon budget of the extratropics is characterized by land and ocean sinks of about 2/3 of anthropogenic CO_2 emissions (partly balanced by weak tropical sources). Interannual variability in the carbon cycle is mostly associated with tropical changes associated with the El-Nino/Southern Oscillation phenomenon, which has been well studied, but relatively little is known about changes in the major extratropical sink regions that are impacted by the NAM and SAM.

We propose a three-year interdisciplinary research program to systematically investigate the mechanisms by which the NAM and SAM affect components of both terrestrial and marine carbon fluxes. Using a suite of remotely sensed and in-situ data, models of physical and biogeochemical processes on land and in the ocean, and atmospheric inverse modeling, we will quantify the effect of climate variations associated with the NAM and SAM on various time scales. The proposed research requires understanding of large-scale dynamics of the atmosphere and oceans, marine and terrestrial carbon cycling, and atmospheric transport inversion modeling of CO2 fluxes. The proposed research has substantial implications not only for our interpretation of secular variations in the carbon cycle over the past few decades, but for projections of future concentrations of atmospheric carbon as well.

This proposal directly addresses the following question from the NRA: ***How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?***

1. Introduction

Overview

About half of the CO_2 released by fossil fuel combustion is currently taken up by sink processes in the ocean and the terrestrial biosphere (IPCC, 2001). Among the most robust results of atmospheric inverse analyses of CO_2 variations is that these sink processes are particularly strong in the middle and high latitudes of each hemisphere (Gurney et al, 2002). Northern hemisphere terrestrial processes and uptake in the North Atlantic Ocean account for 3.3 +/- 1.3 Pg C yr^{-1} (1 Pg = 10^{15}g), and the extratropical southern oceans account for another 1.0 +/- 1.5 Pg C yr^{-1}. These important carbon sink regions are currently experiencing rapid climate change which is likely to have important impacts on the global carbon cycle.

A large fraction of recent climate change observed in the middle and high latitudes of each hemisphere are related to systematic secular variations in the leading modes of extratropical climate variability: the Northern and Southern annular modes. Since the annular modes have marked climate impacts throughout the ocean and land surfaces of their respective hemispheres, they likely play an important role in the global carbon cycle. Previous work on climate-related variability in the carbon cycle has focused largely on the tropics, because much of the interannual variability in atmospheric CO_2 growth rates is associated with the El Nino Southern Oscillation (ENSO). In contrast, very little is known about the linkages between the annular modes and the global carbon cycle. The annular modes may be particularly important for understanding secular variations in global carbon since, unlike ENSO, there have both exhibited strong secular trends over the past several decades. In the proposed research, we will systematically explore the relationships between these important patterns of extratropical climate variability and the global carbon cycle. The research requires not only an understanding of large scale atmospheric dynamics, but of the physical and biogeochemical processes that underlie the exchange of carbon at both the ocean and land surface as well. Hence, the proposed research requires an interdisciplinary approach.

Motivation

The growth rate of atmospheric CO_2 from year to year is far from being constant, but varies substantially around the long term mean (1982 to 2002) of about 1.5 ppm yr^{-1} (Bacastow 1976; Keeling et al. 1989; Conway et al. 1994) (Figure 1). These fluctuations are equivalent to the transfer of up to several Pg C in or out of the atmosphere and close to the magnitude of the fossil fuel emissions. Since variability of anthropogenic CO_2 emissions is low, the observed variability in atmospheric CO_2 growth rates must be a consequence of variations in the exchanges with the ocean and terrestrial biosphere, respectively. The relative roles of these two reservoirs in contributing to this observed variability in atmospheric CO_2 are not well known nor are the processes underlying these variations understood (e.g. Quay 2002; LeQuéré et al. 2003).

The existence of large interannual variability in the carbon cycle provides evidence that, despite strong heterogeneity at small scales, the response of the land and ocean carbon cycle to climatic forcing is reasonably coherent at spatial scales of several 100s if not 1000s of kilometers. This suggests that the global carbon cycle is sensitive to changes in the physical climate system, and therefore might respond in a substantive manner to possible future climate change. It is thus important to quantify the relative role of the ocean and land biosphere for atmospheric CO_2 fluctuations on interannual to decadal time scales as well as to understand the mechanisms underlying these variations if we want to understand how future climate change might affect the uptake of anthropogenic CO_2 by the oceans and the terrestrial biosphere.

The quantification of interannual to decadal variability in the global carbon cycle has been the subject of numerous studies. Most of these studies can be divided into those that used large-scale observations of atmospheric constituents (CO_2, O_2, $\delta^{13}C$ of CO_2) to decipher the flux variability ("top-down" approach) and those that use in-situ observations and/or models to constrain the fluxes at the earth surface ("bottom-up" approach). Figure 2 shows a recent summary of such bottom- up and top-down approaches. No clear consensus exists between the various methods, particularly at interannual time scales. Land variations tend to be larger than those of the ocean, which reflects the fact that the characteristic exchange timescale for a surface ocean CO_2 anomaly is about one year, which leads to a strong damping effect of short-term variations. On decadal timescales, the various methods agree that the land and ocean variations are of about equal magnitude.

Much of the research on the causes of the observed variations has focused on the response of the global carbon cycle to El Niño/Southern Oscillation (ENSO). This is in one part due to the early recognition that the global mean atmospheric growth rate tends to correlate with ENSO (see Figure 1) (Bacastow 1976). As a consequence of these research efforts, substantial progress has been made in our understanding how ENSO affects the carbon cycle on land and in the ocean (Feely et al. 1987; Inoue and Sagimuru 1992; Feely et al. 1995; Boufin et al. 1999; Feely et al. 1999; Loukos et al. 2000; Rayner et al, 1999; Lucht et al, 2002; Schaefer et al, 2002).

By contrast to the rapid evolution of our understanding of the response of the global carbon cycle to ENSO, our understanding of the role of extratropical variations in the global carbon cycle is very small. This is worrisome for two reasons. First, virtually all climate model simulations for the 21st century suggest that the high latitudes are going to experience a larger climate change than the low latitudes (IPCC, 2001). Secondly, observations of past trends in many high latitudes locations (particularly in the northern hemisphere) indicate that substantial changes have already occurred (Myneni et al, 1997; Tucker et al, 2001, Lucht et al, 2002). A number of important and large carbon pools that are very vulnerable to climate change are located at high latitudes (Gruber et al. 2003), and high latitude regions of both hemispheres account for nearly all of the carbon sink under current conditions (Gurney et al, 2002). It is therefore critical to undertake a concerted coupled ocean-atmosphere-land biosphere investigation of how the global carbon cycle is responding to extratropical climate variability. Satellite observations will play an extremely important role in undertaking this study, as in-situ observations at higher latitudes are often very sparse and intermittent. Because the dominant modes of climate variability in the extratropics of both hemispheres are the annular modes, we propose to carefully analyze the mechanisms by which these variations modulate the terrestrial and marine carbon cycles. These modes have undergone significant secular trends in recent decades, accounting for large factions of extratropical climate change (Thompson et al. 2000). If these trends continue, the analysis we undertake here will provide enhanced predictability for future changes in the carbon cycle over coming decades.

This proposal directly addresses the following question from the NRA: ***How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?***

In this proposal, we outline a strategy for systematically quantifying and understanding the mechanisms whereby extratropical climate variability impacts the global carbon cycle. Section 2 overviews the relevant scientific background: Section 2.1 discusses the dominant patterns of extratropical climate variability; Section 2.2 discusses the relationships between climate variability and the terrestrial carbon cycle, and Section 2.3 reviews relevant aspects of the ocean carbon cycle. In Section 3, we outline the principal research objectives of the proposed research, and in Section 4, we detail the proposed research.

2. Scientific background

2.1 The dominant modes of climate variability

Considerable research effort has been placed in understanding the link between the ENSO phenomenon and the global carbon cycle. In contrast, relatively little effort has been spent understanding the linkages between carbon fluxes at Earth's surface and the leading patterns of extratropical climate variability. Here we briefly overview the key aspects of extratropical climate variability that is relevant for the proposed research.

Climate variability in the extratropical circulations of both hemispheres is dominated by the Northern and Southern Hemisphere annular modes (NAM and SAM, respectively). The NAM and the SAM are both characterized by meridional seesaws in geopotential height between the polar regions and the middle latitudes (bottom left panels of Figures 3 and 4). Periods when geopotential height is anomalously low over the pole (the so-called high index polarity of the annular modes) are characterized by stronger than normal zonal flow along ~55°-60° latitude. In the Northern Hemisphere, the stronger than normal zonal flow associated with the high index polarity of the NAM sweeps relatively warm air into much of the northern land masses, and also brings enhanced precipitation to northern Europe and, to a lesser extent, northwestern North America (Hurrell 1995; Thompson and Wallace 2000, 2001). In the Southern Hemisphere, stronger than normal flow associated with the high index polarity of the SAM acts to substantially strengthen the westerlies that drive the surface circulation of the Southern Ocean. The observed structure of the NAM in temperature and precipitation is shown in the bottom panels of Figure 3, and is documented extensively in recent papers by Hurrell (1995), Thompson and Wallace (1998, 2000), and in the review volume by Hurrell et al. (2002), among others. The observed structure of the SAM is shown in the lower panels of Figure 4, and is documented in, for example, Kidson (1998), Karoly (1990), Hartmann and Lo (1998), and Thompson and Wallace (2000).

The Northern Hemisphere annular mode (NAM) is alternatively referred to as the North Atlantic Oscillation (Hurrell et al. 2002) and the Arctic Oscillation (Thompson and Wallace 1998). The physical distinction (or lack thereof) between the NAM and the NAO is currently under investigation by the atmospheric dynamics community, but the distinction has no bearing on the proposed research. The Southern Hemisphere annular mode (SAM) is alternatively referred to as the Antarctic Oscillation (Thompson and Wallace 2000) and the High Latitude Mode (Kidson 1988).

There are two aspects of the NAM and the SAM that provide key background and motivation for the proposed research: 1) both annular modes have marked climate impacts at the surface of Earth throughout their respective hemispheres; and 2) both patterns have exhibited statistically significant trends towards their high index polarity over the past few decades. Over the land areas, the high index polarity of the NAM is associated with warmer than normal conditions throughout North America and Eurasia (Figure 3, bottom middle; Hurrell 1995; Thompson and Wallace 2000, 2001), wetter than normal conditions throughout Northern Europe (Hurrell 1995), and drier than normal conditions throughout southern Europe (Hurrell 1995) and the Middle East

(Cullen et al. 2001) (Figure 3, bottom right). Over the ocean areas, the high index polarity of the NAM is associated with colder than normal conditions over the Labrador Sea region but warmer than normal conditions over the Greenland/Iceland/ Norwegian Sea regions, conditions which favor enhanced deep water formation to the west of Greenland but decreased deep water formation to the east of Greenland (Dickson et al. 1997). Also over the ocean areas, the high index polarity of the NAM is associated with stronger than normal westerly flow across the North Atlantic (Kushnir et al. 1997;), and by a strengthening of the trade winds that extends deep into the subtropics throughout the Pacific and Atlantic halves of the hemisphere (Thompson and Wallace 2000). In all cases listed above, the low index polarity of the NAM is associated with climate anomalies in the opposite sense.

The largest climate impacts observed in association with the SAM are found over the Southern Ocean and Antarctica (Figure 4, bottom panels; Thompson and Wallace 2000; Thompson and Solomon 2002); i.e., much of South America and Africa lie too far equatorward to be strongly impacted by variations in the SAM. Over the Southern Ocean, the high index polarity of the SAM is associated with a marked strengthening of the subpolar flow along ~55-60°S (Figure 4, bottom; Thompson and Solomon 2002) and by zonally coherent fluctuations in Southern Ocean sea levels (Hughes et al. 2003). Based on model simulations, Hall and Visbeck (2002) suggest that the strengthening of the westerly winds over the Southern Ocean that is associated with high values of the SAM index leads to a strengthening of the northward Ekman drift, which causes negative SSTs over much of the region north of the polar front. They also suggest an increase in the convergence in the subantarctic region.

The recent trends in the annular modes have contributed substantially to observed climate change over the past few decades (Figures 3 and 4; Hurrell 1995; Thompson and Wallace 1998, 2001; Thompson and Solomon 2002). In the NH, the largest trends have occurred during the NH winter months (Thompson and Wallace 2001); in the SH the largest trends have occurred during the SH spring- summer season (Thompson and Solomon 2002). In both hemispheres, the trends impact precisely those regions of the world that account for nearly all of the current carbon sinks, both on land and in the ocean.

The results in Figures 3-4 demonstrate the striking contribution of the trends in the annular modes to climate trends in their respective hemispheres. Since the late 1960s, the trend in the NAM is linearly consistent with virtually all of the structure in recent NH wintertime surface temperature trends, roughly 50% of the 3 K warming over Eurasia, and roughly 30% of the 1.7 K warming of the NH land areas as a whole from 1968-1997 (Thompson et al. 2000). In fact, the trend in the NAM has accounted for a larger fraction of the recent decreased incidence of extreme cold events throughout much of the NH than has the observed global warming over this same period (Thompson and Wallace 2001). The trend in the NAM is also consistent with most of the ~40-50% increases in precipitation over Northern Europe and the ~40% decreases in precipitation over Southern Europe and the Mediterranean (Thompson et al. 2000). Similarly, a large fraction of recent surface temperature trends over Antarctica and virtually all of the strengthening of the circumpolar flow over the Southern Ocean during the SH summer-fall season are related to the trend in the SAM.

Despite the evident importance of the annular modes in recent climate change, the linkages between the annular modes and the global carbon cycle remain largely unknown. Investigating these linkages will require not only an understanding of the annular modes, but of the physical and biogeochemical processes that underlie the exchange of carbon at both the ocean and land surface as well. These physical processes form the basis for the next two sections.

2.2 Climate Variability and the Terrestrial Carbon Cycle

Atmospheric inversion studies as well as most land ecosystem models show that a substantial fraction of the interannual variability observed in atmospheric CO_2 is associated with changes in the net exchange of CO_2 between the atmosphere and the land biosphere (e.g., see Figure 2). The impact of the ENSO phenomenon on the net exchange of CO_2 between the atmosphere and the land biosphere has received considerable attention in the literature (Bacastow et al, 1976; Keeling et al, 1989; Rayner et al, 1999; Schaefer et al, 2002). In contrast, very little attention has been placed on the relationship between the terrestrial carbon cycle and climate variations at higher latitudes, in particular those associated with the NAM and the SAM.

Variations in the terrestrial carbon cycle are associated with changes in the rate of photosynthesis, ecosystem respiration, decomposition, and/or disturbances such as fire and deforestation. The net ecosystem exchange (NEE) of carbon between terrestrial and the atmosphere is defined as the difference between two (usually much larger) fluxes due to photosynthesis (gross primary production, GPP) and respiration (R). Respiration by plants is referred to as autotrophic respiration (R_a) and decomposition of dead organic matter by microbes is referred to as heterotrophic respiration (R_h). Climate variability affects both GPP and R at many temporal and spatial scales. On subdiurnal time scales, photosynthesis responds to changes in radiation, temperature, and humidity at leaf to canopy scales, and is linked by stomatal physiology to transpiration and the surface energy budget. On synoptic to seasonal time scales, anomalies in regional precipitation, evaporation, temperature, and snow cover influence both GPP and respiration by impacting soil moisture and soil temperature. On seasonal to interannual time scales, net primary production (NPP = GPP – Ra) reflects accumulated biogeochemical responses to climate anomalies and is manifested in changes in plant growth, which in turn can lead to secular trends in carbon fluxes and storage.

The mechanisms by which climate variations modulate the terrestrial carbon cycle are complex. Ecosystem respiration generally increases with temperature, but is also modulated by soil moisture, the size of the respiring carbon pools, and possibly by substrate quality. The impact of climate variations on photosynthesis is even more complicated, and reflects both physiological and biogeochemical responses to many meteorological "drivers."

The NAM has a pronounced impact on high latitude climate and therefore has a substantial impact on the flux of carbon between the atmosphere and the land biosphere. For example, the secular trend in land-surface temperatures in some high-latitude regions is an order of magnitude stronger than for the global mean, and is strongly associated with the trend in the NAM. Both GPP and decomposition are expected to be impacted by these trends, and the net effect on the global carbon cycle reflects the balance between climate forcing of the component fluxes. High-latitude warming is manifested in lengthened growing seasons in some areas, and is detectable in satellite vegetation data in terms of both phase and amplitude of seasonal greening, especially in those areas most strongly impacted by climate change associated with the NAM (Myneni et al, 1997; Tucker et al, 2001, see Figure 5). An accelerated carbon cycle in these regions is also associated with a pronounced increase in the seasonal amplitude of atmospheric CO_2 (Keeling et al, 1996), and probably indicates increased storage of carbon as biomass (Lucht et al, 2002). Nevertheless, boreal warming is also likely to lead to more rapid rates of decomposition and perhaps to drier soils, which could release some stored carbon (e.g., Goulden et al, 1996).

Climate variability associated with the NAM is also likely to impact the timing of growing season onset through changes in snowpack and soil temperature during winter. In some areas, warmer winter climate can actually lead to colder soil temperatures due to reduced depth of insulating snow cover, which may lead to inhibition of springtime decomposition. NAM-related changes in the hydrologic cycle could also be associated with drought conditions, and thereby affect carbon losses due to changes in fire frequency. Photosynthesis is modulated by changes in relative humidity during the growing season, whereas respiration and decomposition are relatively unaffected. NAM-related carbon cycle variability is expected to manifest differently in different regions and in different seasons. We plan to quantify the magnitude and spatial patterns of variation of each component carbon flux associated with NAM-related climate variations on many time scales. By mechanistically separating the effects of anomalies in temperature, precipitation, and leaf area index on GPP, R_a, and R_h over a period of 20 years, we will greatly enhance our ability to predict changes that are likely to occur with secular trends in the NAM.

2.3 Climate variability and the ocean carbon cycle

The impact of climate variations on the ocean carbon cycle is not well established because of the sparseness of in situ observations of parameters relevant to the ocean carbon cycle. The tropical Pacific has received most attention, as this region is at the heart of the El Niño/Southern Oscillation (ENSO) phenomenon. The response of the ocean carbon cycle in this region to ENSO is large and has been well described (Feely et al. 1987; Inoue and Sagimuru 1992; Feely et al. 1995; Boutin et al. 1999; Feely et al. 1999; Loukos et al. 2000; Chavez et al. 1999). In the equatorial Pacific, it is sufficient to first order to understand how equatorial upwelling responds to variations in meteorological forcing in order to predict the response of the carbon cycle. It is unlikely that this is the case in the extratropics, where the interactions between biological, physical and chemical factors play a much more important role. Substantial variability of the ocean carbon cycle occurs at mid to high latitudes, due to variability of the mixed layer depth and of export production, which constitute key drivers (see Figure 6).

The exchange flux of CO_2 across the air-sea interface (F_{ex}) is usually estimated on the basis of a bulk formula that relates the flux to the air-sea CO_2 partial pressure difference and a gas exchange coefficient, k_{ex}, which itself is a strong function of windspeed (u) and to a much lesser degree temperature:

$$(1)\ F_{ex}=k_{ex}(1-\gamma_{ice})(p\mathrm{CO_2}^{atm}-p\mathrm{CO_2}^{oc})$$

where γ_{ice} is the fraction covered by sea-ice. In (1), $k_{ex}=f(\mathrm{T,u})$, and $p\mathrm{CO_2}^{oc}=f(\mathrm{T,S,DIC,Alk})$. DIC and Alk are mainly controlled by ocean transport and mixing and their interaction with photosynthesis, respiration and remineralization processes. The interplay between the SST forcing and the mixing/biology induced forcing determines the net response of oceanic $p\mathrm{CO_2}$ to changes in the physical environment. Variations in wind speed modulate then these oceanic $p\mathrm{CO_2}$ anomalies into the actual air-sea flux anomalies.

The main drivers for interannual variations in *DIC* are changes in the strength of upwelling and variability in the entrainment of DIC from below as a consequence of mixed layer depth variations. In nutrient limited regions, enhanced upward mixing/transport of DIC and nutrients leads to enhanced primary production and export of carbon, thereby reducing the DIC anomaly. In light limited regions, enhanced mixing will likely lead to reduced primary production and export, thereby enhancing the mixing/transport induced DIC anomaly. We therefore expect a fundamentally different response of ocean biology at high latitudes (light limited) relative to the lower latitudes that are most often nutrient limited. At the same time, regions and times of enhanced vertical mixing/transport are usually characterized by lower than normal temperatures, which leads to a tendency to compensate the DIC effect on $p\mathrm{CO}_2$.

Ocean carbon-cycle response to NAM

Bates (2001) and Gruber et al. (2002) demonstrated that interannual variations of the NAM have a profound impact on the carbon cycle near Bermuda, primarily by controlling the variability in winter time convection, which then has a profound influence on the entire seasonal cycle (see Figure 7). Gruber et al. (2002) suggested that the fundamentally different response of the carbon cycle in subtropical latitudes and subpolar latitudes to variations in mixed layer depth might lead to a coordinated basin scale response in the case of the North Atlantic. This is because the meridionally asymmetric forcing associated with NAM (cold anomalies in the Labrador Sea; warm anomalies in the subtropical gyre) could be rectified by the asymmetric response, leading to positive $p\mathrm{CO}_2$ anomalies at all latitudes during positive phases of the NAM. The inverse modeling analysis of atmospheric CO_2 variations by Bousquet et al. (2000) finds CO_2 flux variability over the North Atlantic which is consistent with this hypothesis. They also find variability over the North Pacific of similar magnitude, correlated to some degree with ENSO and the Pacific Decadal Oscillation (PDO), possibly indicating that a mechanism similar to that in the North Atlantic is occurring in the North Pacific.

Ocean carbon-cycle response to SAM

During the positive phases of the SAM, the anomalous westerlies over the Antarctic Circumpolar Current (ACC) lead to an increase in the northward Ekman transport at latitudes from around 60°S to 45°S and an increase in the upwelling near the Polar Front (Hall and Visbeck 2002). The poleward shift of the polar jet leads to anomalous easterlies at mid-latitudes, causing poleward anomalous Ekman transport. The increased equatorward Ekman transport south of ~45°S and the increased poleward Ekman transport at around 35 to 40°S cause an enhanced convergence within the Subantarctic Zone (SAZ), which is the zone between the Sub- antarctic Front and the Subtropical Front (Belkin and Gordon 1996). The SAZ plays a fundamental role in the dynamics of the Southern Ocean (Sarmiento et al. 2003) in that it is characterized by the deepest winter mixed layers in the Southern Ocean. In addition, it represents the formation region of Subantarctic Mode Water (SAMW) that ventilates the upper portions of the Southern hemisphere thermocline (McCartney,1977). Hall and Visbeck (2002) suggested that much of the region south of the subtropical front would have negative SST anomalies during positive phases of the SAM, mostly due to the increased advection of cold SSTs equatorward. Rintoul and England (2002) support this suggestion, by arguing that the SST anomalies observed within the SAZ are too large to be caused by local air-sea fluxes and must therefore be advected into the region. We suspect that the SST decrease in the SAZ together with the stronger Ekman convergence will lead to deeper mixed layers and an increased rate of formation of SAMW.

The increased upwelling near the polar front brings highly enriched DIC waters to the surface, which are then swept equatorward. As biology in these areas is not limited by macronutrients, the additional nutrients brought up with this anomalous upwelling do not fuel extra production. We expect lower than normal production, particularly in the SAZ, where the deeper than normal mixed layer leads to an intensification of the light limitation. As we expect the reduction in $p\mathrm{CO}_2$

due to the lower than normal SSTs to be relatively small, we argue that the positive DIC anomalies will cause positive pCO_2 anomalies throughout the Southern Ocean south of the Subtropical Front. This effect will be compensated to some degree by an expected increase of anthropogenic CO_2 into the ocean, as the increased upwelling and increased formation of SAMW will provide an enhanced conduit of anthropogenic CO_2 into the interior ocean. However, we don't expect this anomalous flux to exceed the negative anomaly associated with the natural CO_2 flux. In summary, we postulate that positive phases of the SAM will cause a negative CO_2 flux anomaly in the Southern Ocean.

3. Objectives

The over arching objective of the proposed research is to understand and quantify the relationships between large-scale climate variability and the global carbon cycle, with particular emphasis on the linkages with extratropical climate variability. In the first half of the proposal, we reviewed the dominant patterns of interannual variability in the extratropical circulations and the role that these patterns have played in observed climate change over the past few decades (Section 2.1), discussed the physical and biogeochemical processes that influence both the terrestrial and ocean carbon cycle (Sections 2.2, 2.3), and outlined the potential impact of the leading modes of extratropical climate variability on the flux of carbon at Earth's surface in both hemispheres (Sections 2.2, 2.3). In the second half of the proposal, we outline the workplan that will be used to guide the proposed research. The workplan is divided into four objectives, each of which reflects a necessary step towards better understanding the linkages between climate variability and the global carbon cycle.

1: Quantify and analyze anomalies in the flux of CO_2 at the land-atmosphere interface
2: Quantify and analyze anomalies in the flux of CO_2 at the ocean-atmosphere interface
3: Synthesize ocean/atmosphere/land CO_2 flux anomalies
4: Assess relationships with modes of extratropical climate variability

4. Workplan

Objective 1: Quantify and analyze anomalies in the flux of CO_2 *at the land surface*

We propose to use a numerical model that represents the exchanges of energy, water, and carbon at the land surface. The model we will use is a new version of the simple biosphere model (SiB3, Sellers et al, 1996, Denning et al, 1996). The model predicts exchanges of heat, water, and CO_2 on subhourly time steps, using linked photosynthesis (Farquahar et al, 1980) and stomatal physiology (Collatz et al, 1991, 1992) logic. We have previously used the model to analyze variations of GPP and ecosystem respiration and their dependence on climate variability (Schaefer et al, 2002; Fig 9). The simulations proposed here will use a recently developed parameterization of allocation and carbon cycling in live biomass, litter, and soil derived from similar logic in the CASA model (James Collatz, personal communication, see attached letter of collaboration). The model also predicts the temperature, water, and ice content in 10 soil layers, and includes an adaptive grid for predicting temperature and density of up to five layers of snow. Simulation of drought stress and deep soil moisture is much improved over earlier versions of the model (Liu et al, 2003). We diagnose instantaneous impacts of physiological stresses such due to environmental forcing and accumulate them as daily means. These diagnostics will allow us to analyze mechanistic responses of each flux component to specific types of climate forcing (e.g., reduction of GPP in μMol m^{-2} s^{-1} due to root zone water stress or temperature, see Schaefer et al, 2002).

We propose to perform a 20+ year analysis of daily gridded maps of GPP and autotrophic and heterotrophic respiration, using SiB3 driven by a combination of satellite imagery and climate data. The model time step is 10 minutes, and we will analyze the variability of the carbon fluxes on synoptic, monthly, and interannual time scales. The analysis will be driven by climate data products and a 20-year timeseries of satellite imagery. Land cover type will be specified from the University of Maryland classification (Defries and Townshend, 1994), which was derived from temporal variations of NDVI data. Leaf area index, fractional vegetation cover, and canopy structure will be specified from a new 8 km NDVI data set for the period 1982-2002, produced by Compton Tucker and colleagues by merging the AVHRR record with newer data from SeaWiFS and MODIS.

Climate data required for this analysis include air temperature, precipitation, wind speed, downward solar radiation, and downward longwave radiation. The data must be specified at sub-diurnal time scales, so that simulations can be evaluated against data from eddy covariance measurements. This limits the choice of forcing data to meteorological reanalyses. We recognize the limitations of reanalysis estimates of some variables, especially precipitation. We propose to evaluate the sensitivity of our results to errors in the reanalysis fields by performing the simulations with several different driver data sets. We will use meteorological reanalysis products produced by the US National Center for Environmental Prediction (NCEP, Kalnay et al, 2002) and possibly also the 40-year reanalysis being completed by the European Centre for Medium-Range Weather Forecasting (ERA40). To address problems in analyzed precipitation timeseries, we will scale gridded values to match monthly mean observed precipitation measurements (e.g., Willmott and Matsuura, 1995; GPCP; GPCC). Analyses will be performed with and without each of he observational datasets and compared.

If the proposal by Steven Pawson is funded, they will provide an optimized version of SiB using a 4-dimensional variational data assimilation approach to atmospheric CO_2 inversions, including carbon fluxes due to fires. In turn, we will provide to them an analysis of the effects of the annular modes of climate variability on the component fluxes in their model. The success of the research proposed here is not dependent on the Pawson proposal being funded.

Simulated variations in NEE of CO_2 and their responses to climate variations will be compared in detail to observed NEE at eddy covariance sites in many parts of the world. We will pay particular attention to flux tower sites with sufficiently long records to compare simulated to observed fluxes across synoptic, seasonal, and interannual time scales.

Objective 2. Quantify and analyze anomalies in the flux of CO_2 *at the ocean-atmosphere interface.*

We propose to investigate the magnitude, timing and causes of air-sea CO_2 flux variability using a two pronged approach. In the first approach, we will further develop, test, and employ a diagnostic model of the upper ocean carbon cycle that is driven by satellite observations of SST, chlorophyll, wind, and sea-surface height. While potentially very promising, this first approach is limited as continuous records for satellite chlorophyll are available only after 1997. In order to extend the timeframe, but also in order to better test some of the assumptions that we use in the diagnostic model, we employ a prognostic coupled physical-carbon cycle model that we run in hindcast mode using reanalyzed surface forcings. The two approaches are described in detail below.

Diagnostic ocean carbon model

The diagnostic model developed by LeQuéré and Gruber (2002, see Figure 8) consists of a simple mass balance model of the upper ocean mixed layer DIC and Alk content. As we are primarily interested in the interannual to decadal variations, we disregard the mean seasonal cycle and look only at the deviations from the mean seasonal cycle.

The temporal evolution of the anomalous DIC (δDIC) in the mixed layer of depth *h* is given by:

$$(2)\quad h\frac{\delta DIC}{dt} = \delta F_{ex} + \delta F_{ncp} + \delta F_{ent} + \delta F_{ek} + \delta F_{adv}$$

where δF denote anomalous fluxes (i.e. departures from the monthly mean), and where the subscripts *ex, bio, ent, ek, adv* stand for gas exchange, net community production, entrainment, Ekman pumping, and advection, respectively. A similar equation can be written for Alk, except that there is no corresponding term for δF_{ex}. We compute δF_{ex} from (1) by considering only deviations in oceanic pCO_2, as interannual variations in atmospheric pCO_2 are substantially smaller than those of the ocean.

The deviation of the surface ocean pCO_2 from its monthly mean is linked to the deviations of temperature, salinity, DIC and Alk and the corresponding partial derivatives:

$$(3)\quad \delta pCO^{oc}{}_2 = \delta T\frac{\partial pCO_2}{\partial T} + \delta S\frac{\partial pCO_2}{\partial S} + \delta DIC\frac{\partial pCO_2}{\partial DIC} + \delta Alk\frac{\partial pCO_2}{\partial Alk}$$

Equations (2) and (3) form the basic equations of our diagnostic model.

The partial derivatives in (3) can be computed from the known CO_2 chemistry in seawater, variations in k_{ex} and γ_{ice} can be inferred from satellite measurements of winds, SST, and sea-ice concentrations, so the challenge remains to estimate *h* and the δF terms in (3). We propose to do this as follows:

$$(4)\quad \delta F_{ncp} = ef - ratio\delta NPP$$

$$(5)\quad \delta F_{ent} = \frac{h\delta h}{h+\delta h}(\overline{DIC_{tc}} - \overline{DIC_{ml}})$$

$$(6)\quad \delta F_{ek} = h\delta w_{ekman}(\overline{DIC_{tc}} - \overline{DIC_{ml}})$$

$$(7)\quad \delta F_{adv} = -h\delta \vec{u}_{sfc}(\nabla_h DIC)$$

where the subscripts *tc* and *ml* refer to thermocline and mixed layer, respectively, and where NPP is net primary production, ef-ratio is the ratio of new export or export production to NPP, δw_{ekman} is the anomalous vertical Ekman pumping velocity, $\delta \vec{u}_{sfc}$ is the large-scale horizontal velocity.

All of the above terms can be estimated by a combination of satellite observations (for the δ terms) and in situ climatologies (for the stationary terms). We will use ocean color from SeaWiFS and MODIS and various NPP algorithms (e.g. Behrenfeld and Falkowski 1997 or Howard and Yoder (1997)) to estimate NPP, and then employ either the models of Laws et al. (2000) or Dunne et al. (2003) for estimating the ef-ratio. To estimate δw_{ekman} we will use satellite derived winds (e.g. from Quikscat or ERS) and then standard algorithms to derive the anomalous Ekman pumping strength. For $\delta \vec{u}_{sfc}$ we will use satellite derived sea-surface heights and compute anomalous barotropic geostrophic velocities from them. To those we will add the anomalous surface Ekman velocities. We will evaluate these estimates using both our own prognostic model (see below) and results from the ECCO (Estimating the Circulation and Climate of the Ocean) models through an independently funded collaborative project with D. Menemenlis at JPL.

The most difficult parameter to estimate from satellite observations is the interannual variability of the mixed layer depth, δh. Assuming that the interannual variations in h are proportional to the climatological mean seasonal changes in the heat content of the water column, we can use the local anomalous changes in SSH to estimate first the anomalous thermal heat content (Chambers et al. 1997), and then use the climatological mean penetration of the seasonal heating and the climatological mean h to estimate δh from the anomalous heat content. We have tested this methodology at the timeseries stations HOT (22°N, 158°W), BATS (31°N, 68°W), and Kerfix (50°S, 68°E) as well as against XBT derived mixed layer depths over broader regions, but for the period from 1993 to 2002 only (data from the Joint Environmental Data Center (http://jedac.ucsd.edu). These tests yielded good agreements (δh were within +/- 10m of those inferred from the in situ measurements. We will evaluate our results against in situ observations from time-series sites (e.g., Station'S' and BATS in the subtropical Atlantic (Gruber et al. 2002), HOT (Keeling et al. 2003; Brix et al. 2003) in the subtropical Pacific) and other regions where repeat observations are available, as well as the testing against the prognostic model calculations detailed below. The proposed work will also take the effects of Ekman pumping, advection, and alkalinity changes into account, which LeQuere and Gruber (2001) have neglected so far.

While this diagnostic model might become a very important tool in the future to elucidate interannual variations in air-sea CO_2 fluxes from space, the relatively short timespan for many critical parameters (e.g. satellite chlorophyll) limit this approach to essentially the period since the late 1990s. As we also interested in the secular trends observed in the high latitude of the southern and northern hemispheres that occurred over the last 20 years, we propose to use a prognostic model to evaluate air-sea CO_2 flux variability over the last 50 years.

Prognostic Model

The prognostic model that we propose to use is currently being developed as part of an NSF funded project to study interannual variability in the subtropical gyres. The model is a coupled physical-ecological-biogeochemical model that is driven by reanalyzed anomalies of air-sea heat fluxes, freshwater fluxes, and wind stresses. The physical model is the three dimensional Upper Ocean Model (UOM) as described in Danabasoglu and McWilliams (2000), which resolves the physics of the upper 500 to 1000m of the water column. We will employ a 1 degree resolution version of this model. The model is particularly attractive because of its enhanced resolution in the upper ocean and detailed representation of upper ocean physics, incorporating the upper-ocean boundary layer scheme (Large et al., 1994).

The ecological model that we are currently coupling to UOM consists of a slightly adapted and simplified version of the global ecosystem model of Moore et al. (2002a). The most important adaptation is a reduction of the degrees of freedom for the phytoplankton cell quotas, which determine the stoichiometric uptake ratios between nutrients and carbon. The ecosystem model has been coupled with a full water-column biogeochemistry module that incorporates carbonate chemistry, air-sea CO_2 and O_2 exchange, dissolved organic matter dynamics, iron cycling (atmospheric deposition, recycling, and scavenging), and particle export (Doney et al. 2001, 2002).

The climatological mean state of this biological model has been extensively tested against observations (Moore et al. 2002a, 2002b; Doney et al. 2002) and demonstrated generally good skill in reproducing the large-scale ocean biogeochemical patterns found in nature. Specific metrics of model performance include: JGOFS and historical time-series data across diverse biogeographical regimes; satellite ocean color; gyre-scale patterns of primary and export production; air-sea CO_2 fluxes; and subsurface nutrient, oxygen, iron and carbonate system fields. The incorporation of iron limitation is critical for reproducing the observed high-nutrient, low-chlorophyll (HNLC) conditions in the Southern Ocean and the subarctic and equatorial Pacific regions.

The coupled ocean biogeochemistry-physical model will be initialized with climatological observations and then run for 50 years from 1948 until 2003 using meteorological forcing derived from NCEP (Kalnay et al. 1996) and ECMWF and following the guidelines of the European Northern Ocean Carbon Exchange Study (NOCES) project (see http://www.ipsl.jussieu.fr/OCMIP/phase3/).

Before any detailed analysis of the model results can be conducted, we will evaluate the computed variability in the circulation as well as in the marine carbon cycle. Extended comparisons are planned with physical data observed in situ, as available, for example, from the Upper Ocean Thermal Center (http://www.aoml.noaa.gov/phod/uot) and from the Joint Environmental Data Center (http://jedac.ucsd.edu). Detailed comparisons with satellite chlorophyll will be crucial, as this constitutes the only biological parameter available on a global scale.

Objective 3: Synthesize ocean/atmosphere/land CO_2 *flux anomalies*

We will use inverse analysis to develop synthesized estimates of the ocean/land/atmosphere fluxes of CO_2 that will be used to independently verify the relationships between large scale climate variability and the global carbon cycle. In this case, the net surface exchange of CO_2 over large areas will be quantified by inverse analysis using tracer transport models. We will use atmospheric inversions to estimate regional land-atmosphere and ocean-atmosphere CO_2 fluxes over 22 regions for each month in the 20-year timeseries (1981-2000) (i.e., the GlobalView flask record compilation).

The interannual inverse analysis will be performed using the TransCom archive of atmospheric model response to monthly pulses of CO_2 flux from each of 11 ocean and 11 land regions (see Figure 10). Twelve different transport models were used to track the evolution of pulses of tracer corresponding to emissions of 1 GtC yr^{-1} for three years, until they were well-mixed in the simulated atmosphere (Gurney et al, 2000, 2002, 2003). Monthly fluxes and their uncertainties can then be estimated for each of the 22 regions by constructing linear combinations of the tracer timeseries that optimally match the observed timeseries at each of about 75 stations worldwide. An example of interannual variations in the estimated flux from Europe among the 12 different transport models is shown in Fig 10. Although the various models disagree about the total regional flux in most regions, the interannual variability and seasonal cycles of the fluxes are quite consistent among the 12 sets of estimates.

The forward, gridded estimates of net CO_2 flux from land and ocean based on process modeling and remote sensing (discussed earlier) will be aggregated to monthly mean regional fluxes and compared to the timeseries estimated from the atmospheric CO_2 record. We will analyze systematic differences between forward and inverse estimates in terms of climate sensitivity, and in terms of uncertainties in each. Uncertainties in the forward models will be estimated by the sensitivity experiments and model evaluation data comparisons described in previous sections. The inversion analyses include formal statistical error estimation for each model, and the spread of estimated fluxes among the twelve models gives an indication of the effect of transport error on the regional flux estimates. We will include model transport error in our error estimation for the fluxes, by methods outlined in Engelen et al (2002).

A significant issue in atmospheric CO_2 inversion modeling is the specification of prior estimates of regional fluxes and their uncertainties. This is particularly problematic given the large seasonal and interannual variability in the fluxes, and has often been treated by fairly arbitrary choices that are constant in time and space. We propose to use the process-based analysis of global CO_2 fluxes and their sensitivity to the driving data to produce much more realistic prior fluxes and uncertainties for the inverse analysis. This will in turn lead to more precise estimates of regional fluxes from the atmospheric CO_2 data.

The TransCom archives contain 3 years of simulated concentrations for 12 models for pulses released from 22 regions for each of 12 months (a total of over 38,000 years of gridded global concentration records). Preliminary analysis shows strong, consistent responses of these models to interannual variability in the CO_2 record (Fig 10), but unfortunately each model used only a single year of atmospheric circulation to produce the Green's function for each pulse. The advantage of having 12 different realizations of the transport allows us to include a measure of transport error in the uncertainty analysis of the inversion calculation, but the use of the TransCom archive precludes an analysis of interannually-varying atmospheric transport on the estimated fluxes. In year one, we will use the TransCom archive to produce a preliminary analysis of regional interannual variability in the carbon cycle. In year two, we will produce a second analysis using the priors and prior uncertainties obtained by the first pass of the forward models. Finally, in year three of the proposed research, we will perform a tracer transport calculation with interannually-varying winds, using the (MATCH or TM3) model.

Objective 4: Assess relationships between carbon fluxes and modes of extratropical climate variability.

We will apply the numerous data products generated in Objectives 1-3 to systematically examine the relationships between the extratropical climate variability and variations in the carbon cycle on a range of timescales. Emphasis will be placed on the *physical and biogeochemical processes* whereby extratropical climate variability impacts the global carbon cycle, with particular focus on the impact of the NAM and SAM on the flux of carbon at Earth's surface on both interannual and secular timescales.

The PI has extensive experience in applying statistical techniques to extract physical relationships from climate data. We will exploit a suite of linear analysis techniques to explore the relationships between extratropical climate variability and the component fluxes of carbon at Earth's surface, including simple linear regression and linear matrix methods such as Empirical Orthogonal Function analysis and Maximum Covariance Analysis (Bretherton et al. 1992). We will exploit daily resolution data whenever possible, as it affords maximum degrees of freedom (the efolding timescale of the annular modes is ~7-10 days), and thus a more precise treatment of statistical significance and reproducibility. The fraction of secular variability in the carbon cycle that is linearly congruent with variability in the annular modes will be extrapolated from relationships derived on daily timescales using the methodologies outlined in Thompson et al (2000) and Thompson and Wallace (2001).

We will analyze the effects of climate variations associated with the annular modes on air-sea and air-land CO_2 fluxes derived from observations and models described above, and optimized using inverse modeling of atmospheric CO_2. It is inadequate to simply correlate analyzed CO_2 fluxes against the annular modes because even if the processes controlling the carbon fluxes are strongly impacted by climate variations there are likely significant time lags, cancellation, and indirect effects to consider. Soil respiration, for example, responds to soil moisture and soil temperature anomalies that accumulate over time, so changes in winter climate may affect decomposition rates in spring and summer. Similarly, interannual variations in soil temperature and winter snowpack may result in changes in the timing of the spring thaw and therefore lead to changes in carbon flux due to changes in the onset of photosynthesis that are not directly correlated with the NAM. Climate variations may impact both GPP and Rh and lead to cancellation or amplification in the net flux. We will therefore employ model diagnostics to examine the mechanisms responsible for carbon cycle variability, and develop quantitative relationships between NAM and SAM related climate variations and changes in the carbon cycle, taking these time lags into account. We will analyze not only the variations in total carbon flux, but in GPP, R_a, and R_h on land and on NPP, DIC, mixed-layer depth, sinking particle flux, and air-sea gas exchange in the ocean.

5.0 Expected results and significance

The proposed research will provide the first comprehensive analysis of the relationships between extratropical climate variability and the global carbon cycle. The proposed research will quantify the mechanisms whereby the annular modes impact the global carbon cycle, and will quantify the contribution of the these patterns to variations in the carbon cycle on various timescales, including climate change timescales. The results have substantial implications for our interpretation of secular variations in the carbon cycle over the past few decades, and for projections of future concentrations of atmospheric carbon.

The results will also provide a wealth of data products that will quantify variations in the components of the CO_2 flux at the land and ocean surface on time scales from days to decades which are consistent with the atmospheric CO_2 record (Objectives 1-3). These products include daily analyses of photosynthesis, respiration, and decomposition (Objective 1), the contributions of changes in DIC, pCO_2, and air-sea gas exchange to CO_2 flux variability from satellite observations (Objective 2), and net fluxes derived from atmospheric inversions (Objective 3).

7.0 Work Plan

Year 1:

Enhance the diagnostic ocean model by adding horizontal transport, Ekman pumping, and alkalinity cycling, and test the inferred variability of CO_2 flux components and inferred physical parameters. Produce first global estimate of CO_2 flux variability from satellite observations. Couple the marine ecosystem model to the Upper Ocean Model and perform detailed tests with regard to its modeled physical and biological variability.

Test the terrestrial model's new biogeochemical cycling module by comparing simulated fluxes to eddy covariance data, and perform a 20-year simulation driven by NCEP reanalysis. Compare the resulting net fluxes to the interannual variations computed by inverse modeling.

Quantify the climate impacts of the annular modes that play a key role in modulating the flux of carbon at both the land and ocean surface.

Year 2:

Analyze the diagnostically computed CO_2 flux in the context of the variability in various physical forcings at the sea surface. Combine these flux variability estimates with the ocean inverse estimates of Gloor et al. (2003) to estimate total CO_2 flux variability for the use in atmospheric CO_2 inversion studies. Simulate and analyze a 50 year hindcast run from 1958 to the present using the coupled physical/biogeochemical/ecological model. Undertake detailed physical and biological evaluations with in situ observations.

Evaluate the sensitivity of the terrestrial flux simulations with respect to the climate drivers (NCEP, ECMWF, gauge-corrected precipitation), and to parameters in the model. Recalculate inversion fluxes using new prior and uncertainty data from the forward models. Evaluate model sensitivities by comparison to the inversion analyses.

Quantify the relationships between the annular modes and the computed fluxes of carbon. Develop hypotheses regarding the key physical and biogeochemical processes that underlie the observed relationships by considering both the impacts of the annular modes on surface climate and their impacts on the component fluxes of carbon.

Year 3:

Analyze the diagnostic ocean model in detail with the prognostic model, i.e. using the diagnostically inferred fluxes to inform the prognostic model. Analyze the diagnostically and prognostically simulated CO_2 flux variability in detail in the context of the global carbon cycle as well as in the context of the modes of extratropical variability.

Improve the inverse model with interannually-varying transport by performing a 20-year simulation of atmospheric transport with the MATCH model for regional monthly basis pulses.

Provide quantitative, mechanistic, multiply-constrained analyses of the effects of extratropical climate variability on ocean NPP, DIC, pCO_2, export production, and air-sea gas exchange, and on terrestrial GPP, respiration, and decomposition. Continue to quantify the relationships between the annular modes and the component fluxes of carbon at Earth's surface. Analyze results derived from the inverse model.

Quantify the role of the annular modes in secular changes in the carbon cycle.

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Management Plan

Dr. Dave Thompson's expertise focuses on improving our understanding of global climate variability through the use of observational data. His 1998 paper on the annular modes has over 300 citations. He will be responsible for leading aspects of the proposed research related to large-scale climate variability, and for providing leadership and assistance to all project members. Dr. Thompson will be supervising one graduate student researcher, Amy Hawes, who will assist him in performing the proposed analyses. He will also supervise the research coordinator, Jillian L'Ecuyer, who will be responsible for web page development, technical writing tasks, and for logistical duties associated with communication and collaboration.

Dr. Scott Denning has focused his research on the interactions between terrestrial ecosystems and the atmosphere, with particular emphasis on using atmospheric observations to understand the global carbon cycle. He will be responsible for the proposed work related to the data and analysis of carbon fluxes at the land surface. Dr. Denning will be supervising one research associate and a graduate student researcher, who will be performing the land-surface modeling and analyses described in the workplan. Dr. Denning will also supervise research associate John Kleist, who will be responsible for scientific and systems programming tasks and will assist with the implementation of the land-surface model.

Dr. Nicholas Gruber is known for his work on ocean biogeochemical cycles on regional to global scales, and for his work investigating the cycles of carbon, oxygen and nitrogen and their isotopes. On this project he will be responsible for the research related to the data and analysis of carbon fluxes at the ocean surface, for supervising the researchers assisting with the ocean surface aspects of this project.

Results will be reported to NASA in the form of two annual technical reports, due 60 days before the end of year one and year two, and a final technical report, due 60 days after the end of year three. Two publications in peer-reviewed journals are anticipated per year, starting in the second year of the project. Intermediate results will be presented by Thompson and Denning at a yearly science team meeting, and will also be presented to a wider audience, either by the PIs or their graduate student researchers, at the annual Fall AGU meeting.

No other support is anticipated on this project.

Table 1. Sample of data sources used in the proposed research

Field(s)	Data source	Reference
Various	NCEP/NCAR Reanalysis	Kalnay et al. (1996)
SST and surface winds	NCAR (COADS data)	Woodruff et al. 1987, 1993
SST	NOAA NCDC	Reynolds and Smith (1994)
SST	Climate Research Unit (CRU)	Parker et al. 1995
Surface temperature	CRU	Jones et al. 1994
Gridded precipitation	CRU	Hulme 1992, 1994
Precipitation	NOAA CPC (merged satellite)	Xie and Arkin 1997

Variable	Parameterization	Field	Satellite
k_g	Wanninkhof 1992	Wind	QuikScat/ERS
γ_{ice}	SST<-1.8	SST	AVHRR/Reynolds and Smith (1994)
δT	Reynolds and Smith (1994)	SST	Various
δh	see text	h	TOPEX/Poseidon
Wind	direct	Wind	QuikScat/ERS
NPP	Behrenfeld and Falkowsky	chla	SeaWiFS
efratio	Laws et al. (2001)	chla and SST	SeaWiFS

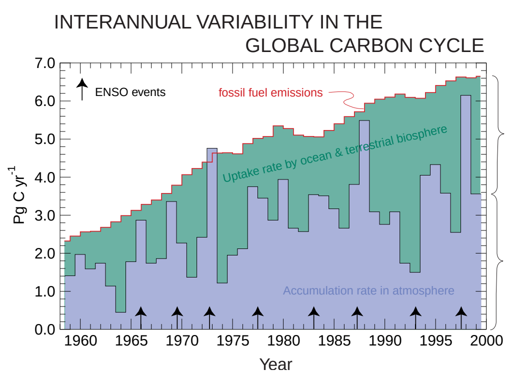

Figure 1. Interannual variability in the global carbon cycle. From 1958 to 2000, the long-term mean atmospheric CO_2 growth rate (blue area) has increased from about 1.5 PgC/yr to over 3 PgC/yr. However, the year to year growth rate varied over this period substantially around this mean, while the fossil fuel emissions show a more or less steady increase. This indicates that the CO_2 uptake by the ocean and land biosphere (green area) is varying by several PgC/yr. Adapted from Sarmiento and Gruber (2002).

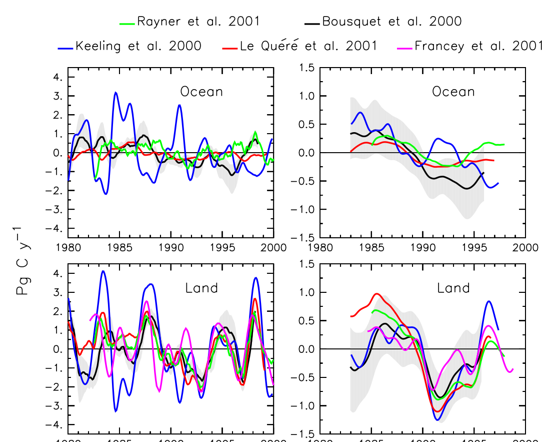

Figure 2. Variability in ocean and land CO_2 fluxes. Positive values indicate a CO_2 flux anomaly from the ocean or land to the atmosphere. Curves have been smoothed to remove variations less than a year (left panels) and less than five years (right panels). From LeQuéré et al. (2003).

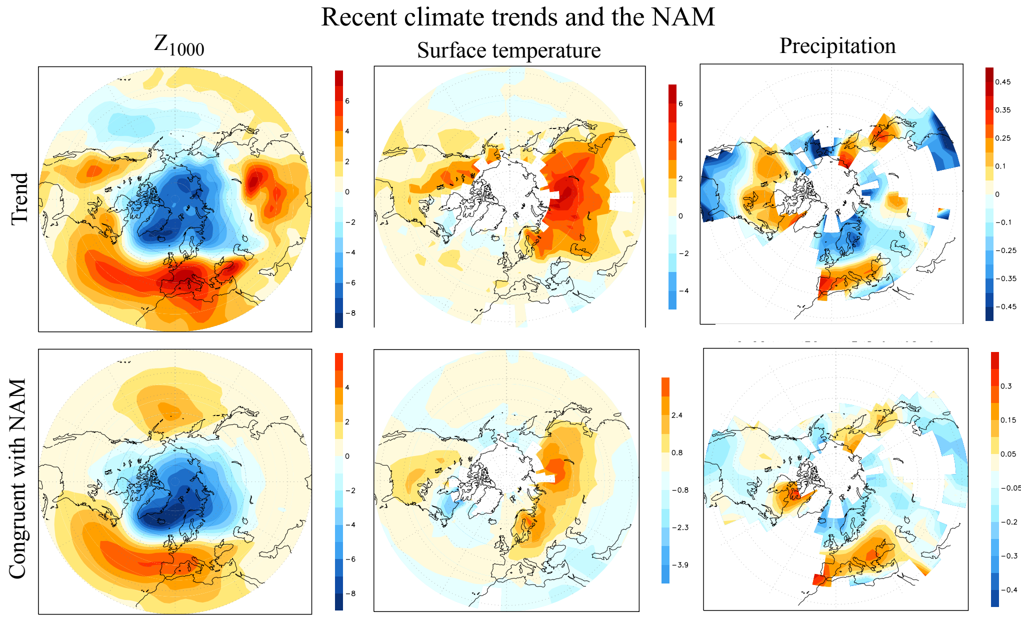

Figure 3. Top: 30-year (1968-1997) linear January-March trends in sea-level pressure expressed as 1000-hPa geopotential height, Z_{1000} (*left*); surface air temperature (*middle*); and precipitation (*right*). Bottom: The components of the trends that are linearly congruent with the NAM. Units are meters/30-years (Z_{1000}), K/30-years (temperature), and % of JFM climatology/30-yr (precipitation). Note that the bottom panels are identical to the structure of the NAM in the month-to-month variability, but the amplitudes are scaled by the linear trend in the NAM. See Thompson et al 2000 for details.

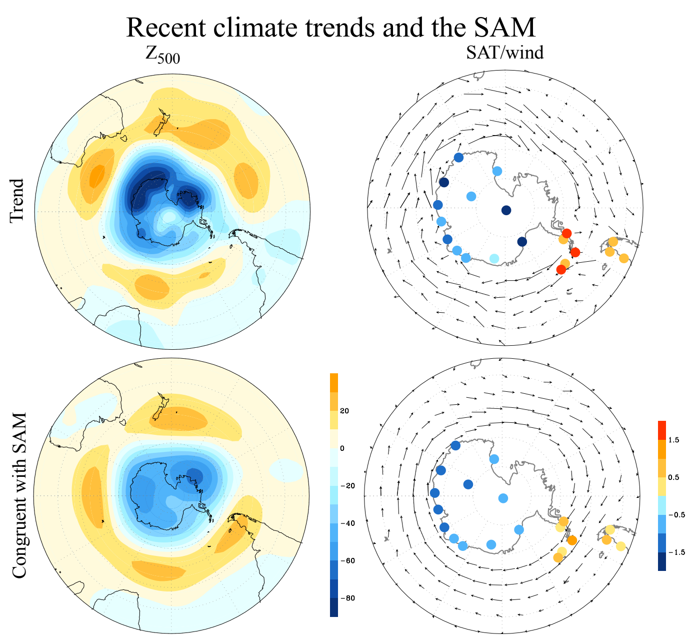

Figure 4. Top: 22-yr (1979-2000) December-May linear trends in 500-hPa geopotential height (*left*); 32-yr (1969-2000) linear trends in surface temperature and 22-yr (1979-2000) linear trends in 925-hPa winds (*right*). Bottom: The components of the trends that are linearly congruent with the SAM. Shading is drawn at 10 m $(30\text{yr})^{-1}$ for 500-hPa height, and at increments of 0.5 K $(30\text{yr})^{-1}$ for surface temperature. The longest vector corresponds to ~4 m/s. Note that the bottom panels are identical to the structure of the SAM in the month-to-month variability, but the amplitudes are scaled by the linear trend in the SAM. See Thompson and Solomon (2002) for details.

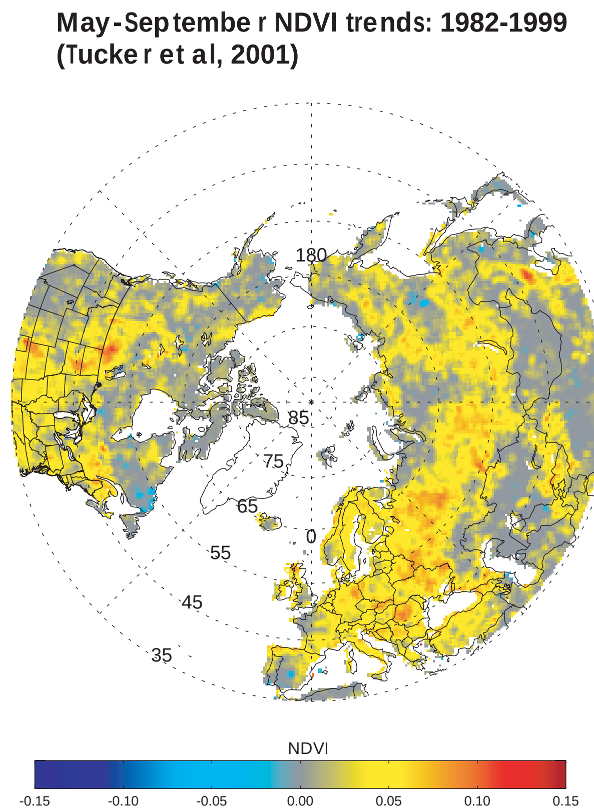

Figure 5. Trend in nodmalized-difference vegetation index derived from AVHRRimagery over 18 years. Regions with strongest trends have experienced strong NAM-related climate change during the period (compare Fig. 3)

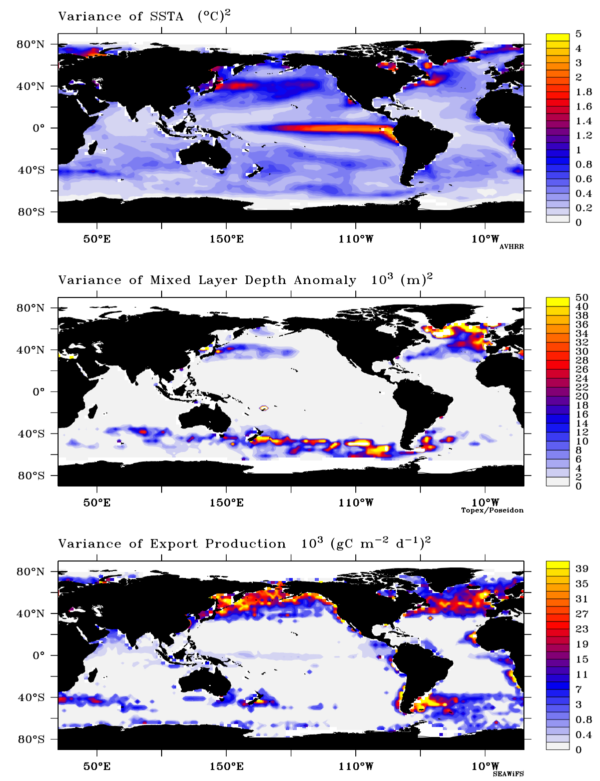

Figure 6. Maps of satellite based estimates of interannual variance of key drivers for the ocean carbon cycle: (a) Sea-surface temperature, (b) mixed layer depth, and (c) Export production. Sea-surface temperature is based on AVHRR, mixed layer depth has been deduced from Topex/Poseidon's measurements of sea surface height and AVHRR, and export production has been estimated based on SeaWiFS. See section 2.3 for details.

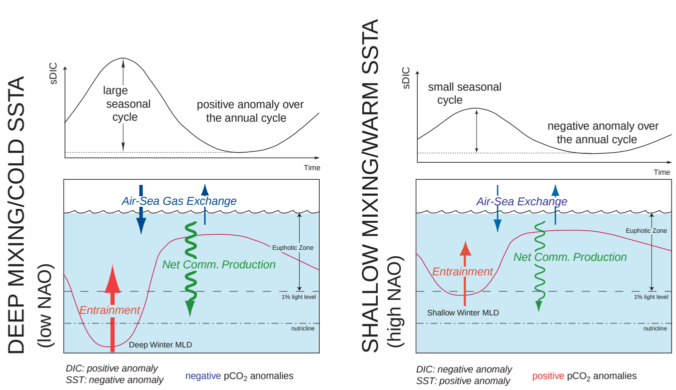

Figure 7. Schematic depiction of the seasonal carbon cycle near Bermuda, modified in response to interannual variations in mixed layer depth and sea surface temperature. In warmer than normal years, having shallow winter mixed layers (typically positive NAM index), little DIC and little nutrients are brought into the upper ocean, promoting less net community production than normal. Also, the uptake of CO_2 from the atmosphere is reduced because of positive SST anomalies and reduced wind speeds. As a result, the seasonal cycle of sDIC is suppressed. In contrast, colder years exhibit deeper mixed layers with larger entrainment, enhanced net community productivity, and higher CO_2 uptake from the atmosphere, producing an enhanced seasonal cycle of sDIC.

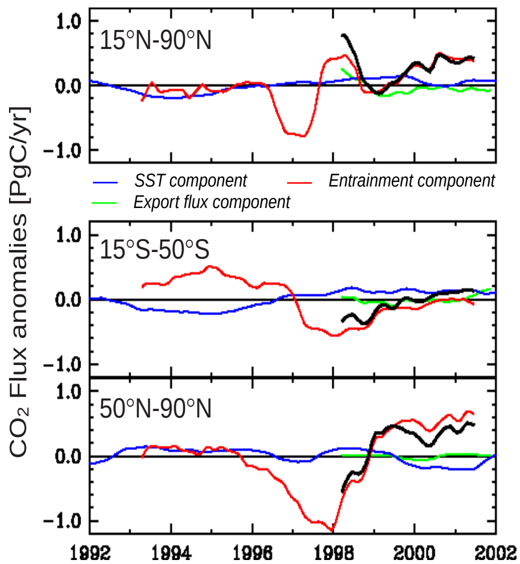

Figure 8. Interannual CO_2 flux variations estimated on the basis of a satellite data based diagnostic modeling approach (See workplan for details). In summary, the diagnostic model separately estimates the contribution of variations in SST (blue), entrainment and ocean circulation (red), and biological export flux (green) to air-sea CO_2 fluxes and then sums them up (black line). From LeQuéré and Gruber (2002).

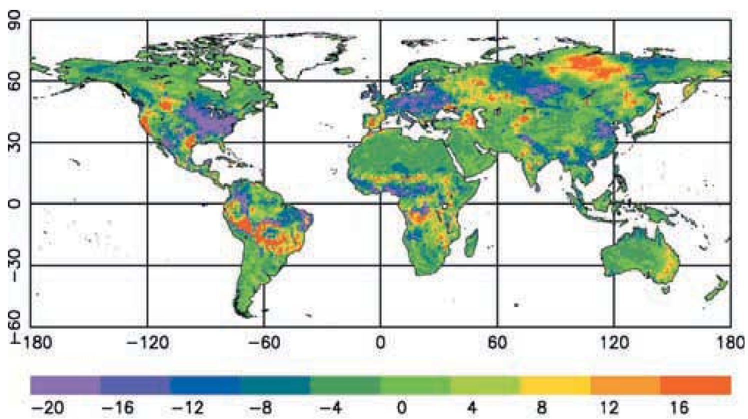

Figure 9. Monthly anomaly in net ecosystem CO2 exchange (NEE) for July 1984, relative to the mean July from 1982-1992 simulated by SiB2 (Schaefer et al, 2002).

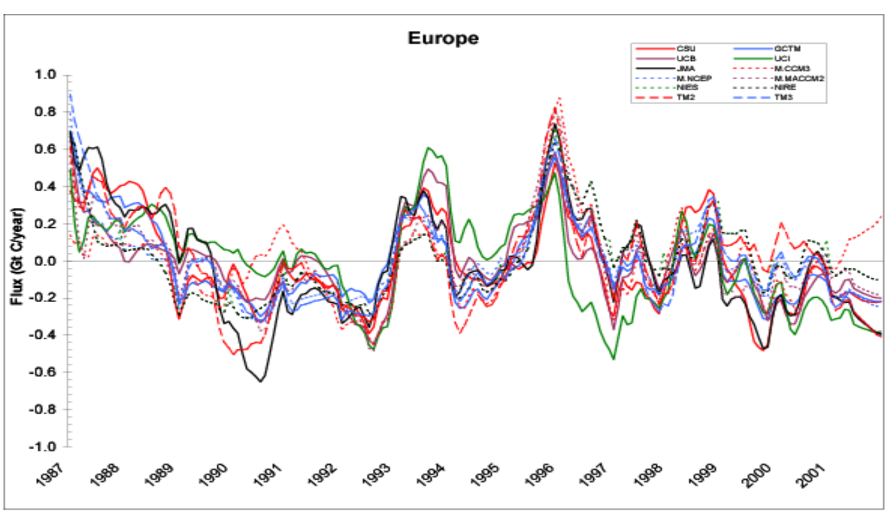

Figure 10. Monthly anomalous flux of CO_2 from vegetation and soils to the atmosphere in Europe, estimated from measured atmospheric CO_2 mixing ratio by synthesis inversion of 12 tracer transport models participating in the TransCom intercomparison experiment.