

Theme 2: Monitoring, diagnosis and prediction of the global C cycle.

1. Abstract

The current increase in atmospheric CO₂ from burning fossil fuels and biomass burning is strongly modulated by physical and biological processes acting across the whole of the Earth's land and water surfaces. A range of feedbacks couples these biogeochemical processes to the climate system, with the potential to accelerate climate change. Quantifying biogeochemical cycles (particularly carbon) is therefore fundamental both to understanding how the Earth is changing and to managing climate change and the Earth's resources. Satellite sensors currently (and with great future potential) provide a range of key measurements that, in combination with process-based models and ground data, allow us to build carbon cycle diagnosis and prediction systems in which Earth observation (EO) is used to attribute current fluxes to processes and constrain predictions of the future global carbon cycle. The primary goal of the carbon cycle theme is to test and improve models and flux estimates through unparalleled exploitation of global EO data. This involves measurement and modelling activities for the land, ocean and atmosphere, with coupling of domains through models. For land, a major drive will be on producing improved physically-based links between biospheric models and EO measurements. For the ocean, a range of satellite sensors will be used to clarify the physical and biological processes driving carbon exchange at the ocean surface. The atmospheric focus will be on exploiting CO₂ and CH₄ measurements from the new generation of satellite sensors. The diagnosis and prediction tools will be embedded in a global system with capacity for detailed regional analyses, and will include a unified treatment of uncertainty to support informed decisions by policy-makers.

Resource requirements: 54.9 FTEs.

2. Background and motivation

The overarching questions in Earth Systems Science relevant to NERC strategic policy are: "How is the Earth changing?" and "What are the consequences of these changes for life on Earth?" Deeply implicated in these questions is the carbon (C) cycle:

- land and ocean fluxes strongly modulate the build-up of atmospheric CO₂ due to fossil fuel emissions, and C cycle feedbacks are expected to have an important but highly uncertain influence on climate change over the next century (IPCC 2007);
- the C cycle is fundamentally linked with resources and resource management, since marine and terrestrial productivity are expressions of C fixation;
- the C cycle is influenced by environmental degradation and modification, and hence firmly tied to biodiversity and sustainability;
- the C and water cycles are intimately linked through vegetation processes and surface energy balances, with important implications for future water resources.

In addition, anthropogenic changes to the C cycle are highly relevant to climate change policies and agreements (e.g. UK Government Climate Change Bill, 2006), but progress with post-Kyoto mechanisms, for example, is hampered by poor quantification of several key C cycle processes.

The science challenges addressed in the C cycle theme address five major questions:

1. How do the land and ocean modulate and control atmospheric CO₂ and CH₄ and their variability?
2. What is the likely behaviour of their sources and sinks under climate change and human disturbance?
3. What are the key interactions and feedbacks between the carbon and water cycles, and with climate?
4. How can EO, ground data and models be improved and best integrated to define C cycle dynamics?
5. How can the C cycle be managed to mitigate climate change (crucial for evidence-based policy)?

Answering these questions needs a full system approach across the land, ocean and atmospheric domains, in which the capability of satellites to provide global, near-simultaneous, consistent and repetitive observations is fundamental. Satellite data also provide major new opportunities:

1. measurements of CO₂, CH₄ and other greenhouse gases (GHGs);
2. lengthening time series from the modern, more powerful generation of sensors;
3. new types of measurement of surface properties (e.g., biomass, fire emissions, wave breaking);
4. rapid development of methods to assimilate satellite data into C models;
5. integration of information sources, e.g. improved fire characterisation through advances in surface and atmospheric measurements from space, combined with new statistical and physical models.

The NCEO provides the coherent approach needed to integrate observations in a modelling framework, and to express the intimate links between the C cycle and climate, hydrology and atmospheric composition. This unified model-data framework will also provide estimates of the uncertainty in C flux predictions, which is a prerequisite for any rational approach to C cycle policy and management.

The structure of the C cycle theme is set out in Fig. 1. Our primary aim is to make **optimal** use of EO and other data to improve our estimates of surface fluxes of CO₂ and CH₄, both now and in the future, at regional to global scales. Observations and models are combined through data assimilation, using observation operators (dashed lines) that consistently link model state to measurements. Surface flux models can also be used as prior information for atmospheric inversion schemes. The quantities to be derived are **surface fluxes of CO₂ and CH₄, and the parameters and processes underlying these fluxes**. Note that in building this coherent structure we will make a major contribution to implementing the recommendations of the IGOS-P Carbon Theme Report for Integrated Global Carbon Observing Strategy (2003).

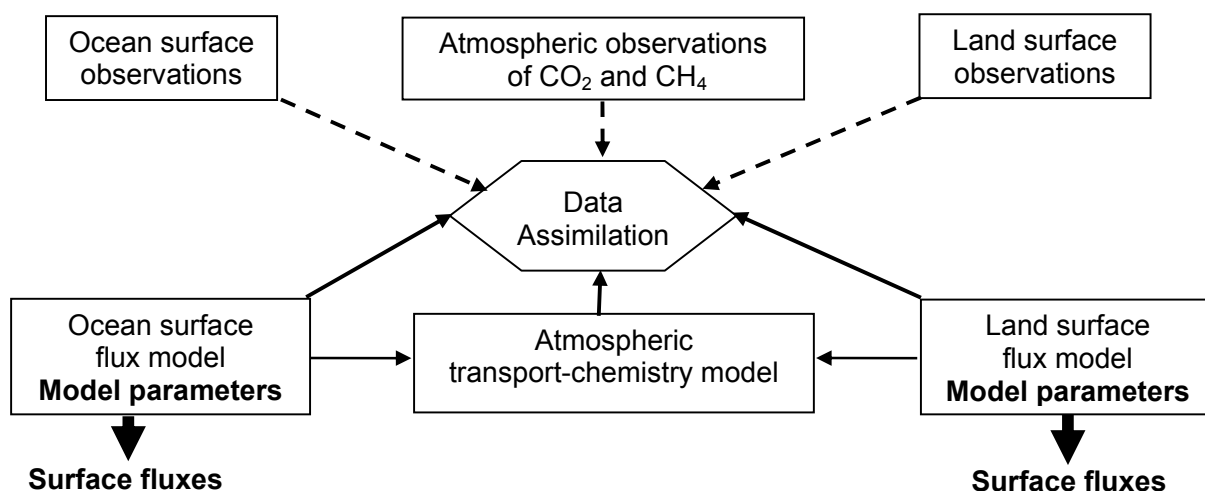


Figure 1: *Schematic showing the structure of the Carbon Cycle Theme*

The land and ocean domains rely on different sensors and models, though with many common concepts, such as biological functional type, physically-based observation operators and data assimilation, which provide unity in approach. The two domains are most strongly linked through the atmosphere, and we will develop this link using the new CO₂ column content data from satellites in the early period of NCEO.

The structure of the theme is based on the highly successful inter-disciplinary capabilities built up in CASIX, CTCD and DARC, with particular strengths in EO data assimilation linked to state-of-the-art radiative transfer models, quantifying fire emissions from space, use of space radar to measure forest properties (including co-proposal of the BIOMASS mission under study by ESA), satellite measurements of CO₂, ground-based and aircraft instrumentation, uncertainty modelling, ocean bio-geochemistry and C-cycling from ocean colour data and coupled circulation-ecosystem models for N Atlantic & global oceans and shelf seas for deriving global and regional CO₂ fluxes. It also reflects UK excellence in atmospheric trace gas retrieval and the strategic need to develop expertise for upcoming satellites to measure CO₂ column content. These considerations drive the following sub-themes (STs), with ST 3.10 acting as a key integrator:

1. Data assimilation in terrestrial C models
2. Carbon fluxes from biomass burning.
3. Integrated ground & airborne observations to improve EO inversions and C models.
4. The carbon balance of the tropics and avoided deforestation.
5. Quantification of sea surface processes.
6. Quantification of ocean biogeochemistry and carbon fluxes.
7. Quantification of bio-physical interactions and air-sea CO₂ fluxes.
8. Data assimilation techniques for marine ecosystem models.
9. Reanalysis, validation and prediction of marine carbon estimates.
10. Integrating satellite measurements of atmosphere, land and ocean to quantify surface C fluxes and their causes.

3. Specific Objectives

Sub-theme 3.1: Data assimilation in terrestrial C models

3.1.1: Summary

A recent comparison of coupled climate-carbon cycle models [1] revealed large uncertainties in describing the land C cycle, as noted in IPCC AR4 (2007). A crucial factor is the lack of strong data constraints on the models. EO data can play a major role in addressing this problem through advanced data assimilation (DA) techniques combined with observation operators that consistently link ecosystem state to measurements. Up to now, the emphasis has been on using derived EO products (e.g. LAI/fAPAR) with C models [e.g. 2]. Whilst this approach can be of great value and is further developed here, it has important weaknesses: (i) similar products from different sources are inconsistent; (ii) product derivation uses different assumptions from those in ecosystem models; (iii) the error properties of the products are poorly known, reducing their value in DA. These problems can be avoided, as demonstrated in [3, 4], by schemes that use observation operators based on Radiative Transfer to link model state with low-level EO measurements (radiance/backscatter/coherence). Building on recent CTCD progress in assimilating both flux and stock data [5] and EO optical data [3] into C models, we will develop this joint model-data concept inside a global DA system to parameterise, test and improve C models. These methodological developments underpin the key drive of this sub-theme, **to provide major improvements in our knowledge of C dynamics at global and regional scales by producing a rigorously-founded carbon DA system for land**. The approach using land surface constraints will be combined with fire (ST 3.2), atmospheric (ST 3.10) and hydrological constraints (Theme 4), fed through to the global application of the Land Data Assimilation Scheme (LDAS) within Theme 1, and will involve close cooperation with Theme 7.

3.1.2: Work Description and Methodology

The major objectives in this sub-theme are: (1) to develop C models and observation operators to assimilate the full range of EO data; and (2) use DA and model-data fusion to test C models and constrain parameterizations. We will exploit both simple (DALEC) and more complex (JULES/SDGVM) C models. Our aim is develop generic assimilation and testing approaches that will be used within the LDAS.

1a) *High Level Assimilation (HLA) and interpretation*. High level EO products, including LAI from MODIS, fAPAR from various sensors (AVHRR, SeaWiFS, MERIS and MODIS) and biomass from PALSAR are readily assimilated into C models, using e.g. the Ensemble Kalman Filter. These products relate to the phenology, growth rate and state of the vegetation, and so constrain biomass, GPP and NPP estimates. The EO observations can also be used to quantify major trends and anomalies. We will use HLA to make rapid progress in developing and testing the C models, and produce global estimates of the C budget. Model-data comparison will provide the first examinations of major weaknesses and biases in the C models.

1b) *Low Level Assimilation* (LLA). To address weaknesses in HLA we will assimilate low-level satellite products, such as reflectance (MODIS, MERIS, SeaWiFS, etc.) and backscatter (PALSAR). This requires more complex Observation Operators (radiative transfer models) that are consistent with radiation schemes in the C models. C model structure will be updated, e.g. to provide a better representation of canopy structure, and accurate, fast Observation Operators will be developed, based on spectral invariant [6, 7] representations of numerical 3D RT simulations or two-stream models [8]. Testing will be undertaken at experimental sites in key biomes (SpecNet sites, and ST 3.3). As the techniques mature they will replace the use of HLA. The Observation Operator development and testing will inform the spectral simulator component of the LDAS.

2a) Some components of the C cycle (e.g. drought effects and respiration) are not currently monitored from space. We will use C and water flux data from key biomes (eddy covariance and ecological data from FluxNet sites and ST3.3) and EO data (Theme 4) to test alternative C model structures (i.e. C-water relations) in the assimilation scheme, and, using a mixture of EnKF and Metropolis approaches, assess state and parameter uncertainty and quantify global parameter variation. From the resulting optimal C model structure, we will provide parameter prior distributions for key biomes to be used in global assimilation with atmospheric CO₂ data ([9]; ST 3.10, Theme 1).

2b) Global assimilation requires spatially distributed priors for model parameters and initial conditions. We will determine methods for extrapolating parameters from FluxNet sites with realistic errors, using ongoing experiments such as the CTCD-led Reflex initiative (www.carbonfusion.org), and comparison of model parameters from sites within biomes (in 2a). Initial conditions for C models are usually determined by a spin-up procedure that can be time-consuming and dependent on uncertain steady-state assumptions. We will use DA to determine initial conditions (i.e. a global estimate of C stocks), with an assessment of error.

3.1.3: Deliverables

- (a) Tested and parameterized C dynamics components delivered to JULES;
- (b) A robust framework for testing C models against EO, ground and airborne data;
- (c) Improved model representations of radiative transfer for LLA, with uncertainty estimates, feeding through to the spectral simulator development in the Climate Theme;
- (d) Primary deliverable: Global estimates of the terrestrial C cycle with quantified uncertainty (linked to Climate Theme and requiring input from STs 3.2 & 3.10 and Theme 4).

3.1.4: Key links to other programmes and organisations

IPY, LBA and FluxNet will provide data on fluxes and biosphere structure. Observation operator and model development will be in consultation with the global C modelling community (including JULES, AIMES and the CTCD & DARC-led CarbonFusion initiative). The improved C models will be provided to ST 3.10, the Climate Theme and UKMO.

Sub-theme 3.2: C fluxes from biomass burning

3.2.1 Summary

Fire perturbs a greater area over a wider variety of biomes than any other ‘natural’ disturbance, with global mean annual C emissions 30-50% of those from fossil fuel burning [10]. It has major effects on the C and other biogeochemical cycles, and on ecosystem services such as biodiversity and soil fertility, as well as emitting CO₂, CO, CH₄, tropospheric ozone precursors and aerosols. Many data indicate order of magnitude diurnal and inter-annual variations in burning, and that it may be the largest source of inter-annual variability in land-atmosphere C fluxes [11]. Fire is thus a critical element in global and regional C cycle assessments. However, there are large gaps in our knowledge of fire, including its extent, severity and effects. We cannot even adequately quantify the fraction of annual atmospheric CO₂ growth rate change explained by fire [12].

For observed spatio-temporal variations in atmospheric CO₂ and other trace gas concentrations, including CO and CH₄, to be correctly interpreted by biospheric models and properly attributed in atmospheric composition

studies, the magnitude and variability of pyrogenic emissions must be properly represented. Furthermore, the atmospheric chemistry-transport models (CTMs) describing the fate of the emitted gases and aerosols require data on the timing and convective strength of fire plumes to couple them to the correct meteorology and injection height [13]. Current methods do not provide these data. In turn, atmospheric measurements combined with CTMs provide important constraints on the fire emissions calculated from surface observations, but these have not been extensively exploited. Hence there is strong two-way interaction between this ST and Theme 3. Important recent advances in using EO to address these issues include: (i) development by Wooster and colleagues of Fire Radiative Power (FRP) measures from geostationary and other sensors to estimate fuel burned and emissions (and potentially associated injection heights); (ii) new methods to estimate daily burnt area and severity by Lewis and colleagues. This ST will exploit these developments **to provide major improvements in our knowledge of fire dynamics at global and regional scales**, and supply key fire and emissions data to ST 3.1, 3.4 & 3.10, and Themes 1 & 3.

3.2.2 Work description and methodology

1. We will develop the best possible fire-related flux estimates using: (i) thermally-derived FRP measures [14] to deliver estimates of total fuel consumed and C/trace species emitted, exploiting the full set of geostationary sources (SEVIRI, GOES, MTSAT, FY2C.); (ii) burnt area and fire severity measures from a forward modelling approach [15]. Polar orbiters will be used to derive FRP estimates of pyrogenic fluxes at the higher latitudes badly covered by geostationary systems. We will compare these estimates with enhancements in atmospheric constituents (e.g. CO, CH₄, aerosols, and later CO₂), initially via the event-driven approach of [16], and then more rigorously using CTMs (with Theme 3). These data will be used as constraints in DA (ST 3.1 & 3.10) and Theme 1.

2. The biases and uncertainties in EO-derived emission estimates will be quantified for use in DA and to help develop the stochastic fire representations needed by prognostic biosphere models. Occurrence frequencies of anthropogenic vs natural ignitions are important in such models [17], and we will assess whether they can be separated by exploiting lagged TRMM lightning detections and active fire/burnt area detections.

3. We will improve our knowledge of heat loss partitioning in fires and relationships to fuel consumption and smoke emission, in order to scale results from small-scale experimental fires to wildfires. This will use instrumented experimental test burns in UK uplands (ST 3.3), savannahs and forests, including ground-based sensing of smoke plume constituents and concentrations, and the newly developed Wildland Fire Dynamics Simulator (WFDS [18]; collaborators Papadakis and Mell). We will exploit WFDS and satellite observations of fire intensity and plumes to evaluate FRP-derived pyro-convective injection heights.

4. Using modelling and airborne EO, we will investigate whether multi- or hyper-spectral IR observations can provide information on proportions of flaming to smouldering activity, opening the way to develop optimised per-fire emissions factors from future sensors, such as the planned GMES Sentinel 2 satellite IR Element. We will exploit airborne and spaceborne remote sensing data to measure the as yet un-investigated extremes of regional fire regimes, currently quantified using only statistical extrapolation, but which in some areas may be responsible for a significant fraction of overall emissions. If IR Element data are unavailable we will explore use of the existing Bi-Spectral Infrared Detection satellite archive for this purpose.

3.2.3 Deliverables

a) Provision of integrated records of FRP-derived C (and trace gas) emissions and burnt area for assimilation into C cycle models, use in CTM parameterisations and to evaluate, parameterise and develop stochastic fire models (links to Themes 1, 3 and ST 3.1, 4 and 10; supplied to Informatics). Comparisons with elevated trace gas and aerosol signatures and evaluation of ability to separate anthropogenic from natural ignitions.

b) Field and model-based evaluation of relationships between fuel combustion and emission release rates, and scaling of heat loss processes (radiative, convective, conductive etc). Determination of whether FRP measures provide appropriate information for deriving plume injection height data for use in CTMs.

c) Evaluation of multi-/hyper-spectral data for fire type determination and emissions factor refinement, and of higher spatial resolution data for characterising the lower intensity components of regional fire regimes.

3.2.4 Key links to other programmes and organisations

KCL is the only group worldwide producing geostationary FRP estimates and UCL are involved in MODIS burnt area product definition; both feed into the international efforts coordinated by GOFC-GOLD. Operational FRP from multiple geostationary sensors is under consideration by EUMETSAT and UKMO. Wooster leads a QUEST fire element bid currently under consideration. There are strong links to STs 3.1, 3.4 & 3.10 and Themes 1 & 3.

Sub-theme 3.3: Integrated ground & airborne observations to improve EO inversions and C models

3.3.1 Summary

Ground-based and aircraft measurements form an essential element in coherent use of EO data to study the C cycle, needed to: (i) quantify and test relationships between EO signals and canopy structure and function; (ii) develop and test EO operators and inversions (with ST 3.1); (iii) quantify the impact of upscaling from data-rich environments to comparatively sparse and/or large-scale global observations (e.g. eddy towers, tall towers, EO products); (iv) understand the vertical transport of surface fluxes to the Planetary Boundary Layer and beyond, and hence their relation to trace gas measurements by satellites; (v) provide the key underpinning science that ensures processes and parameterisations are adequately represented in C models, as demonstrated by recent CTCD work [19, 20] (Theme 1 and ST 3.1). They also stimulate new EO approaches and products (e.g. SAR interferometry to measure peat swelling) and provide some key variables (e.g., soil texture) that cannot be measured from space. Finally, EO, aircraft and ground observations need to be considered as part of a global observing system, and this ST contributes to this overall capability.

This sub-theme is built on world-class field measurement expertise and a superb range of instrumentation built up by CTCD and its partners, supported by an all-terrain field vehicle, and including:

- the University of Edinburgh airborne geophysical research facility, which is instrumented for C flux and EO research;
- eddy covariance flux towers (fixed and mobile) and an instrumented tall tower in Angus, Scotland;
- the world-leading system for measuring partitioned soil C fluxes (incl. methane), developed by CTCD;
- a mobile mass spectrometer and tuneable diode laser unit for ¹³C discrimination;
- ground-based spectral sensors and an ASD spectral radiometer;
- automated stations to measure, *inter alia*, weather, soil moisture & temperature and PAR.

3.3.2 Methodology

The measurements in this ST will be at three UK sites (Alice Holt, Harwood Forest, Pennine Moorlands) with measurement infrastructures and long-term research records of internationally recognised status, but significantly extended and generalised using other UK and international networks (including the ABACUS Arctic IPY project, led by Williams, CarboEurope and Fluxnet). The UK sites are representative of biomes with significant global C stocks and related C-cycle feedback uncertainties (coniferous & deciduous forests, natural peatlands) of direct relevance to UK, EU and global C policy. Crucially, all sites allow the effects of management practice on C cycling and stocks to be addressed. The work has three components:

1. *Process and state measurements.* Measurements of surface directional reflectance, vegetation height, LAI, biomass, vegetation and soil moisture, PRI and fAPAR will be obtained at each site (supplemented by data from previous campaigns). These will be used to: (i) validate coarser resolution EO products (e.g. from MODIS, MERIS, PALSAR); and (ii) provide data to test EO operators (ST 3.1). At each site, high temporal resolution CO₂ and CH₄ flux data will be obtained and partitioned into flux components to improve process descriptions in biospheric models (this will include post-burn soil flux monitoring). Supporting studies will use novel incubation techniques developed by CTCD [19] to parameterise the environmental controls on soil

CO₂ and CH₄ fluxes. The combined EO and ground datasets will be used to test the C models (ST 3.1). Ground-based data will be integrated with airborne, profiled tall tower and SCIAMACHY column CH₄ data to investigate the impacts of upscaling (link to ST 3.10).

2. *Catchment scale and forest stand manipulations.* We will deploy the full suite of CTCD instruments to uniquely provide the EO component for a major UK experiment designed to investigate the consequences of peatland water table manipulation on CO₂ and CH₄ fluxes from 100 ha replicated catchments (in collaboration with NERC UKPopNet and RSPB EU LIFE-Nature). Airborne and spaceborne optical, thermal and SAR data will be used to stratify forest sites (chronosequences and varied management practices), and to relate stand structure and vegetation dynamics to ground measurements of seasonal NEE.

3. *Technological developments.* (i) A second tall profiled tower analysis system will be commissioned in the Pennines, to provide both local and regional flux estimates. These data (and those from the existing Angus tower) will be assimilated into atmospheric transport models (with Theme 3) to estimate trace gas fluxes for the whole of northern Britain, where there are large and highly vulnerable soil C stocks [21], for comparison with OCO/GOSAT retrievals (ST 3.10). (ii) We will assess whether SAR interferometry can measure seasonal and inter-annual peat depth variations, using corner reflectors that ‘float’ on the peat surface.

3.3.3 Deliverables

- (i) Datasets of soil and canopy state and CO₂ and CH₄ fluxes at a range of scales (individual plots, catchments, airborne campaigns, tall towers) including data during burn activities (with ST 3.2).
- (ii) Validation of EO datasets and testing of operators (with ST 3.1).
- (iii) Key process equations and parameters for partitioned model CO₂ and CH₄ fluxes (with ST 3.1).
- (iv) Investigation and modelling of C effects and feedbacks due to climate change and land management.

3.3.4 Key links to other programmes and organisations

Measurements from collaborative sites, needed for generalisation, rely on existing agreements with UK (e.g. UKPopNet; ABACUS [Arctic IPY project], RSPB) and international (e.g. CarboEurope, ESF RSTCB network) partners, and also access agreements with United Utilities and the Forestry Authority. Importantly, this ST will contribute to our continued participation in CEOS EO Cal/Val activities (<http://wgcv.ceos.org>).

Sub-Theme 3.4: The Carbon Balance of the Tropics and Avoided Deforestation

3.4.1 Summary

The tropical C balance is one of the most poorly understood elements of the global C cycle. Atmospheric inversions indicate a mean value close to zero (with large uncertainties), despite extensive deforestation and associated large fluxes of C to the atmosphere (IPCC, 2001). The size of these fluxes is so uncertain that the IPCC (2001) would not attach a value to it, and the AR4 (2007) indicates a very large range of estimates for this term. Hence the magnitude of the biospheric sink needed to balance this source term, the processes driving this sink and the sustainability of these processes are equally uncertain. At the same time, tropical forests are critical reservoirs of biodiversity and terrestrial C that are seriously threatened by degradation and climate change, and, especially in Indonesia, protect huge stores of peat C. A key objective of both the UNFCCC and the UN Convention on Biological Diversity is to mitigate the adverse effects of climate change on the composition, resilience and productivity of natural and managed ecosystems. Crucial discussions on post-Kyoto mechanisms to generate carbon credits for ‘avoided deforestation’ and ‘avoided peatland degradation and burning’ are severely hampered by the lack of relevant scientific data to quantify their benefits for mitigating climate change. EO has a key role to play by providing (i) baseline values and monitoring of the rates of forest loss, degradation & burning (including underlying peat burning), and the associated emission rates; (ii) types and rate of regrowth. However, this has to be supported by other data (including fire and atmospheric measurements) and models to provide emission rates. Working in an international context, this ST aims to integrate the NCEO’s modelling and data capabilities to provide better quantification of C fluxes from tropical deforestation, and make a unique contribution to UNFCCC information needs by exploiting the JAXA PALSAR. The major value of this L-band radar, which has been

producing operational data since October 2006, is its ability both to see through the clouds and smoke that seriously affect optical systems in the tropics, and to give information on forest biomass.

3.4.2 Work description and methodology

The methodological objective of this ST is to assess and use PALSAR data to deliver validated maps of rates of deforestation & forest degradation, and the types and rates of regrowth in tropical forests. Initial assessments will be at large study areas in Indonesia subject to legal and illegal logging, fire and forest conversion to oil palm and timber plantations (such processes are also representative for Africa and S America), where there are good ground data from WWF and past and continuing work by Page. These methods will then be extended to regional and global scale, in collaboration with JRC and the JAXA Kyoto and Carbon Panel (K & C; this provides important links to research in Africa and Brazil). The science objective is to derive emission estimates by integrating PALSAR (and optical) measurements with ground data (as demonstrated by Page [22]) and exploiting new information on fire emissions (ST 3.2) and their atmospheric signature (ST 3.10 and Theme 3). We will also perform model runs (STs 3.1 & 3.10) with improved fire representations, drawing on new QUEST fire work, in order to assess the ability of models to simulate tropical fluxes, including tropical uptake, with the expectation that this will identify needs for significant model improvement.

3.4.3 Deliverables

- a) Assessment of PALSAR's ability to measure rates (by area) of forest loss, degradation and regrowth.
- b) Upscaling to regional and national scale for the post-2006 period and study of feasibility of transfer to Africa and Latin America.
- c) In collaboration with JRC, global integration of radar data with results from optical data.
- d) Integration of EO, ground data and modelling to provide partitioned CO₂ fluxes for tropical forest areas.

3.4.4 Key links to other programmes and organisations

This ST is closely tied to DEFRA information needs for UNFCCC discussions on the avoided deforestation mechanism. WWF believe this to be crucial to protect biodiversity, and will provide substantial ground & satellite data holdings and manpower, together with good contacts to local, provincial and national administrations, local companies, NGOs, academic institutions and other stakeholders. The JAXA K & C Initiative (Quegan is a Panel member) gives access to PALSAR data and to research teams in Indonesia, Africa and Amazonia. JRC are key collaborators to provide global context and African contacts. Page (Leicester) is involved in highly relevant GMES GSE Forest Monitoring and FP6 RESTORPEAT projects and will supervise the student for this ST. Advantage will be taken of the NERC-funded 2008 OP3 Bornean Danum Valley ground and airborne campaign which will include tower-based measurements of CO₂.

Sub-Theme 3.5: Quantification of Sea Surface Processes

3.5.1 Summary

Satellite sensors provide a primary means to monitor the transfer of energy, momentum and material between the oceans and the rest of the Earth system, which occurs mainly at the sea surface. Interpretation of EO data from passive/active microwave sensors remains crude, and the basic science linking characteristics of the sea surface to air-sea fluxes and EO signatures must be strengthened. This sub-theme addresses specific topics where increased understanding is both vital and achievable. Recent and continuing *in situ* measurements of physical processes that mediate air-sea exchange (surface waves, wave breaking, bubble clouds) will underpin an advanced description of the sea surface. New algorithms for estimating air-sea transfer coefficients, surface characteristics (e.g. wave breaking) and upper-ocean forcing from EO data will be developed, with the primary focus on **estimating the transfer velocity of CO₂**. Altimetry will provide novel products, but other EO and model data will be assessed to form the best possible local and global products.

3.5.2 Work description and methodology

The following work will be undertaken:

- i) Revise the description of the sea surface, sub-surface bubbles, direct and bubble-mediated gas transfer.
- ii) Revise the model of nadir backscatter, retrieval of transfer velocity from altimetry, and global calculation of transfer velocities.
- iii) Combine EO data, *in situ* data and model outputs to generate merged products.

3.5.3 Deliverables

Interim deliverables: a) a description of the sea surface and sub-surface bubbles; b) models of microwave nadir scattering of the sea surface; and direct and bubble-mediated gas transfer. Primary deliverable: **Validated retrieval algorithms for surface properties, momentum and CO₂ transfer coefficients.**

3.5.4 Key links to other programmes and organisations

- 1) ERI's role in major projects (e.g. NERC-funded SOLAS projects: DOGEE, SEASAW & HiWASE) ensures recent progress in measuring sea surface characteristics and air-sea fluxes is fully exploited.
- 2) Air-sea transfer coefficients will be kept as general as possible (encompassing all poorly-soluble gases) to feed the Data Synthesis Project (UK SOLAS KT) and other flux projects within WCRP, IGBP, etc.
- 3) The surface and sub-surface description will enable the effects of bubbles on marine optics to be studied and linked to internal and external projects to retrieve bio-optical parameters.
- 4) Parameterisations and EO retrieval algorithms will be used within the Unified Model and sub-models and made available to external operational and climate models (internal links and multiple KT opportunities).

Sub-theme 3.6: Quantification of ocean biogeochemistry and carbon fluxes

3.6.1 Summary

Ocean colour (OC) or visible spectral radiometry deals with light re-emerging from the ocean after scattering and absorption of incident sunlight by particles, phytoplankton (energising photosynthesis), dissolved and detrital organic C compounds (from lysis, respiration and photo-chemical breakdown) and water. Remotely-sensed OC data provides an integrated quasi-steady state observation of the whole of the global ocean and all types of ocean environments (seasonally-variable nutrient & light climates): oligotrophic gyres; equatorial ecosystems; mid and high-latitude, seasonally-productive systems; highly-productive upwelling and convergent zones. Primary production (PP) derived from OC data gives an estimate of the total C sequestered by phytoplankton (~35-70 Gt C yr⁻¹). Hitherto EO-based PP models have used chlorophyll (Chla) as the state variable [23-25]. New methods invoke Inherent Optical Properties (IOPs; the spectral absorption & backscattering of the ocean) [26]. Using IOP models and IOP-OC data, we will describe the pelagic ocean C-cycle, with improved PP models, re-cycling rates and respiration, to: (i) determine phytoplankton function types (PFTs) used in ecosystem models; (ii) provide parameter data for ecosystem models; (iii) partition the pelagic C-pool into particulate, dissolved, organic and inorganic components.

This sub-theme has the following objectives:

- a) quantify the global oceanic organic C cycle using OC data, partitioned into phytoplankton (pigments, biomass, size structure & PFTs), particulate organic C, coloured dissolved organic matter (CDOM), dissolved and particulate inorganic components.
- b) quantify ocean gross, net and new PP (GPP, NPP, New-P) and phytoplankton photosynthetic parameters (e.g. Photosynthetic Quantum Efficiency, PQE), partitioned to PFTs.
- c) quantify phytoplankton and community respiration and production:respiration (P:R) balance, partitioned to PFTs; initial estimation of net autotrophic or heterotrophic state of the oceans linked to CO₂ fluxes.
- d) parameterise the light field from IOPs for improved ecosystem models (links to ST 3.7 & 3.8).

3.6.2 Work description and methodology

- i) *Partitioning the ocean organic carbon budget*

- a) Derive phytoplankton, detrital and dissolved components of the pelagic C-pool from IOP-OC data.
- b) Develop statistical models linking organic C in various components to production and PFTs.
- c) Determine seasonal, inter-annual, intra-decadal and regional variability in PFTs and their relationship to physical-chemical drivers.

ii) *Improved estimates of marine PP and rate processes from OC data*

- a) Develop new and export PP algorithms to quantify the transfer of C through the pelagic ecosystem and 'permanent' sequestration from the atmosphere.
- b) Quantify relationships between *in situ* PQE data and Chl & bio-optical indicators from EO data.
- c) Use EO and *in situ* data to quantify the variability in PQE in phytoplankton communities (PFT estimates) and physical-chemical drivers (light, temperature, nutrients, stratification, turbulence).
- d) Determine the PFT-specific P:R balance from EO estimates of PP and published data for respiration.
- e) Apply EO estimates of global P:R balance to partition the ocean into regions dominated by autotrophic or heterotrophic processes.

3.6.3 Deliverables

- a) Global & regional (N Atlantic/shelf sea) climatologies of PFTs, coloured dissolved organic matter (CDOM), particulate-C and particle size concentration.
- b) Quantified global & regional estimates of primary production (GPP, NPP, New-P, f-ratio) & C-export.
- c) Global and regional climatologies of photosynthetic parameters (e.g. PQE).
- d) Improved estimates of global and regional autotrophic/heterotrophic balance.

3.6.4 Key links to other programmes and organisations

KT activities (DEFRA, EA, UKMO) include development of ecosystem monitoring products (e.g. CDOM in river runoff, PFTs in relation to food for fish stocks, HABs and nuisance blooms, baseline maps and decadal changes in phytoplankton composition). Obvious benefit to QUEST C-cycle modelling. Oceans 2025 (NERC Marine Centres research) is an associated project, providing *in situ* data (AMT; coastal observations).

Sub-theme 3.7: Quantification of bio-physical interactions and air-sea CO₂ fluxes

3.7.1 Summary

This ST will improve understanding of how physical and ecosystem processes interact to modulate air-sea CO₂ fluxes. The impact of variability in ocean processes on fluxes will be quantified from EO data (SST, ocean colour, sea level, sea ice), supported by *in situ* measurements (funded by Oceans 2025 and other links). Its objectives are to: (i) identify and characterize circumstances in time and space where physical and biological factors (STs 3.5, 3.6) converge to significantly change the CO₂ flux (hotspots); (ii) quantify the relative contribution of each of the control factors, including feedbacks. Regions to be studied include upwelling zones, marginal ice zones in polar regions and land-shelf-ocean interaction zones, where *in situ* data already exist. The role of tropical and extra-tropical storms in creating temporary hotspots will be investigated. Feedbacks of biological absorption on ocean heating will be quantified [27, 28, 29] and impacts on ecological niche development and air-sea CO₂ exchange will be investigated. Results will inform model reanalysis and interpretation activities in ST 3.9.

3.7.2 Work description and methodology

i) *Biophysical control of fluxes*

- a) Correlate EO data (SST, OC, sea level anomaly, sea ice) to identify potential air-sea exchange hotspots.
- b) Develop, test and analyze conceptual models relating EO data to controlling factors through multivariate analysis methods (multivariate statistics, neural nets).
- c) Relate b) to opportunistic *in situ* pCO₂ measurements to quantify the relative contribution of biological and physical controls on air-sea CO₂ fluxes.

ii) *Biological feedbacks of fluxes*

- a) Quantify biogenic absorption and scattering impacts on radiative heating of the surface ocean.
- b) Investigate biophysical feedbacks on ecological niches and air-sea fluxes of CO₂.

3.7.3 Deliverables

- a) Global maps of air-sea exchange hotspots.
- b) Quantification of the relative importance of different biological and physical processes for hotspot fluxes.
- c) Quantification of biogenic absorption and scattering contribution to radiative heating of ocean surface.

3.7.4 Key links to other programmes and organisations

Existing and new pCO₂ data will be made available from CDIAC (international data centre), CAVASOO, CARBOOCEAN (EU projects) and NERC Ships (funded through NERC KT grant CARBONOPS). Other *in situ* data (from AMT, Oceans 2025) will also be required. Identification of key hotspots and processes will feed international efforts to identify and monitor vulnerabilities in the C system (e.g. IOCCP, GEOSS).

Sub-theme 3.8: Data assimilation for marine ecosystem models

3.8.1 Summary

Existing oceanic and shelf seas ecosystem models contain large uncertainties in their process descriptions, but are the only tools available to quantify the marine C budget. DA allows systematic use of EO data to reduce the errors in simulations by reducing uncertainty in initial conditions or model parameters. We will pursue field estimation techniques (to constrain model initial conditions) together with reanalysis simulations of the global C cycle and parameter estimation techniques to define parameter sets for use in long-term hindcast and climate change simulations. This ST will cooperate strongly with Theme 7 with the aim of improved quantification of the ocean C cycle. Its objectives comprise:

- a) DA of EO IOP products and photosynthetic parameters into 3-D ecosystem models to generate internally consistent fields of biogeochemical and pelagic ecosystem variables.
- b) DA of satellite and *in situ* data to improve simulations by constraining poorly known model parameters.

3.8.2 Work description and methodology

i) *Sequential assimilation for shelf seas*. The in-water light field is determined by the IOPs of optically active materials in the water column, derivable from EO data [26]. We will develop methods to assimilate IOPs into models of the more optically-complex shelf-seas (closely related to the observation operator approach in ST 3.1). IOPs also provide information on the physical environment, enabling us to characterise the land-ocean interface. The relationship between the physical consequences of IOPs (e.g. dependence of settling velocity on turbulence and erosion rate) along with their relationship to salinity, as a proxy for freshwater, will be explored with the aim of improving the underlying transport models. Univariate assimilation techniques will be applied principally for SST and SSH to constrain the hydrodynamic models. PML has developed an EnKF assimilation system [30, 31] which has been applied to the European regional shelf-seas ecosystem model (ERSEM [32]) and will adapt these techniques to assimilate IOPs and satellite-derived photosynthetic parameters (from ST 3.6). We will assess which combinations of physical and ecosystem assimilation measurements are most effective in reducing simulation errors in shelf seas ecosystem models. We will also investigate approximations to EnKF appropriate for large scale multi-annual 3D simulations (e.g. the Single Evolution Extended Kalman Filter, SEEK) and test them against full EnKF. The resulting assimilations will be used to constrain reanalysis simulations of the global shelf seas C budgets (ST 3.9).

ii) *Parameter estimation for the open ocean*. Oceans 2025 is developing site-based test-beds to optimize the free parameters of ecosystem models and evaluating the models on the basis of their design. We will build on this work to assimilate a diverse range of EO data from satellites and *in situ* platforms (CARBOOCEAN, AMT etc.). This will complement site-based test-beds by: (a) providing additional data to constrain the models and (b) ensuring that the models are robust over basin scales. New techniques are required to achieve this. Computational requirements dictate a 1-D approach. A global 1-D test-bed array will be set up relying

on 3-D model output as physical forcing data. The sensitivity of the results to uncertainties in these data and in the observations will be investigated with a view to developing robust techniques that weight different observations appropriately. EO-based techniques will be developed to reduce the susceptibility of 1-D methods to the effects of horizontal fluxes and representation errors and to allow for geographical variation in parameters. The test-beds will be used to calibrate and evaluate NERC QUEST marine ecosystem models.

3.8.3 Deliverables Techniques to constrain the light field in coupled hydrodynamic-ecosystem models by assimilating IOPs; parameter estimation techniques and parameter sets for global and shelf seas ecosystem models.

3.8.4 Key links to other programmes and organisations

pCO₂ and other *in situ* data will come from CDIAC, CAVASOO, CARBOOCEAN, CARBONOPS, AMT and Oceans 2025. The UKMO will undertake the following collaborative work aligned with this ST: a) Sequential assimilation of satellite products by extending their current chlorophyll assimilation scheme, jointly developed with NOCS, to use additional ocean colour information, thus improving the representation of biogeochemical fields in NCOF models; b) Assessing the feasibility of sequential assimilation using IOPs and water-leaving radiances instead of geophysical products. UKMO/Hadley/QUEST will benefit from optimized marine ecosystem models and better understanding of model capabilities.

Sub-theme 3.9: Reanalysis, validation and prediction

3.9.1 Summary

The air-sea exchange of CO₂ is highly dependent on the internal ocean C-budget. This is not directly accessible from EO, but full budgets (transport, export, burial) can be obtained from coupled hydrodynamic-ecosystem models. The accuracy of these models is often questionable, so an optimal picture of the ocean C-cycle comes from synthesizing observations and model output using DA. EO provides the only systematic global data for such a study. Here, EO data (SST, SSH, with Argo data used to constrain the hydrography) will be used to constrain the model's physical properties using established techniques. Using EO to constrain biological properties is less well established, due to uncertainties in the observations and in the relationship between the observed and modeled variables. Sequential assimilation of chlorophyll has been studied in CASIX, but we here shift the focus to IOPs and radiances and using EO data for parameter estimation, drawing on techniques developed in ST 3.8.

Because of the differing range of scales and processes, the deep ocean and coastal ocean each has a production and verification phase and an analysis phase. For both, the aim is to produce high accuracy, error-quantified model products [33] and to use these to help answer key questions about the marine C cycle. Objectives of this work are:

- a) To produce multi-year re-analyses of coupled hydrodynamic-ecosystem models of the open and coastal ocean constrained by sequential assimilation of EO data.
- b) To conduct long-term coupled hydrodynamic-ecosystem simulations for hindcast and forecast, with unknown parameters constrained by EO data.
- c) To quantify the inter-annual variability in the oceanic and shelf seas' contribution to the global C-budget through analysis of EO constrained model simulations.

3.9.2 Work description and methodology

i) *Re-analysis, validation and error quantification of C-cycle: open ocean.* We will conduct a 13-year (1997-2010) re-analysis of the global ocean C-cycle using coupled hydrodynamic-ecosystem models (drawing on the NCOF partnership, CASIX, MARQUEST and Oceans 2025), to quantify the inter-annual variability in the ocean-atmosphere flux of CO₂. NCOF models (FOAM-HadOCC, moving to NEMO) will be used at a range of resolutions; high resolution basin scale models will focus on the N. Atlantic, Arctic and Southern Oceans. Forecasts and hindcasts of air-sea O₂ and CO₂ fluxes will be made with coarser resolution models for time periods beyond the availability of EO data with sequential assimilation. The analysis of O₂ is

particularly important: recent work (e.g. IPCC AR4) has highlighted the rapid decline of mid-depth ocean O₂ concentrations, indicating an important additional constraint on surface fluxes. We will use NEMO with the QUEST ocean biogeochemical-ecosystem scheme (MARQUEST) and validate with EO and *in situ* data.

ii) *Re-analysis, validation and error quantification of C-cycle: coastal ocean.* We will conduct a 13-year re-analysis of key shelf-sea regions to quantify the inter-annual variability of shelf-sea C-budgets and air-sea CO₂ fluxes, with a focus on error-quantification of the re-analysis using independent *in situ* data sets. The technology for global scale coastal ocean simulations comes from the NERC eScience Global Coastal Ocean Modelling System (GCOMS) project (2006-2009) and draws on the POLCOMS-ERSEM model [32] applied to large scale shelf-sea domains around the world. The coupled model, with assimilation of physical and biological variables (ST 3.8), will be applied to several coastal ocean regions observed to play an important role in the C-cycle, including temperate seas (e.g. NW European shelf), upwelling regions (e.g. Humboldt current) and tropical regions (e.g. South China Sea). For each region, we will conduct high-resolution (~0.1°) simulations with full DA to provide the products for (iv). As computer resources increase, the number of regions may be increased to the ~50 considered in the GCOMS project.

iii) *Analysis: open ocean.* The simulations in (i) will be used to address fundamental questions about oceanic air-sea CO₂ fluxes:

1. How does the inter-annual variability in CO₂ fluxes relate to climate indices (e.g. ENSO and NAO) and what are the causal mechanisms?
2. Are oceans net autotrophic or net heterotrophic?
3. Does the answer to 2 agree with that obtained from EO data alone?
4. Is it possible to decouple physical from biological effects?

iv) *Analysis: coastal ocean.* We will quantify the inter-annual variability in the shelf seas' contribution to C-cycling at the land-sea, shelf-sea/deep-ocean and pelagic-benthic interfaces through analysing the multi-annual model simulation from (ii). Questions we will address are:

1. How efficient and widespread is 'shelf sea pumping'?
2. How has the functioning of shelf-seas (air-sea exchange, PP, P-R) changed over the past decade?
3. How important is the land-sea boundary to the shelf-sea C-cycle: can we decouple variability in the inorganic C inputs from variability in the biological signal?

3.9.3 Deliverables

Analyses as outlined above, multi-year model data sets, synthesised model products, global ocean and shelf-sea CO₂ flux maps.

3.9.4 Key links to other programmes and organisations

EU and NERC programmes (as for 3.8) will provide *in situ* data for error quantification, and allow assessment of the uncertainties in the model hindcast products and how EO assimilation improves them. Oceans 2025, MARQUEST and GCOMS are important associated NERC model development projects. These activities will exploit existing and develop new KT with key partnerships: UKMO, NCOF.

3.10: Integrating satellite measurements of atmosphere, land and ocean to quantify surface C fluxes and their causes.

3.10.1 Summary

Satellite observations of column CH₄ (SCIAMACHY, IASI) and CO₂ (SCIAMACHY, AIRS, OCO & GOSAT) have the potential to transform our knowledge of land-ocean-atmosphere GHG fluxes. Current surface flux estimates are obtained by inverting global 3-D atmospheric transport models using the ground-based network of atmospheric concentration measurements. These have limited accuracy because of the sparsity of the measurements and errors in modelling atmospheric transport. New EO observations give global coverage and can provide improved flux inversions, as long as their uncertainties and biases are small

enough and well characterised. By combining atmospheric chemistry-transport models (CTMs) with process-driven models for surface GHG fluxes in a DA approach, the controlling model parameters can also be estimated, and further constraints from observations of the surface can be exploited. This ST therefore focuses on **using satellite measurements of column GHG concentrations with land and ocean observations to constrain the surface fluxes of methane and carbon dioxide and estimate their biophysical drivers**. It integrates most of the observational and modelling aspects of the Theme, and is strongly coupled to Theme 3. Its initial focus will be on CH₄, for which there are largely unexplained changes in atmospheric growth rate (IPCC 2007), new satellite observations of atmospheric distribution and variability [34], and potentially significant sources related to climate warming at high latitudes and in the deep ocean. Added to these science drivers is pragmatism: the methodology developed for CH₄ with current datasets can be transferred to CO₂ data from the upcoming OCO & GOSAT satellites.

3.10.2 Work description and methodology

We will first focus on CH₄ with SCIAMACHY and IASI data, building the full machinery for coupling a CTM to a land biosphere model in order to infer surface fluxes and model parameters. At the same time, we will perform preparatory work for the OCO & GOSAT missions, due to launch in 2008/9, so that this machinery can be transferred to the CO₂ problem once validated data come on-stream. This maximises scientific return while minimising risk.

1. A parameterised biospheric methane surface flux model will be developed, based on available models [35, 36, 37]. Emissions from coal mining, oil & natural gas production, ruminants, etc. will be taken from the literature, but improved with new information on lakes, wetlands and rice paddies from ALOS PALSAR L-band radar and Envisat, and emissions from fires (ST 3.2). We will also seek to improve the representation of NPP, soil temperature and hydrology using satellite data. Ocean fluxes will be taken from the literature. These prior spatial maps of surface fluxes and their uncertainties will be used in atmospheric inversion. (NB: CH₄ satellite data, with its bias/precision, and CTM development will be provided by Theme 3.) In a second step, DA will be used to infer process parameters and learn about the controlling processes; optimum approaches, e.g. EnKF vs adjoint-based, to this difficult problem will be investigated in Theme 7. Extensive simulations will be used to assess the accuracy of the estimated parameters and the accuracy needed in space-based CH₄ measurements to improve on inversions using the ground-based network of CH₄ measurements.

2. This generic machinery will be transferred to the CO₂ problem, with the addition of an ocean CO₂ surface flux model. The major drive is to exploit OCO and GOSAT, but initial simulation experiments will assess the ability to invert satellite/ground/aircraft CO₂ data to both surface fluxes and model parameters. This will benefit from Mission Preparatory work quantifying the bias and precision of CO₂ data from SCIAMACHY, AIRS, OCO & GOSAT. Deriving global spatio-temporal patterns of CO₂ fluxes and their drivers is our main aim, but the high spatial resolution of OCO/GOSAT will be used to estimate regional scale (~100 km) fluxes.

3. Mission Preparatory funding will support: a) comparison of daily and seasonal observations with model results and with ground and aircraft flux and concentration data (e.g., FTS, NOAA ESRL, Carbo-Europe, CARIBIC, NIES); b) comparison of observations from different satellite instruments; c) development of new products with existing data, e.g. aerosol co-retrieval, AIRS/SCIAMACHY combination for height information, ocean products and independent O₂ determination; d) a multiple tracer approach (CO/CO₂/CH₄/aerosol) to source attribution (biogenic, pyrogenic, etc.), linked to ST 3.2.

3.10.3 Deliverables

a) Development of a biospheric methane model compatible with JULES.

b) An infrastructure to use surface flux models with CTMs and satellite column CH₄ and CO₂ data to improve estimates of surface fluxes and their drivers, as part of a national and global C accounting scheme.

c) A critical assessment of the added value from using EO data with *in situ* data to estimate CH₄ and CO₂ fluxes and processes, tied to the bias and precision of the data.

3.10.4 Key links to other programmes and organisations

Inputs from NOAA ESRL, Carbo-Europe, TCOS Siberia and CARIBIC are needed for Cal/Val.

4. Satellite observational requirements for the whole theme

Key land surface sensors include AVHRR, SeaWiFS, MERIS, MODIS, PALSAR, MSG, GOES-E & W, FY2C and TRMM. MODIS follow-on and the GMES IR element are important future sensors. For the ocean, ocean colour measurements will be provided by SeaWiFS, MODIS and MERIS, sea surface temperature measurements by MODIS, AVHRR and (A)ATSR, wind speed and various wave height / surface roughness characteristics from active and passive microwave sensors, with the emphasis on altimeters (ERS-1/2, Topex/Poseidon, GFO, JASON, ENVISAT) which provide wind speed, wave height and (more experimentally) other wave characteristics. SAR (Radarsat, ASAR, TerraSAR) and microwave sensors (SSM/I, AMSR-E) will be used to detect marginal sea-ice in ST7; continuity is planned for these missions. Atmospheric measurements will be provided by SCIAMACHY, AIRS, IASI, MOPITT, OCO and GOSAT.

5. Resource requirements and justification

ST1 requires DA (Williams, Edinb.) allied to EO expertise (Lewis, UCL; Quegan, Sheffield), with 2 RAs totalling 8.3 FTE. ST2 (Wooster, KCL) requires 1 RA @ 4.15 FTE, fieldwork in the UK, Canada and S Africa (including helicopter hire) to participate in controlled burning experiments, and mass processing requirements. ST3 needs 1 RA @ 4.15 FTE at York (Ineson) and 1 PhD at Edinburgh (Grace, Moncrieff). It involves renting space on and instrumentation of a tall tower in the North of England, a sustained programme of flights by the Edinburgh aircraft, and significant amounts of consumables and fieldwork by York, UCL and Edinburgh. ST4 requires 1 RA @ 4.15 FTE (Quegan, Sheffield) and 1 student (Page, Leicester), together with support for 3 trips to Indonesia for fieldwork, and organisation costs of a workshop with local researchers and organisations on each trip. ST5 requires 1 RA @ 3 FTE (Woolf, ERI). ST6 and ST7 are led by PML (Aiken, Hardman-Mountford, Smyth, Sathyendranath) with input from Lavender (U.Ply), Watson (UEA) and Mitchelson-Jacob (UWB). ST6 requires 3 RAs at PML & U.Ply (total 6 FTE), ST7 requires 4 RAs at PML, U.Ply, UEA and UWB (total 6 FTE). ST8 is led by PML (Allen, Blackford) with input from POL (Holt) and NOCS (Hemmings), requiring 7 FTE (2 PML, 2 POL, 3 NOCS). ST9 is led by POL (Holt) with input from PML (Allen, Blackford), NOCS (Hemmings) and UEA (Watson), and requires 8 FTE (3 POL, 2 PML, 2 NOCS, 1 UEA). It has intensive computer requirements, and draws on NERC's commitment to HPC and exploring opportunities in peta-scale computing (application submitted to CCLRC Daresbury strategic initiative programme), in addition to existing clusters at PML & POL. ST10 (Woodward, Sheffield) requires a full-time modeller @ 4.15FTE to work on land surface flux models. It relies on CTM support from Theme 3, and Mission Preparatory support for OCO/GOSAT readiness (Monks, Leicester). Administrative support (3 days per week, Grade 5 pt.1) is essential to manage the diverse range of institutions and associated Themes. RAs and PIs are expected to attend 1 UK and 1 overseas conference p.a., and UCL's average involvement in CEOS WGCV needs extra T & S support. Visits to partners (~4-6 per RA and PI p.a.) are essential for cohesion. All RAs need access to a high spec PC/LINUX machine, replaced once in the 5-year period, but the higher processing demands at UCL and KCL require more powerful machines, and data storage equipment, also necessary at Edinburgh. Consumables are costed at ~£500 p.a. per institution on average, with necessary substantial additions as noted above.

6. Knowledge Transfer

All STs have significant KT elements for UNFCCC carbon accounting and Hadley Centre IPCC forecasts. 3.2 involves specific links with the Met services to develop FRP products; 3.3 has several elements developed to meet information needs of the Forestry Commission, regional nature conservancy, utility companies and DEFRA; 3.4 is strongly driven by DEFRA and WWF guidance on information needs for post-Kyoto mechanisms and biodiversity protection. 3.5 to 3.9 all link to NCOF activities and inform DEFRA's monitoring activities in the areas of marine ecosystem health and climate change (MCCIP). The ocean activities are closely aligned with IOCCP efforts to coordinate ocean C activities within GEOSS.

7. Risk assessment

MODIS, MERIS, SeaWiFS, AVHRR, MOPITT and the geostationary satellites are all low-risk since they are operational with well-founded replacement plans or with more than five years of data already available. The GMES IR Element and MODIS follow-on are less certain within the NCEO timeframe. PALSAR has been routinely gathering data since October 2006, but failure inside its expected 5-year lifetime would affect biomass estimation (3.1) and tropical deforestation mapping (3.4). No viable replacement for biomass will occur within the lifetime of NCEO, but optical data could be exploited for deforestation at a lower level of innovation but still of great value. Failure in all current ocean colour sensors (SeaWiFS, MODIS, MERIS, all already beyond scheduled lifespan) prior to the launch of new sensors (earliest planned VIIRS on NPP in 2009/10) would create a gap in the ocean colour data record; this risk is partly mitigated by the planned launch of the Indian OCM on Oceansat-2 in 2008, and would not significantly influence the work proposed in NCEO because good historical records can be used (1997 onwards). There is also a good historical altimeter database, continuous from 1991. Currently data from ENVISAT and JASON continue the series. Both are likely to fail during the life of NCEO but follow-on missions are planned. Again, failure would not significantly impact the planned work in NCEO as the historical record can be used. The risk associated with the launches of OCO and GOSAT is mitigated since both would have to fail or be seriously delayed, and much of the early science gain comes from work on current observing systems, e.g. SCIAMACHY and AIRS. The value of OCO and GOSAT CO₂ retrievals over the ocean remains to be proven.

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