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The Arctic Flux Study: a regional view of trace gas release

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Abstract. Fluxes of trace gases from northern ecosystems represent a highly uncertain and potentially significant component of the arctic land–atmosphere system, especially in the context of greenhouse-induced climate change. The initial goal of the Arctic Flux Study (a part of NSF's Arctic System Science Program) is a regional estimate of the present and future movement of materials between the land, atmosphere and ocean in the Kuparuk River basin in northern Alaska. We are measuring rates and controls of processes along a north–south transect running from the marshy coastal plain to mountain valleys. Important vertical fluxes under study are the release of CO_2 and CH_4 from soils and water, lateral fluxes are surface water, nutrients, and organic matter.

A hierarchy of measurements allow the rates and understanding of processes to be scaled from plots to the landscape, regional, and circumarctic level. These include gas flux measurements in small chambers, measurements over larger areas by eddy correlation from small towers, and measurements at the landscape scale from airplane overflights. Experimental manipulations of carbon dioxide, soil moisture, nutrients and soil temperature from this and other studies give information on process controls. The distribution of plant communities has been described at several landscape-scale sites and a hierarchic GIS has been developed for the region at three scales (plot, landscape, region). Climate is measured at six sites and hydrological processes are being studied at each watershed scale. In the soils, measurements are being made of soil organic matter and active layer thickness and of availability of soil organic matter for microbial transformation into CO_2 and CH_4.

Fluxes and process understanding have been incorporated into a hierarchy of models at different scales. These include models of regional climate nested in a GCM; of regional- and continental-scale plant productivity and carbon cycling including CO_2 release under altered climates; watershed and regional models of hydrology; and surface energy budgets.

After the first year of study the regional climate model has been successfully configured to the northern Alaska region. We have also measured a large release of carbon dioxide from tundra soils in all but the coldest and wettest parts of the transect. The rates from eddy correlation towers (landscape level) agree closely with rates from chambers (plot level). Observations, experimental manipulations and modelling analyses result in the prediction that the combination of warmer and drier soils is responsible for the large CO_2 release.

Key words. Arctic, tundra ecosystem, global warming, carbon dioxide, methane, trace gases, modelling.

INTRODUCTION

Greenhouse warming in northern land areas is predicted by global climate models to be several times greater than the global mean of 1.5–4.5°C (IPCC, 1992). During the past several decades, the observed warming has been much stronger over the northern land areas than over the Arctic Ocean (Kahl *et al.*, 1993) or subpolar oceans (Chapman & Walsh, 1993). The warming has been particularly large over Siberia, north western Canada and much of Alaska, where warming rates over the past 30 years are approxi-

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mately 1°C per decade. The warming over many of these areas has been strongest in the spring, when small changes in the surface energy balance can influence the snow melt, runoff, vegetative activity and trace gas fluxes from northern ecosystems. A warming of approximately 1°C per decade also is apparent in summer (July–August) temperatures of the past 20 years at the northern Alaskan coastal stations, Barrow and Prudhoe Bay (Oechel *et al.*, 1993).

Large portions of northern land areas are underlain by permafrost, in which the summer thaw is limited to a thin (often < 1 m) active layer. The soil active layer and upper permafrost layer of northern ecosystems contain up to 455 Gt of carbon, which is equivalent to approximately 60% of the ~ 750 Gt C currently in the atmosphere as CO_2. Arctic tundra ecosystems alone contain more than 50 Gt C below ground as dead organic matter (Oechel *et al.*, 1993). If the thawing becomes more widespread, these large stores of carbon may be released to the atmosphere as CO_2, CH_4 and other trace gases, thereby amplifying the greenhouse effect. In fact, the warming of the 1970s and 1980s over the Alaskan North Slope appears to have changed the tundra from a net sink to a net source of carbon for the atmosphere (Oechel *et al.*, 1993). Although environmental conditions varied considerably from year to year, the daily and seasonal patterns of carbon flux were dominated by carbon loss to the atmosphere during the snow melt-to-freezeup period of 5 different years sampled over the past decade. (However, the measurements during four of these years were made at only one site: Toolik Lake in the northern foothills of the Brooks Range.) The carbon loss measured along a transect during 1990 indicated that the loss increased from the wetter to the drier tundra sites, suggesting that the carbon loss from these ecosystems is not caused directly by the increase in temperature but indirectly, by a lowering of the water table and by enhanced soil aeration. Hinzman & Kane (1992) have predicted that a drier active layer will result from additional evapotranspiration for a warmer climate. An emerging possibility, then, is that the initial response to warming and drying may be a loss of carbon from the terrestrial system, whereas at longer intervals invasion by shrub and tree species could conceivably result in increased above-ground carbon storage (Oechel & Vourlitis, 1994; Shaver *et al.*, 1992).

Vegetation changes have already begun to occur in tussock tundra over the past decade, with an increase in deciduous shrubs and a decline in sedges (Chapin *et al.*, 1995). These changes are expected responses to warming based on experiments simulating climatic warming and the pollen record, and may have important feedbacks to regional climate through changes in water and energy flux.

Existing ecosystem processes are closely tied to the hydrology; specifically, the importance of the moisture levels of the active layer in producing greenhouse gases. In areas of continuous permafrost, as exists on the North Slope of Alaska, all subsurface flow in the hydrologic cycle is confined to the shallow active layer. The thickness of this active layer is very sensitive to the surface energy balance and therefore would respond to warming of the atmosphere. Kane *et al.* (1991) have shown that the active layer thickness near Toolik Lake would approximately double for an average annual temperature increase of 4°C (from the present depth of 50 cm).

The findings described above have potential global implications and are consistent with other recent large-scale assessments of the global carbon budget. Tans *et al.* (1990) argued that a high-latitude carbon source is necessary to balance an observed north–south gradient of atmospheric CO_2 (Webb & Overpeck, 1993). Smith & Shugart (1993) used a simple compartment model of terrestrial carbon reserves to simulate the response to the temperature and precipitation changes projected by two coarse-resolution global climate models. Their simulation indicated that the resulting soil and vegetation changes could be 'a significant source of CO_2 in the first 50–100 years following climate warming, increasing the atmospheric CO_2 concentration by up to a third of the present level' (Smith & Shugart, 1993, p. 523). This response is much more rapid than the changes in species composition that might lead to an increase of carbon storage. A key limitation of the Smith and Shugart study is the use of a fixed rate of carbon transfer associated with each class of vegetation dynamics. Because these rates will vary strongly, not only with vegetation type but with temperature and precipitation, Smith and Shugart note that 'a detailed analysis using specific rates of response for important terrestrial ecosystems must await a large-scale coordinated ecological research programme' (Smith and Shugart, 1993: 525). We agree with this conclusion and the study described in this paper (the so-called Flux Study) represents the high latitude component of such an effort.

Another central issue in the transient response of terrestrial ecosystems is the spatial pattern of the climate change. As noted by Webb & Overpeck (1993: 498) in their editorial on the above studies, 'the simple extrapolation of the measured fluxes to other high-latitude ecosystems overlooks any regional variability in climate change, and fails to account for possible effects of increased precipitation on soil carbon storage'. Karl *et al.* (1993) indeed did find some observational evidence for recent increases in high-latitude precipitation, consistent with coarse-resolution climate model predictions of greenhouse warming scenarios. The relative importance of the higher temperatures (favouring drier soils) and increased precipitation (favouring wetter soil) is crucial to the ecosystem response. A coupled atmosphere–land model, which represents a vehicle for addressing these competing effects over a regional scale, is an integrating element of the Flux Study. This regional model will provide high-resolution scenarios of greenhouse-induced climate change over a high-latitude domain, thus providing the spatially and seasonally varying fields of temperature and precipitation required for assessments of the potential changes in the carbon flux over topographically and vegetatively complex regions.

Finally, studies to date of the high-latitude surface fluxes of carbon have not considered the horizontal transports associated with the hydrologic cycle. Kling *et al.* (1991) found supersaturated levels of dissolved CO_2 in the soil water, lakes and streams of northern ecosystems. From these data they calculated that previous estimates of the release of CO_2 to the atmosphere from arctic tundra should be increased by 7–20% to account for release by aquatic pathways. The hydrologic component of the Flux Study includes the measurements, scaling and modelling needed to understand such findings and places them into the broader contexts of the regional carbon budget and global change.

On the basis of the recent findings summarized above, it appears that high-latitude changes are now under way. Since these changes have global implications, there is an urgent need for a more comprehensive understanding and prediction of the carbon fluxes from northern terrestrial ecosystems. The Flux Study responds directly to this need. Specifically, the study has two goals:

1. a quantitative understanding of the variables and processes controlling the fluxes of CO_2 and methane from Arctic ecosystems to the atmosphere and ocean; and
2. a determination of how these fluxes will change in response to future variations in climate and the Arctic system.

The hypotheses we are testing are as follows:

Hypothesis 1. The Arctic terrestrial and freshwater system is presently a source of CO_2 and CH_4.

Hypothesis 2. Greenhouse-induced changes of temperature and moisture will be large enough to trigger changes in trace gas fluxes from Arctic land areas. These changes of trace gas fluxes will result in climate feedbacks that are at least as large as feedbacks resulting from vegetation and albedo changes.

Hypothesis 3. Trace gas flux sensitivities are such that, over the next 50 years, changes in moisture will exert a greater control on the regional fluxes than will changes in temperature or vegetation. Beyond 50 years, Arctic vegetative changes will contribute more significantly to Arctic climate feedbacks.

Hypothesis 4. Climate change and the related oxidation of soil organic matter will increase the nutrient flux to streams, lakes and the Arctic Ocean.

Hypothesis 5. Arctic trace gas feedbacks will be sufficient to impact climate beyond the Arctic.

The Flux Study necessarily includes studies of surface-water and energy fluxes. Energy and water fluxes clearly shape the regional temperature regime, which is a primary factor in determining the surface state (frozen vs. thawed), trace gas fluxes, rates of productivity and the link to regional climate. Moreover, the land surface hydrology, with its horizontal fluxes of freshwater, carbon, and nutrients, provides the project with an important scientific link to the Ocean/Atmosphere/Ice Interactions (OAII) component of NSF's ARCSS (Arctic System Science) programme. The hydrologic transports of nutrients, gases, and organic matter across landscapes to the Arctic Ocean have been identified as integrating processes of ARCSS. In particular, the movement of freshwater to the ocean provides another linkage between the Arctic land surface and global climate through its effect on the circulation of the Arctic Ocean and outflow to the North Atlantic.

Ecosystem models can be used for scaling to the circumarctic and global scales. When used judiciously in conjunction with field data and atmosphere/land process models they are valuable tools for the extrapolation of observational and modelling results obtained from a regional study (McGuire *et al.*, 1992; Schimel *et al.*, 1991). These models will permit the Flux Study to address more thoroughly the feedbacks involving changes in ecosystems. Baskin's (1993) summary of a recent meeting of the International Geosphere/Biosphere Programme (IGBP) Scientific Advisory Council points to the timeliness of an ecosystem modelling component. While the first experiments coupling global climate models (GCMs) to ecosystem models are planned for 1995, these experiments must contend with 'mismatches' in the spatial resolution and in the time stepping of GCMs ($\Delta x \sim 300$ km, $\Delta t \sim 10$ min) and ecological models ($\Delta x < 50$ km, $\Delta t \sim$ months-years). The Arctic/Alaskan regional focus will enable the Flux Study to bridge such gaps and to serve as a prototype for IGBP studies of decadal-scale changes involving ecosystems. Moreover, the Terrestrial Ecosystem Model (TEM) to be used in the Flux Study is a means to 'fill in the blind spot in global ecosystem modelling' (Baskin, 1993: 1693).

The Flux Study thus combines intensive field measurements at several sites along a north–south gradient on the Alaskan North Slope with a wider effort to place the measurements into a regional, circumarctic and, ultimately, a global framework. The philosophy underlying our approach is that the most efficient strategy to scale up field measurements to the entire Arctic is to measure intensively a single, reasonably large area containing sufficient variation and diversity that the major conceptual and scaling problems may be addressed within the programme. By focusing on a single area, studies of different aspects of the Arctic system can be performed in a logistically co-ordinated way and can be more easily and economically integrated. The extrapolation required to the regional and global scales will draw upon the co-ordinated use of a hierarchical Geographic Information System (GIS), delineation of functional landscape units via remote-sensing techniques, formulations of hydrologic and soil processes, the coupling of a regional atmospheric model and a surface model and ecosystem modelling. The GIS and the regional modelling provide frameworks for nesting a region of intensive study within a broader (circumpolar/global) area with which interactions and feedbacks may occur.

The main field work for the Flux Study began in the spring of 1994. This paper therefore necessarily deals primarily with strategies and plan for the study rather than with results to date.

THE CO-ORDINATED FLUX STUDY PROGRAMME

Future changes of trace gas fluxes in the Arctic will result from (1) changes in the physical environment (e.g. the climate and hydrology), and (2) changes to the biological systems. Predictions of trace gas flux must include both factors, and the various projects within the Flux Study must address both factors. Several synthetic efforts will bring together the various individual projects in order to obtain the assessments of present-day regional fluxes and predictions of future fluxes.

Direct measurements at various scales

Primary elements of the co-ordinated field programme will be plot-level measurements of CO_2, CH_4, H_2O and the surface energy balance; and regional aircraft measurements of CO_2, H_2O and energy flux. Measurements of surface characteristics and satellite-derived reflectance spectra will be used in conjunction with a GIS to determine relationships between quantities sensed from space and measurements made at the plot-level.

A GIS data base

Many parts of the project will contribute to the GIS, which will include maps of surface reflectance, soil moisture status, vegetation, geology and geomorphology, terrain, indices derived from remotely sensed data (e.g. greenness index, wetness index, Normalization Difference Vegetation Index (NDVI)), soil carbon data, plant canopy and biomass and trace gas fluxes. In addition to the construction of new GISs for Happy Valley and Barrow, additions will be made to existing GISs for Toolik Lake, Imnavait Creek and Prudhoe Bay. A GIS for the entire Kuparuk Basin will be constructed from diverse information including digital terrain elevation maps and Thematic Mapper data.

Field manipulation

The most direct way to test our understanding of controls over trace gas fluxes is to manipulate those factors thought to control the fluxes. Factors to be manipulated include temperature, moisture and species composition. The field manipulation experiments provide the opportunity to study various processes that contribute to trace gas fluxes: productivity, root and soil respiration and turnover of specific soil organic fractions.

Regional atmospheric modelling

To obtain atmospheric model simulations of seasonal climatologies for the North Slope, an existing Mesoscale Model (Reg CM2) of the National Center for Atmospheric Research (NCAR) is being adapted to a domain of 3000×3000 km^2. This model will be coupled to other models to assess the interactions leading to feedbacks between the Arctic land surface and the larger earth system.

Land surface process modelling

This effort includes a model of the energy and moisture balances at the terrestrial surface. Atmospheric forcing will come from direct measurements and from the regional atmospheric model. The GIS of vegetation parameters, soil type, and land-surface parameters will be necessary to run the land-surface model on a grid and to produce simulations of carbon fluxes over a region.

Hydrological modelling

The hydrology model, a physically based watershed model, will include snow melt, evapotranspiration, freeze–thaw of the active layer, surface and subsurface (active layer) flow, and channel routing. Atmospheric forcing will come from the regional atmospheric model. The model will be applied to three nested watersheds: Imnavait Creek (2.2 km^2) Upper Kuparuk River (146 km^2), and the entire Kuparuk River drainage (8142 km^2).

Subsurface process modelling

This effort includes models of soil processes and an ecosystem–biogeochemical model of carbon and nitrogen pools as well as vegetation and decomposition processes. These models will utilize GIS data on thaw depth, soil carbon properties, surface reflectance characteristics and topography/vegetation.

Ecosystem modelling

Two existing terrestrial models will be adapted. The Generic Ecosystem Model (GEM) will predict conditions such as temperature and CO_2 changes. The Terrestrial Ecosystem Model (TEM) will add a soil moisture/hydrology formulation for permafrost regions. It will interact with a Flux Study GIS to produce spatial data on net primary production and CO_2 and CH_4 exchanges with the atmosphere for the Kuparuk Basin (10 km^2 scale) and later for the circumarctic region (0.5° scale). The Flux Study data will allow a Prentice-style model to be applied in a future project to predict plant community change.

Table 1 lists the principal investigators, their major contributions to the integrated programme, and an indication of whether each effort has a significant component in field/laboratory work and/or synthesis/modelling/scaling.

FIELD MEASUREMENTS

The measurement component of the Flux Study is initially concentrating on the 8400 km^2 Kuparuk River watershed (Fig. 1). The Kuparuk River passes through the four major physiographic provinces of the North Slope: the Brooks Range, Southern Arctic Foothills, Northern Arctic Foothills, and Arctic Coastal Plain. The vegetation is broadly representative of a large part of the circumpolar tundra zone (Alexandrova, 1980), where much of the carbon in Arctic ecosystems is stored. Logistically, the transect also is relatively easy to study and parts of the transect are the focus of other Arctic research programmes such as the Arctic Long-Term Ecological Research (LTER) project and the former DOE-sponsored R4D project. Hierarchical (1:10, 1:500, and 1:1500) GIS data bases already exist for Imnavait Creek and Toolik Lake, while a 1:1500-scale GIS exists for Prudhoe Bay. Through time, the Flux Study measurements are scheduled to encompass all of Arctic Alaska and Russia.

Initially, major study sites include Prudhoe Bay, Happy Valley, and Imnavait Creek (near Toolik Lake) (Fig. 1). These sites have strong historical data bases on climate and hydrology, and GIS data bases of vegetation and soils already exist for each site. Research at secondary sites

TABLE 1. Summary of major tasks by Flux Study investigators. 'F' denotes a key role in field/measurement projects; 'S' a key role in scaling/modelling/synthesis

Investigators	Major tasks	Role
Chapin/Bonan	Measure water vapour, energy, CO_2 fluxes over vegetation types Carry out coordinated field experiments to diagnose mechanisms by which fluxes vary Measure the components of terrestrial CO_2 flux, using isotopes Adapt land-surface/soil model to the Arctic	FS
Everett/Nelson	Measure active layer thickness Model active layer sensitivities (on a regional scale)	FS
Hobbie	Measure fluxes of CO_2 and CH_4 to atmosphere via streams and lakes Measure organic carbon and nutrient flux to streams Adapt biogeochemical models of carbon cycling to the Arctic (GEM, TEM)	FS
Kane	Measure hydrology and meteorology (rates and nutrient chemistry of streamflow and soil moisture) Develop physically-based hydrological model; apply to Imnavait Creek, the headwaters of the Kuparuk River and then the entire Kuparuk River	FS
Oechel	Measure CO_2 fluxes (chamber, tower, aircraft) Scale CO_2 fluxes from plot-to-plot to regional scale; use remote-sensing data to relate landscape units to CO_2 flux	FS
Ping	Fractionate and characterize soil organic matter Estimate substrate quantities of trace gases and availability for gas flux	F
Reeburgh	Measure methane: surface flux and soil profile Determine controls on spatial/temporal variability of methane flux	F
Walker/Schimel	Develop GIS data bases (at several scales) Determine linkages between GIS data and satellite measurements (e.g. NDVI) as basis for extrapolation to larger scales Model evapotranspiration (H_2O flux) and photosynthesis (CO_2 flux)	FS
Walsh/Weller	Configure regional model of Arctic atmosphere/land system Simulate atmospheric component of hydrological budget Use regional model and GCM forcing to obtain high resolution projections of Arctic climate change	S

along this transect has begun and will be increased, providing a test of our ability to extrapolate within and between climatic/vegetation zones. Secondary sites include Toolik Lake, a 'replicate' site in the same climatic zone as Imnavait Creek, and Franklin Bluffs (a wet tundra site that is warmer than Prudhoe Bay). Permanent eddy correlation flux towers have been established at Happy Valley and Prudhoe Bay. Intensive chamber flux, vegetation sampling, scaling and 'rapid GIS' will be done in the tower footprints.

The study also builds on previous research on trace gas flux, climate and soils at a coastal site at Barrow (Fig. 1), for which there is a 25-year historical record of soil thaw, soil carbon, vegetation and CO_2 flux. A north–south transect to Atkasook, which is being studied less intensively than the Kuparuk Drainage, will allow integration with the Atmospheric Radiation Measurement (ARM) programme of DOE. Primary and secondary study sites include Imnavait Creek, Prudhoe Bay, Toolik Lake, Happy Valley, Franklin Bluffs, Barrow and Atkasook.

During the 1994 field season, local (2 km radius) measurements of trace gas flux (CO_2 and H_2O) and energy have begun at Happy Valley, Imnavait Creek, Toolik Lake, Prudhoe Bay and Barrow (Fig. 2). The fluxes are measured by eddy-correlation with towers placed in predominant vegetation types. Wind from different sectors are sampled to obtain trace gas fluxes from various vegetation and micro-habitat types. These measurements are correlated to flux measurements using chambers (Vourlitis *et al.*, 1994) throughout the duration of the Flux Study, to other measurements at larger scales (aircraft: Desjardins *et al.*, 1989), and to vegetation and surface characteristics including spectral characteristics, soils and vegetation. Tower measurements have been made on intensive sampling grids at Happy Valley and Prudhoe Bay in 1993–94 to co-locate with the GIS and other intensive data on vegetation, soils and spectral properties.

Point (chamber) measurements are being made in the upwind footprint of the towers to determine the components contributing to the tower flux measurement. One objective is to determine to what extent different and perhaps minor vegetation types contribute to the regional carbon flux. Portable tower and chamber measurements will be made along the transect to enable the scaling of the site data to aircraft measurements. Regional (200 km transect) measurements of energy, water vapour and CO_2 flux are being made by the NOAA Long EZ flux aircraft. These measurements will be expanded in 1995–96 and will include the use of a GIS of surface cover types (and possibly terrain information) that may be related to observed CO_2 fluxes. In 1997, models of CO_2 flux will be used to predict

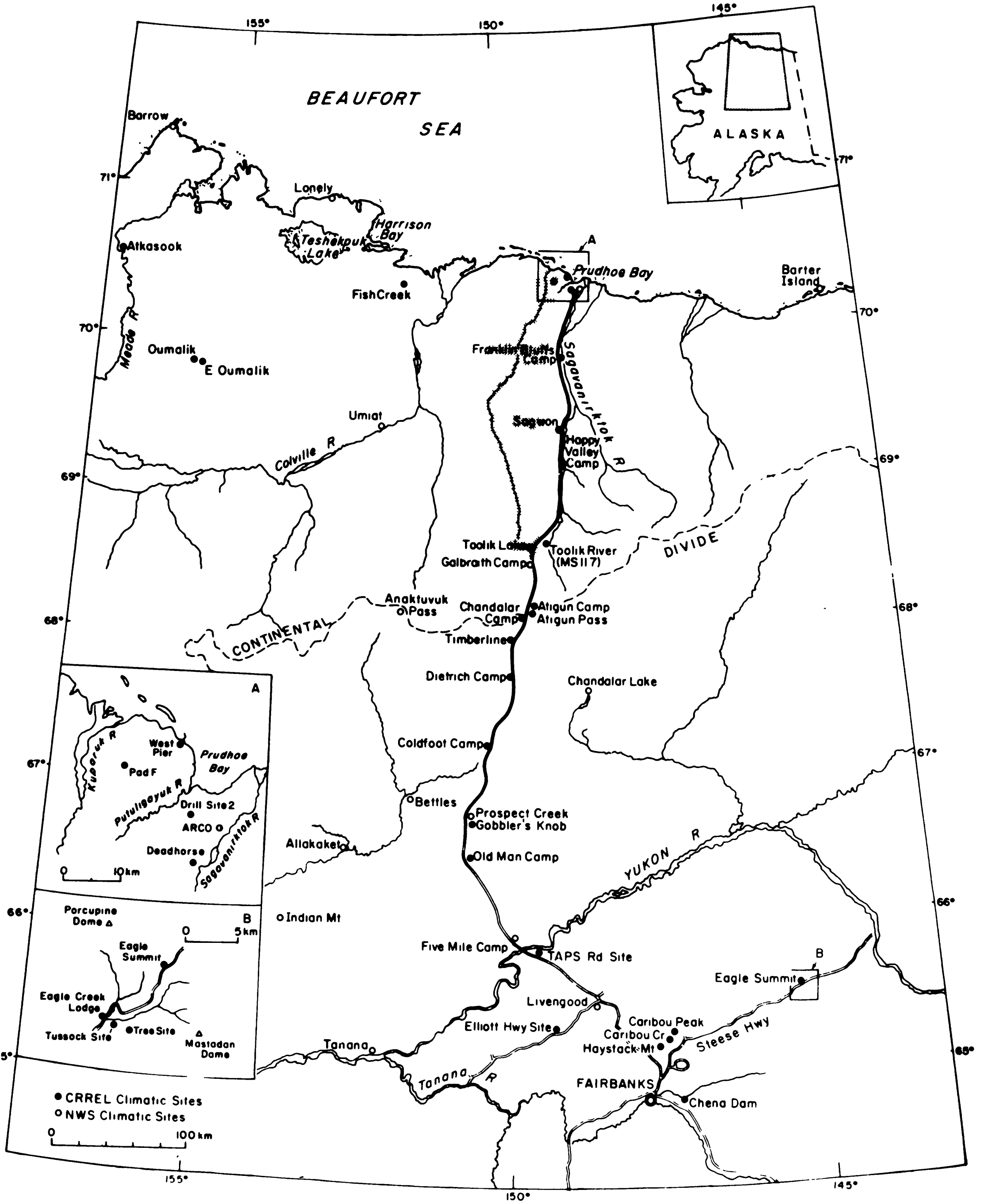

FIG. 1. Map of the Flux Study field sites, including the Kuparuk River Basin (shaded).

flux from surface characteristics. If successful, the CO_2 flux will be calculated for the entire Kuparuk Basin and measurements will be begun in other Arctic regions.

The meteorological and hydrologic data collection effort concentrates on three nested watersheds in the area surrounding the north–south transect: (1) Imnavait Creek with a drainage area of 2.2 km^2, (2) Upper Kuparuk River basin with a drainage area of 146 km^2 and (3) the larger Kuparuk River basin with a drainage area of 8142 km^2. The five meteorological stations already in place are located at Imnavait Creek; upstream of the Dalton Highway crossing of the Kuparuk River near Toolik Lake; Sagwon near Pump Station 2; Franklin Bluffs; and a site on the Kuparuk River near Prudhoe Bay (Fig. 1). The DOE-funded R4D research

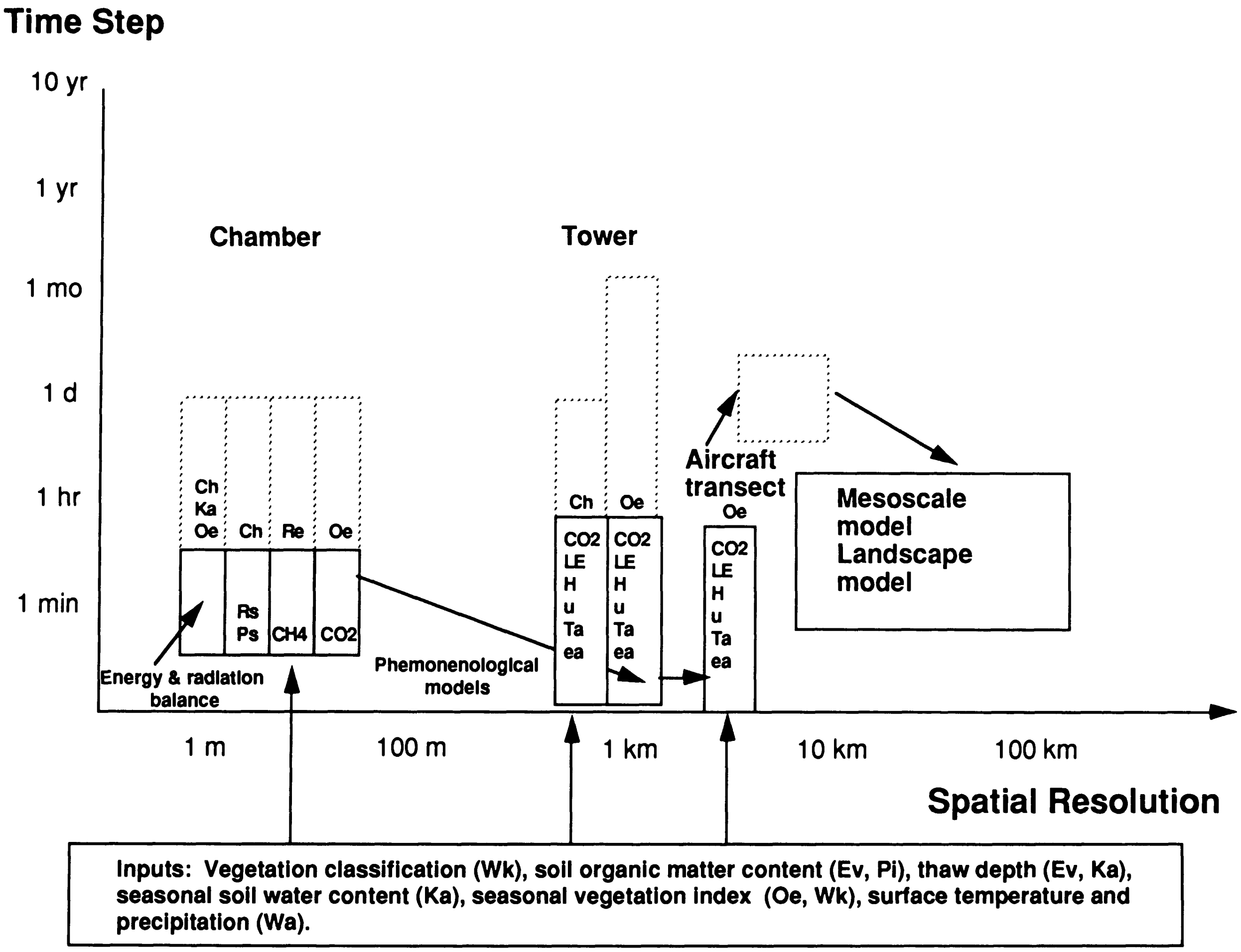

FIG. 2. Time–space matrix of trace gas flux measurements. Bo, Gordon Bonan; Ch, Terry Chapin; Ev, Kay Everett; Ho, John Hobbie; Ka, Doug Kane; Oe, Walt Oechel; Pi, Chien Lu Ping; Re, Bill Reeburgh; Wa, John Walsh/Gunter Weller, Wk, Skip Walker, ea, evaporation; H, sensible heat; LE, latent heat; Ps, photosynthesis; Rs, respiration; Ta, air temperature; u, momentum.

programme (1984–April 1993) maintained and expanded the meteorological data collection network. These stations collect an array of data throughout the year, including precipitation, air temperature, wind speed and direction, and relative humidity profiles. Complete radiation balance data also is collected from the pre-snow melt period to the end of the summer. An additional meteorological station (West Kuparuk meteorological site) was operational in July 1994.

In co-operation with the Water Resources Division of the USGS, streamflow monitoring and water quality measurements are made at the outlet of each watershed. Detailed snow surveys will be carried out in spring (prior to ablation) along a transect from the northern foothills of the Brooks Range to the coast. These measurements are necessary for modelling efforts and will provide a critical measure of the success of the seasonal simulations made with the regional atmospheric model. Soil moisture measurements also are made at selected sites, thereby providing additional validation data for the soil modelling efforts and all of the process studies which are measuring gaseous fluxes.

The flux of CO_2 and CH_4 across the stream–atmosphere and lake–atmosphere interfaces is monitored with floating chambers. In 1994 and 1995, the data will be collected in the upper Kuparuk watershed so that estimates can be made of the loss to the atmosphere by this pathway from an entire watershed. The concentrations of nutrients and organic carbon and nitrogen in stream waters are also being measured. These data, when combined with streamflow data, will give improved estimates of transport of inorganic and organic forms of nitrogen and phosphorus. It is expected that future research will allow these fluxes to be extrapolated to whole basin fluxes and eventually to river fluxes to the Arctic Ocean. This hydrology–nutrient–organic matter flux to the ocean is an important cross-system link between the Land/Atmosphere/Ice Interactions (LAII) and Ocean/Atmosphere/Ice Interactions (OAII) components of the overall ARCSS programme.

Measurements of biomass, spectral reflectance, canopy light-interception, leaf area and leaf-nitrogen concentration are used in developing empirical relations between satellite-derived vegetation indices (e.g. NDVI), biomass, LAI and geographic variables and for parameterizing models relating reflectance information to key biophysical processes. In subsequent years, identical GIS data bases will be developed at Prudhoe Bay and Happy Valley, two of the other major study sites to be used by all projects along the north–south transect.

Thaw depth at several sites is being monitored both mechanically and with thermal instrumentation. These data are necessary for soil model parameterizations. Fractionation and characterization of soil organic matter is being done. Measurements of soil properties, organic matter and carbon cycling are being used to assess the quality and quantity of carbon in the organic, active and upper permafrost layers.

Finally, the Flux Study will include manipulation experiments in order to study the mechanisms by which water, energy and CO_2 fluxes might change under future climates. This has two parts: (1) a study of the components of CO_2 flux under natural conditions, and (2) experiments in which we manipulate vegetation and climate in order to determine their impact on components of the fluxes. The components of the CO_2 flux under unmanipulated conditions are studied using vegetation data, soil carbon–isotope measurements, energy/water-budget measurements, and CO_2 fluxes at a few intensive sites. We will determine the relative contribution to above-ground CO_2 flux from soil and, after labelling plants (and, therefore, roots) with $^{13}CO_2$, will use carbon isotopes to separate soil CO_2 flux into root and soil components. This analysis will depend heavily on chemical analysis of classes of organic components of soil organic matter. The manipulation experiments, to be initiated in 1994, will involve a series of imposed perturbations of vegetation, water table and air temperature. In these experiments we will make relevant measurements of methane flux, productivity, components of water, energy and CO_2 flux, and soil carbon and thermal regime, to determine how and why the fluxes change when vegetation and/or climate are altered. Because of the potential importance of the interaction between carbon and nutrients, these experiments may entrain other Arctic tundra researchers from the LTER and EPA Trace Gas programmes.

SCALING/MODELLING/SYNTHESIS

The LAII Flux Study is a highly interdisciplinary project addressing a wide variety of spatial scales. The investigators are drawing upon existing modelling expertise to model key components of the Arctic system. The strategy is to (1) enhance our understanding through inter- and cross-comparisons of the various modelling components, and (2) develop an integrated (coupled) modelling capability as the project evolves. Since the latter capability does not yet exist, the scaling and parameterizational efforts will necessarily be major elements of the Flux Study.

Much of the Flux Study relies on GIS and remotely sensed information for the spatial modelling of hydrological, pedagogical, and biological characteristics. An existing hierarchic GIS (Walker & Walker, 1991) will be expanded to accommodate new sites for the Flux Study. The hierarchic structure of the GIS provides a geographic framework for the plot-, landscape- and regional-level investigations. The GIS uses standard hierarchic classification schemes for vegetation (Braun–Blanquet) and soils (U.S. Soil Taxonomy). These and other standard methods will aid in the development of consistent legends and GIS techniques that can be applied to comparative studies of other Arctic and non-Arctic regions. The GIS project will produce maps of variables important to other investigations within the Flux Study and will provide (1) geo-referenced data for the development of satellite-based algorithms, and (2) fields of surface information as boundary conditions required by grid-point models. The GIS data also will permit systematic analysis of relationships between surface variables, trace gas fluxes, plant biophysical processes and spectral reflectance as observed from space, thus facilitating progress toward the Flux Study's goal of understanding the controls on trace gas flux variability.

Available high altitude aerial photographs and satellite imagery will be used to identify surface types that will relate as closely as possible to the more detailed geobotanical units of the GIS for the Kuparuk River basin. Trace gas fluxes will be correlated with the surface types, vegetation indices and surface-moisture indices derived from the Landsat Thematic Mapper data. During later years of the project, we will co-ordinate with NASA overflights in the Arctic and sub-Arctic to obtain data from sensors that mimic data that will be obtained with the EOS package of satellites to be launched in the late 1990s. These data will be useful for extrapolation and testing of algorithms derived from handheld spectrometer measurements.

Several numerical modelling efforts are under way as part of the Flux Study. Figs 2 and 3 show how time–space scale matrices for trace gas flux measurements and modelling efforts relate to each other, and how the various investigations interact.

We will also develop and test a land-surface process model for Arctic and sub-Arctic regions. This model will provide the land-surface boundary conditions (sensible and latent heat, albedo, emitted infrared radiation, wind stress) for mesoscale and regional atmospheric models. As part of the Flux Study, this model will be coupled to the regional atmospheric model in order to study the climatic effects of land-surface processes in the Arctic. More generally, this work will lead to better representations of high-latitude land-surface processes in global climate models.

This work complements the hydrologic modelling. The hydrologic model is directed toward the watershed scale and includes lateral water flow, while the land-surface model emphasizes controls over the vertical flux of water and has the goal of simulating these one-dimensional fluxes at the grid points used by the regional (MM4) atmospheric model.

We will provide the maps of vegetation type, soil type and land-surface parameters. Among the land-surface parameters, the more important ones for the land-surface model are leaf and stem area indices (monthly), fractional vegetation cover (monthly), rooting depth (m), stomatal resistance and soil texture (porosity, wilting point). For simulations of carbon fluxes, the land-surface model requires photosynthetic and respiratory parameters appropriate to the vegetation type, soil carbon ($g\ m^{-2}$), soil nitrogen

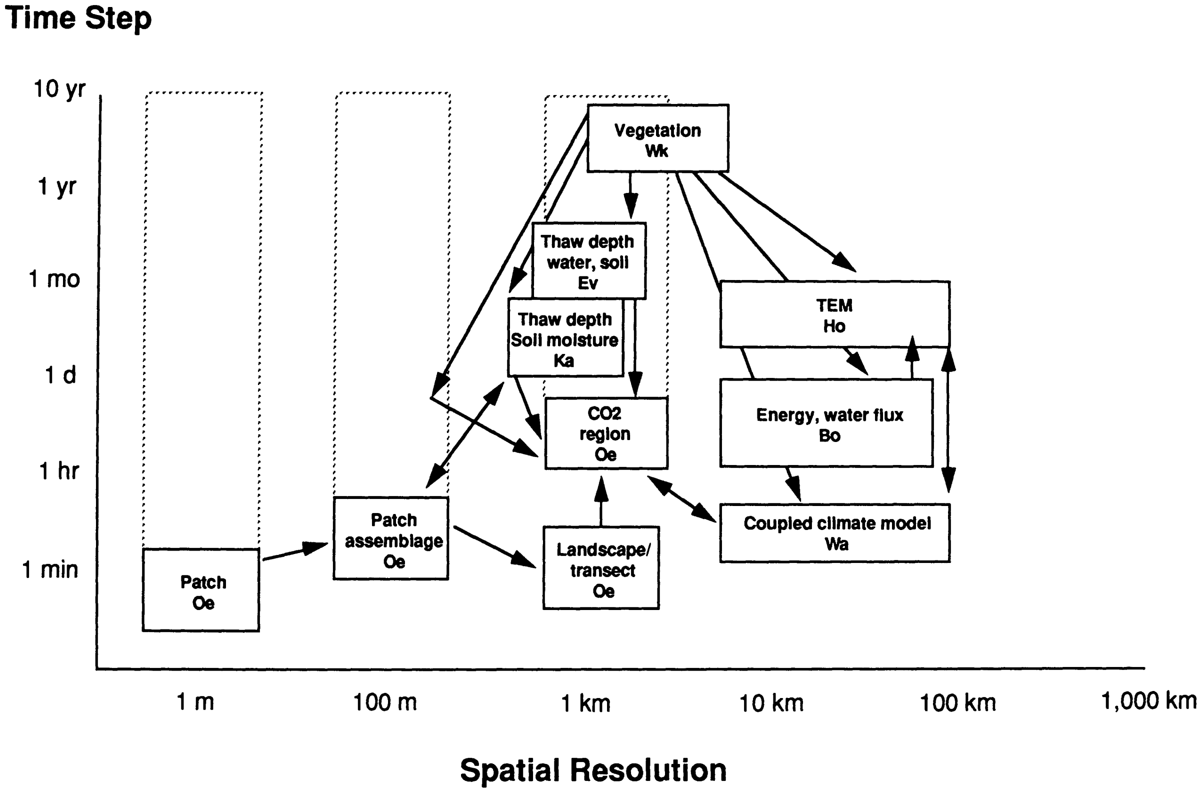

FIG. 3. Time–space matrix of model interactions and hierarchies for trace gas fluxes. Bo, Gordon Bonan; Ev, Kaye Everett; Ho, John Hobbie; Ka, Doug Kane; Wa, John Walsh/Gunter Weller.

(g m^{-2}) and soil temperature and moisture for decomposition rates. With the simulation of carbon cycling using the Generic Ecosystem Model (GEM) (Rastetter *et al.*, 1989) and with the Terrestrial Ecosystem Model (TEM) (Raich *et al.*, 1991), it will be possible to make comparisons of carbon fluxes simulated by different models forced by the same input. Finally, the atmospheric forcing required for the soil/vegetative models includes air temperature, precipitation rates, water vapour pressure, solar radiation (direct, diffuse), and wind speed. These variables can be better obtained from direct measurements (single-point testing) or from the regional atmosphere model (two-dimensional fields). The temporal resolution of the required forcing data is approximately 30 min.

In addition to developing GIS data bases for all modelling efforts, we will develop empirical relationships between vegetation indices and the interception of photosynthetically active radiation, biomass, leaf area index, NPP and canopy nitrogen. These relationships, together with theory, will permit the extrapolation of basic canopy properties over the landscape at the scales of SPOT/TM and AVHRR data (30 m/l km). Existing models also permit inferences of photosynthesis and minimal stomatal resistance from the vegetation index. If successful, models of carbon gain may be readily extrapolated to the regional scale. In addition, vegetation maps from the intensive research sites at Toolik Lake, Imnavait Creek, Happy Valley, Prudhoe Bay and Barrow will be used as training sites to extrapolate to a broader region using a 'semi-supervised' classification approach and Landsat Thematic Mapper data.

CONCLUSIONS AND OUTLOOK

The LAII Flux Study is a complex and interdisciplinary research project consistent with the international global change research effort. In order to achieve the objectives of the Flux Study, large-scale and long-term studies, monitoring programmes, and synthesis and modelling efforts must be undertaken. All these studies have begun. In the first phase of the project studies will be on a small scale, which in subsequent years will expand to larger scales. Individual representative sites distributed primarily along north–south transects across the North Slope will be studied during 1994–96, focusing on the Kuparuk Basin. This will extend in later years to a study of the entire North Slope and the circumarctic regions. It is during these later phases that the Flux Study's scientific payback will occur and its policy implications will emerge. We are optimistic that the LAII

Flux Study will serve as a model for other efforts in the U.S. Global Change Research Program.

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