## Appendix F: Additional Calculations

In addition to the standard calculations specified in Appendix A, a number of the modelling groups performed additional calculations that did not follow the specifications.

Some of these are mentioned in the body of the report, particularly those that provide a basis for comparison with our 'core' results. Some are included in the various figures and tables, flagged as 'non-standard' cases. In this appendix we list these and additional 'non-standard' calculations. Some of these results may be obtainable from the Carbon Dioxide Information Analysis Center. In other cases, results may be obtainable from the individual modellers.

The cases discussed in the report are:

**Feedback** Model R* includes effects of feedbacks from climate change. This is discussed in Section 12b. For Model T, the information regarding the inclusion of temperature feedbacks was inconsistent.

**WEC scenarios** These additional scenarios are discussed in Section 12a. The only calculations are from Model W.

**Alternative terrestrial representation** Model B was used for the 7 stabilisation cases and for IS92a. For each of these histories, 3 sets of calculations were run, differing in the way the terrestrial component was treated. One set use the prescribed 'land-use' flux while the others simulated the land-use flux by calculations within the model. In all cases a residual flux was estimated from an inverse initialisation and was extrapolated into the future as a constant. This is discussed in Section 12c.

Other calculations contributed are:

**Model B** In addition to the calculations described above, Model B was used to estimate the decline in atmospheric $CO_2$ given zero emissions after 1990, using the total model and the ocean-only component.

**Model G** In this case, the concentration profiles for stabilisation differed from those specified. For stabilisation at 450 ppmv, the difference is small. For stabilisation at 650 ppmv, the target date for stabilisation was earlier, giving a profile with an effective compression of the time-scale. This led to emission estimates which, compared to models using the specified profile, were initially higher and then had a more rapid decline after the peak. Figure 8a shows the integrated emissions.

The profile that was used was intended to follow a 'business-as-usual' type of emission history for as long as possible consistent with achieving the specified stabilisation.

**Model J** This model was used to define a reference response function to be used in the definition of Global Warming Potentials (see Section 9). This was defined as the response relative to an emission profile designed to give constant concentrations from 1990 onwards. The response was defined using a 10 GtC pulse injected in 1995. In addition, two other response functions were calculated using Model J. These were defined by adding 10 GtC pulses in 1995 to the DEC0% and IS92a emissions.

**Model V** The concentration profile for S650 differed from that specified. This was intended to correspond to a depletion of fossil fuel reserves.

**Model Z** An additional forward calculation used a scenario from Bashmakov.

## Appendix G: Notation

| | |
|---|---|
| $C_0$ | Initial (mean pre-industrial) atmospheric $CO_2$ concentration. |
| $C(t)$ | Atmospheric $CO_2$ concentration at time $t$, in ppmv. |
| $D_{\rm n}(t)$ | Net carbon flux from land-use change. |
| $D_{\rm g}(t)$ | Gross carbon flux from land-use change. |
| $F$ | Radiative forcing. |
| $F_X$ | Radiative forcing due to constituent $X$. |
| $G$ | Generic notation for response functions (Green's functions). |
| $g$ | Laplace transform of $G$. |
| $G_{\rm a}$ | Total atmospheric response function. |
| $g_{\rm a}$ | Laplace transform of $G_{\rm a}$. |
| $G_{\rm a:bio}$ | Function defining response of biota to atmospheric perturbation. |
| $g_{\rm a:bio}$ | Laplace transform of $G_{\rm a:bio}$. |
| $G_{\rm a:oc}$ | Function defining response of ocean to atmospheric perturbation. |
| $g_{\rm a:oc}$ | Laplace transform of $G_{\rm a:oc}$. |
| $N_{\rm a}$ | Excess atmospheric carbon (in Gt) $= 2.123[C(t) - C_0]$. |
| $n_{\rm a}$ | Laplace transform of $N_{\rm a}$. |
| $N_{\rm b}$ | Perturbation to biotic carbon reservoir (excluding land-use term). |
| $n_{\rm b}$ | Laplace transform of $N_{\rm b}$. |
| $N_{\rm o}$ | Perturbation to ocean carbon content. |
| $n_{\rm o}$ | Laplace transform of $N_{\rm o}$. |
| $p$ | Laplace transform variable. |
| $Q, Q(t)$ | Total anthropogenic source, $= Q_{\rm foss} + D_{\rm n}$ |
| $q(p)$ | Laplace transform of $Q(t)$. |
| $Q_{\rm foss}$ | Fossil carbon source. |
| $Q_{\rm foss}(t)$ | Fossil carbon source. |
| $r$ | Airborne fraction: $\dot{N}_{\rm a}/Q$ |
| $\bar{r}$ | Average airborne fraction $\Delta N_{\rm a}/\int Q\,dt$ |
| $S$ | Generic notation for sinks. |
| $S_{\rm ocean}$ | Net ocean carbon sink. |
| $S_{\rm fert}$ | $CO_2$ sink from $CO_2$-fertilisation. |
| $S_{\rm resid}$ | Residual $CO_2$ sink. |
| $t$ | Time in years. |
| $t_s$ | Time of stabilisation of concentration. |
| $z_{\rm pen}$ | Penetration depth for bomb-$^{14}$C. |
| $\delta(t)$ | Dirac delta function. |

## Appendix H: Glossary

**Advection** Transport by large scale motion (of the ocean in the context of this report).

**Airborne fraction** The proportion of $CO_2$ emissions remaining in the atmosphere.

**Anthropogenic $CO_2$ flux** Defined as being the net carbon input to the atmosphere due to human influence but excluding natural responses to such input. The precise distinctions are somewhat arbitrary: we include all the fossil (industrial) source, plus the net carbon flux associated with current and past changes in land-use.

**Bomb-$^{14}C$** Excess $^{14}C$ due to atmospheric testing of nuclear weapons.

**Buffer factor** (Revelle factor) Specification of the relation between $CO_2$ partial pressure and total inorganic carbon in the ocean surface.

**Eddy diffusion** Mathematical representation of large-scale mixing.

**ENSO** El-Nino/Southern Oscillation. Combined interannual fluctuation in atmosphere/ocean properties. The atmospheric component (Southern Oscillation) is characterised by abnormal east-west pressure gradients across the Pacific. The ocean component (El Nino) is characterised by abnormally warm waters in the eastern Pacific. There is a small-scale variation in atmospheric $CO_2$ correlated with ENSO events.

**Feedback** Process where a response to some forcing acts to change the amount of forcing: 'positive feedback' if the response adds to the forcing and 'negative feedback' if the response counteracts the forcing.

**$CO_2$-Fertilisation** The effect of higher $CO_2$ levels in producing greater plant growth. The direct effect on growth is well established by laboratory studies on many species. However the key issue for the problems discussed in this report is the extent to which such enhanced growth leads to a sustainned increase terrestrial carbon.

**Fossil $CO_2$ source** The earlier IPCC (1990, 1992) reports denoted this component as 'industrial', referring to the production rather than the end-use. This component includes use of fossil fuel (and ideally losses such as leakage and gas flaring) non-fuel uses of fossil carbon (to the extent that such products are oxidised to $CO_2$) and production of cement.

**Forward** Calculation where the chain of inference follows the direction of cause and effect. In the present context, deducing atmospheric $CO_2$ concentrations from specified emissions. (c.f. *inverse*).

**GCM** General Circulation Model. Computer model of the atmosphere (AGCM) or ocean (OGCM) that solves (approximately) the dynamical equations which determine the atmospheric (or oceanic) motion.

**GEOSECS** Geochemical Ocean Sections. An observational program conducted during 1973–74. The most important data for carbon cycle studies are the $^{14}C$ profiles.

**GtC** Gigatons of carbon. 1 Gt= $10^{15}$ g. Carbon is exchanged between reservoirs, taking a range of chemical forms and so, for uniformity, the amounts are characterised in terms of the mass of carbon. 1 GtC corresponds to $\frac{44}{12}$ Gt of $CO_2$. One of the few contexts in which the mass of $CO_2$ is used is in GWPs defined per unit mass.

**GWP** Global Warming Potential. Numerical index designed to facilitate comparisons between radiatively active gases.

**Industrial $CO_2$** See fossil.

**Inverse** Calculation where the chain of inference reverses the direction of cause and effect. In the present context, using specified atmospheric $CO_2$ concentrations to deduce the emission histories that would produce these concentrations. (c.f. *forward*).

**IPCC** Intergovernmental Panel on Climate Change. A body established by the World Meteorological Organisation and the United Nations Environment Program.

**KOALA** Key Ocean/Atmosphere/Land Assessments. Working title of this document.

**Koala** Australian marsupial with a six-foot long appendix.

**Land-use change flux** This is defined as the net carbon flux to the atmosphere from current and past changes in land-use, e.g. deforestation, regrowth, conversions between cropland and pasture, etc. The changes in soil carbon associated with such changes can continue for many decades after the original change in land-use.

**Mixed layer** Surface layer of the ocean with relatively little variation in the vertical direction due to the action of surface wind stress.

**ppmv** Parts per million by volume. Measure of trace gas content. The unit ppmv is a measure of atmospheric mixing ratio, although common usage is to apply the term concentration (incorrectly) as equivalent. $CO_2$ mixing ratios are generally expressed relative to dry air.

**Pre-industrial** Period prior to the large increase in fossil carbon emissions, i.e. before about 1800 or 1750.

**Profile** Specification of future variation expressed as a function of time without reference to specific societal actions. (c.f. *scenario*).

**Radiative Forcing** Influence perturbing the radiative balance of the earth.

**Reservoir** A part of the earth/ocean/atmosphere system treated as a single entity in terms of its carbon content for purposes of description or modelling.

**Response Function** Mathematical function of time, specifying the proportion of a unit perturbation remaining after time $t$.

**Scenario** Specification of future variation (particularly with reference to $CO_2$ emissions in this report) derived from specific assumptions about societal behaviour. (c.f. *profile*).

**Sink** Process leading to net removal of carbon from the atmosphere.

**Source** Process giving a net input of carbon to the atmosphere.

**STUGE** An intgrated assessment model for greenhouse change studies.

**TTO** Transient Tracers in the Ocean. An ocean measurement program.

**WOCE** World Ocean Circulation Experiment. An ongoing (1994) program measuring physical and chemical properties of the oceans.

## Ulrich Siegenthaler 1941–1994

Uli Siegenthaler was born in in Frutigen, Switzerland in 1941.

The formal milestones of his scientific career are:

**1960-66** Studies in physics at the Eidgenssische Technische Hochschule, Zurich.

**1966** Diploma thesis (Master's degree) in physics.

**1967-71** Doctorate studies at Physics Institute, University of Bern (Prof. H. Oeschger)

**1971** Dr. phil. nat. (Ph.D.) summa cum laude. Thesis subject: Oxygen-18, deuterium and tritium in the water cycle.

**1971-81** Assistant, then senior assistant at Physics Institute, University of Bern.

**1981** Lektor, Physics Institute, University of Bern.

**1983** Privatdozent, University of Bern.

**1990** Associate Professor (nebenamtlicher Extraordinarius) for experimental physics, University of Bern.

**1993** Elected as a Fellow of the American Geophysical Union.

Uli also spent time at:
Geoscience Group, Weizmann Institute, Rehovot, Israel;
Institute for Environmental Physics, Heidelberg, FRG;
Atmospheric and Oceanic Sciences Program, Princeton University.

Among the various committtees and boards on which Uli served are

- International Commission on Atmospheric Chemistry and Global Pollution (1985-1990);
- Comittee Scientifique du PNEDC (Programme National pour l'Etude de la Dynamique du Climat; French climate research programme)
- Expert for German Climate Research Programme (1990);
- International Scientific Steering Committee for JGOFS (Joint Global Ocean Flux Study);
- Chairman, Swiss National SCOPE Committee;
- Swiss National IGBP Committee;
- Eidg. Kommission Nukleare Entsorgung (Swiss Federal Commission on Nuclear Waste Disposal);
- Vorstand (committee) Bernische Naturforschende Gesellschaft;
- The advisory boards for Tellus B, Climate Dynamics, Radiocarbon.

His own description of his research activities was:

- Modelling of the global carbon cycle, in particular of the role of the ocean:
  anthropogenic $CO_2$ increase and isotopic perturbations ($^{13}C$, $^{14}C$) due to human activities,
  natural perturbations of the carbon cycle (glacial-interglacial $CO_2$ variations; $^{14}C$ variations),
  3-dimensional modelling of the oceanic carbon cycle (with J. Sarmiento, Princeton);

- Greenhouse effect and climatic change;

- Build-up and supervision of a stable isotope laboratory for measuring $^{18}O/^{16}O$, $^{13}C/^{12}C$ and (since 1990) $^{15}N/^{14}N$ in the environment;

- Experimental studies of the carbon cycle by means of stable isotope analyses:
  studies on concentration and isotopic composition of $CO_2$ in atmosphere and soils,
  dependence of $^{13}C/^{12}C$ fractionation of plants on environmental stress (ozone; water), in collaboration with botanists,
  stable isotopes in $CO_2$ from old polar ice cores as a constraint on the cause of glacial-postglacial $CO_2$ concentration variations;

- Palaeoclimate studies: rapid variations in the late glacial (Younger Dryas) as recorded in stable isotopes in lake sediments; stable isotopes in tree rings as climate records;

- Use of isotopes (tritium, $^{18}O/^{16}O$) in hydrology: determination of age and origin of groundwater (till about 1983); stable isotopes in the atmospheric water cycle.

His university teaching included both introductory physics, atomic physics and advanced courses in a range of aspects of environmental physics.

Those of us in the carbon cycle community will appreciate the importance of Uli's work. For the work presented in this report, two items have proved to be key contributions:

- The box-diffusion model work from 1975. This is still used widely and it forms the basis of several of the model calculations presented in this report.

- The pioneering inversion calculation (Siegenthaler and Oeschger, 1987) in which the inverse calculations were used to deduce terrestrial fluxes from the $CO_2$ concentrations measured in ice-cores.

Uli leaves a wife and two children.

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