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Supplement of

Biogeochemical protocols and diagnostics for the CMIP6 Ocean Model Intercomparison Project (OMIP)

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CFC HOWTO

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So you want to simulate CFC-11 and CFC-12 in your ocean model according to standard OCMIP-2 protocols? This document provides step-by-step information to do just that.

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1 Recuperation of OCMIP-2 files by ftp:

To comply with OCMIP-2 guidelines, all modelers must make simulations according to OCMIP-2 standard boundary conditions. To do so, one must first recuperate the following files via this Web page (you can save a file to disk by clicking a link while holding down the Shift key).

- `rgasx_ocmip2.f`
- `gasx_ocmip2.nc.gz`
- `vgasx_ocmip2.jnl`
- `read_cfc atm.f`
- `cfc_interp.f`
- `cfc1112.atm`
- `sc_cfc.f`
- `sol_cfc.f`

After transferring the file `gasx_ocmip2.nc.gz` (binary mode), one must then uncompress it:

```
gunzip gasx_ocmip2.nc
```

Other files are text and need no special treatment after transfer. Use of these files is described below.

2 Model runs

2.1 Gas exchange flux

For simulations of CFC-11 and CFC-12, we will directly model the finite air-sea flux \mathbf{F} . In other words, surface CFC concentrations will NOT be set equal to temperature-derived equilibrium values determined from the solubility. Modelers must use the formulation for the standard OCMIP-2 air-to-sea flux,

$$(1a) \quad \mathbf{F} = \mathbf{Kw} (\mathbf{C}_{\text{sat}} - \mathbf{C}_{\text{surf}})$$

with

$$(1b) \quad \mathbf{C}_{\text{sat}} = \alpha * p_{\text{CFC}} * P/P_0$$

where

- \mathbf{Kw} is the gas transfer (piston) velocity [m/s] ;
- \mathbf{C}_{surf} is the modeled surface ocean CFC-11 (or CFC-12) concentration [mol/m³];
- α is the CFC solubility for water-vapor saturated air [mol/(m³ * picoatm)];

- **pCFC** is the partial pressure of CFC-11 (or CFC-12) in dry air at one atmosphere total pressure [in picoatm], which is the same as the dry air mixing ratio of CFC-11 or (CFC-12) multiplied by 10^{12} ;
- **P** is the total air pressure at sea level [atm], locally;
- **Po** is 1 atm.

All right hand terms, except P and Po, in equations (1a) and (1b) are different for CFC-11 and CFC-12, as well as other tracers.

2.2 The Piston Velocity K_w

For simulations of CFC-11 and CFC-12, modelers must use the standard OCMIP-2 formulation for the piston velocity K_w . The monthly climatology of K_w , to be interpolated linearly in time by each modeling group, is computed with the following equation adapted from Wanninkhof (1992, eq. 3):

$$(2) \quad K_w = (1 - F_{ice}) [X_{conv} * a * (u^2 + v)] (Sc/660)^{-1/2}$$

where

- **F_{ice}** is the fraction of the sea surface covered with ice, which varies from 0.0 to 1.0, and is given as monthly averages from the Walsh (1978) and Zwally et al. (1983) climatology (OCMIP-2 modelers must reset **F_{ice}** values less than 0.2 to zero, after interpolation to their model grid)
- **u²** is the instantaneous SSMI wind speed, averaged for each month, then squared, and subsequently averaged over the same month of all years to give the monthly climatology. (see the OCMIP-1 README.satdat for further details);
- **v** is the variance of the instantaneous SSMI wind speed computed over one month temporal resolution and 2.5 degree spatial resolution, and subsequently averaged over the same month of all years to give the monthly climatology. Again, see the OCMIP-1 README.satdat for further details.
- **a** is the coefficient of 0.337, consistent with a piston velocity in cm/hr. We adjusted the coefficient **a** for OCMIP-2, in order to obtain Broecker et al.'s (1986) radiocarbon-calibrated, global CO₂ gas exchange of 0.061 mol CO₂ / (m² * yr * uatm), when using the satellite SSMI wind information (**u² + v**) from Boutin and Etcheto (pers. comm.). Our computed value for **a** is similar to that determined by Wanninkhof (**a** = 0.31), who used a different wind speed data set and assumptions about wind speed variance; we use the observed variance.
- **X_{conv}** = 1/3.6e+05, is a constant factor to convert the piston velocity from [cm/hr] to [m/s]. This conversion factor is already included in the forcing field **xK_w**, provided below.
- **Sc** is the Schmidt number which is to be computed using modeled SST, using the formulation from Zheng et al (1998). The function `sc_cfc.f` computes the Sc's (unit-less) for both CFC-11 and CFC-12.

Practically speaking, to use equation (2) each group will interpolate the OCMIP-2 standard information to their own model grid. The standard information is provided by IPSL/LSCE as a monthly climatology on the 1 x 1 degree grid of Levitus (1982) in netCDF format (in file `gasx_ocmip2.nc`). Gridded variables in that file include

- the variable **Fice**,
- the second term, [$\mathbf{Xconv} * \mathbf{a} * (\mathbf{u2} + \mathbf{v})$], denoted as **xKw** [m/s]
- the mask **Tmask** (1 if ocean; 0 if land),
- the total atmospheric pressure at sea level **P** [atm]
- the longitude **Lon** at the center of each 1 x 1 degree grid box,
- the latitude **Lat** at the center of each 1 x 1 degree grid box.

For the variables **Fice** and **xKw**, continents on the 1 x 1 degree standard grid have been flooded with adjacent ocean values. Such an approach avoids discontinuities at land-sea boundaries during interpolation. See the Fortran program `rgasx_ocmip2.f` for an example of how to read the information in `cfc1112.atm` into your interpolation routines. After compilation, to link and use `rgasx_ocmip2.f`, one must have already installed netCDF.

<<http://www.unidata.ucar.edu/packages/netcdf/>>

The file `gasx_ocmip2.nc` may also be inspected with software that uses netCDF format, such as `ncdump` or `Ferret`. `Ferret` will be used for some of the analysis during OCMIP-2. We encourage participants to become familiar with `Ferret` now

<<http://ferret.wrc.noaa.gov/Ferret/>>

After installation, one can visualize maps of the standard information in `gasx_ocmip2.nc`, by using the `Ferret` script `vgasx_ocmip2.jnl`.

After launching `Ferret`, simply issue the following command (at `Ferret`'s "yes?" prompt)

```
yes? go vgasx_ocmip2.jnl
```

2.3 Oceanic and Atmospheric Components

Apart from **Kw**, there are two other terms in equation (1a). The ocean component **Csurf** [in mol/m³] is computed by the model each timestep; the atmospheric component **Csat** is specified *a priori* via the three remaining terms:

1. **alpha**: The CFC solubility **alpha** is to be computed using modeled SST and SSS, both of which vary in time at each grid point. For OCMIP-2 we use the solubility formulation determined by Warner and Weiss (1985, Table 5 for solubility in [mol/(l * atm)]). The function `sol_cfc.f` determines **alpha** accordingly, for both CFC-11 and CFC-12, but changes the units to [mol/(m³ * picoatm)] so that model CFC concentrations can then be carried in SI units [mol/m³].
2. **pCFC**: Extrapolated records for observed CFC-11 and CFC-12 [in picoatm] constructed at 41S and 45N (Walker et al., pers. comm.). For OCMIP-2, each station will be treated as representative of its own hemisphere, except between 10S and 10N where those station values will be interpolated linearly as a function of latitude. Thus there are 3 zones:
 - 90S-10S, where CFC's are held to same value as at the station at 41S;

- 10S-10N, a buffer zone where values are interpolated linearly; and
 - 10N-90N where values are held to the same value as at the measuring station at 45N.
3. **P:** Is the total atmospheric pressure [atm] from the monthly mean climatology of Esbensen and Kushnir (1981). The latter, given originally on a 4 x 5 degree grid (latitude x longitude) in bars, is converted to atm by multiplying by (1/1.101325). Land and sea ice values in the original data set were filled with average values from adjacent ocean points. These monthly mean arrays were then linearly interpolated to the 1 x 1 degree grid of Levitus (see netCDF file gasx_ocmip2.nc).

Technical notes:

1. The Fortran subroutine `cfc_interp.f` interpolates **pCFC** spatially following the above algorithm. The code allows, in one pass, to spatially interpolate atmospheric pCFC-11 and pCFC-12, at a given timestep, to all grid points as a function of latitude.
2. The ASCII file `cfc1112.atm` provides mid-year values of atmospheric pCFC-11 and pCFC-12 [in piconatm] at both stations for the period from 1931 to 1997. See the program `read_cfc1112.f`.
3. Temporal interpolation of atmospheric pCFC-11 and pCFC-12 is to be made linearly for each time step, based on mid-year values (file `cfc1112.atm`).

3 Duration of simulation

Following the atmospheric record, the standard OCMIP-2 simulation for CFC-11 and CFC-12 will begin at the beginning of 1931 with zero concentrations in the atmosphere and ocean. CFC simulations will stop at the end of 1997.

4 Output type and frequency

1. **Early Output:** prior to 1982 (no oceanic CFC data are available).
 - Frequency: monthly averages every 10 years (1940, 1950, 1960, 1970, 1980)
 - Type:
 - 3-D Fields:
 - * CFC-11 and CFC-12 tracer distributions [mol/m³]
 - 2-D Fields:
 - * Monthly mean flux of CFC-11 and CFC-12 [mol/(m²*s)]
 - * Cumulative flux of CFC-11 and CFC-12 [mol/m²]
 - * Model SST (online models every year; offline models year 1940 only) [C]
 - * Model SSS (online models every year; offline models year 1940 only) [psu]
2. **Late Output:** from 1982 to 1997

- Frequency: monthly averages every year
- Type: same as above

3. **Transport Output:** in 1990 (just one year)

- Frequency: monthly averages
- Type:
 - The rate of change of each tracer ($[\text{mol}/\text{m}^3\text{s}]$ at tracer grid points) due to advection, diffusion, and convection,

Split according to process and direction

- * Total rate of change dC/dt
- * Rate of change due to advection (from x, y, and z directions, separately),
- * Rate of change due to diffusion (from x, y, and z directions, separately), and
- * Rate of change due to convection (from z direction), if modeled

- Tracer fluxes (3-D) $[\text{mol}/\text{m}^2\text{s}]$

Split according to process and direction

- * advective fluxes (from x, y, and z, separately) at advection grid points,
- * diffusive fluxes (from x, y, and z, separately) at diffusion grid points, and
- * convective fluxes (z), if modeled, at "convection" grid points

Conventions for the direction of fluxes:

- * rectangular grid: positive from the west, from the south, and from below
- * curvilinear grid: positive from i, j, k directions
- * *other grids* (e.g., AWI, MPI, and ULG): contact orr@cea.fr

4. **Equilibrium Output:** *All models* provide first output year (1940); *Online models* also provide output for the year 1990

- Frequency: monthly averages
- Type:
 - Active tracers (T and S) in 3-D
 - Advection field (u,v,w) $[\text{m}/\text{s}]$ as separate scalar values at advection grid points (u,v,w), which usually do not coincide
 - Tracer diffusion coefficient $[\text{m}^2/\text{s}]$ as separate values at diffusion grid points

5 Output Format

Each modeling group must provide their output in the standard OCMIP-2 format. Model output that does not follow these formatting conventions cannot be included for analysis during OCMIP-2. Model groups must use the standard routines that we have developed specifically for writing output in standard form for OCMIP-2.

5.1 Spatial information

Some of the models participating in OCMIP-2 are *Irregular*, which means that one 1-D array in latitude and one 1-D array in longitude are insufficient to describe the position of all grid points. Models with an irregular grid require a 2-D array in latitude and a 2-D array in longitude to describe the horizontal positioning of grid points. During OCMIP-2, regularly spaced models (those for which 1-D arrays in latitude and longitude are sufficient), will still write their output in the same *irregular* format. This will allow consistency between models for analysis, although at the price of somewhat larger output files.

Following the GDT conventions, all OCMIP-2 models will provide latitude and longitude information at the center of each tracer grid box and on all four corners (lower left, lower right, upper left and upper right) that are associated with each tracer grid point. Here is an example of a 2-D array in longitude and its corresponding boundary array (both with indices at their maximum values):

```
lon(imt, jmt)
bounds_lon(imt, jmt, 2, 2)
```

where

- `bounds_lon(i, j, 1, 1)` is the longitude of the *lower left* corner of the grid box i, j , where the meanings of *lower* and *left* are obvious for rectangular grids; for curvilinear grids, those terms correspond to the direction from grid boxes with smaller j and smaller i , respectively;
- `bounds_lon(i, j, 2, 1)` is the *lower right* corner;
- `bounds_lon(i, j, 1, 2)` is the *upper left* corner; and
- `bounds_lon(i, j, 2, 2)` is the *upper right* corner.

Analogous arrays are needed for latitude.

5.2 Output routines

For 1 and 2 each modeling group must use the three routines listed in the following table. Input to these routines consists of your model's output and characteristics. The first routine `write_nc_MaskAreaBathy.f` must be called only once (for the 1st output year–1940). The second routine `write_nc_CFC_year.f` must be called for every output year (see previous section 4). The third routine `write_nc_SurfTS_year.f` must also be called for every output year for online models, but only once (the first output year) for offline models.

| Routine | Input | Units | Comments |
|---------------------------------------|---|------------------------------|----------|
| <code>write_nc_MaskAreaBathy.f</code> | Tracer Mask Surface Area Bathymetry | Land=0/Ocean=1 m^2 m | (1) |

| | | | |
|------------------------|---------------------|-------------------------|-----|
| write_nc_CFC_year.f | Conc. of CFC-11 | mol/m ³ | |
| | Conc. of CFC-12 | mol/m ³ | |
| | Mean Flux of CFC-11 | mol/(m ² *s) | |
| | Mean Flux of CFC-12 | mol/(m ² *s) | |
| | Cum. Flux of CFC-11 | mol/m ² | |
| | Cum. Flux of CFC-12 | mol/m ² | |
| write_nc_SurfTS_year.f | Sea Surf. Temp. | degrees C | (2) |
| | Sea Surf. Salinity | psu | |

-
- (1) Also includes other input arguments, as necessary to define position of grid boxes (latitude, longitude, and depth specifications)
- (2) For online models, monthly SST and SSS should be saved each year for which other output is written (with write_nc_CFC_year.f); for offline models, monthly SST and SSS may be saved for just one year, since there is no year-to-year variation.

Please send e-mail now (orr@cea.fr) concerning whether you have an offline or online model.

Conventions

1. Longitudes must be expressed in degrees as eastward positive (e.g., 120W is to be expressed as -120; 120E is to be expressed as +120).
2. Latitudes must be expressed in degrees as northward positive. (e.g., 90S is to be expressed as -90; 90N is to be expressed as +90).
3. Depth must be expressed in meters as positive downward (e.g., the depth of 1000 m is to be expressed as 1000).
4. For irregular model grids which must be stored as a 1-D vector instead of a 2-D array (e.g., model AWI), you must set jmt=1, and not imt=1.
5. You must provide model output on a grid without overlapping boxes. For example, if for longitudes of your model
 - $i = 1$ is the same as $i = imt-1$ and
 - $i = 2$ is the same as $i = imt$,

then you must only provide model output for values from $i=2$ to $i=imt-1$. Future reference to i during OCMIP-2 analysis will thus be shifted by one, relative to that used in your model.

5.3 Downloading the output routines

The output routines for your model class can be found in

<http://www.ipsl.jussieu.fr/OCMIP/phase2/simulations/CFC/distrib/> or, in the HTML version of this document, by clicking on the three links below, while holding down the Shift key.

- write_nc_MaskAreaBathy.f
- write_nc_CFC_year.f
- write_nc_SurfTS_year.f

Routines for writing out results for 3 and 4 will be made available soon.

You will also need to transfer the subroutine handle_errors.f to properly deal with errors while you are writing your netCDF files.

5.4 Compiling the output routines

Here is an example of how you would compile one of the output routines:

```
f77 -c -O -L/usr/local/lib -lnetcdf -I/usr/local/include \  
    write_nc_MaskAreaBathy.f
```

Because we have made these routines F77 compatible, you may need a function len_trim.f (from F90), which we also provide and which returns the length of a character string (after neglecting trailing blanks).

5.5 Using the output routines

These routines write out your model results following the naming and output conventions (netCDF, COARDS, GDT) chosen for OCMIP-2. The output filename is constructed automatically within each routine from three of the arguments: the tracer name, the year, and the *standard model code*

<<http://www.ipsl.jussieu.fr/OCMIP/phase2/#modgroups>> used during OCMIP-2 to identify your group.

For example, after compiling and linking the OCMIP-2 output routines, we add the following code to the IPSL routines to store output in standard OCMIP-2 form

```
    call write_nc_CFC_year("IPSL", "NGL46_SI",  
& imt, jmt, kmt,  
& 1985, 60*60*24*365, 1200,  
& CFC11, CFC12,  
& MF_CFC11, MF_CFC12,  
& CF_CFC11, CF_CFC12)
```

By line, the arguments include

1. the OCMIP-2 *model code* AND your own *model version* indicator (in GDT 1.2 terminology, these 2 variables refer to the *institution* and *production*, respectively);
2. dimensions;

3. the year, the number of seconds per year (in your model), and the number of timesteps per year;
4. the 12 monthly means for the 3-D tracer arrays for CFC-11 and CFC-12;
5. the 12 monthly means for the 2-D air-sea flux for CFC-11 and CFC-12; and
6. the end-of-year 2-D cumulative flux (from t=0) for CFC-11 and CFC-12.

All arguments are input. The only output is the final netCDF file, ("IPSL_CFC_1985.nc"), which contains the information for analyzing the IPSL results for 1985. This file along with all others from the 3 routines above should be 6. Filenames should NOT be changed. At IPSL, files will subsequently be (1) tested for consistency, (2) included in the OCMIP-2 data base, and (3) processed for base analysis.

5.6 Need more details?

See <http://www.ipsl.jussieu.fr/OCMIP/tech>. for additional information about the format netCDF and other conventions (COARDS, GDT) chosen for storing OCMIP-2 model output.

If you have other questions, please contact Patrick.Brockmann@ipsl.jussieu.fr, or orr@cea.fr

6 Transfer of output

All files written by the OCMIP-2 output routines should be grouped according to type of analysis (1, 2, 3, and 4). To do so, just recuperate the shell script stocmip2.sh, copy it to the directory where you have stored your standard OCMIP-2 output, cd to that same directory, and issue the following two commands:

```
./stocmip2.sh  
gzip *.tar
```

If gzip is not available on your machine, the alternative is to use compress.

Given the requested fields and frequencies specified in section (4) above, model output could be quite large, depending upon model resolution. If output is larger than 200 Mb per simulation, we request that it be written to tape (DDS, DDS2, Exabyte, or DLT) and mailed to

```
James ORR - OCMIP  
Laboratoire des Sciences du Climat et de l'Environnement  
Unite mixte de recherche CEA-CNRS  
L'Orme des Merisiers - Bat.709 - CEA Saclay  
F-91191 Gif sur Yvette CEDEX  
FRANCE
```

If smaller than 200 Mb, an attempt can be made to send this output via ftp (contact orr@cea.fr for details). The first analysis will be undertaken at IPSL (France) and at Penn. State (U.S.A.).

7 Who has submitted what?

For a record of who has submitted what model output, see
<<http://www.ipsl.jussieu.fr/OCMIP/phase2/progress/>>.

8 References

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9 Contacts

orr@cea.fr, brock@lsce.saclay.cea.fr

10 Same document, another format?

This document is available in other formats:

- HTML (<HOWTO-CFC.html>)
- Postscript (<HOWTO-CFC.ps>)
- ASCII (<HOWTO-CFC.txt>)
- LaTeX (<HOWTO-CFC.tex>)
- DVI (<HOWTO-CFC.dvi>)
- RTF - as 2 files

1. *Table of Contents* <HOWTO-CFC.rtf>
2. *Body* <HOWTO-CFC-0.rtf>

Abiotic-HOWTO

J. Orr, R. Najjar, C. Sabine, and F. Joos

Revision: 1.16, Date: 2000/01/08 18:46:21

This document provides step-by-step guidelines to make the so-called solubility pump runs for CO₂ and C-14 according to the standard OCMIP-2 protocols. No biological effects are included. The ocean model carries only DIC and DIC₁₄. We describe five types of abiotic simulations: (1) **Equilibrium** run, (2) **Historical** run for 1765-2000, (3) **Future** runs (IPCC S650 and CIS92A) for DIC only, (4) a 1000-yr **Pulse** Input run for DIC only, and (5) three **Control** runs needed for drift correction for the Abiotic transient runs (i.e., the **Historical**, **Future**, and **Pulse** simulations).

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1 Recuperation of OCMIP-2 files by ftp:

To comply with OCMIP-2 guidelines, all modelers must make simulations according to OCMIP-2 standard boundary conditions. To do so, one must first recuperate the following files via this Web page. (you can save a file to disk by clicking on its link while holding down the Shift key)

- Files concerning gas exchange (same for all OCMIP-2 runs)
 - rgasx_ocmip2.f
 - gasx_ocmip2.nc.gz
 - vgasx_ocmip2.jnl
- Files concerning atmospheric CO₂ and C-14, for transient simulations
 - splco2.dat
 - stab.dat
 - cis92a.dat
 - c14nth.dat
 - c14equ.dat
 - c14sth.dat
 - read_co2atm.f
 - read_c14atm.f
 - c_interp.f
 - try_c_interp.f
 - locate.f
- Files concerning abiotic model
 - scco2.f
 - co2flux.f
- Files concerning standard carbonate chemistry (same for all OCMIP-2 carbon runs)
 - README.Cchem
 - Makefile
 - co2calc.f
 - drtsafe.f
 - ta_iter_1.f
 - test.r
 - test.out.gz

After transferring these files (in binary mode), modelers must then uncompress (gunzip) the file containing the gas exchange boundary conditions (gasx_ocmip2.nc.gz):

```
gunzip gasx_ocmip2.nc
```

Other files are text and need no special treatment after transfer. Use of these files is described below.

2 Model runs

2.1 Conservation equations

For the inorganic carbon and radiocarbon, both passive tracers, the conservation equations carried in the model are

$$(1a) \quad d[\text{DIC}]/dt = L([\text{DIC}]) + \mathbf{Jv} + \mathbf{J}$$

and

$$(1b) \quad d[\text{DIC14}]/dt = L([\text{DIC14}]) - \text{Lambda} * [\text{DIC14}] + \mathbf{Jv14} + \mathbf{J14}$$

where

- **[DIC]** is the model's concentration (moles/m³) of total dissolved inorganic carbon;
- **[DIC14]** is the model's DIC-normalized concentration (also in moles/m³) of total dissolved inorganic C-14 (see below);
- **L** is the 3-D transport operator, which represents effects due to advection, diffusion, and convection;
- **Lambda** is the radioactive decay constant for C-14 ($\ln(2) / 5730 \text{ year} = 1.2097e-04 \text{ year}^{-1}$), converted to s⁻¹ using the number of seconds/year in your particular model;
- **Jv** is the "virtual" source-sink term representing the changes in surface **[DIC]** due to evaporation and precipitation, which must be accounted for because of the relatively high background concentration of **[DIC]**;
- **Jv14** is the "virtual" source-sink term for changes in surface **[DIC14]** due to evaporation and precipitation (E-P changes in background concentrations are of the same order as observed variability);
- **J** is the source-sink term due to air-sea exchange of CO₂; and
- **J14** is the source-sink term due to air-sea exchange of ¹⁴CO₂.

The source-sink terms **Jv**, **Jv14**, **J**, and **J14** are added only as surface boundary conditions. That is they are equal to zero in all subsurface layers. These source-sink terms are equivalent to the fluxes, described below, divided by the surface layer thickness **dz1**.

$$\mathbf{Jv} = \mathbf{Fv}/\mathbf{dz1}$$

$$\mathbf{Jv14} = \mathbf{Fv14}/\mathbf{dz1}$$

$$\mathbf{J} = \mathbf{F}/\mathbf{dz1}$$

$$\mathbf{J14} = \mathbf{F14}/\mathbf{dz1}$$

2.2 Virtual flux (Fv)

In models where surface salinity is restored to observed values, this results in a surface flux of salt, not a surface flux of water as in the real world. Such surface salt fluxes are typically found in models with a rigid lid, and even in some models with a free surface (e.g., the OGCM from Louvain-la-Neuve). For simplicity, we categorize both classes of models as "rigid-lid-like". Conversely, non-rigid-lid-like models have a free surface and restore surface salinity by an equivalent flux of water leading to dilution or concentration (e.g., the MPI LSG model). Salinity in the latter type of free-surface model is conserved; E-P fluxes are taken into account by the velocity fields and thus do not need to be explicitly formulated in the transport model.

Yet for all rigid-lid-like models, we must explicitly take into account the concentration-dilution effect of E-P (Evaporation minus Precipitation), which changes surface [DIC] and [Alk]. Thus we add the virtual flux to the surface layer, each time step according to

$$(2a) \quad \mathbf{Fv} = \mathbf{DICg} * (\mathbf{E-P})$$

$$(2b) \quad \mathbf{Fv14} = \mathbf{DIC14g} * (\mathbf{E-P})$$

where DICg and DIC14g are the model's globally averaged surface concentrations of DIC and DIC14, respectively. Both global averages must be computed at least once per year. For rigid-lid-like models with only salinity restoring, we suggest that (P - E) be computed as

$$(3) \quad \mathbf{P - E} = (\mathbf{S} - \mathbf{S}') / \mathbf{Sg} * \mathbf{dz1} / \mathbf{Tau}$$

where \mathbf{S}' is the observed local salinity to which modeled local salinity \mathbf{S} is being restored, \mathbf{Sg} is the model's globally averaged surface salinity, $\mathbf{dz1}$ is the top layer thickness, and \mathbf{Tau} is the restoring time scale for salinity. For rigid-lid-like models which in addition include explicit P - E water fluxes, that term must of course also be added to eq (3).

2.3 Air-sea gas exchange fluxes (F and F14)

For simulations of DIC and DIC14, OCMIP-2 simulations will directly model the finite air-sea fluxes \mathbf{F} and $\mathbf{F14}$, respectively. Modelers must use the formulation for the standard OCMIP-2 air-to-sea flux,

$$(4a) \quad \mathbf{F} = \mathbf{Kw} (\mathbf{Csat} - \mathbf{Csurf})$$

$$(4b) \quad \mathbf{F14} = \mathbf{Kw} (\mathbf{14Csat} - \mathbf{14Csurf})$$

with

$$(5a) \quad \mathbf{Csat} = \mathbf{alphaC} * \mathbf{pCO2atm} * \mathbf{P/Po}$$

$$(5b) \quad \mathbf{14Csat} = \mathbf{Csat} * \mathbf{Ratm}$$

where

- \mathbf{Kw} is the CO₂ gas transfer (piston) velocity [m/s] ;
- \mathbf{Csurf} is the surface aqueous [CO₂] concentration [mol/m³], which is computed from the model's surface [DIC], T, S, and [Alk] (see section 2.5);
- $\mathbf{14Csurf}$ is the surface ocean [14CO₂] (see section 2.5);

- **alphaC** is the C solubility for water-vapor saturated air [mol/(m³ * uatm)];
- **pCO2atm** is the partial pressure of CO2 in dry air at one atmosphere total pressure [in microatm], which is the same as the dry air mixing ratio of CO2 multiplied by 10⁶ ;
- **P** is the total air pressure at sea level [atm], locally;
- **Po** is 1 atm; and
- **Ratm** is the normalized atmospheric ratio of C-14/C-12, which for our purposes we divide by the analogous ratio for the standard **Rstd**

$$(6) \quad \mathbf{Ratm} = (1 + \mathbf{D14Catm}/1000)$$

where **D14Catm** is the atmospheric Delta C-14, the fractionation corrected ratio of C-14/C-12, given in permil (see below).

Those familiar with C-14, may be surprised that in equation (6) we define **Ratm**, without multiplying the right hand term by **Rstd** (1.176e-12). Instead, we prefer to be able to compare **[DIC14]** to **[DIC]**, directly, in order to simplify early interpretation and code verification. With the above formulation for the OCMIP equilibrium runs (where pCO2atm=278 ppm and D14Catm=0‰), if both tracers are initialized identically, the only difference between units for the **[DIC]** and **[DIC14]** tracers will be due to radioactive decay. For the anthropogenic runs, there will also be contributions due to differences between atmospheric records for **pCO2atm** and **D14Catm**.

2.4 The Piston Velocity Kw

For simulations of DIC and DIC14, modelers must use the standard OCMIP-2 formulation for the piston velocity **Kw** for CO2. The monthly climatology of **Kw**, to be interpolated linearly in time by each modeling group, is computed with the following equation adapted from Wanninkhof (1992, eq. 3):

$$(7) \quad \mathbf{Kw} = (1 - \mathbf{Fice}) [\mathbf{Xconv} * \mathbf{a} * (\mathbf{u2} + \mathbf{v})] (\mathbf{Sc}/660)^{-1/2}$$

where

- **Fice** is the fraction of the sea surface covered with ice, which varies from 0.0 to 1.0, and is given as monthly averages from the Walsh (1978) and Zwally et al. (1983) climatology (OCMIP-2 modelers must reset **Fice** values less than 0.2 to zero, after interpolation to their model grid)
- **u2** is the instantaneous SSMI wind speed, averaged for each month, then squared, and subsequently averaged over the same month of all years to give the monthly climatology. (see the OCMIP-1 README.satdat for further details);
- **v** is the variance of the instantaneous SSMI wind speed computed over one month temporal resolution and 2.5 degree spatial resolution, and subsequently averaged over the same month of all years to give the monthly climatology. Again, see the OCMIP-1 README.satdat for further details.
- **a** is the coefficient of 0.337, consistent with a piston velocity in cm/hr. We adjusted the coefficient **a** for OCMIP-2, in order to obtain Broecker et al.'s (1986) radiocarbon-calibrated, global CO2 gas exchange of 0.061 mol CO2 / (m² * yr * uatm), when using the satellite SSMI wind information (**u2** + **v**) from Boutin and

Etcheto (pers. comm.). Our computed value for \mathbf{a} is similar to that determined by Wanninkhof ($\mathbf{a} = 0.31$), who used a different wind speed data set and assumptions about wind speed variance; we use the observed variance.

- $\mathbf{Xconv} = 1/3.6e+05$, is a constant factor to convert the piston velocity from [cm/hr] to [m/s]. This conversion factor is already included in the forcing field \mathbf{xKw} , provided below.
- \mathbf{Sc} is the Schmidt number which is to be computed using modeled SST, using the formulation from Wanninkhof (1992). The function `scco2.f` computes the \mathbf{Sc} (unit-less) for CO₂.

Practically speaking, to use equation (2) each group will interpolate the OCMIP-2 standard information to their own model grid. The standard information is provided by IPSL/LSCE as a monthly climatology on the 1 x 1 degree grid of Levitus (1982) in netCDF format (in file `gasx_ocmip2.nc`). Gridded variables in that file include

- the variable \mathbf{Fice} ,
- the second term, $[\mathbf{Xconv} * \mathbf{a} * (\mathbf{u2} + \mathbf{v})]$, denoted as \mathbf{xKw} [m/s]
- the mask \mathbf{Tmask} (1 if ocean; 0 if land),
- the total atmospheric pressure at sea level \mathbf{P} [atm]
- the longitude \mathbf{Lon} at the center of each 1 x 1 degree grid box,
- the latitude \mathbf{Lat} at the center of each 1 x 1 degree grid box.

For the variables \mathbf{Fice} and \mathbf{xKw} , continents on the 1 x 1 degree standard grid have been flooded with adjacent ocean values. Such an approach avoids discontinuities at land-sea boundaries during interpolation. See the Fortran program `rgasx_ocmip2.f` for an example of how to read the information in `gasx_ocmip2.nc.gz` into your interpolation routines. After compilation, to link and use `rgasx_ocmip2.f`, one must have already installed netCDF.

`<http://www.unidata.ucar.edu/packages/netcdf/>`

The file `gasx_ocmip2.nc` may also be inspected with software that uses netCDF format, such as `ncdump` or `Ferret`. `Ferret` will be used for some of the analysis during OCMIP-2. We encourage participants to become familiar with `Ferret` now

`<http://ferret.wrc.noaa.gov/Ferret/>`

After installation, one can visualize maps of the standard information in `gasx_ocmip2.nc`, by using the `Ferret` script `vgasx_ocmip2.jnl`.

After launching `Ferret`, simply issue the following command (at `Ferret`'s "yes?" prompt)

```
yes? go vgasx_ocmip2.jnl
```

2.5 Oceanic and Atmospheric Components

Apart from \mathbf{Kw} , there are a total of four other terms in equation (4a) and (4b) which require further development.

2.5.1 Ocean

The oceanic terms **Csurf** and **14Csurf** [in mol/m³] are not carried as tracers, so they must be computed each timestep to determine gas exchange

Csurf is the surface [CO₂] concentration [mol/m³], which is computed from the model's surface [**DIC**], **T**, **S**, and [**Alk**] through the equations and constants found in the subroutine `co2calc.f`. As input, we must provide alkalinity, which we determine as a normalized linear function of salinity.

$$(8) \quad [\text{Alk}] = \text{Alkbar} * \text{S}/\text{Sbar}$$

where [**Alkbar**] is 2310 microeq/kg and **Sbar** is the model's annual mean surface salinity, integrated globally (horizontally). Two other input arguments, both nutrient concentrations, are needed as input. Although accounting for both of their equilibria makes a difference, neither nutrient is included in the solubility pump run. Hence we take concentrations of both as being constant, equal to the global mean of surface observations: 0.5 micromol/kg for phosphate and 7.5 micromol/kg for silicate. Note that for the later OCMIP-2 run which includes the biological pump, we will use observed seasonal distributions of surface phosphate.

IMPORTANT: The carbonate chemistry subroutine `co2calc.f` was originally designed to require tracer input (**[DIC]**, [**Alk**], [**PO4**], and [**SiO2**]) on a per mass basis (umol/kg); however, for OCMIP-2 `co2calc.f` has been modified to pass tracer concentrations on a per volume basis (mol/m³), as carried in ocean models. To do so, we use the mean surface density of the ocean (1024.5 kg/m³) as a constant conversion factor; we do NOT use model-predicted densities. For example, OCMIP-2 modelers should used $\text{SiO}_2 = 7.7\text{e-}03$ mol/m³ and $\text{PO}_4 = 5.1\text{e-}04$ mol/m³ as input arguments; again both are constant for the abiotic simulation. The output arguments `co2star` (**Csurf**) and `dco2star` (**Csat - Csurf**) are also returned in mol/m³.

14Csurf is the surface ocean [¹⁴CO₂], defined as

$$(9) \quad \mathbf{14Csurf} = \mathbf{Csurf} * \mathbf{Rocn},$$

where

$$(10) \quad \mathbf{Rocn} = [\mathbf{DIC14}]/[\mathbf{DIC}].$$

Furthermore, for comparison to ocean measurements, we compute

$$(11) \quad \mathbf{D14Cocn} = 1000 * (\mathbf{Rocn} - 1).$$

Following equation (4), we do not include **Rstd** when calculating **D14Cocn** in the model.

2.5.2 Atmosphere

The atmospheric components **Csat** and **14Csat** in equations (4a) and (4b) are specified *a priori* via four remaining terms:

1. **alphaC**: The CO₂ solubility **alphaC** is to be computed using modeled SST and SSS, both of which vary in time at each grid point. For OCMIP-2 we use the solubility formulation of Weiss (1974), corrected for the contribution of water vapor to the total pressure (Weiss and Price, 1980, Table IV for solubility in [mol/(l * atm)]). The solubility **alphaC** is calculated within the routine `co2calc.f`.
2. **pCO2atm**: For the *Equilibrium run*, pCO₂atm is held constant at 278 ppm. For the anthropogenic perturbation, we define the equilibrium state as year 1765.0. Then for the *Historical run*, the model must be

integrated until the end of 1999, following the observed record until 1990.5 (splco2.dat) and IPCC scenario S650 (stab.dat) until 2000.0 (Enting, 1994). That same scenario, *Future run S650*, will be continued from 2000.0 to 2300.0. Similarly, a second *Future run CIS92A* (see also cis92a.dat) will be run from 1990.0 to 2100.0, after initializing with model output from the *Historical run* in 1990.0. Additionally a *Pulse run* will be made, where preindustrial atmospheric CO₂ is doubled and allowed to decline for 1000 years. Finally to eliminate effects due to model drift, we will make essentially two *Control runs*: (1) the first will be held to the same atmospheric boundary conditions as the *Equilibrium run*, carrying both DIC and DIC₁₄ during 1765-2000 but only DIC from 2000-2300; (2) the second will be analogous to the Pulse run, made in forward mode for 1000 years, except that atmospheric CO₂ will not be doubled on the first time step.

3. **D14Catm**: is atmospheric Delta C-14 [in permil]. For the *Equilibrium run*, D14Catm is held constant at 0‰. For the *Historical run*, we define the equilibrium state as year 1765.0. Then the model must be integrated until the end of year 1999 following the observed record (Enting, 1994). The observed atmospheric C-14 record is given for three latitudinal bands:

- 90S-20S
- 20S-20N
- 20N-90N

There will be NO future or pulse simulations for C-14.

4. **P**: Is the total atmospheric pressure [atm] from the monthly mean climatology of Esbensen and Kushnir (1981). The latter, given originally on a 4 x 5 degree grid (latitude x longitude) in bars, is converted to atm by multiplying by (1/1.101325). Land and sea ice values in the original data set were filled with average values from adjacent ocean points. These monthly mean arrays were then linearly interpolated to the 1 x 1 degree grid of Levitus (see netCDF file gasx_ocmip2.nc).

Technical notes:

1. The ASCII file splco2.dat provides values of atmospheric pCO₂ [in microatm], every half year, for the period from 1765.0 to 1990.5. Thereafter, there are two files used for future scenarios: for *scenario S650*, the ASCII file stab.dat provides half-year values of atmospheric pCO₂ [in microatm] for the period from 1990.5 to 2300.5; for *scenario CIS92A*, the ASCII file cis92a.dat provides yearly values of atmospheric pCO₂ for the period from 1990.5 to 2100.5. The subroutine read_co2atm.f reads atmospheric CO₂ information from all three files.
2. The ASCII files c14nth.dat, c14equ.dat, and c14sth.dat provide mid-year values of atmospheric D14Catm [in permil] for the period from 1764.5 to 2000.0. See the subroutine read_c14atm.f
3. The Fortran subroutine c_interp.f temporally interpolates (linearly) both **pCO₂atm** and **D14Catm** at a given timestep. That routine is called by the demonstration program try_c_interp.f, which spatially assigns **D14Catm** to the three latitudinal bands for C-14 (see above). Thus both routines together effect (1) temporal interpolation for both **pCO₂atm** and **D14Catm** and (2) spatial "interpolation" for **D14Catm** as a function of latitude.

3 Initialization and duration of simulations

1. **Equilibrium run**:

- *Initial Conditions:* These don't really matter for the Abiotic Equilibrium run. That is, the final steady-state distributions for DIC and DIC14 do not depend on the initial conditions because exchange with the atmosphere will ultimately determine their final steady-state inventories. However, a judicious choice of initial conditions can reduce the integration time required to reach steady-state. Unfortunately, initial conditions must be quite close indeed to the steady-state solution if there is to be a significant reduction in computing time. The choice of initial conditions is left to the discretion of each of the modeling groups. For initial debugging, groups may prefer to initialize DIC14 to the same 3-D field as used for DIC. That way the only difference between the two tracers is driven by radioactive decay.
- *Duration:* The Equilibrium run for abiotic DIC and DIC14 should be continued until at least both the following criteria are reached:
 - For DIC, we recommend that the globally integrated air-sea flux should be less than 0.01 Pg C/yr
 - For C-14, we recommend that 98% of the ocean volume should have a drift of less than 0.001‰/year (Aumont et al., 1998, p. 105). In terms of C-14 age, this drift is equivalent to a change of 8.27 yr per 1000 years of simulation.

For most models, these criteria can be reached only after integrations of at least few thousand model years.

2. Historical run:

- *Initial Conditions:* The historical abiotic simulation for both DIC and DIC14 will be initialized with final output (on Dec. 31) from the **Equilibrium run** or "steady-state" simulation.
- *Duration:* The historical simulation will begin at the beginning of 1765 (Jan 1, i.e., 1765.0). The anthropogenic simulation will be continued until the year 2000.0.
 - CO₂: Until 1990.5, **pCO₂atm** will follow the splco2.dat; then from 1990.5 to 2000.0, the atmosphere will follow IPCC scenario S650 in stab.dat.
 - C-14: Atmospheric **D14Catm** will follow values in c14nth.dat, c14equ.dat, and c14sth.dat (for 90S-20S, 20S-20N, and 20N-90N, respectively) until 2000.0. For lack of data, atmospheric C-14 between 1995.5 and 2000.0 is held constant at 107‰.

3. Future runs (DIC only):

- *Future run CIS92A:*
 - *Initial Conditions:* 3-D DIC field, 2-D Cumulative Fluxes and 2-D Cumulative Virtual Flux fields to be initialized with output from the Historical run at 1990.0
 - *Duration:* to be continued using atmospheric CO₂ from IPCC Scenario CIS92A until the year 2100.0
- *Future run S650:*
 - *Initial Conditions:* 3-D DIC field, 2-D Cumulative Fluxes and 2-D Cumulative Virtual Flux fields to be initialized with output from the Historical run at 1990.0
 - *Duration:* to be continued using atmospheric CO₂ from IPCC Scenario S650 until the year 2300.0

4. Pulse input response function (DIC only):

- *Initial Conditions:* Ocean DIC is to be initialized with final output from the Equilibrium run; Atmospheric CO₂ is to be doubled (556 ppm, where 1 ppm = 2.123 Pg C) at t=0, and then be controlled only via air-sea fluxes. Thus the model is then to be run in forward mode (atmospheric CO₂ is calculated). The Injection HOWTO describes other forward simulations in more detail.

- *Duration*: The total integration will be for 1000 years (1765.0 - 2765.0).

5. Control Runs

- *Historical Control* (DIC and DIC14); and *Future Control* (DIC only):
 - *Initial Conditions*: Ocean DIC is to be initialized with final output from the Equilibrium run; Atmospheric CO₂ and C-14 are to be held at preindustrial conditions (278 ppm, 0‰) throughout the duration of the simulation.
 - *Duration*: The total integration for DIC will be for 535 years (1765.0 - 2300.0). However the integration including DIC14 is only necessary for the first 235 years (*Historical Control* run 1765.0 - 2000.0).
 - *Historical-Future transition*: If run separately, the *Future Control* run should be initialized with the 3-D DIC fields AND the 2-D Cumulative Fluxes (i.e., both air-sea gas cumulative flux and virtual cumulative flux) from the last time step of 1999 (end of *Historical Control* run).
- *Pulse Control* (DIC only):
 - *Initial Conditions*: Ocean DIC is to be initialized with final output from the Equilibrium run; Atmospheric CO₂ is to be initialized with the quantity of CO₂ equivalent to 278 ppm (1 ppm = 2.123 Pg C) at t=0, and then be controlled only via air-sea fluxes. Thus the model is to be run in forward mode (atmospheric CO₂ is calculated). The Injection HOWTO describes other forward simulations in more detail.
 - *Duration*: The total integration will be for 1000 years (the equivalent of 1765.0 - 2765.0).

There are no *Future* or *Pulse* simulations for DIC14.

4 Output type and frequency

1. Equilibrium Output: steady-state "natural" simulation

- *Type*: (N.B. Below, the terms 3-D, 2-D, and 0-D refer to spatial dimensions; another dimension must be added for time).

3-D fields:

- Concentrations for both passive tracers **[DIC]** and **[DIC14]** (both in mol/m³); and
- Alk (in eq/m³), as determined from equation (8);

2-D fields

- $p\text{CO}_2\text{surf} = C_{\text{surf}}/\alpha_C$ (uatm);
- $dp\text{CO}_2 = (C_{\text{surf}} - C_{\text{sat}}*P/P_0)$ (uatm);
- Air-sea DIC gas exchange flux **F** (mol/(m² * s));
- Air-sea DIC14 flux **F14** (mol/(m² * s));
- Virtual DIC flux **Fv** (mol/(m² * s));
- Virtual DIC14 flux **Fv14** (mol/(m² * s));

- *Frequency*: Monthly means and annual mean for the final year of equilibrium simulation.

2. **Historical Output:** for anthropogenic run for CO₂ and C-14 (1765.0-2000.0)

- *Type:* Same as for the Equilibrium run (except Alk, which is the same), plus

2-D fields

- Surface **DIC** concentration (mol/m³);
- Surface **DC14ocn** (permil), see equation (11);
- Vertical Inventory of DIC (mol/m²), i.e., the vertical integral of its concentration with depth, throughout the water column.
- Vertical Inventory of **DC14ocn** (permil * m), i.e., the vertical integral of its level with depth, throughout the water column (permil*m are strange but useful units).
- End-of-the-year cumulative air-sea gas exchange fluxes **F** and **F14**, accumulated every time step since year=1765.0 (mol/m²).
- End-of-the-year cumulative virtual fluxes **Fv** and **Fv14**, accumulated every time step since year=1765.0 (mol/m²).

0-D fields

- Globally averaged atmospheric **pCO2atm** (uatm) and **DC14atm** (permil);
- Globally averaged air-sea fluxes **F** and **F14** (mol/(m² * s))
- Globally averaged virtual fluxes **Fv** and **Fv14** (mol/(m² * s))
- Globally averaged **DIC** and **DIC14** (mol/m³), i.e., a *Volume integral*
- Globally averaged surface **DIC** and **DIC14** (mol/m³), i.e., a *Surface integral*
- Globally averaged **pCO2surf** (uatm)
- Globally averaged **dpCO2** (uatm)
- Globally averaged surface **DC14ocn** (permil), see equation (11);
- Globally averaged **DC14ocn** (permil), see equation (11);
- Globally averaged cumulative air-sea fluxes (end-of-month) for F and F14 (mol/m²);
- Globally averaged cumulative virtual fluxes (end-of-month) for Fv and Fv14 (mol/m²)

- *Frequency:*

0-D fields:

- Monthly means during every year (1765-1999, inclusive)

2-D fields:

- Monthly means for 1838, 1839, 1900, and every year from 1948-1999 (inclusive).

3-D fields:

- Monthly means for 1838, 1953, 1954, 1957, 1965, 1972, 1973, 1974, 1977, 1978, 1981, 1982, 1983, 1985, 1986, 1987, 1988, 1989, 1991, 1993, 1995, 1997, 1999.
- Annual means for 1838, 1839, 1900, and every year from 1953-1999 (inclusive).

3. **Future Output:** for future runs CIS92A and S650

- *Type:* Same as the Historical run, but only for the DIC component, not DIC14

- *Frequency:*

0-D fields:

- (a) **CIS92A**: Monthly means during every year (1990-2099, inclusive)
- (b) **S650**: Monthly means during every year (1990-2299, inclusive)

2-D and [3-D] fields:

- * **CIS92A**

- (a) Monthly means for 2000 and 2099.
- (b) Annual means for 2000, 2010, every 20 years for 2020-2080, and 2099.

- * **S650**

- (a) Monthly means for 2000, 2100, 2200, and 2299.
- (b) Annual means for 2000, 2010, every 20 years for 2020-2280, and 2299.

4. **Pulse Output**: for OCMIP models to be included in next IPCC analysis

- *Type*: Same as the Future run for 0-D and 2-D fields; **No** 3-D fields!
- *Frequency*:

0-D fields

- * 0.0-10.0 years: monthly means (12 x 10 = 120 records)
- * 10.0-100.0 years: annual means (i.e., 90 records)
- * 100.0-1000.0 years: annual means every 10 years (i.e., 90 records)
- * Final year (999.0-1000.0): annual mean (i.e., 1 record)

2-D fields

- * 0.0-10.0 years: annual means each year (11 records)
- * 10.0-100.0 years: annual means every 10 years (90 records)
- * 100.0-1000.0 years: annual means every 100 years (90 records)
- * Final year (999.0-1000.0): annual mean (1 record)

5. **Control Output**:

- *Type*:
 - *Historical Control* (1765.0 - 2000.0) - ζ Just like Historical run
 - *Future Control* (2000.0 - 2300.0) - ζ Just like Future run—only DIC component, not DIC14.
 - *Pulse Control* (0.0 - 1000.0) - ζ Just like Pulse run—only DIC component.

- *Frequency*:

0-D fields:

- (a) *Historical Control*: Monthly means during every year (1765-1999, inclusive)
- (b) *Future Control*: Monthly means during every year (2000-2300, inclusive)
- (c) *Pulse Control*: just like Pulse run
 - * 0.0-10.0 years: monthly means (12 x 10 = 120 records)
 - * 10.0-100.0 years: annual means (i.e., 90 records)
 - * 100.0-1000.0 years: annual means every 10 years (i.e., 90 records)
 - * Final year (999.0-1000.0): annual mean (i.e., 1 record)

2-D fields:

- (a) *Historical Control*: Annual means for 1838, 1839, 1900, and every year from 1948-1999 (inclusive).
- (b) *Future Control*: Annual means for 2000, 2010, every 20 years for 2020-2080, 2099, every 20 years for 2100-2280, and 2299.
- (c) *Pulse Control*: just like Pulse run
 - * 0.0-10.0 years: annual means each year (11 records)
 - * 10.0-100.0 years: annual means every 10 years (90 records)
 - * 100.0-1000.0 years: annual means every 100 years (90 records)
 - * Final year (999.0-1000.0): annual mean (1 record)

3-D fields:

- (a) *Historical Control*: Annual means for 1838, 1839, and every year from 1953-1999 (inclusive)
- (b) *Future Control*: Annual means for 2000, 2010, every 20 years for 2020-2080, 2099, every 20 years for 2100-2280, and 2299.
- (c) *Pulse Control*: None!

5 Output Format

Each modeling group must provide their output in the standard OCMIP-2 format. Model output that does not follow these formatting conventions cannot be included for analysis during OCMIP-2. Model groups must use the standard routines that we have developed specifically for writing output in standard form for OCMIP-2.

If this is the first OCMIP-2 simulation you have made, you will need to recuperate the routine `write_nc_MaskAreaBathy.f` to write out characteristics of your model grid, mask, and bathymetry using the standard OCMIP-2 format. Use of this routine is detailed in the CFC HOWTO (section 5.1).

Otherwise if you have submitted OCMIP-2 model output previously, you will only need to resubmit the output file produced by `write_nc_MaskAreaBathy.f` under two conditions:

1. either your model's grid, mask, or bathymetry have changed; or
2. you have been notified by the OCMIP-2 analysis center at IPSL that your output file from this subroutine did not pass the routine integrity tests.

5.1 Output routines

Each modeling group must use the routines listed in the following table to store results in standard OCMIP-2 format for the Equilibrium Output, Historical Output, Future Output, Pulse Output, and Control Output.

Input to these routines consists of your model's output and characteristics. The first routine `write_nc_Abiotic_equil.f` must be called ONLY once, at the end of model spin-up. We define the final output of that run to be the initial conditions (at 1765.0) for the transient runs. The Historical routines (`write_nc_Abiotic_hist_year_3D.f` `write_nc_Abiotic_hist_year_2D.f`) must be called for the appropriate *output years* of the Historical run (see previous section Output type and frequency); conversely the

Historical routine (`write_nc_Abiotic_hist_year_0D.f` is called only once, after building a 1-D time series of global mean information. The same strategy holds for the output routines for the other Abiotic transient runs:

- Future runs (`write_nc_Abiotic_futr_year_3D.f`, `write_nc_Abiotic_futr_year_2D.f`, and `write_nc_Abiotic_futr_year_0D.f`);
- Pulse run (`write_nc_Abiotic_puls_year_2D.f`, and `write_nc_Abiotic_puls_year_0D.f`); and
- Control runs
 - *Historical Control*: `write_nc_Abiotic_ctrlH_year_3D.f`, `write_nc_Abiotic_ctrlH_year_2D.f`, and `write_nc_Abiotic_ctrlH_year_0D.f`;
 - *Future Control*: `write_nc_Abiotic_ctrlF_year_3D.f`, `write_nc_Abiotic_ctrlF_year_2D.f`, and `write_nc_Abiotic_ctrlF_year_0D.f`; and
 - *Pulse Control*: `write_nc_Abiotic_ctrlP_year_2D.f`, and `write_nc_Abiotic_ctrlP_year_0D.f`.

The routine `write_nc_Abiotic_TS_year.f` should be called only once for offline models; for online models, it should also be called a second time, in the year 1990.

| Routine | Input | Units | Comments |
|--|--|--|----------|
| <code>write_nc_Abiotic_equil.f</code> | 1) Conc. of DIC 2) Conc. of DIC14 3) Alk from eq. (8) 4) Surf. ocean pCO2 5) Delta pCO2 (δpCO_2) 6) Gas Exch. Flux of DIC 7) Gas Exch. Flux of DIC14 8) Virtual Flux of DIC 9) Virtual Flux of DIC14 | mol/m^3 mol/m^3 eq/m^3 uatm uatm $\text{mol}/(\text{m}^2 \cdot \text{s})$ $\text{mol}/(\text{m}^2 \cdot \text{s})$ $\text{mol}/(\text{m}^2 \cdot \text{s})$ $\text{mol}/(\text{m}^2 \cdot \text{s})$ | (*) |
| <code>write_nc_Abiotic_hist_year_3D.f</code> | 1) Conc. of DIC 2) Conc. of DIC14 | mol/m^3 mol/m^3 | |
| <code>write_nc_Abiotic_hist_year_2D.f</code> | 1) Surf. ocean pCO2 2) Delta pCO2 (δpCO_2) 3) Gas Exch. Flux of DIC 4) Gas Exch. Flux of DIC14 5) Virtual Flux of DIC 6) Virtual Flux of DIC14 7) Surface DIC 8) Surface Delta C-14 | uatm uatm $\text{mol}/(\text{m}^2 \cdot \text{s})$ $\text{mol}/(\text{m}^2 \cdot \text{s})$ $\text{mol}/(\text{m}^2 \cdot \text{s})$ $\text{mol}/(\text{m}^2 \cdot \text{s})$ mol/m^3 permil | |


```

8) Gm Cum. Gas Flux of DIC      mol/m^2      1765->
9) Gm Cum. Virt. Flux of DIC   mol/m^2      1765->

write_nc_Abiotic_puls_year_2D.f 1) Surf. ocean pCO2           uatm
                                2) Delta pCO2 (dpCO2)        uatm
                                3) Gas Exch. Flux of DIC     mol/(m^2*s)
                                4) Virtual Flux of DIC       mol/(m^2*s)
                                5) Surface DIC                   mol/m^3
                                6) Vert. Integral of DIC         mol/m^2
                                7) Cum. Gas Flux of DIC          mol/m^2      1765->
                                8) Cum. Virt. Flux of DIC         mol/m^2      1765->

write_nc_Abiotic_puls_year_0D.f 1) Glob_mean (Gm) pCO2atm     uatm
                                2) Gm Gas Ex. Flux of DIC       mol/(m^2*s)
                                3) Gm Virtual Flux of DIC       mol/(m^2*s)
                                4) Gm DIC                       mol/m^3
                                5) Gm Surface DIC               mol/m^3
                                6) Gm pCO2surf                  uatm
                                7) Gm Delta pCO2 (dpCO2)        uatm
                                8) Gm Cum. Gas Flux of DIC       mol/m^2      1765->
                                9) Gm Cum. Virt. Flux of DIC     mol/m^2      1765->

write_nc_Abiotic_TS_year.f      1) Potential temperature     degrees C    (*)
                                2) Salinity                       psu

write_nc_Abiotic_ctrlE_year_3D.f -> Same args as "write_nc_Abiotic_hist_year_3D.f"
write_nc_Abiotic_ctrlE_year_2D.f -> Same args as "write_nc_Abiotic_hist_year_2D.f"
write_nc_Abiotic_ctrlE_year_0D.f -> Same args as "write_nc_Abiotic_hist_year_0D.f"

write_nc_Abiotic_ctrlL_year_3D.f -> Same args as "write_nc_Abiotic_futr_year_3D.f"
write_nc_Abiotic_ctrlL_year_2D.f -> Same args as "write_nc_Abiotic_futr_year_2D.f"
write_nc_Abiotic_ctrlL_year_0D.f -> Same args as "write_nc_Abiotic_futr_year_0D.f"

write_nc_Abiotic_ctrlP_year_2D.f -> Same args as "write_nc_Abiotic_puls_year_2D.f"
write_nc_Abiotic_ctrlP_year_0D.f -> Same args as "write_nc_Abiotic_puls_year_0D.f"

```

```

-----
(*) For the equilibrium run: for online models, all 2- and 3-D fields
    should be averaged for each month over the last year of the
    simulation.

```

5.2 Downloading the output routines

The output routines can be transferred to your machine by clicking on the links below, while holding down the Shift key.

- [write_nc_MaskAreaBathy.f](#) (This routine is the same as linked to the CFC HOWTO; thus, there is no need to recuperate it if you have already contributed OCMIP-2 CFC results).
- [write_nc_Abiotic_equil.f](#)
- [write_nc_Abiotic_hist_year_3D.f](#)
- [write_nc_Abiotic_hist_year_2D.f](#)
- [write_nc_Abiotic_hist_year_0D.f](#)
- [write_nc_Abiotic_futr_year_3D.f](#)
- [write_nc_Abiotic_futr_year_2D.f](#)
- [write_nc_Abiotic_futr_year_0D.f](#)
- [write_nc_Abiotic_puls_year_2D.f](#)
- [write_nc_Abiotic_puls_year_0D.f](#)
- [write_nc_Abiotic_TS_year.f](#)
- [write_nc_Abiotic_ctrlH_year_3D.f](#)
- [write_nc_Abiotic_ctrlH_year_2D.f](#)
- [write_nc_Abiotic_ctrlH_year_0D.f](#)
- [write_nc_Abiotic_ctrlF_year_3D.f](#)
- [write_nc_Abiotic_ctrlF_year_2D.f](#)
- [write_nc_Abiotic_ctrlF_year_0D.f](#)
- [write_nc_Abiotic_ctrlP_year_2D.f](#)
- [write_nc_Abiotic_ctrlP_year_0D.f](#)

You will also need to transfer the subroutine `handle_errors.f` to properly deal with possible errors while you are writing your netCDF files.

5.3 Compiling the output routines

Here is an example of how you would compile one of the output routines:

```
f77 -c -O -L/usr/local/lib -lnetcdf -I/usr/local/include \
    write_nc_Abiotic_equil.f
```

Because we have made these routines F77 compatible, you may need a function `len_trim.f` (from F90), which we also provide and which returns the length of a character string (after neglecting trailing blanks).

5.4 Using the output routines

5.4.1 Equilibrium Output

The Abiotic-run output routines store your model results following the naming and output conventions (netCDF, GDT version 1.2) chosen for OCMIP-2. The output filename is constructed automatically within each routine from three of the arguments: the tracer name, the year, and the *standard model code* `<http://www.ipsl.jussieu.fr/OCMIP/phase2/#modgroups>` used during OCMIP-2 to identify your group.

For example, after compiling and linking the OCMIP-2 output routines, we add the following code to the IPSL routines to store output in standard OCMIP-2 form

```
    call write_nc_Abiotic_equil("IPSL", "NGL46_SI",
    & imt, jmt, kmt,
    & 60*60*24*365, 1200,
    & MDIC, MDIC14, Alk,
    & MpCO2surf, MdpCO2,
    & MF, MF14,
    & MFv, MFv14)
```

By line, the arguments include

1. the OCMIP-2 *model code* AND your own *model version* indicator (in GDT 1.2 terminology, these 2 variables refer to the *institution* and *production*, respectively);
2. dimensions;
3. the number of seconds per year (in your model), and the number of timesteps per year;
4. the 12 monthly means for the 3-D tracer arrays for DIC (mol/m³) and DIC14 (mol/m³) and for the Alk computed from eq. (8) (eq/m³).
5. the 12 monthly means for the 2-D arrays for surface ocean pCO₂ (pCO₂surf, in uatm) and the sea-air pCO₂ difference (dpCO₂, in uatm).
6. the 12 monthly means for the 2-D air-sea flux for F and F14 (both in mol/(m²*s)); and

7. the 12 monthly means for the 2-D arrays for the surface "virtual" fluxes F_v and F_{v14} (both in $\text{mol}/(\text{m}^2\cdot\text{s})$);

When do I call the above Equilibrium output routine? It should be called only once, at the end of the simulation after building monthly arrays (12 members) for each of the 2-D and 3-D spatial fields given as arguments.

5.4.2 Historical Output

We need to use a slightly different routines for saving transient results from the Historical run. Unlike the equilibrium run, we separately store 3-D, 2-D, and 0-D data. The reason is that we store the higher dimensional data less often, to save space.

For your 3-D model output for the Abiotic Historical run, use

```

      call write_nc_Abiotic_hist_year_3D("IPSL", "NL46_SI",
&   imt, jmt, kmt, nt,
&   1985, 60*60*24*365, 1200,
&   MDIC, MDIC14)

```

Note that we have also added the dimension nt on line 2. You must use nt to signal if you are passing annual means ($nt=1$) or monthly means ($nt=12$). The argument nt is used in the same fashion for routines that follow. The 3-D input arrays MDIC and MDIC14 are as described for the Equilibrium run.

When do I call the above 3-D Historical output routine? It should be called for each of the following times:

- with $nt=12$ (monthly means, 12 records per year) for each of the years 1838, 1953, 1954, 1957, 1965, 1972, 1973, 1974, 1977, 1978, 1981, 1982, 1983, 1985, 1986, 1987, 1988, 1989, 1991, 1993, 1995, 1997, 1999.
- with $nt=1$ (annual means, 1 record per year) for each of the years 1838, 1839, 1900, and every year for 1953-1999 (inclusive).

For your 2-D Historical output, use

```

      call write_nc_Abiotic_hist_year_2D("IPSL", "NL46_SI",
&   imt, jmt, nt,
&   1985, 60*60*24*365, 1200,
&   MpCO2surf, MdpCO2,
&   MF, MF14,
&   MFv, MFv14,
&   Ms_DIC, Ms_DC14ocn,
&   Mi_DIC, Mi_DC14ocn,
&   CF_F, CF_F14,
&   CF_Fv, CF_Fv14)

```

For 2-D output, we no longer need the dimension kmt , formerly in line 2. Conversely, we need supplemental 2-D model output for the Historical run which was not included in the equilibrium output. This supplemental 2-D output is needed to due to the Historical run's transient nature and our asynchronous saving of its 2-D and 3-D output. Supplemental 2-D Historical output includes

- line 7: the mean surface DIC (mol/m^3) and DC14ocn (permil), see eq. (11);
- line 8: the mean vertical inventory of DIC (mol/m^2) and DC14ocn (permil * m);
- line 9: the end-of-year 2-D cumulative flux for F (mol/m^2) and F14 (mol/m^2);
- line 10: the end-of-year 2-D cumulative flux for Fv and Fv14 (both in mol/m^2)

Cumulative fluxes (lines 9 and 10 above) must be initialized to zero and integrated with respect to time (i.e., each time step) from year=1765.0. Note that these values should be output only at the end of each year, regardless of whether $nt=12$ or $nt=1$.

When do I call the above 2-D Historical output routine? It should be called with $nt=12$ for each of the following years: 1838, 1839, 1900, and every year for 1948-1999 (inclusive).

For 0-D (1-D with time) Historical output, use

```

      call write_nc_Abiotic_hist_year_0D( "IPSL", "NL46_SI",
& nrec, times,
& G_pCO2atm, G_DC14atm
& G_F, G_F14,
& G_Fv, G_Fv14,
& Gv_DIC, Gv_DIC14,
& G_DIC, G_DIC14,
& G_pCO2surf, G_dpCO2,
& G_DC14ocn, Gv_DC14ocn,
& G_CF_F, G_CF_F14,
& G_CF_Fv, G_CF_Fv14)

```

By line, the arguments include

1. the OCMIP-2 *model code* AND your own *model version* indicator (in GDT 1.2 terminology, these 2 variables refer to the *institution* and *production*, respectively);
2. the number of records saved and the array of the times (in decimal years) at which they were saved—for monthly means, *times* should be set to the corresponding time at mid-month (see below for exact values).
3. the corresponding arrays of the history of the global mean atmospheric CO₂ (model input, in uatm) and global mean atmospheric C-14 (in permil, calculated from model input as an area weighted mean of your ocean grid boxes that you have identified as being in the 90S-20S, 20S-20N, and 20N-90N latitudinal bands);
4. the corresponding array of the history of the global mean air-sea flux F ($\text{mol/m}^2\text{*s}$) and F14 ($\text{mol/m}^2\text{*s}$);
5. the history of the global mean virtual fluxes Fv ($\text{mol/m}^2\text{*s}$) and Fv14 ($\text{mol/m}^2\text{*s}$);
6. the history of the global mean concentrations of DIC (mol/m^3) and DIC14 (mol/m^3);
7. the history of the global mean surface concentrations of DIC (mol/m^3) and DIC14 (mol/m^3);

8. the history of global mean surface ocean pCO₂ (pCO₂surf, in uatm), and the global mean sea-air pCO₂ difference (dpCO₂, in uatm);
9. the history of global mean surface ocean DC14ocn (in permil), and the whole-ocean global mean DC14ocn (in permil);
10. the history of the global mean cumulative fluxes F and F14 (in mol/m², integrated since 1765.0) at the end of each month, with each month indicated by its mid-month time given in line 2; and
11. the history of the global mean cumulative fluxes Fv and Fv14 (in mol/m², integrated since 1765.0) at the end of each month, with each month indicated by its mid-month time given in line 2.

When do I call the above 0-D Historical output routine? It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency is regular: every month throughout the entire run (i.e., all years 1765-1999, inclusive). Thus modelers must use *nrec* = 2820, and fill the 1-D temporal array *times* with the appropriate values (i.e., 1765.04167, 1765.125, 1765.2083, 1765.29167, 1765.375, ... 1999.875, 1999.9583).

5.4.3 Future Output

Another similar set of 3 routines is needed for storing results from the Future runs CIS92A and S650. Here we have removed arguments related to C-14 and added an argument for indicating which future run (CIS92A or S650) is appropriate (see line 2). Note that this argument must be given in UPPER case. These 3 routines are given below (details of other arguments are the same as given above):

```

      call write_nc_Abiotic_futr_year_3D("IPSL", "NL46_SI",
& "S650",
& imt, jmt, kmt, nt,
& 2000, 60*60*24*365, 1200,
& MDIC)

```

```

      call write_nc_Abiotic_futr_year_2D("IPSL", "NL46_SI",
& "S650",
& imt, jmt, nt,
& 2000, 60*60*24*365, 1200,
& MpCO2surf, MdpCO2,
& MF,
& MFv,
& Ms_DIC,
& Mi_DIC,
& CF_F,
& CF_Fv)

```

When do I call the above 2-D and 3-D Future output routines? They should both be called for each of the following times:

- For **CIS92A**
 - with $nt=12$ for both of the following years: 2000 and 2099
 - with $nt=1$ for each of the following years: 2000, 2010, 2020, 2040, 2060, 2080, and 2099.
- For **S650**
 - with $nt=12$ for each of the following years: 2000, 2100, 2200, 2299
 - with $nt=1$ for each of the following years: 2000, 2010, 2020, 2040, 2060, 2080, 2100, 2120, 2140, 2160, 2180, 2200, 2220, 2240, 2260, 2280, 2299.

```

      call write_nc_Abiotic_futr_year_0D("IPSL", "NL46_SI",
& "S650",
& nrec, times,
& G_pCO2atm,
& G_F,
& G_Fv,
& Gv_DIC,
& G_DIC,
& G_pCO2surf, G_dpCO2,
& G_CF_F,
& G_CF_Fv)

```

When do I call the above 0-D Future output routine? It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency is regular: every month throughout the entire run (i.e., all years 1990-2299, inclusive). Thus modelers must use $nrec = 3720$, and they must fill the 1-D temporal array (*times*) with appropriate corresponding values (i.e., 1990.04167, 1990.125, 1990.2083, 1990.29167, 1990.375, ..., 2299.875, 2299.9583).

5.4.4 Pulse Output

Another set of 2 routines is needed for storing the 2-D and 0-D results from the Pulse run; for that run there is **NO** 3-D output. Differences relative to the Pulse output routines are

- the scenario specification has been removed (only 1 pulse run is to be made); and
- the nt term has been removed from the 2-D routine since 2-D output is to be saved only for annual means, not monthly means.

```

      call write_nc_Abiotic_puls_year_2D("IPSL", "NL46_SI",
& imt, jmt,
& 1, 60*60*24*365, 1200,
& MpCO2surf, MdpCO2,
& MF,
& MFv,

```

```

& Ms_DIC,
& Mi_DIC,
& CF_F,
& CF_Fv)

```

When do I call the above 2-D Pulse output routine? It should be called using annual means, for each of the following years: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 999. These details are given in a structured way in the previous section (Output type and Frequency).

```

call write_nc_Abiotic_puls_year_0D("IPSL", "NL46_SI",
& nrec, times,
& G_pCO2atm,
& G_F,
& G_Fv,
& Gv_DIC,
& G_DIC,
& G_pCO2surf, G_dpCO2,
& G_CF_F,
& G_CF_Fv)

```

When do I call the above 0-D Pulse output routine? It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency (spacing between individual members of the array *times*) is NOT regularly spaced in time. For the 0-D *Pulse* run, output as specified by *times* must be given for

- every month from years 0.0 to 10.0 (i.e., $12 \times 10 = 120$ records), with corresponding monthly means provided at mid-month (i.e., for *times* = 0.04167, 0.1250, 0.2083, 0.29167, 0.3750, ... 9.875, 9.9583);
- every year from years 10.0 to 100.0 (i.e., 90 records), with corresponding annual means provided at mid-year (i.e., for *times* = 10.5, 11.5, 12.5, ... 99.5);
- every 10 years from years 100.0-991.0 (i.e., 90 records), with corresponding annual means provided at mid-year (i.e., for *times* = 100.5, 110.5, 120.5, 130.5, ... 990.5); and
- the final year (i.e., 1 record), with its corresponding annual means provided at mid-year (i.e., for *times* = 999.5).

Thus with this irregular spacing, models must use $nrec = 301$ (i.e., $120 + 90 + 90 + 1$).

5.4.5 Control Output

Finally we need to store output for the control run. The control run is necessary because 3-D tracer fields and associated fluxes in our **Equilibrium** run never reach perfect equilibrium. The associated drift affects results for the transient runs. Correcting for drift may be important when comparing model differences, particularly integrated quantities, over long time periods. The control run is needed to drift-correct models, before comparison. It is desirable that all groups make all three control runs, but this may not be possible for some, due to CPU requirements. Below are a few guidelines to help you decide when the Control runs are necessary and what shortcuts can be taken:

1. If you will make the *Pulse* run, you MUST also make the equivalent *Pulse Control* run.
2. If you have NOT respected the Equilibrium drift criteria you MUST make the *Historical Control* and *Future Control* runs.
3. If you have respected the recommended Equilibrium drift criteria, you may skip making the *Historical Control* and *Future Control* runs. However, we do HIGHLY RECOMMEND that you make these simulations, if you can afford them, i.e., if they do not represent a large proportion of your annual CPU budget. Having this output will simplify analysis and eliminate guess work.
4. If you have respected the Equilibrium drift criteria and choose not to submit *Historical Control* and *Future Control* output, you MUST still provide an indication of the drift of your model. In other words, you must use the three *ctrlH* routines (see below) to provide your output for another year. For instance, you could provide output from the 0-D, 2-D, and 3-D *ctrlH* routines for the year 1775. We would then compute your model drift and treat it as constant.

Those who will be making all the CO₂ Injection simulations can economize a little. That is, with those runs, one automatically makes both the *Late Control* and the *Pulse Control* runs, simultaneously. The first of the ten Injection tracers is the control tracer. Unfortunately, the *Injection* runs do NOT offer an opportunity to skip the *Historical Control* run. For more details, see the final version of the Injection HOWTO.

Arguments of the **Control** output routines are the same as those used in the *Historical*, *Future*, and *Pulse* output routines, as described below.

1. **Historical Control** output (for 1765-1999, inclusive): We save both the DIC and DIC14 related components. We use 3 routines, with the same arguments as the 0-D, 2-D, and 3-D *Historical output routines*.
 - **When do I call the above 3-D Historical Control output routine (write_nc_Abiotic_ctrlH_3D.f)?** It should be called with *Annual means (nt=1)* for 1765, 1838, 1839, 1900, and every year from 1953-1999 (inclusive).
 - **When do I call the above 2-D Historical Control output routine (write_nc_Abiotic_ctrlH_2D.f)?** It should be called with *Annual means (nt=1)* for 1765, 1838, 1839, 1900, and every year from 1948-1999 (inclusive).
 - **When do I call the above 0-D Historical Control output routine (write_nc_Abiotic_ctrlH_0D.f)?** It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency is regular: every month throughout the entire run (i.e., all years 1765-1999, inclusive). Thus modelers must use *nrec = 2820*, and fill the the 1-D temporal array *times* with the appropriate values (i.e., 1765.04167, 1765.125, 1765.2083, 1765.29167, 1765.375, ... 1999.875, 1999.9583). The *Historical Control* Run uses the same *nrec* and *times* array as does the *Historical* run.
2. **Future Control** output (for 2000-2764, inclusive): We save only the DIC-related component. We use 3 routines with the same arguments as the 0-D, 2-D, and 3-D *Future output routines*.
 - **When do I call the above 3-D Future Control output routine (write_nc_Abiotic_ctrlF_3D.f)?** It should be called with *Annual means (nt=1)* for years 2000, 2010, 2020, 2040, 2060, 2080, 2099, 2100, 2120, 2140, 2160, 2180, 2200, 2220, 2240, 2260, 2280, 2299.

- **When do I call the above 2-D Future Control output routine (write_nc_Abiotic_ctrlF_2D.f)?** It should be called with *Annual means* ($nt=1$) for years 2000, 2010, 2020, 2040, 2060, 2065, 2080, 2099, 2100, 2120, 2140, 2160, 2165, 2180, 2200, 2220, 2240, 2260, 2265, 2280, 2299.
 - **When do I call the above 0-D Future Control output routine (write_nc_Abiotic_ctrlF_0D.f)?** It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency is regular: every month throughout the entire run (i.e., all years 2000-2300, inclusive). Thus modelers must use $nrec = 3600$, and they must fill the 1-D temporal array *times* with appropriate corresponding mid-month values (i.e., 2000.04167, 2000.125, 2000.2083, 2000.29167, 2000.375, ..., 2299.875, 2299.9583). Note that $nrec$ and *times* are NOT identical to those used when calling the analogous 0-D routine to save Future output (i.e., $nrec$ is smaller; *times* starts 10 years later).
3. **Pulse Control** output (for 2000-2764, inclusive): We save only the DIC-related component. We use 2 routines with the same arguments as the 0-D and 2-D *Pulse output routines*.
- **When do I call the above 2-D Pulse Control output routine (write_nc_Abiotic_ctrlIP_2D.f)?** It should be called with *Annual means* ($nt=1$) for years 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 999.
 - **When do I call the above 0-D Pulse Control output routine (write_nc_Abiotic_ctrlIP_0D.f)?** It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency is NOT regularly spaced in time. For the 0-D *Pulse Control* run, output as specified by *times* must be given for
 - every month from years 0.0 to 10.0 (i.e., $12 \times 10 = 120$ records), with corresponding monthly means provided at mid-month (i.e., for *times* = 0.04167, 0.1250, 0.2083, 0.29167, 0.3750, ... 9.875, 9.9583);
 - every year from years 10.0 to 100.0 (i.e., 90 records), with corresponding annual means provided at mid-year (i.e., for *times* = 10.5, 11.5, 12.5, ... 99.5);
 - every 10 years from years 100.0-991.0 (i.e., 90 records), with corresponding annual means provided at mid-year (i.e., for *times* = 100.5, 110.5, 120.5, 130.5, ... 990.5); and
 - the final year (i.e., 1 record), with its corresponding annual means provided at mid-year (i.e., for *times* = 999.5).

Thus with this irregular spacing, models must use $nrec = 301$ (i.e., $120 + 90 + 90 + 1$).

5.4.6 Names of Output files

All arguments of the Abiotic routines are input; none are output. With the arguments as listed in the nine routines above, The corresponding output netCDF files are

- "IPSL_Abiotic_equil.nc";
- "IPSL_Abiotic_hist_1985_3D.nc", "IPSL_Abiotic_hist_1985_2D.nc", "IPSL_Abiotic_hist_global_0D.nc";
- "IPSL_Abiotic_S650_2000_3D.nc", "IPSL_Abiotic_S650_2000_2D.nc", "IPSL_Abiotic_S650_global_0D.nc";
- "IPSL_Abiotic_puls_0001_2D.nc", "IPSL_Abiotic_puls_global_0D.nc".

- "IPSL_Abiotic_ctrlH_1985_3D.nc", "IPSL_Abiotic_ctrlH_1985_2D.nc",
"IPSL_Abiotic_ctrlH_global_0D.nc";
- "IPSL_Abiotic_ctrlF_2000_3D.nc", "IPSL_Abiotic_ctrlF_2000_2D.nc",
"IPSL_Abiotic_ctrlF_global_0D.nc";
- "IPSL_Abiotic_ctrlP_0001_2D.nc", "IPSL_Abiotic_ctrlP_global_0D.nc".

These files along with all others produced by the Abiotic routines should be transferred to IPSL (see section Transfer of output). Filenames should NOT be changed. Subsequently, at IPSL, files will be (1) tested for consistency, (2) included in the OCMIP-2 data base, and (3) processed for base analysis.

5.5 Need more details?

See <<http://www.ipsl.jussieu.fr/OCMIP/tech>>. for additional information about the format netCDF and other conventions (COARDS, GDT) chosen for storing OCMIP-2 model output.

If you have other questions, please contact orr@cea.fr or Patrick.Brockmann@ipsl.jussieu.fr.

6 Transfer of output

We provide details only for transferring Equilibrium Output. Output from the other Abiotic simulations (Historical Output, Future Output, Pulse Output, and Control Output) should be transferred in an analogous fashion.

The Equilibrium Output files `IPSL_Abiotic_equil.nc` and `IPSL_Abiotic_TS_year.nc` should first be compressed.

```
gzip IPSL_Abiotic_equil.nc IPSL_Abiotic_TS_year.nc
```

If gzip is not available on your machine, the alternative is to use `compress`. After compression, you should ftp your files to LSCE for processing and analysis. Your model output could be quite large depending upon model resolution. Fear not though, because we have the disk space to accommodate output from all OCMIP models. Contact us if the ftp transfer rate is inadequate. In that case, you'll need to write your output to tape (DDS, DDS2, Exabyte, or DLT) and mail it to

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FRANCE

Here are the commands to transfer your output by ftp:

```
ftp: ftp.cea.fr
user: anonymous
passwd: your full email
cd incoming2/y2k01/OCMIP
mkdir <your group name>
mkdir <your group name>/Abiotic
cd <your group name>/Abiotic
binary
prompt
mput <your group name>*nc*
```

Then e-mail us (orr@cea.fr and Patrick.Brockmann@ipsl.jussieu.fr) that your transfer is complete.

To avoid confusion, you can create further subdirectories (Abiotic/equil, Abiotic/hist, Abiotic/futr, Abiotic/puls, and Abiotic/ctrl) to distinguish the five different types of runs. The ftp archive is erased automatically every 8 days, so be sure to contact us as soon as you have completed transfer, and save your output files at least until we have notified you that they have been transferred to the OCMIP-2 model output archive.

7 References

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8 Contacts

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9 Same document, another format?

This document is available in other formats:

- HTML (<HOWTO-Abiotic.html>)
- Postscript (<HOWTO-Abiotic.ps>)
- ASCII (<HOWTO-Abiotic.txt>)
- LaTeX (<HOWTO-Abiotic.tex>)
- DVI (<HOWTO-Abiotic.dvi>)

Biotic-HOWTO

R. G. Najjar and J. C. Orr

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This document provides step-by-step guidelines to make the so-called “nutrient-restoring” runs for phosphate, oxygen, dissolved organic phosphorus, dissolved inorganic carbon and alkalinity according to the standard OCMIP-2 protocols.

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1 Recuperation of OCMIP-2 files by ftp:

To comply with OCMIP-2 guidelines, all modelers must make simulations according to OCMIP-2 standard boundary conditions. To do so, one must first recuperate the following files via this Web page (you can save a file to disk by clicking a link while holding down the Shift key)

- Files concerning gas exchange (same for all OCMIP-2 runs)
 - rgasx_ocmip2.f
 - gasx_ocmip2.nc.gz
 - vgasx_ocmip2.jnl
- Files concerning phosphate maps
 - README.po4maps
 - po4mapnew.dat.gz
 - readmap.f
 - nutrient-doc
 - feb0m.ps
 - aug0m.ps
 - dif0m.ps
- Files concerning common biotic model
 - bio.f
 - bio.h
 - jbio.f
 - co2flux.f
 - o2flux.f
 - o2sato.f
 - scco2.f
 - sco2.f
- Files concerning standard carbonate chemistry (same for all OCMIP-2 carbon runs)
 - README.Cchem
 - Makefile
 - co2calc.f
 - drtsafe.f
 - ta_iter_1.f
 - test.r

– test.out.gz

After transfer, the files containing the OCMIP-2 boundary conditions for gas exchange (gasx_ocmip2.nc.gz) and phosphate restoring po4map.dat.gz should be uncompressed as follows:

```
gunzip gasx_ocmip2.nc
gunzip po4mapnew.dat
```

Other files are text and need no special treatment after transfer. Use of these files is described below.

2 Model runs

2.1 Surface phosphate restoring

F. Louanchi has created a monthly climatology of phosphate in the upper ocean that is to be used to nudge the model towards observations in the upper 75 m. These data are on a 2 x 2 degree grid for the six following depth levels: 0, 10, 20, 30, 50 and 75 m. The data are in the file po4mapnew.dat.gz. See the files README.po4maps, readmap.f, and nutrient-doc for further information. All modelers are required to linearly interpolate the phosphate maps spatially and temporally to their model grid. Units of the phosphate maps are mmol/m³ and these will have to be converted by each group to model units of mol/m³.

2.2 Conservation equations

There are five tracers carried in this run: phosphate (PO₄), dissolved organic phosphorus (DOP), oxygen (O₂), dissolved inorganic carbon (DIC) and alkalinity (Alk). The corresponding conservation equations are

$$(1a) \quad d[\text{PO}_4]/dt = L([\text{PO}_4]) + \text{JbPO}_4$$

$$(1b) \quad d[\text{DOP}]/dt = L([\text{DOP}]) + \text{JbDOP}$$

$$(1c) \quad d[\text{O}_2]/dt = L([\text{O}_2]) + \text{JbO}_2 + \text{JgO}_2$$

$$(1d) \quad d[\text{DIC}]/dt = L([\text{DIC}]) + \text{JbDIC} + \text{JgDIC} + \text{JvDIC}$$

$$(1e) \quad d[\text{Alk}]/dt = L([\text{Alk}]) + \text{JbAlk} + \text{JvAlk}$$

where

- **L** is the 3-D transport operator, which represents effects due to advection, diffusion, and convection;
- **[]** or "square brackets" indicate concentrations in moles/m³ (or eq/m³ for Alk);
- **JbX** is the biological source sink term for X;
- **JvDIC** and **JvAlk** are the "virtual" source-sink terms for changes in surface *DIC* and *Alk*, respectively, due to evaporation and precipitation; and
- **JgDIC** and **JgO₂** are the source-sink terms due to air-sea exchange of CO₂ and O₂, respectively.

The source-sink terms **JvDIC**, **JvAlk**, **JgDIC**, and **JgO2** are added only as surface boundary conditions. That is they are equal to zero in all subsurface layers. These source-sink terms are equivalent to the fluxes, described below, divided by the surface layer thickness **dz1**.

$$\mathbf{JvDIC} = \mathbf{FvDIC}/\mathbf{dz1}$$

$$\mathbf{JvAlk} = \mathbf{FvAlk}/\mathbf{dz1}$$

$$\mathbf{JgDIC} = \mathbf{FgDIC}/\mathbf{dz1}$$

$$\mathbf{JgO2} = \mathbf{FgO2}/\mathbf{dz1}$$

The **Jb** terms are rather detailed and are described in the OCMIP-2 simulation design document; they are not repeated here. We have supplied some Fortran code, found in the files bio.h, bio.f, and jbio.f. This code should be used to compute the Jb terms. However, this code serves only as a template, which must be modified by each group to suit their particular model.

2.3 Virtual fluxes (FvDIC and FvAlk)

In models where surface salinity is restored to observed values, this results in a surface flux of salt, not a surface flux of water as in the real world. Such surface salt fluxes are typically found in models with a rigid lid, and even in some models with a free surface (e.g., the OGCM from Louvain-la-Neuve). For simplicity, we categorize both classes of models as "rigid-lid-like". Conversely, non-rigid-lid-like models have a free surface and restore surface salinity by an equivalent flux of water leading to dilution or concentration (e.g., the MPI LSG model). Salinity in the latter type of free-surface model is conserved; E-P fluxes are taken into account by the velocity fields and thus do not need to be explicitly formulated in the transport model.

Yet for all rigid-lid-like models, we must explicitly take into account the concentration-dilution effect of E-P (Evaporation minus Precipitation), which changes surface **[DIC]** and **[Alk]**. Thus we add the virtual flux to the surface layer, each time step according to

$$(2a) \quad \mathbf{FvDIC} = \mathbf{DICg} * (\mathbf{E-P})$$

$$(2b) \quad \mathbf{FvAlk} = \mathbf{Alkg} * (\mathbf{E-P})$$

where **DICg** and **Alkg** are the model's globally averaged surface concentrations of DIC and Alk, respectively. Both global averages must be computed at least every five years. For rigid-lid-like models with only salinity restoring, we suggest that **(P - E)** be computed as

$$(3) \quad \mathbf{P - E} = (\mathbf{S} - \mathbf{S}')/Sg * \mathbf{dz1} / \mathbf{Tau}$$

where **S'** is the observed local salinity to which modeled local salinity **S** is being restored, **Sg** is the model's globally averaged surface salinity, **dz1** is the top layer thickness, and **Tau** is the restoring time scale for salinity. For rigid-lid models (or free surface models) which in addition include explicit P - E water fluxes, that term must of course also be added to eq (3).

IMPORTANT: It is critical that the virtual fluxes do not result in a net flux of alkalinity to or from the model. There are at least two ways of getting around this. One possibility is to insure that the global mean of E - P used in equations (2a) and (2b) is equal to zero. This could be achieved by subtracting off the global mean E - P before computing the virtual flux. A second possibility is to update the inventory of alkalinity periodically so that the inventory of alkalinity + 16*phosphate is at its initial value. See also Section 3.

2.4 Air-sea gas exchange fluxes (F_{gDIC} and F_{gO2})

For simulations of DIC and O₂, OCMIP-2 simulations will directly model the finite air-sea fluxes F_{gDIC} and F_{gO2} , respectively. Modelers must use the formulation for the standard OCMIP-2 air-to-sea flux:

$$(4a) \quad F_{gDIC} = K_{wCO2} (CO_{2sat} - CO_{2surf})$$

$$(4b) \quad F_{gO2} = K_{wO2} (O_{2sat} - O_{2surf})$$

with

$$(5a) \quad CO_{2sat} = \alpha_C \cdot p_{CO2atm} \cdot P/P_o$$

$$(5b) \quad O_{2sat} = O_{2sato} \cdot P/P_o$$

where

- K_{wCO2} and K_{wO2} are the CO₂ and O₂ gas transfer (piston) velocities [m/s], respectively;
- CO_{2surf} is the surface aqueous CO₂ concentration [mol/m³], which is computed from the model's surface [DIC], T, S, [Alk], and [PO₄]; (see section 2.6);
- O_{2surf} is the surface O₂ concentration [mol/m³] computed by the model;
- α_C is the CO₂ solubility for water-vapor saturated air [mol/(m³ * uatm)];
- p_{CO2atm} is the partial pressure of CO₂ in dry air at one atmosphere total pressure [in uatm], which is the same as the dry air mixing ratio of CO₂ multiplied by 10⁶ ;
- O_{2sato} is the O₂ saturation concentration at one atmosphere total pressure for water saturated air [mol/m³];
- P is the total air pressure at sea level [atm], locally; and
- P_o is 1 atm.

2.5 The Piston Velocities (K_{wCO2} and K_{wO2})

For simulations of DIC and O₂, modelers must use the standard OCMIP-2 formulation for the piston velocities of CO₂ (K_{wCO2}) and O₂ (K_{wO2}). The monthly climatologies of K_{wCO2} and K_{wO2} are to be interpolated linearly in time by each modeling group. They are computed with the following equations adapted from Wannikhof (1992, eq. 3):

$$(6a) \quad K_w = (1 - F_{ice}) [X_{conv} \cdot a \cdot (u^2 + v)] (Sc_{CO2}/660)^{-1/2}$$

$$(6b) \quad K_w = (1 - F_{ice}) [X_{conv} \cdot a \cdot (u^2 + v)] (Sc_{O2}/660)^{-1/2}$$

where

- F_{ice} is the fraction of the sea surface covered with ice, which varies from 0.0 to 1.0, and is given as monthly averages from the Walsh (1978) and Zwally et al. (1983) climatology (OCMIP-2 modelers must reset F_{ice} values less than 0.2 to zero, after interpolation to their model grid)

- **u2** is the instantaneous SSMI wind speed, averaged for each month, then squared, and subsequently averaged over the same month of all years to give the monthly climatology. (see the OCMIP-1 README.satdat for further details);
- **v** is the variance of the instantaneous SSMI wind speed computed over one month temporal resolution and 2.5 degree spatial resolution, and subsequently averaged over the same month of all years to give the monthly climatology. Again, see the OCMIP-1 README.satdat for further details.
- **a** is the coefficient of 0.337, consistent with a piston velocity in cm/hr. We adjusted the coefficient **a** for OCMIP-2, in order to obtain Broecker et al.'s (1986) radiocarbon-calibrated, global CO₂ gas exchange of 0.061 mol CO₂ / (m² * yr * uatm), when using the satellite SSMI wind information (**u2 + v**) from Boutin and Etcheto (pers. comm.). Our computed value for **a** is similar to that determined by Wanninkhof (**a** = 0.31), who used a different wind speed data set and assumptions about wind speed variance; we use the observed variance.
- **Xconv** = 1/3.6e+05, is a constant factor to convert the piston velocity from [cm/hr] to [m/s]. This conversion factor is already included in the forcing field **xKw**, provided below.
- **ScCO2** and **ScO2** are the Schmidt numbers for CO₂ and O₂, respectively. They are to be computed using the formulation of Wanninkhof (1992) for CO₂ and Keeling et al. (1998) for O₂. The corresponding Fortran functions are `scco2.f` and `sco2.f`. Both **ScCO2** and **ScO2** are unitless.

Practically speaking, to use equations (4) and (6), each group will interpolate the OCMIP-2 standard information to their own model grid. The standard information is provided by IPSL/LSCE as a monthly climatology on the 1 x 1 degree grid of Levitus (1982) in netCDF format (in file `gasx_ocmip2.nc`). Gridded variables in that file include

- the variable **Fice**,
- the second term, [**Xconv** * **a** * (**u2** + **v**)], denoted as **xKw** [m/s]
- the mask **Tmask** (1 if ocean; 0 if land),
- the total atmospheric pressure at sea level **P** [atm]
- the longitude **Lon** at the center of each 1 x 1 degree grid box,
- the latitude **Lat** at the center of each 1 x 1 degree grid box.

For the variables **Fice** and **xKw**, continents on the 1 x 1 degree standard grid have been flooded with adjacent ocean values. Such an approach avoids discontinuities at land-sea boundaries during interpolation. See the Fortran program `rgasx_ocmip2.f` for an example of how to read the information in `gasx_ocmip2.nc` into your interpolation routines. After compilation, to link and use `rgasx_ocmip2.f`, one must have already installed netCDF.

```
<http://www.unidata.ucar.edu/packages/netcdf/>
```

The file `gasx_ocmip2.nc` may also be inspected with software that uses netCDF format, such as `ncdump` or `Ferret`. `Ferret` will be used for some of the analysis during OCMIP-2. We encourage participants to become familiar with `Ferret` now.

```
<http://ferret.wrc.noaa.gov/Ferret/>
```

After installation, one can visualize maps of the standard information in `gasx_ocmip2.nc`, by using the Ferret script `vgasx_ocmip2.jnl`.

After launching Ferret, simply issue the following command (at Ferret's "yes?" prompt)

```
yes? go vgasx_ocmip2.jnl
```

2.6 Oceanic and Atmospheric Components

Apart from `Kw`, there are other terms that require further development to simulate air-sea gas exchange.

2.6.1 Ocean

The oceanic term **CO2surf** [in mol/m^3] is not carried as a tracer, so it must be computed each timestep to determine gas exchange.

CO2surf is the surface `[CO2]` concentration, which is computed from the model's surface `[DIC]`, `[Alk]`, `T`, `S`, and `[PO4]` through the equations and constants found in the subroutine `co2calc.f`. Silicate is also needed as an input, as it affects the equilibria; for that, we use its global mean surface value of 7.5 umol/kg .

IMPORTANT: The carbonate chemistry subroutine `co2calc.f` was originally designed to require tracer input (`[DIC]`, `[Alk]`, `[PO4]`, and `[SiO2]`) on a per mass basis (umol/kg); however, for OCMIP-2 `co2calc.f` has been modified to pass tracer concentrations on a per volume basis (mol/m^3), as carried in ocean models. To do so, we use the mean surface density of the ocean (1024.5 kg/m^3) as a constant conversion factor; we do NOT use model-predicted densities. Output arguments `co2star` (**CO2surf**) and `dco2star` (**CO2sat - CO2surf**) are also returned in mol/m^3 .

2.6.2 Atmosphere

The atmospheric components **CO2sat** and **O2sat** in equations (4a) and (4b) are specified *a priori* via four remaining terms:

1. **alphaC**: The CO_2 solubility **alphaC** is to be computed using modeled SST and SSS, both of which vary in time at each grid point. For OCMIP-2 we use the solubility formulation of Weiss (1974), corrected for the contribution of water vapor to the total pressure (Weiss and Price, 1980, Table IV for solubility in $[\text{mol}/(\text{l} * \text{atm})]$). The solubility **alphaC** is calculated within the routine `co2calc.f`.
2. **pCO2atm**: This is held constant at 278 ppm. For the OCMIP-2 simulations, modelers should pass **pCO2atm** as one of the the input arguments (`xco2`) to `co2flux.f` in units of ppm. This in turn is passed to `co2calc.f`.
3. **O2sato**: This is computed from the model T and S in units of mol/m^3 , using the formulation of Garcia and Gordon (1992). The subroutine `o2sato.f` performs this function.
4. **P**: Is the total atmospheric pressure [atm] from the monthly mean climatology of Esbensen and Kushnir (1981). The latter, was given originally on a 4×5 degree grid (latitude x longitude) in bars. We converted **P** to atm by multiplying it by $(1/1.101325)$. Land and sea ice values in the original data set were filled with average values from adjacent ocean points. These monthly mean arrays were then linearly interpolated to the 1×1 degree grid

of Levitus (see netCDF file gasx_ocmip2.nc). The atmospheric pressure, is passed as an input argument, in atm, to both co2flux.f and o2flux.f.

3 Initialization and duration of simulations

It is up to the discretion of the modeler as to how to initialize their simulations, but the following criteria must be upheld:

1. The global mean inventory of alkalinity + 16*phosphate must be initialized to $2370 + 16*2.17$ ueq/kg = 2404.72 ueq/kg (or 2.4636 eq/m³) and maintained at that level.
2. The global mean PO₄ + DOP concentration must be set equal to $2.17 + 0.02 = 2.19$ umol/kg (or 0.002245 mol/m³)

As for the duration of simulations, the biotic equilibrium simulation should be continued at least until the globally integrated air-sea CO₂ flux is less than 0.01 Pg C/yr. For most models, this criterion can be reached only after an integration of at least a few thousand model years.

To approach equilibrium more rapidly, some modelers use the acceleration technique where the timestep increases in deeper layers (Bryan, 1984). When modelers use this technique, one complication is that the global inventory of certain biogeochemical tracers (those without external sources or sinks) cannot be conserved. As a fix, those at NCAR suggest that modelers who use such a technique should periodically adjust global tracer inventories to their initial values. In any case, some method must be used to avoid losing mass from the system. Furthermore, we strongly recommend that the deep acceleration method be switched off and that the model be run for at least an additional 500 years, before final "equilibrium" output is stored for later OCMIP-2 analysis.

4 Output type and frequency

The Biotic simulation represents only one equilibrium run per model. Therefore only time-averaged fields of the seasonal cycle of the final "steady-state" solution need be saved. Modelers must submit results based on an average of the last 10 years of the simulation. Below are listed the required fields. The spatial dimension is indicated in square brackets; another dimension must be added for time, i.e., 12 months per year):

- 3-D Monthly mean tracer concentrations for both active tracers: potential temperature T (degrees C) and salinity S (psu);
- 3-D Monthly mean tracer concentrations for all five passive tracers ([PO₄], [DOP], [O₂], [DIC], and [Alk]) for the whole water column (mol/m³);
- 2-D Monthly mean $p\text{CO}_2\text{surf} = \text{CO}_2\text{surf}/\alpha\text{C}$ (uatm);
- 2-D Monthly mean $dp\text{CO}_2 = (\text{CO}_2\text{surf} - \text{CO}_2\text{sat}*\text{P}/\text{Po})$ (uatm);
- 2-D Monthly mean air-sea CO₂ flux **FgDIC** (mol/m²/s);

- 2-D Monthly mean air-sea O₂ flux **FgO₂** (mol/m²/s);
- 2-D Monthly mean virtual DIC flux **FvDIC** (mol/m²/s);
- 2-D Monthly mean virtual flux of total Alkalinity **FvAlk** (eq/m²/s);
- 2-D Monthly mean downward flux of particulate organic phosphorus interpolated to the compensation depth (75 m) **PnewPOP** (mol/m²/s);
- 2-D Monthly mean total downward flux of dissolved organic phosphorus (DOP) interpolated to the compensation depth (75 m) **PnewDOP** (mol/m²/s);
- 2-D Monthly mean advective net downward flux of DOP interpolated to the compensation depth (75 m) **PnewDOPa** (mol/m²/s);
- 2-D Monthly mean diffusive net downward flux of DOP interpolated to the compensation depth (75 m) **PnewDOPd** (mol/m²/s); and
- 2-D Monthly mean convective net downward flux of DOP interpolated to the compensation depth (75 m) **PnewDOPc** (mol/m²/s).

5 Output Format

Each modeling group must provide their output in the standard OCMIP-2 format. Model output that does not follow these formatting conventions cannot be included for analysis during OCMIP-2. Model groups must use the standard routines that we have developed specifically for writing output in standard form for OCMIP-2.

If this is the first OCMIP-2 simulation you have made, you will need to recuperate the routine `write_nc_MaskAreaBathy.f` to write out characteristics of your model grid, mask, and bathymetry using the standard OCMIP-2 format. Use of this routine is detailed in the CFC HOWTO (section 5.1).

Otherwise if you have submitted OCMIP-2 model output previously, you will only need to resubmit the output file produced by `write_nc_MaskAreaBathy.f` under two conditions:

1. either your model's grid, mask, or bathymetry have changed; or
2. you have been notified by the OCMIP-2 analysis center at IPSL that your output file from this subroutine did not pass the routine integrity tests.

5.1 Biotic-run output routines

For the Biotic simulation, each modeling group will need to store both their active and passive tracer output in OCMIP-2 standard format. Thus modelers need to call two additional routines. They should be called just once each. Those output routines and the fields which are passed as arguments are detailed in the following table.

| Routine | Input | Units | Comments |
|---------|-------|-------|----------|
|---------|-------|-------|----------|

| | | | |
|---------------------------|--|-------------------------|-----|
| write_nc_Biotic_equil.f | 1) Conc. of PO4 | mol/m ³ | (*) |
| | 2) Conc. of DOP | mol/m ³ | |
| | 3) Conc. of O2 | mol/m ³ | |
| | 4) Conc. of DIC | mol/m ³ | |
| | 5) Conc. of Alk | eq/m ³ | |
| | 6) Surf. ocean pCO2 | uatm | |
| | 7) Delta pCO2 (dpCO2) | uatm | |
| | 8) Mean Gas Flux of CO2 | mol/(m ² *s) | |
| | 9) Mean Gas Flux of O2 | mol/(m ² *s) | |
| | 10) Mean Virtual Flux of CO2 | mol/(m ² *s) | |
| | 11) Mean Virtual Flux of Alk | mol/(m ² *s) | |
| | 12) Mean Downward flux of POP at compensation Z | mol/(m ² *s) | |
| | 13) Mean Downward flux of DOP at compensation Z | mol/(m ² *s) | |
| | 14) Mean Downward advective flux of DOP at compensation Z | mol/(m ² *s) | |
| | 15) Mean Downward diffusive flux of DOP at compensation Z | mol/(m ² *s) | |
| | 16) Mean Downward convective flux of DOP at compensation Z | mol/(m ² *s) | |
| write_nc_Biotic_TS_year.f | 1) Potential temperature | degrees C | (*) |
| | 2) Salinity | psu | |

(*) For online models, all 2- and 3-D fields should be averaged for each month over the last 10 years of the simulation.

5.2 Downloading the output routines

The output routines can be transferred to your machine by clicking on the links below, while holding down the Shift key.

- [write_nc_MaskAreaBathy.f](#)
- [write_nc_Biotic_equil.f](#)
- [write_nc_TS_year.f](#)

- write_nc_Biotic_TS_year.f

You will also need to transfer the subroutine handle_errors.f to properly deal with errors while you are writing your netCDF files.

5.3 Compiling the output routines

Here is an example of how you would compile one of the Biotic run output routines:

```
f77 -c -O -L/usr/local/lib -lnetcdf -I/usr/local/include \
    write_nc_Biotic_equil.f
```

Because we have made the OCMIP-2 output routines F77 compatible, you may need a function len_trim.f (from F90), which we also provide and which returns the length of a character string (after neglecting trailing blanks).

5.4 Using the output routines

The Biotic-run output routines store your model results following the naming and output conventions (netCDF, GDT version 1.2) chosen for OCMIP-2. The output filename is constructed automatically within each routine from three of the arguments: the tracer name, the year, and the *standard model code*

<<http://www.ipsl.jussieu.fr/OCMIP/phase2/#modgroups>> used during OCMIP-2 to identify your group.

For example, after compiling and linking the OCMIP-2 output routines, we add the following code to the IPSL routines to store output in standard OCMIP-2 form

```
    call write_nc_Biotic_equil ("IPSL", "NGL46_SI",
& imt, jmt, kmt,
& 60*60*24*365, 1200,
& MPO4, MDOP, MO2, MDIC, MAlk,
& MpCO2surf, MdpCO2,
& MFgDIC, MFgO2,
& MFvDIC, FvAlk,
& MPnewPOP, MPnewDOP,
& MPnewDOPa, MPnewDOPd, MPnewDOPc)
```

By line, the arguments to write_nc_Biotic_equil include

1. the OCMIP-2 *model code* AND your own *model version* indicator (in GDT 1.2 terminology, these 2 variables refer to the *institution* and *production*, respectively);
2. dimensions;
3. the number of seconds per year (in your model), and the number of timesteps per year;

4. the 12 monthly means for the 3-D tracer arrays for passive tracers PO4, DOP, O2, DIC, and Alk;
5. the 12 monthly means for the 2-D arrays for surface ocean pCO2 (pCO2surf) and the sea-air pCO2 difference (dpCO2).
6. the 12 monthly means for the 2-D arrays for the air-sea fluxes for CO2 and O2;
7. the 12 monthly means for the 2-D arrays for the surface "virtual" fluxes for DIC and Alk;
8. the 12 monthly means for the 2-D arrays for the total downward fluxes of POP and DOP (at the compensation depth); and
9. the 12 monthly means for the 2-D arrays for the advective, diffusive, and convective components of the downward flux of DOP (at the compensation depth).

All arguments are input. The only output is the final netCDF file ("IPSL_Biotic_equil.nc") which contains the information for analyzing the IPSL monthly results for the steady-state climatological solution.

Furthermore, we need monthly 3-D data for potential temperature T and salinity S from each model. Again as an example, we add the following code to the IPSL routines to store output in standard OCMIP-2 form.

```

      call write_nc_Biotic_TS_year("IPSL", "NGL46_SI",
&  imt,jmt,kmt,
&  year, 60*60*24*365, 1200,
&  MT,MS)

```

where the arguments include

1. the OCMIP-2 *model code* AND your own *model version* indicator (in GDT 1.2 terminology, these 2 variables refer to the *institution* and *production*, respectively);
2. dimensions;
3. the year, the number of seconds per year (in your model), and the number of timesteps per year;
4. the 12 monthly means for the 3-D tracer arrays for potential temperature T and salinity S;

The only output is the final netCDF file ("IPSL_Biotic_TS_year.nc") which contains the information for analyzing the IPSL monthly results for the steady-state climatological solution.

Both "IPSL_Biotic_equil.nc" and "IPSL_Biotic_TS_year.nc" should be 6. Filenames should NOT be changed. Subsequently at IPSL, files will be (1) tested for consistency, (2) included in the OCMIP-2 data base, and (3) processed for base analysis.

5.5 Need more details?

See <http://www.ipsl.jussieu.fr/OCMIP/tech> for additional information about the format netCDF and other conventions (COARDS, GDT) chosen for storing OCMIP-2 model output.

If you have other questions, please contact Patrick.Brockmann@ipsl.jussieu.fr or orr@cea.fr

6 Transfer of output

Both `IPSL_Biotic_equil.nc` and `IPSL_Biotic_TS_year.nc` should first be compressed

```
gzip IPSL_Biotic_equil.nc IPSL_Biotic_TS_year.nc
```

If `gzip` is not available on your machine, the alternative is to use `compress`. After compression, you should send your files to LSCE for processing and analysis. However, model output could be quite large depending upon model resolution. If output is larger than 300 Mb, you may wish to try to send it by ftp, but you should first send us e-mail to verify that enough disk space is available. If not, you'll need to write your output to tape (DDS, DDS2, Exabyte, or DLT) and mail it to

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FRANCE

If smaller than 300 Mb, please first attempt to send this output via ftp:

```
ftp: ftp.cea.fr
user: anonymous
passwd: your full email
cd incoming2/ba9901/OCMIP
mkdir <your group name>
mkdir <your group name>/Biotic
cd <your group name>/Biotic
binary
prompt
mput <your group name>*.nc*
```

Then e-mail us (Patrick.Brockmann@ipsl.jussieu.fr and orr@cea.fr) that your transfer is complete.

7 Who has submitted what?

For a record of who has submitted what model output, see
<<http://www.ipsl.jussieu.fr/OCMIP/phase2/progress/>>.

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9 Contacts

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10 Same document, another format?

This document is available in different formats:

- HTML (<HOWTO-Biotic.html>)
- Postscript (<HOWTO-Biotic.ps>)
- ASCII (<HOWTO-Biotic.txt>)
- LaTeX (<HOWTO-Biotic.tex>)
- DVI (<HOWTO-Biotic.dvi>)

Injection-HOWTO

O. Aumont and J. C. Orr

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This document provides step-by-step guidelines to make simulations of deep-ocean CO₂ sequestration according to standard protocols from OCMIP-2 and GOSAC. Simulations are made abiotically without CaCO₃ sediments. Thus tracers are carried only as DIC. Each model run carries ten tracers, thereby simultaneously simulating the control, "permanent sequestration", the anthropogenic invasion of CO₂, and injection at 7 different sites. In GOSAC's **REQUIRED Standard scenario**, atmospheric pCO₂ is prescribed and CO₂ is injected at 1500 m (**Run C1500**). An analogous simulation is **STRONGLY ENCOURAGED** where injection occurs instead at 3000 m (**Run C3000**). Additionally, we include two **OPTIONAL** simulations: (1) an analogous run with injection at 800 m (**Run C800**) and (2) an **Emissions case** where fossil emissions to the atmosphere are prescribed and injection is made at 1500 m (**Run E1500**).

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1 Introduction

To help reduce the rate of increase of atmospheric CO₂, one could in principle divert CO₂ emissions from coastal power plants to the deep ocean and thereby short-circuit the naturally slow air-sea exchange of CO₂ (Marchetti, 1977). However two key scientific questions remain to be answered before such a practice could ever be implemented. Accurate answers to these questions are needed in order to fully address other crucial concerns—socioeconomic, political, legal, and technological—all of which must play a role in future decisions that governments must make concerning possible mitigation strategies. The first of these scientific questions is, "how extensively would deep-ocean injection affect the marine biota in the vicinity of the injection site?" The second question is, "if fossil CO₂ is to be injected into the ocean, how long might it stay isolated from the atmosphere?"

Our focus is on the second question, using the only means available, simulations in global-scale ocean models. Previous studies have addressed this same question, first with relatively simplistic box models and subsequently with one ocean general circulation model (OGCM) from MPI. A good summary of previous work is provided by Dewey et al. (1996). OGCM's describe ocean circulation in three dimensions. Thus they can be used to make assessments concerning the dependence of injection site location and depth upon the effectiveness of the ocean to retain sequestered CO₂. Unfortunately, model estimates can be biased due to model simplifications, omissions, and uncertainties. Substantial effort is usually required in regards to model validation and comparison before one can be sure of predicted results.

Here we provide the necessary protocols, boundary conditions, and code so that different groups using different OGCM's can make ocean CO₂ injection simulations in a consistent manner. Our objective is to begin to estimate the effect of uncertainties in model-predicted ocean circulation patterns on model-based estimates of the long term retention of CO₂ injected in the ocean. This work is carried out under the framework of GOSAC (Global Ocean Storage of Anthropogenic Carbon), an international effort during 1998 to 2000, which is jointly funded by the EC Environment and Climate Programme and the IEA Greenhouse Gas R& D Programme. GOSAC also provides support for European modeling groups to participate in the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP), a project of the Global, Analysis, Interpretation, and Modeling Task Force (GAIM) of the International Geosphere-Biosphere Programme (IGBP). Simulations described here are required for the seven GOSAC modeling groups. Non-european modeling groups (those not funded by GOSAC) are also strongly encouraged to make the simulations described in this document and to submit results for common analysis.

The protocols stipulated in this document are nearly the same as those tested in one of the GOSAC models, i.e., that from IPSL. Orr and Aumont (1999) discuss those preliminary tests and compare results to previous work.

2 Recuperation of files by ftp:

2.1 OCMIP-2 files

All injection simulations are to be made with an abiotic ocean. They must comply with previous OCMIP-2 guidelines, namely the abiotic simulation for DIC. Thus modelers should refer to the Abiotic HOWTO available on this Web site. The standard OCMIP-2 files necessary for the injection simulations are listed below. They can be retrieved directly from this Web page (you can save a file to disk by clicking a link while holding down the Shift key).

- `rgasx_ocmip2.f`

- gasx_ocmip2.nc.gz
- vgasx_ocmip2.jnl
- sc_co2.f
- sol_co2.f

After transferring the file `gasx_ocmip2.nc.gz` (binary mode), one must then uncompress it:

```
gunzip gasx_ocmip2.nc
```

Other files are text and need no special treatment after transfer. Use of these files is described below.

2.2 GOSAC files

In addition to following the guidelines described in the Abiotic HOWTO of OCMIP-2, all modelers must also follow the GOSAC guidelines given here to make the injection simulations. The appropriate files are listed below. They are used to read the prescribed boundary conditions, to perform the injection, and to provide some basic diagnostics. Just like the previous OCMIP-2 files, the files below can be retrieved directly from this Web page.

- pco2.s650.dat
- emissions.dat
- sitepos.dat
- initnl.f
- initgos.f
- gosac.f
- concent.f
- emit.f
- writegos.f
- gosac.h
- gosac.nl

All the files are text and need no special treatment after transfer. Use of these files is described below; comments within each file provide further details.

3 Model runs

Since the injection simulations are based on the abiotic DIC runs, modelers **must** have read the related Abiotic HOWTO, also on this Web site. In the rest of this Injection-HOWTO, we describe only the sequestration of CO₂ within the ocean and its effects on atmospheric CO₂ and oceanic DIC.

3.1 Injection sites

Seven injection sites have been designated by GOSAC participants:

1. Bay of Biscay
2. New York
3. Rio de Janeiro
4. San Francisco
5. Tokyo
6. Jakarta
7. Bombay

Exact locations of these sites are shown in Fig. 1. They are also listed in the ASCII file `sitepos.dat`. All sites are located along coastlines near populated areas where large amounts of CO₂ are emitted to the atmosphere. Only two of these sites are in the Southern Hemisphere. Protocols call for each model to make injections at all sites simultaneously. Models will make separate simulations for up to three injection depths: 800 m, 1500 m, 3000 m.

To determine the 7 grid cells in your model where CO₂ is to be injected, we use a simple algorithm (see `initgos.f`) to find each site's nearest grid cell that has a water column of at least 3000 m and is within 1000 km of the nearest coastline. These constraints are considered, roughly, as the current technical and economical limits of feasibility.

3.2 Tracers

Ten tracers are necessary to perform an injection simulation. Each of the ten tracers is carried simply as total dissolved inorganic carbon (DIC). These oceanic tracers exchange CO₂ with three different atmospheric boxes, all of which are defined in section "Atmosphere description". The ten oceanic tracers are defined as follows:

Tracer 1

Control scenario: no effect of the anthropogenic perturbation on atmospheric CO₂ is included. This tracer is used to remove the drift of the model.

Tracer 2

Future scenario: The effect of the anthropogenic perturbation on atmospheric CO₂ is included, as is the resulting invasion of anthropogenic CO₂ into the ocean; however, no injection is performed. Reference to this tracer allows us to determine, by difference, the total effect of ocean injection on atmospheric pCO₂ and oceanic DIC.

Tracer 3

Injection scenario (“Permanent sequestration”): Like Tracer 2 but in addition it includes the effect due to the reduction of atmospheric CO₂ caused by the diversion of fossil carbon into the deep ocean (sequestration) instead of the atmosphere. However, Tracer 3 ignores the impact of direct injection of CO₂ within the deep ocean on the oceanic DIC. Tracer 3 differs from Tracer 2 when atmospheric CO₂ is computed (i.e., in the Emission case **E1500**), but not when atmospheric CO₂ is prescribed (scenarios **C800**, **C1500**, and **C3000**). For the Emission case, Tracer 3 is used to compute atmospheric CO₂, air-sea CO₂ fluxes, and the distribution of oceanic DIC when CO₂ sequestration is made in an ideal permanent reservoir that allows no leakage back to the atmosphere.

Tracers 4-10

These seven tracers simulate, individually for each injection site, the effects of injected CO₂ on oceanic DIC. The impact of CO₂ sequestration on atmospheric pCO₂ is also considered, just as with Tracer 3. Tracers 4-10 are summed along with Tracer 3 to determine the loss of sequestered CO₂ to the atmosphere and to evaluate the direct effect of the injection on the DIC distribution. These seven tracers are necessary to determine the efficiency of each site in retaining injected CO₂.

3.3 Conservation equations

Each of the ten tracers is carried as dissolved inorganic carbon (DIC) and has the following conservation equation

$$(1) \quad d[\text{DIC}]/dt = L([\text{DIC}]) + \mathbf{J}_v + \mathbf{J} + \mathbf{J}_i$$

where

- **[DIC]** is the model’s concentration (moles/m³) of tracer representing total dissolved inorganic carbon;
- **L** is the 3-D transport operator, which represents effects due to advection, diffusion, and convection;
- **J_v** is the “virtual” source-sink term representing the changes in surface **[DIC]** due to evaporation and precipitation;
- **J** is the source-sink term due to air-sea exchange of CO₂; and
- **J_i** is the source term due to the injection of anthropogenic CO₂ within the deep ocean.

The source-sink terms **J_v** and **J** are added only as surface boundary conditions. That is, they are equal to zero in all subsurface layers. These two source-sink terms are equivalent to the corresponding fluxes (described in the Abiotic-HOWTO) divided by the surface layer thickness **dz₁**.

$$\mathbf{J}_v = \mathbf{F}_v/dz_1$$

$$\mathbf{J} = \mathbf{F}/dz_1$$

The virtual flux **F_v** is described in the Abiotic-HOWTO (Section 2.2).

For the last seven tracers (4-10), which are used to study the injection efficiency, each source term **J_i** is added only to the grid cell of the model located nearest the corresponding injection site. Conversely, **J_i** is set to zero for the first

three tracers. The J_i source is equivalent to the quantity of CO₂ injected at each site (Q) divided by the volume dV of the corresponding grid cell of the model.

$$J_i = Q/dV$$

3.4 Air-sea gas exchange fluxes (F)

For simulations of CO₂ sequestration, air-sea fluxes F for each tracer must be modeled according the OCMIP-2 guidelines described in the related Abiotic-HOWTO,

$$(2) \quad F = Kw (C_{sat} - C_{surf})$$

with

$$(3) \quad C_{sat} = \alpha C * pCO_{2atm} * P/Po$$

where

- Kw is the CO₂ gas transfer (piston) velocity [m/s] ;
- C_{surf} is the surface aqueous [CO₂] concentration [mol/m³], which is computed from the model's surface [DIC], T, S, and [Alk];
- αC is the C solubility for water-vapor saturated air [mol/(m³ * uatm)];
- pCO_{2atm} is the partial pressure of CO₂ in dry air at one atmosphere total pressure [in microatm], which is the same as the dry air mixing ratio of CO₂ multiplied by 10⁶ ;
- P is the total air pressure at sea level [atm], locally; and
- Po is 1 atm.

The three terms P , Kw , and αC are identical for all the ten tracers. They are described in the Abiotic-HOWTO. Conversely, C_{surf} depends on which of the 10 tracers is considered. Furthermore, pCO_{2atm} depends on which oceanic tracer is considered for the Emissions run (**E1500**) but not for the other simulations. The dependencies of both terms are described below.

3.5 Oceanic Component

The oceanic term C_{surf} is not carried as a tracer. Thus to determine gas exchange, it must be computed each timestep for each of the ten tracers.

C_{surf} is the surface [CO₂] concentration [mol/m³], which is computed from the model's surface [DIC], T, S, and [Alk] through the equations and constants found in the subroutine co2calc.f. We inject anthropogenic carbon as CO₂, which does not affect Alkalinity. Thus Alkalinity is identical for all ten tracers. It is determined as a normalized linear function of salinity:

$$(4) \quad [Alk] = Alkbar * S/Sbar$$

where [Alkbar] is 2310 microeq/kg and Sbar is the model's annual mean surface salinity, integrated globally (horizontally).

IMPORTANT: The carbonate chemistry subroutine `co2calc.f` was originally designed to require tracer input (*DIC*, *Alk*, *PO4*, and *SiO2*) on a per mass basis (umol/kg); however, for OCMIP-2 `co2calc.f` has been modified to pass tracer concentrations on a per volume basis (mol/m³), as carried in ocean models. To do so, we use the mean surface density of the ocean (1024.5 kg/m³) as a constant conversion factor; we do NOT use model-predicted densities. For example, OCMIP-2 modelers should use $SiO2 = 7.7e-03$ mol/m³ and $PO4 = 5.1e-04$ mol/m³ as input arguments; again both are constant for the abiotic simulation. The output arguments `co2star` (**Csurf**) and `dco2star` (**Csat - Csurf**) are also returned in mol/m³.

3.6 Three atmospheres

3.6.1 Atmosphere description

In the injection simulation, a set of three different atmospheric boxes, each which is global in nature, exchange CO₂ with the ocean:

1. The first atmospheric box **B(1)** is related to the control scenario. In equation (2), **Csurf** is calculated from Tracer 1.
2. The second atmospheric box **B(2)** is related to the future scenario. **Csurf** is computed from Tracer 2.
3. The third atmospheric box **B(3)** is related to the injection scenario. **Csurf** is computed from Tracers 3-10.

Each of the three atmospheres is defined as an homogeneous box **B(i)** (with $i=1,2,3$), with global coverage, having a uniform atmospheric concentration of CO₂ **pCO2atm(i)** (in uatm). To this concentration corresponds an atmospheric content of CO₂ (in GtC) **MCO2atm(i)**. The two variables are related by the following equation:

$$(5) \quad \mathbf{MCO2atm(i)} = \mathbf{Matm} * (\mathbf{WCO2/Watm}) * (\mathbf{pCO2atm(i)} * \mathbf{1.0e-06})$$

where

- **Matm** is the total mass of this atmosphere (**Matm = 5.119e+06 GT**);
- **Watm** is the molecular weight, i.e., mass of 1 mole (22.4 L at STP) of air (**Watm = 28.964 g**); and
- **WCO2** is the molecular weight, i.e., the mass of 1 mole of carbon (**WCO2 = 12.0 g**).

3.6.2 Conservation equation for the atmosphere

In each of the three atmospheric boxes **B(i)**, the atmospheric mass of CO₂ **MCO2atm(i)** depends on the following conservation equation:

$$(6) \quad \mathbf{d MCO2atm(i) / dt} = \mathbf{E(i)} + \mathbf{S(i)} - \mathbf{I(i)}$$

where

- **E(i)** is the rate at which anthropogenic CO₂ is added to atmospheric box **B(i)** due to fossil fuel combustion and deforestation (note: **E(1) = 0**);

- $\mathbf{S(i)}$ is the rate at which oceanic CO₂ is added to atmospheric box $\mathbf{B(i)}$, i.e., due to the globally integrated total sea-to-air flux of CO₂;
- $\mathbf{I(i)}$ is the rate at which atmospheric CO₂ is reduced due to deep ocean sequestration, i.e., it is the atmospheric sink (reduction in emissions rate) due to the CO₂ sequestration at all seven deep ocean injection sites (note: $\mathbf{I(1)} = \mathbf{0}$; $\mathbf{I(2)} = \mathbf{0}$; conversely $\mathbf{I(3)}$ is nonzero, but only during the 100-year injection period).

The total sea-to-air flux of CO₂ $\mathbf{S(i)}$ (for atmospheric boxes $i=1,3$) is a *global integral* related to the air-to-sea CO₂ flux $\mathbf{F(n)}$ at *each surface grid box* (for Tracers $n=1,10$)—see definition of \mathbf{F} in the sections *Conservation equations* and *Air-sea gas exchange fluxes*. The value of $\mathbf{S(i)}$ depends on the atmospheric box: $\mathbf{S(1)}$ is equivalent to the spatial integration over the whole surface ocean of the corresponding sea-to-air flux, i.e., $-\mathbf{F(1)}$; likewise, $\mathbf{S(2)}$ is the globally integrated sea-to-air flux $-\mathbf{F(2)}$; however, $\mathbf{S(3)}$ is more complicated. That is, for $\mathbf{S(3)}$, we must additionally account for the sea-to-air flux due to loss of injected CO₂. For atmospheric box $\mathbf{B(3)}$, the sum of both air-to-sea fluxes at each grid box is then

$$(7) \quad \mathbf{F'} = \mathbf{F(3)} + \text{sum}[\mathbf{F(n)} - \mathbf{F(3)}] \quad \mathbf{n} = [4-10]$$

where

- $\mathbf{F(3)}$ is the air-to-sea flux of CO₂ of Tracer 3;
- $\mathbf{F(n)}$ is the air-to-sea flux of Tracer n (For the injection tracers, n from 4 to 10); and
- **sum** represents the summation operator (Sigma); the sum is carried out over the indices from $n=4$ to $n=10$.

Thus, the global sea-to-air flux $\mathbf{S(3)}$ equals $-\mathbf{F'}$ integrated horizontally over the entire surface of the global ocean.

Regarding the injection rate, $\mathbf{I(1)}$ and $\mathbf{I(2)}$ are always zero. Conversely, $\mathbf{I(3)}$ is non-zero, but only during the 100-year injection period. The reason is that unlike $\mathbf{B(1)}$ and $\mathbf{B(2)}$, atmospheric box $\mathbf{B(3)}$ accounts for the effect of CO₂ injection. Furthermore, $\mathbf{I(3)}$ is not exactly equivalent to the total amount of CO₂ that is injected into the deep ocean. In fact, $\mathbf{I(3)}$ is a little less because it requires energy to separate, transport, and pump CO₂ to the deep ocean. Thus we remove less CO₂ from the atmosphere than is added to the ocean. We assume a 14% energy penalty, based on removing CO₂ from gas-fired plants or advanced technology coal-fired plants. Thus

$$(8) \quad \mathbf{I(3)} = \mathbf{N} * \mathbf{Q} / 1.14$$

where

- \mathbf{N} is the total number of injection sites (7); and
- \mathbf{Q} is the amount of CO₂ that is injected at each site (see section *Conservation equations*).

3.6.3 E and $d(\text{MCO}_2\text{atm})/dt$

To close equation (6), either \mathbf{E} or $d(\text{MCO}_2\text{atm})/dt$ must be specified *a priori*; the remaining term is calculated based on the computed air-sea CO₂ flux. The specified term determines the type of run.

Standard case - Required

For the "C" runs, we specify the time evolution of the atmospheric CO₂ $d(\text{MCO2atm})/dt$ and the injection scenario; then with modeled air-sea CO₂ exchange, each model computes the corresponding time evolution of anthropogenic carbon emissions E to each atmospheric box B(1)-B(3).

Emissions case - *Optional*

For the "E" run, we specify the history of the anthropogenic emissions E and the history of injected CO₂; then with modeled air-sea CO₂ exchange, each model computes its corresponding time evolution of atmospheric $p\text{CO2atm}$ for each atmospheric box B(1)-B(3).

When specified, $p\text{CO2atm}$ and E should be interpolated temporally to each time step of the model.

3.7 Gain

The primary emphasis of these runs is to determine the efficiency of the ocean to retain artificially injected CO₂. For each injection site m , we define a Gain $G(m)$ equal to the amount of CO₂ injected at that site which remains in the ocean. The more efficient the injection site m , the greater is its $G(m)$. Thus

$$(9) \quad dG(m) / dt = Q - R(m)$$

where

- Q is the rate at which CO₂ injected is at each site;
- $R(m)$ is the rate at which CO₂ injected at site m is lost from the ocean to the atmosphere.

$R(m)$ is the integral of $-(F(m+3)-F(3))$ with respect to the global surface area of the ocean. We use the $m+3$ index because the seven injection sites ($m=1,7$) correspond to the last seven of the ten ocean tracers ($n=4,10$).

3.8 Technical notes

The following routines are used in the IPSL ocean model to perform the injection simulations. There are provided as templates that modelers may adapt and use in their own models. All the routines are coded in FORTRAN 77.

- `initgos.f` initializes the variables used in the injection simulations. In particular, this routine reads the location of the injection sites, and the atmospheric $p\text{CO}_2$ or the fossil fuel emissions depending on the chosen case.
- `initnl.f` reads input parameters of the simulation from the namelist file (`gosac.nl`).
- `gosac.f` performs the injection in the ocean.
- `concent.f` and `emit.f` are the routines which determine the "allowable" fossil fuel emissions (Standard case) or atmospheric $p\text{CO}_2$ (Emissions case).
- `writgos.f` writes out some basic diagnostics.
- `gosac.h` is a COMMON file in which the main variables are defined.

- gosac.nl is a namelist file in which the characteristics of the simulation are defined: the first and last years of the injection (**gabsyr0**, **gabsyr1**), the type of the simulation (standard case or emissions case, **fname**), the amount of CO₂ injected at each site (**PUMPGOS**), the amount of CO₂ removed from the emissions (**FAGOS**), and the start date of the simulation (**zan**).

4 Description of the simulations

4.1 Initialization

- Standard case (**C1500**) and other "C" runs (**C3000**, **C800**)
 - Tracer 1
 - * Tracer - Initialize with 3-D **DIC** field from from year 2000.0 of the Abiotic **Control** Run;
 - * Cumulative flux (Tracer 1) - Initialize to 2-D cumulative flux field from year 2000.0 of the Abiotic **Control** Run;
 - * Atmospheric pCO₂ - Initialize atmospheric Box **B(1)** to 278 ppm, and hold it constant.
 - Tracers 2-10
 - * Tracers - initialize all nine 3-D tracer fields to the **DIC** field from the end of the Abiotic **Historical** Run (year=2000.0);
 - * Cumulative fluxes - initialize all nine 2-D arrays to to the cumulative flux of **DIC** at the end of the **Historical** run (year=2000.0);
 - * Atmospheric pCO₂ - atmospheric boxes **B(1)** and **B(2)** follow IPCC scenario S650.
- Emissions case (**E1500**)
 - Tracers 1-10
 - * Tracers - Initialize all ten 3-D tracer fields to the **DIC** field from the end of the Abiotic **Equilibrium** Run (equivalent to year 1765.0);
 - * Cumulative fluxes - Initialize all ten 2-D fields to zero;
 - * Atmospheric pCO₂ - Initialize atmospheric boxes **B(1)-B(3)** to 278 ppm.

4.2 Duration

4.2.1 Simulation

All "C" injection simulations (**C800**, **C1500**, **C3000**) begin at year=2000.0 and will be continued until year 2500.0. Thus, the duration of the C simulations is 500 years. Conversely, the "E" simulation (**E1500**) begins in year=1765.0 and ends in year=2500.0; thus its duration is 735 years.

4.2.2 Injection Period

In all simulations, artificial sequestration of anthropogenic CO₂ will occur for 100 years, beginning on the first timestep of the year 2000 (Jan. 1) and continuing until the last timestep of the year 2099 (Dec. 31). Each year during the 100-yr injection period, 0.1 Gt C is injected at each site, for a total of 0.7 Gt C/yr for the global ocean (seven sites). This amount corresponds to the emissions necessary to produce 350 GW by coal-fired plants or 700 GW by gas-fired plants. Meanwhile, 0.6 Gt C/yr should be removed from the fossil fuel emissions to the atmosphere. The difference between the injection and the removal from fossil fuel emissions is due to the 14% cost penalty (see section *Conservation equation for the atmosphere*)

4.3 Atmospheric boundary conditions

The atmospheric boundary conditions depend on the chosen scenario:

Standard scenario (C1500) and other C runs (C3000 and C800)

Atmospheric pCO₂ follows the IPCC S650 stabilization scenario. Atmospheric pCO₂ stabilizes to 650 uatm at year 2200.

The ASCII file pco2.s650.dat (Fig. 2) provides mid-year values of the atmospheric pCO₂ that must be prescribed in the IPCC S650 cases (**C800**, **C1500**, and **C3000**). See *concent.f* and related technical notes in *Model runs*. Concentrations from pco2.s650.dat are to be imposed only in the second and third atmospheric boxes **B(2)** and **B(3)**. Conversely, in the first atmospheric box **B(1)**, atmospheric pCO₂ must be held to its preindustrial value 278 uatm.

Emissions scenario (E1500)

We require a smooth emissions scenario to avoid needlessly complicating analysis. Thus we avoid using historical emissions and IPCC future scenarios. Instead we rely on total emissions deduced from an IPCC S650 "concentration" run in one model. The choice of the model is not critical for our objectives of model comparison. We have chosen to use deduced emissions from the S650 concentration run with the HILDA model because (1) HILDA's deduced emissions are already available from 1765 to 2500, (2) its emissions will produce smooth atmospheric CO₂ (and time derivatives) in the other OCMIP models, and (3) HILDA has been used as the IPCC reference model. For further information about the HILDA model, see http://www.climate.unibe.ch/~joos/model_description/model_description.html.

The ASCII file emissions.dat (Fig.3) provides values of the total emissions every half year that must be prescribed in the *Emissions scenario* (**E1500**). These values should be interpolated at each time step of the model. See *emit.f* and related technical notes in *Model runs*. This emission scenario is prescribed in the second and third atmospheric boxes **B(2)** and **B(3)**. Conversely, in the first atmospheric box **B(1)**, there are no anthropogenic emissions.

5 Output type and frequency

1. [0-D] spatial fields ([1-D] in time):

- Frequency: annual averages every year (from 2000 through 2499)

- Type:
 - Annual average **pCO_{2atm}** of each atmospheric box [uatm]
 - Annual average Gain **G** for each injection site [mol/m²]
 - Globally and annually averaged air-to-sea fluxes **F** for Tracers 1-10 (mol/(m² * s))
 - Globally and annually averaged virtual fluxes **F_v** for Tracers 1-10 (mol/(m² * s))
 - Globally and annually averaged *whole-ocean* concentrations for Tracers 1-10 [mol/m³]
 - Globally and annually averaged *surface* concentrations for Tracers 1-10 [mol/m³]
 - Globally and annually averaged **pCO_{2surf}** (uatm) and **dpCO₂** (uatm) for Tracers 1-10
 - Globally averaged cumulative air-to-sea fluxes (end-of-year) for **F** (mol/m²) and virtual fluxes **F_v** (mol/m²) for Tracers 1-10;
 - Global anthropogenic emissions of carbon **E** for each of the 3 atmospheric boxes [GT C/yr]

2. [2-D] and [3-D] spatial fields:

- Frequency: annual averages for years 2000, 2010, 2020, 2040, 2060, 2080, 2099, 2120, 2140, 2160, 2180, 2200, 2300, 2400, 2499.
- Type: same as for Abiotic Future Run (see Abiotic HOWTO)

Convention for the direction of the air-sea fluxes: positive from the atmosphere to the ocean, except for **S**, which must be given in the opposite sense.

6 Output Format

Each modeling group must provide their output in the standard OCMIP-2 format which is the same as that chosen for GOSAC. Model output that does not follow these formatting conventions cannot be included for analysis during GOSAC. Model groups must use the standard routines that we have developed specifically for writing output in standard form for GOSAC.

6.1 Spatial information

If this is the first OCMIP-2 simulation you have made, you will need to recuperate the routine `write_nc_MaskAreaBathy.f` to write out characteristics of your model grid, mask, and bathymetry using the standard OCMIP-2 format. Use of this routine is detailed in the CFC HOWTO (section 5.1).

Otherwise if you have submitted OCMIP-2 model output previously, you will only need to resubmit the output file produced by `write_nc_MaskAreaBathy.f` under two conditions:

1. either your model's grid, mask, or bathymetry have changed; or
2. you have been notified by the OCMIP-2 analysis center at IPSL that your output file from this subroutine did not pass the routine integrity tests.

6.2 Output routines

Each modeling group must use the routines listed in the following table to store results in standard OCMIP-2 format for the [2-D] and [3-D] spatial fields.

Input to these routines consists of your model's output and characteristics. The routines (`write_nc_Inject_year_3D.f` `write_nc_Inject_year_2D.f`) must be called for the appropriate *output years* of the runs (see previous section *Output type and frequency*); conversely the routine `write_nc_Inject_year_0D.f` is called only once, after building a 1-D time series of global mean information. The fourth and final routine `write_nc_Inject_TS_year.f` should be called only once for offline models; for online models, it should also be called a second time, in the year 2499.

| Routine | Input | Units | Co |
|--|--|-------------------------|----|
| <code>write_nc_Inject_year_3D.f</code> | 1-10) Conc. of Tracer[1-10] | mol/m ³ | |
| <code>write_nc_Inject_year_2D.f</code> | 1-10) Surf. ocean pCO ₂ (Tracer[1-10]) | uatm | |
| | 11-20) Delta dpCO ₂ (Tracer[1-10]) | uatm | |
| | 21-30) Gas Exch. Flux of Tracer[1-10] | mol/(m ² *s) | |
| | 31-40) Virtual Flux of Tracer[1-10] | mol/(m ² *s) | |
| | 41-50) Cum. Gas Flux of Tracer[1-10] | mol/m ² | |
| | 51-60) Cum. virtual Flux of Tracer[1-10] | mol/m ² | |
| <code>write_nc_Inject_year_0D.f</code> | 1-3) Glob_mean (Gm) pCO ₂ atm for B(1)-B(3) | uatm | |
| | 4-10) Storage gain G of site[1-7] | mol/(m ²) | |
| | 11-20) Gm Gas Ex. Flux of Tracer[1-10] | mol/(m ² *s) | |
| | 21-30) Gm Virtual Flux of Tracer[1-10] | mol/(m ² *s) | |
| | 31-40) Gm Tracer | mol/m ³ | |
| | 41-50) Gm Surface Tracer[1-10] | mol/m ³ | |
| | 51-60) Gm pCO ₂ surf | uatm | |
| | 61-70) Gm Delta pCO ₂ (dpCO ₂) | uatm | |
| | 71-80) Gm Cum. Gas Flux of DIC | mol/m ² | |
| | 81-90) Gm Cum. Virt. Flux of DIC | mol/m ² | |
| | 91-93) Fossil emissions E for B(1)-B(3) | GT C/yr | |

6.3 Downloading the output routines

The output routines can be transferred to your machine by clicking on the links below, while holding down the Shift key.

- `write_nc_MaskAreaBathy.f` (This routine is the same as linked to the CFC HOWTO; thus, there is no need to recuperate it if you have already contributed OCMIP-2 CFC results).

- write_nc_Inject_year_3D.f
- write_nc_Inject_year_2D.f
- write_nc_Inject_year_0D.f
- write_nc_Inject_TS_year.f

You will also need to transfer the subroutine `handle_errors.f` to properly deal with errors while you are writing your netCDF files.

6.4 Compiling the output routines

Here is an example of how you would compile one of the output routines:

```
f77 -c -O -L/usr/local/lib -lnetcdf -I/usr/local/include \
    write_nc_Inject_year_3D.f
```

Because we have made these routines F77 compatible, you may need a function `len_trim.f` (from F90), which we also provide and which returns the length of a character string (after neglecting trailing blanks).

6.5 Using the output routines

The Injection-run output routines store your model results following the naming and output conventions (netCDF, GDT version 1.2) chosen for OCMIP-2. The output filename is constructed automatically within each routine from three of the arguments: the tracer name, the year, and the *standard model code*

`<http://www.ipsl.jussieu.fr/OCMIP/phase2/#modgroups>` used during OCMIP-2 to identify your group.

For compatibility with the Abiotic simulations, we separately store 3-D, 2-D, and 0-D data. For your 3-D model output for the Injection run, use:

```
    call write_nc_Inject_year_3D("IPSL", "NL46_SI", "C1500",
    & imt, jmt, kmt, nt,
    & 2010, 60*60*24*365, 1200,
    & TRAN)
```

By line, the arguments include

1. the OCMIP-2 *model code*, your own *model version* indicator, AND the *simulation indicator* (C1500, C3000, C800, or E1500).
2. three spatial dimensions and one temporal dimension *nt* (here, *nt*=1 for annual means);
3. the year, the number of seconds per year (in your model), and the number of timesteps per year;

4. the annual mean concentrations of 3-D Tracers 1-10 [mol/m³].

For your 2-D output, use

```

      call write_nc_Inject_year_2D( "IPSL", "NL46_SI", "E1500",
&  imt, jmt, nt,
&  2020, 60*60*24*365, 1200,
&  MpCO2surf, MdpCO2surf,
&  MF, MFv,
&  CF_F, CF_Fv)

```

For 2-D output, we no longer need the dimension *kmt*, formerly in line 2. The 2-D Injection output also includes

- line 4: the annual mean surface pCO₂ and Delta pCO₂ for Tracer[1-10] (uatm);
- line 5: the annual mean 2-D air-to-sea and virtual fluxes of Tracer[1-10] (mol/m²/s);
- line 6: the end-of-year 2-D cumulative air-to-sea fluxes and cumulative virtual fluxes (mol/m²);

Cumulative fluxes (line 6 above) must be initialized as outlined in Section 4.1, and integrated with respect to time (i.e., each time step).

When do I call the above 2-D and 3-D Injection output routines? They should be called, with **nt=1**, at the end of each of the following years: 2010, 2020, 2040, 2060, 2080, 2099, 2120, 2140, 2160, 2180, 2200, 2300, 2400, 2499.

For 0-D (1-D with time) Injection output, use

```

      call write_nc_Inject_year_0D( "IPSL", "NL46_SI", "C3000",
&  nrec, times,
&  Gm_pCO2atm,
&  G,
&  Gm_F,
&  Gm_Fv,
&  Gm_DIC,
&  Gm_DICs,
&  Gm_pCO2surf, Gm_dpCO2,
&  Gm_CF_F,
&  Gm_CF_Fv,
&  E)

```

By line, the arguments include

1. the OCMIP-2 *model code*, your own *model version* indicator, AND the *simulation indicator*;
2. the number of records saved and the array of the times (in decimal years) at which they were saved;

3. the history of the global mean atmospheric **pCO2atm** for 3 atmospheric boxes B(1), B(2), and B(3) (in uatm). The **pCO2atm(i)** (*i=1,2,3*) is specified *a priori* for the **C** runs, but calculated for Run **E1500** via equation (6)—see subsection *E and d(MCO2atm)/ dt*;
4. the history of the Gain **G** for each of the seven injection sites (mol/m²);
5. the history of the global sea-to-air flux **F** for Tracers 1-10 (mol/(m²*s));
6. the history of the global mean virtual flux **Fv** for Tracers 1-10 (mol/m²*s, see Abiotic HOWTO);
7. the history of the global mean concentrations of Tracers 1-10 (mol/m³);
8. ;
9. the history of the global mean surface concentration of Tracers 1-10 (mol/m³);
10. the history of global mean surface ocean pCO2 (**pCO2surf**, in uatm), and the global mean sea-air pCO2 difference (**dpCO2**, in uatm) for Tracers 1-10;
11. the history of the global mean cumulative fluxes **F** for Tracers 1-10 (in mol/m², integrated since 1765.0) at the end of each year, with each year indicated by its mid-year time given in line 2; and
12. the history of the global mean fossil fuel emissions **E** (in GtC/yr) for each atmospheric box B(1), B(2), and B(3). **E(i)** (*i=1,2,3*) is specified *a priori* for Run **E1500**, but it must be calculated for the **C** runs via equation (6)—see subsection *E and d(MCO2atm)/ dt*.

When do I call the above 0-D output routine? It should be called only once, after constructing 1-D (in time) arrays from all of your model output. The time storage frequency is regular: this routine should be called, using annuals means, for every year during the last 500 years of the run (i.e., all years 2000-2499, inclusive). Thus modelers must use *nrec* = 500, and fill the 1-D temporal array *times* with the appropriate values (i.e., 2000.5, 2001.5, 2002.5 ..., 2498.5, 2499.5).

All arguments of the Abiotic routines are input; none are output. With the arguments as listed in the nine routines above, the corresponding output netCDF files are

- "IPSL-Inject_C1500_2010_3D.nc",
- "IPSL-Inject_E1500_2020_2D.nc",
- "IPSL-Inject_C3000_global.nc";

These files along with all others produced by the Abiotic routines should be transferred to IPSL by ftp. Filenames should NOT be changed. Subsequently, at IPSL, files will be (1) tested for consistency, (2) included in the OCMIP-2 data base, and (3) processed for base analysis.

6.6 Need more details?

See <<http://www.ipsl.jussieu.fr/OCMIP/tech>>. for additional information about the format netCDF and other conventions (COARDS, GDT) chosen for storing OCMIP-2 model output.

If you have other questions, please contact aumont@lsce.saclay.cea.fr, or orr@cea.fr

7 Transfer of output

The files including 0-D, 2-D, and 3-D fields should first be gzipped:

```
gzip *.nc
```

If `gzip` is not available on your machine, the alternative is to use `compress`. After compression, you should send your files to LSCE for processing and analysis. Your model output could be quite large depending upon model resolution. Disk space is not a problem—we have plenty to accommodate output from all OCMIP models. However, you should contact us if the ftp transfer rate is inadequate. In that case, you'll need to write your output to tape (DDS, DDS2, Exabyte, or DLT) and mail it to

```
James ORR  
LSCE, CEA Saclay  
Unite mixte de recherche CEA-CNRS  
Bat. 709, L'Orme des Merisiers  
F-91191 Gif-sur-Yvette CEDEX  
FRANCE
```

Here are the commands to transfer your output by ftp:

```
ftp: ftp.cea.fr  
user: anonymous  
passwd: your full email  
cd incoming2/y2k01/OCMIP  
mkdir <your group name>  
mkdir <your group name>/Inject  
cd <your group name>/Inject  
binary  
prompt  
mput <your group name>*.nc*
```

Then e-mail us (aumont@lsce.saclay.cea.fr and orr@cea.fr) that your transfer is complete.

The ftp archive is erased automatically every 8 days, so be sure to contact us as soon as you have completed transfer, and save your output files at least until we have notified you that they have been transferred to the OCMIP-2 model output archive.

8 References

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9 Contacts

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10 Same document, another format?

This document is available in other formats:

- HTML (<HOWTO-Inject.html>)
- Postscript (<HOWTO-Inject.ps>)
- ASCII (<HOWTO-Inject.txt>)
- LaTeX (<HOWTO-Inject.tex>)
- DVI (<HOWTO-Inject.dvi>)

Helium HOWTO

J.-Cl. Dutay, M.-F. Weirig, P. Jean-Baptiste, E. Maier-Reimer, and J. Orr Revision: 1.8, Date: 2001/04/27 11:48:02

This document provides step-by-step guidelines to make a steady-state simulation for mantle Helium-3 and Helium-4 according to the standard OCMIP-2 protocols. This simulation has two boundary conditions: (1) a loss term due to the sea-to-air flux of mantle helium, and (2) a source term due to emission of rich $^3\text{He}/^4\text{He}$ water along ocean ridges on the seafloor. Globally integrated, the source term amounts to 1000 moles of ^3He per year; regionally, sources are partitioned as a function of ridge position, length, and spreading rate).

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1 Introduction

As opposed to natural C-14/C-12 which enters the ocean through the air-sea interface, waters rich in primordial helium (high $^3\text{He}/^4\text{He}$ ratio) derive from mid-ocean ridges at the ocean floor. This unique boundary condition means that mantle helium can provide independent information concerning patterns of deep-ocean circulation. OCMIP modelers have already made simulations for natural C-14/C-12. Here we describe protocols to make OCMIP simulations for mantle helium.

Primordial He, which also invades the deep sea from the earth's interior via mid-ocean ridges, has a distinctly different $^3\text{He}/^4\text{He}$ ratio than does atmospheric helium. Vent waters, along with their $^3\text{He}/^4\text{He}$ signature, enter the ocean at several hundred degrees centigrade and typically rise a few hundred meters in the water column, before coming to equilibrium and being transported along surfaces of constant density (isopycnals). When it was found that oceanographic circulation patterns deduced from $^3\text{He}/^4\text{He}$ data (Stommel, 1982) contradicted the simple, yet classic model of deep-ocean circulation (Stommel and Arons, 1960), it became obvious to many that the unique signature of $^3\text{He}/^4\text{He}$ could help shed light on the mysteries of deep-ocean circulation. Since then, many $^3\text{He}/^4\text{He}$ samples have been collected throughout the world ocean, largely during the WOCE sampling campaign. One ocean modeling study has been published that has focused on simulating $^3\text{He}/^4\text{He}$ in the LSG model (Farley et al., 1995). They assumed that the boundary condition for $^3\text{He}/^4\text{He}$ is proportional to the spreading rate of the mid-ocean ridges. Other groups have also begun making preliminary simulations for $^3\text{He}/^4\text{He}$.

For this comparison, all 3-D models will make one standard $^3\text{He}/^4\text{He}$ simulation, to near steady state. Following Farley et al. (1995), primordial ^3He and ^4He will be added to the ocean at mid-ocean ridges along the sea floor as a function of ridge positions and spreading rates. ^3He and ^4He will be carried as individual tracers. At the air-sea interface, all ocean models will exchange ^3He and ^4He with the atmosphere using sea-air flux boundary conditions that are analogous to those developed for CO₂ during the first phase of OCMIP. Intercomparison of model results will focus on the $^3\text{He}/^4\text{He}$ distribution in the sea and to a lesser extent on helium fluxes from the ocean to atmosphere. Such comparison should provide unique insight, into the performance of each model's deep-ocean circulation, particularly in regard to evaluating the performance of OCMIP purposeful, deep-ocean CO₂ injection simulations.

2 Recuperation of OCMIP-2 files by ftp:

To comply with OCMIP-2 guidelines, all modelers must make simulations according to OCMIP-2 standard boundary conditions. To do so, one must first recuperate the following files via this Web page (you can save a file to disk by clicking a link while holding down the Shift key).

- *rgasx_ocmip2.f*
- *gasx_ocmip2.nc*
- *vgasx_ocmip2.jnl*
- *sc_helium.f*
- *sol_helium.f*
- *src_helium.f*
- *src_helium.nc*

Use of these files is described below.

3 Model runs

3.1 Gas exchange flux

For simulations of ^3He and ^4He , we will directly model the finite air-sea flux \mathbf{F} . In other words, surface helium concentrations will NOT be set equal to temperature-derived equilibrium values determined from the solubility. Instead, modelers must use the formulation for the standard OCMIP-2 air-to-sea flux,

$$(1a) \quad \mathbf{F} = \mathbf{Kw} (\mathbf{C}_{\text{sat}} - \mathbf{C}_{\text{surf}})$$

with

$$(1b) \quad \mathbf{C}_{\text{sat}} = \alpha * \mathbf{pHe}$$

where

- \mathbf{Kw} is the gas transfer (piston) velocity [m/s] ;
- \mathbf{C}_{surf} is the modeled surface ocean ^3He (or ^4He) concentration [mol m^{-3}] ;
- α is the ^3He (or ^4He) solubility for water-vapor saturated air (in $\text{mol m}^3 \text{atm}^{-1}$). For ^4He ,

$$\alpha(^4\text{He}) = \exp[\mathbf{A1} + \mathbf{A2} * 100/\mathbf{T} + \mathbf{A3} * \ln(\mathbf{T}/100) + \mathbf{S} * (\mathbf{B1} + \mathbf{B2} * \mathbf{T}/100 + \mathbf{B3} * (\mathbf{T}/100)^2)] / 22400,$$
 where \mathbf{T} is the temperature (in Degrees Kelvin), \mathbf{S} is the salinity (on the psu scale), and where the coefficients $\mathbf{A1}$, $\mathbf{A2}$, $\mathbf{A3}$, $\mathbf{B1}$, $\mathbf{B2}$, and $\mathbf{B3}$ are all taken from Wanninkhof (1992, Table A2).
 - To check that you have correctly implemented this equation, the ^4He solubility should be $0.3299 \text{ mol}/(\text{m}^3 * \text{atm}_{\text{He4}})$ at a temperature of 10C (283.15K) and a salinity of 35. Thus for this same \mathbf{T} and \mathbf{S} , \mathbf{C}_{sat} would be $1.7288 * 10^{-6} \text{ mol}/\text{m}^3$, (from equation 1(b) and the partial pressure of ^4He in the atmosphere, given below).
 - The ^3He solubility ($\alpha[^3\text{He}]$) is equal to ^4He solubility multiplied by the isotope fractionation factor = 0.984 (Weiss, 1970; Top et al., 1987; Fuchs et al., 1987)
- \mathbf{pHe} is the partial pressure of ^3He (or ^4He) in dry air at one atmosphere total pressure [in atm] Specifically, $\mathbf{p}^4\text{He} = 5.24 * 10^{-6}$ and $\mathbf{p}^3\text{He} = \mathbf{p}^4\text{He} * 1.38 * 10^{-6}$.

All right hand terms, in equations (1a) and (1b) are different for ^3He and ^4He .

3.2 The Piston Velocity \mathbf{Kw}

For simulations of ^3He and ^4He , modelers must use the standard OCMIP-2 formulation for the piston velocity \mathbf{Kw} . The monthly climatology of \mathbf{Kw} , to be interpolated linearly in time by each modeling group, is computed with the following equation adapted from Wanninkhof (1992, eq. 3):

$$(2) \quad \mathbf{Kw} = (1 - \mathbf{Fice}) [\mathbf{Xconv} * \mathbf{a} * (\mathbf{u2} + \mathbf{v})] (\mathbf{Sc}/660)^{** -1/2}$$

where

- \mathbf{Fice} is the fraction of the sea surface covered with ice, which varies from 0.0 to 1.0, and is given as monthly averages from the Walsh (1978) and Zwally et al. (1983) climatology (OCMIP-2 modelers must reset \mathbf{Fice} values less than 0.2 to zero, after interpolation to their model grid)

- **u2** is the instantaneous SSMI wind speed, averaged for each month, then squared, and subsequently averaged over the same month of all years to give the monthly climatology. (see the OCMIP-1 *README.satdat* for further details);
- **v** is the variance of the instantaneous SSMI wind speed computed over one month temporal resolution and 2.5 degree spatial resolution, and subsequently averaged over the same month of all years to give the monthly climatology. Again, see the OCMIP-1 *README.satdat* for further details.
- **a** is the coefficient of 0.337, consistent with a piston velocity in cm/hr. We adjusted the coefficient **a** for OCMIP-2, in order to obtain Broecker et al.'s (1986) radiocarbon-calibrated, global CO₂ gas exchange of 0.061 mol CO₂ / (m² * yr * uatm), when using the satellite SSMI wind information (**u2** + **v**) from Boutin and Etcheto (pers. comm.). Our computed value for **a** is similar to that determined by Wanninkhof (**a** = 0.31), who used a different wind speed data set and assumptions about wind speed variance; we use the observed variance.
- **Xconv** = 1/3.6e+05, is a constant factor to convert the piston velocity from [cm/hr] to [m/s]. This conversion factor is already included in the forcing field **xKw**, provided below.
- **Sc** is the Schmidt number which is to be computed using modeled SST, using the formulation for ⁴He given by Wanninkhof (1992, Table A1), derived from Jähne (1987a). For ³He, we reduce the Schmidt number (relative to ⁴He) by 15% ($Sc^3He = Sc^4He / 1.15$) based on the ratio of the reduced masses, which is consistent with helium isotopic fractionation measurements from Jähne (1987b). The function *sc_helium.f* computes the Sc's (unit-less) for both ³He and ⁴He.

Practically speaking, to use equation (2), each group will interpolate the OCMIP-2 standard information to their own model grid. The standard information is provided by IPSL/LSCCE as a monthly climatology on the 1 x 1 degree grid of Levitus (1982) in netCDF format (in file *gasx_ocmip2.nc*). Gridded variables in that file include

- the variable **Fice**,
- the second term, [**Xconv** * **a** * (**u2** + **v**)], denoted as **xKw** [m/s]
- the mask **Tmask** (1 if ocean; 0 if land),
- the total atmospheric pressure at sea level **P** [atm]
- the longitude **Lon** at the center of each 1 x 1 degree grid box,
- the latitude **Lat** at the center of each 1 x 1 degree grid box.

For the variables **Fice** and **xKw**, continents on the 1 x 1 degree standard grid have been flooded with adjacent ocean values. Such an approach avoids discontinuities at land-sea boundaries during interpolation. See the Fortran program *rgasx_ocmip2.f* for an example of how to read the 2-D gas exchange fields, written in netCDF format. After compilation, to link and use *rgasx_ocmip2.f*, one must have already installed netCDF.

```
<http://www.unidata.ucar.edu/packages/netcdf/>
```

The file *gasx_ocmip2.nc* may also be inspected with software that uses netCDF format, such as *ncdump* or *Ferret*. *Ferret* is used for some of the analysis during OCMIP-2. We encourage OCMIP members to become familiar with *Ferret*.

```
<http://ferret.wrc.noaa.gov/Ferret/>
```

After installation, one can visualize maps of the standard information in *gasx_ocmip2.nc*, by using the *Ferret* script *vgasx_ocmip2.jnl*.

After launching Ferret, simply issue the following command (at Ferret's "yes?" prompt)

```
yes? go vgasx_ocmip2.jnl
```

3.3 Oceanic and Atmospheric Components

Apart from K_w , there are two other terms in equation (1a). The ocean component C_{surf} [in mol/m^3] is computed by the model each timestep; the atmospheric component C_{sat} is constant specified *a priori* via the three remaining terms:

1. α : The solubility α , different for ^3He and ^4He , will be computed using modeled SST and SSS, both of which vary in time at each grid point. For ^4He we use the solubility formulation provided by Wanninkhof (1992, Table A2), a temperature-dependant polynomial for He solubility, which was derived from measurements by Weiss (1971). The function *sol_hel.f* determines α for both ^3He and ^4He , but changes the units to $[\text{mol}/(\text{m}^3 * \text{atm})]$ so that model helium concentrations can then be carried in SI units $[\text{mol}/\text{m}^3]$.
2. **pHe**: For these simulations we set the partial pressure of atmospheric ^4He ($p^4\text{He}$) to $5.24 * 10^{-6}$ atm, constant in time and space; similarly, $p^3\text{He} = p^4\text{He} * 1.38 * 10^{-6} = 7.23 * 10^{-12}$ atm. ?

3.4 Helium mantle source

^3He is injected at the seafloor along ocean ridges at a global rate of around 1000 mol/yr (Clarke et al., 1969; Craig et al., 1975; Jean-Baptiste, 1992; Farley et al., 1995). We hold the $^3\text{He}/^4\text{He}$ ratio of injected mantle helium to a constant value of $8 * 1.38 * 10^{-6}$ (Farley et al., 1995). Thus the globally integrated source for ^4He is $1000/8/1.38E-6$ (i.e., $90.6 * 10^6$) mol/yr. The mass of mantle helium that is injected is partitioned geographically as a function of ridge positions, lengths, and spreading rates (Farley et al., 1995).

For consistent simulations, we need to position mantle helium sources as a function of the REAL ocean's ridge positions, spreading rates, and depths. To facilitate making these simulations in any model, we have provided the mass/year of injection helium partitioned, as a SCALAR field, on the same 1 x 1 degree grid as used for the OCMIP-2 boundary condition for air-sea gas exchange. To derive that 1 x 1 degree field, we calculated length of the ridges falling within each grid box and multiplied each length by its corresponding spreading rate (i.e., see program *src_helium.f*). The injection points, which define the ridge lengths, and corresponding rates are those used by Farley et al. (1995) (Maier-Reimer, personal communication, 1998). However, that data set does not include known sites in the Western Pacific (**Philippe: references?**), which we have also included in this study. The complete list of sites and spreading rates is given in *sitespread.dat*.

To account for the mantle source, each modeling group will need to interpolate our standard 1 x 1 degree grid of helium sources and corresponding ridge depths to their model. Then, groups will need to adjust the vertical position of helium injection point, where necessary

- If the model bathymetry is deeper than the injection point, then NO Vertical adjustment
- If the model bathymetry is equal to or shallower than the injection point, then inject mantle helium into the deepest ocean box in the same water column.

Technical notes:

1. The 1 x 1 degree grid of sources and sinks is provided as a netCDF file *src_helium.nc*.

2. Variables in that file are
 - *zHe*: the ridge depth already adjusted upward by 300 m (see following note)
 - *rateHe3flux*: the rate of injection of ^3He (mol/yr)
 - *rateHe4flux*: the rate of injection of ^4He (mol/yr)
3. Note that our "ridge depths" are already 300 m shallower than those actually observed, thereby accounting for the typical rise of the warm mantle source waters from the ridge up into the water column. Therefore, modelers should avoid additional coding to account for this effect.
4. Interpolation: When interpolating the mantle source (scalar) information from the 1 x 1 degree grid to your grid, please be sure that you conserve mass. Globally, the rate of injection of ^3He must be 1000 mol/year; that for ^4He should be around 90.6×10^6 mol/year. Groups should scale all local injection rates by a constant to exactly obtain those globally integrated rates.

4 Initialization and duration of simulations

- *Initialization*: Models are to be initialized so that initial concentrations for each grid box are equal to the solubilities of ^3He and ^4He that are in equilibrium with atmospheric partial pressures of ^3He and ^4He , at the $T=10^\circ\text{C}$ and $S=34\%$. Thus initial model concentrations should be
 - **He-4 = $1.73 \times 10^{-6} \text{ mol m}^{-3}$**
 - **He-3 = $2.35 \times 10^{-12} \text{ mol m}^{-3}$**
- *Duration*: The mantle helium simulation should be continued until it reaches at least the following near steady-state criterion: the yearly drift of the globally integrated tracer inventories should be less than 4 mol/year for ^3He , and 1×10^6 mol/year for ^4He . Of course, this drift should be the same as the source (mantle flux at ridges) minus sink (loss due to the sea-to-air flux) terms. If you find it very difficult to reach this steady-state criterion, you should still submit output but please notify us: dutay@cea.fr AND orr@cea.fr. In this case, please send corresponding information about the drift in your model.

5 Output type and frequency

1. Frequency: monthly averages the final year of the simulation
2. Type:
 - 3-D Fields: ^3He and ^4He tracer distributions [mol/m^3]
 - 2-D Fields: Monthly mean air-to-sea flux of ^3He and ^4He [$\text{mol}/(\text{m}^2 \cdot \text{s})$]

6 Output Format

Each modeling group must provide their output in the standard OCMIP-2 format. Model output that does not follow these formatting conventions cannot be included for analysis during OCMIP-2. Model groups must use the standard routines that we have developed specifically for writing output in standard form for OCMIP-2.

If this is the first OCMIP-2 simulation you have made, you will need to recuperate the routine `write_nc_MaskAreaBathy.f` to write out characteristics of your model grid, mask, and bathymetry using the standard OCMIP-2 format. Use of this routine is detailed in the CFC HOWTO (section 5.1).

Otherwise if you have submitted OCMIP-2 model output previously, you will only need to resubmit the output file produced by `write_nc_MaskAreaBathy.f` under two conditions:

1. If your model's grid, mask, or bathymetry have changed; or
2. If you have been notified by the OCMIP-2 analysis center at IPSL that your output file from this subroutine did not pass the routine integrity tests.

6.1 Output routines

Each modeling group must use the output routine listed in the table below to store results in standard OCMIP-2 format for the 5 (Helium Output).

Input to this routine is simply your model's output for the concentrations and air-sea fluxes both tracers (^3He and ^4He). All groups will need to call the 1st output routine `write_nc_Helium.f`, but ONLY once, at the end of 4 (model spin-up). You may be able to skip calling the 2nd routine `write_nc_Helium_TS.f` (see 2nd footnote).

| Routine | Input | Units | Comments |
|-----------------------------------|-----------------------|-------------------------|----------|
| <code>write_nc_Helium.f</code> | Conc. of He-3 | mol/m ³ | (*) |
| | Conc. of He-4 | mol/m ³ | (*) |
| | Mean Flux of He-3 | mol/(m ² *s) | (*) |
| | Mean Flux of He-4 | mol/(m ² *s) | (*) |
| <code>write_nc_Helium_TS.f</code> | Potential temperature | degrees C | (*) (+) |
| | Salinity | psu | |

(*) This is an equilibrium run: All 2- and 3-D fields should be averaged for each month over the last year of the simulation.

(+) You only need to submit this output file if the year from the corresponding "dynamic" output differs from that from your Abiotic or Biotic runs. If the year is identical (same T and S fields), simply copy the Abiotic or Biotic output file, and rename it (e.g., changing "MODEL_Abiotic_TS_1765.nc" -> "MODEL_Helium_TS.nc").

6.2 Downloading the output routines

The output routines `write_nc_Helium.f` and `write_nc_Helium_TS.f` can be transferred to your machine by clicking on their link while holding down the Shift key.

You will also need to transfer the subroutine *handle_errors.f* to properly deal with errors while you are writing your netCDF files.

6.3 Compiling the output routines

Here is an example of how you would compile the output routine with the necessary link to the netCDF library:

```
f77 -c -O -L/usr/local/lib -lnetcdf -I/usr/local/include \
    write_nc_Helium.f
```

Because we have made this routine F77 compatible, you may need a function *len_trim.f* (from Fortran 90), which we also provide and which returns the length of a character string (after neglecting trailing blanks).

6.4 Using the output routine

The output routine writes out your model results following the naming and output conventions (netCDF, COARDS, GDT) chosen for OCMIP-2. The output filename is constructed automatically by the output routine from three of the arguments: the tracer name and the *standard model code* <<http://www.ipsl.jussieu.fr/OCMIP/phase2/#modgroups>> used during OCMIP-2 to identify your group.

For example, after compiling and linking the OCMIP-2 output routine, we add the following code to the IPSL routines to store output in standard OCMIP-2 form

```
    call write_nc_Helium("IPSL", "NGL46_SI",
&   imt, jmt, kmt,
&   60*60*24*365, 1200,
&   Mhe3, Mhe4,
&   MFhe3, MFhe4)
```

By line, the arguments include

1. the OCMIP-2 *model code* AND your own *model version* indicator (in GDT 1.2 terminology, these 2 variables refer to the *institution* and *production*, respectively);
2. dimensions;
3. the number of seconds per year (in your model), and the number of timesteps per year;
4. the 12 monthly means for the 3-D tracer arrays for ³He and ⁴He (both in mol/m³); and
5. the 12 monthly means for the 2-D air-sea flux for ³He and ⁴He (both in mol/(m²*s)).

When do I call the above Equilibrium output routine? It should be called only once, at the end of the simulation after building monthly arrays (12 members) for both of the 2-D and 3-D spatial fields given as arguments.

6.5 Name of Output file

All arguments of the Helium output routine are input; none are output. Using the arguments given above, the model output file (netCDF) would be ("IPSL_Helium.nc"), which contains the information for analyzing the IPSL results for 1985. This file should be 7 (transferred to IPSL). The filename should NOT be changed. At IPSL, files will subsequently be (1) tested for consistency, (2) included in the OCMIP-2 data base, and (3) processed for base analysis.

6.6 Need more details?

See <http://www.ipsl.jussieu.fr/OCMIP/tech>. for additional information about the format netCDF and other conventions (COARDS, GDT) chosen for storing OCMIP-2 model output.

If you have other questions, please contact orr@cea.fr or Patrick.Brockmann@ipsl.jussieu.fr.

7 Transfer of output

```
ftp: ftp.cea.fr
user: anonymous
passwd: your full email
cd incoming2/y2k01/OCMIP
mkdir <your group name>
mkdir <your group name>/Helium
cd <your group name>/Helium
binary
prompt
mput <your group name>*nc*
```

8 References

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9 Contacts

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This document is available in other formats:

- HTML (<HOWTO-Helium.html>)
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